ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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FLUVIAL ARCHITECTURE OF JURASSIC
URANIUM-BEARING SANDSTONES,
COLORADO PLATEAU, WESTERN UNITED STATES

N. TYLER and F.G. ETHRIDGE

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UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

Vanadium- and uranium-bearing sandstones of the Salt Wash Member of the Morrison Formation in southwestern Colorado were deposited in a fluvial system that contained a range of channel-types. Broad and deep, low-sinuosity streams, which were the principal drainage-elements, deposited dip-elongated depositional units. Amalgamation of individual sand-bodies resulted in the multilateral sand-belt geometry of the lower and upper intervals of the Salt Wash. Minor components of the fluvial system were meandering tributaries of the low-sinuosity stream and crevasse-channel and associated splays formed during flooding of the trunk and tributary system.

The Slick Rock uranium district is located in the zone of convergence of smaller streams into trunk rivers. The trunk steams are characterized by individual depositional units stacked into two zones of higher-sandstone content. The northernmost of these axes strongly influenced the pattern of migration and concentration of uranium. Significant ore-deposits in the district are developed within and along the margins of the axis which is principally composed of low-sinuosity stream deposits. An excellent degree of downdip interconnection of these sandstones made them the major conduits of uraniferous ground-water flow. Smaller deposits are contained within meandering-stream sediments. Crevasse-splay sequences are essentially barren. The vertical intensity of inter-connection between multistoried depositional units results in local stacking of mineral deposits.

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INTRODUCTION

Accumulations of epigenetic uranium in sandstone result from the interaction of mineralized groundwater either with reduced host-rock (i.e. roll-type uranium deposits of Wyoming and South Texas, U.S.A.) or with stagnant groundwater and organic material contained within the host-aquifer (i.e. peneconcordant deposits of the Colorado Plateau, U.S.A.). The ore-bearing sandstones are therefore both the plumbing system through which the mineralizing solutions migrate and the hosts of mineralization. The pattern of groundwater migration, and consequently the localization of ore-minerals, is largely controlled by the geometry and degree of connection of the framework sandstones. The degree of primary connection is a complex attribute dependent on the arrangement (packing) of sand-bodies in space, the frequency and extent to which they touch, and the degree to which they are in mutual communication (Allen, 1978). Geometry, arrangement of sand-bodies in space, and the intensity of connection jointly describe the architecture (Allen, in Miall, 1978) of a fluvial sequence.

The concept of fluvial architecture — the way various elements in a fluvial sequence are stacked (Miall, 1978) — is relatively new. Miall (1978) reviewed the origin and evolution of the concept. Notable field analyses that bear further mention are those of Moody-Stuart (1966) and Campbell (1976). Recent attention has focused on the modelling of fluvial architecture (see, for examples, Allen, 1978, and Bridge and Leeder, 1979).

The Salt Wash Member of the Morrison Formation, described in this paper, was the subject of several pioneering studies of fluvial architecture. Stokes (1954) mapped sedimentary trends and their relation to ore-bodies. Craig et al. (1955) and Mullens and Freeman (1957) documented the broad geometry and distribution of sandstone within the Member. Shawe, Simmons, and Archbold (1968), who undertook a study of specific sites of the Salt Wash, documented the multilateral nature of the sandstones. Recently, Peterson (1980) and Tyler (1981) examined the relation between sedimentology and ore-deposits in two of the uranium districts of the Salt Wash Member.

This paper describes the relation between fluvial architecture and mineralization in a part of the Salt Wash Member of the Morrison Formation in the western United States. The Slick Rock vanadium and uranium district of southwestern Colorado (Figure 1) was chosen for detailed study because of the wealth of subsurface information arising out of over 80 years of exploration and mining. Special emphasis has been placed on the internal arrangement of depositional units, sand-body geometry, spatial arrangement of sand-bodies, degree of connection between sandstones, and overall distribution of sandstone within the Member. This paper concludes with a discussion of the relation between fluvial architecture and the location of vanadium-uranium ore-bodies.

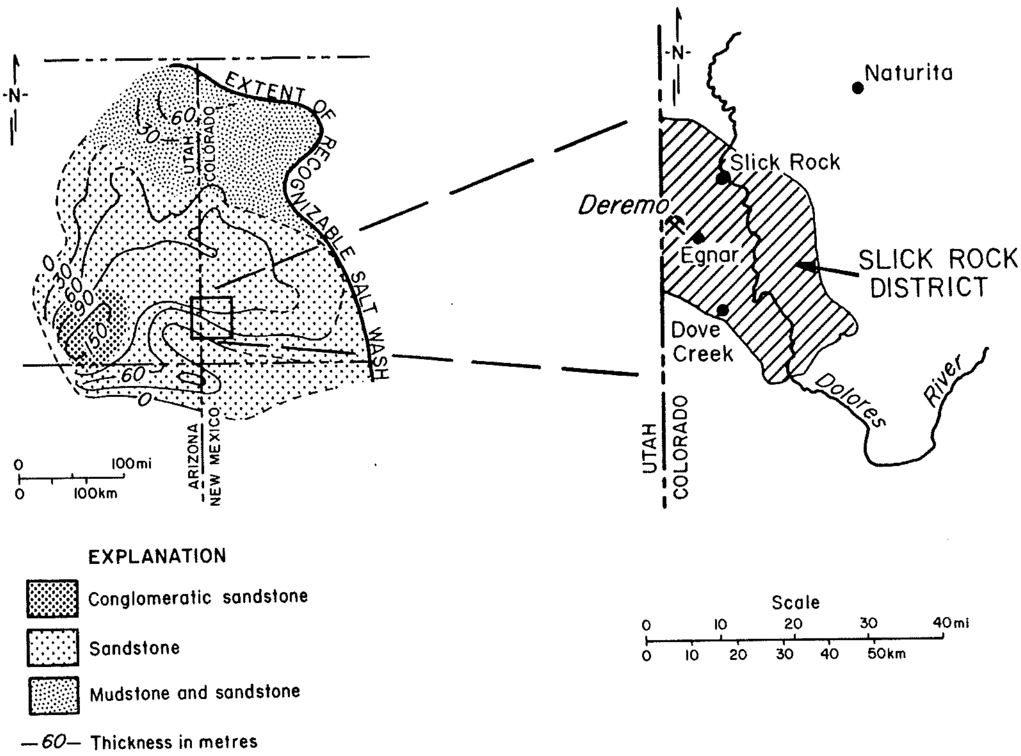


Figure 1 : *Geometry of the Salt Wash Member of the Morrison Formation (modified from Craig et al., 1955) and geographic location of the Slick Rock District within this sedimentary sequence.*

GEOLOGIC SETTING

The Upper Jurassic Morrison Formation (Figure 2) constitutes the uppermost unit of an assemblage of stable-shelf, non-marine rocks on the Colorado Plateau. This formation extends throughout the northern Rocky Mountains to the border between the United States and Canada, westwards into central Utah, and eastwards into Kansas (Campbell, 1976). The Salt Wash Member crops out over much of the stable platform of the Colorado Plateau of the western United States, in Arizona, New Mexico, Colorado, and Utah. The assemblage has a clearly-defined broad, fan-shaped geometry (Figure 1). The thickness and grain-size of the Member decrease towards the northeast. Paleocurrent azimuths follow a radiating pattern towards the north, east, and southeast. On the basis of these criteria, it has been suggested that the unit was deposited by an aggrading distributary system of braided channels on a fan-shaped alluvial plain or alluvial fan (Craig et al., 1955; Mullens and Freeman, 1957). More-recent studies concluded that the Salt Wash fluvial system is more complex, consisting of both low- and high-sinuosity channel deposits that interfinger with well-drained floodplain and lacustrine sediments (Ethridge et al., 1980; Peterson, 1980; Tyler, 1981).

In the Slick Rock District, the Salt Wash Member overlies and erodes the Tidwell Member, a floodplain-dominated fluvial deposit that defines the base of the Morrison Formation (Figure 2). The Morrison rests upon the aeolian Junction Creek sandstone and lacustrine-evaporative deposits of the Summerville Formation. Conformably overlying the Salt Wash Member is a thick, poorly-exposed shale sequence, the Brushy Basin Member, which constitutes the upper member of the Morrison Formation. This Member grades into the Lower Cretaceous Burro Canyon Formation, a similar assemblage of mudstones and minor sandstones.

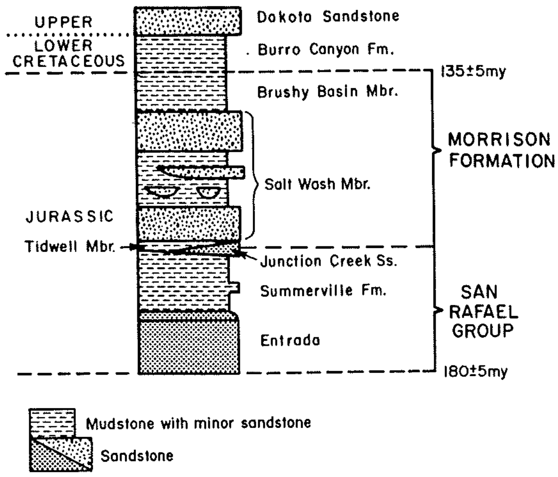


Figure 2 : *Stratigraphic setting of the Salt Wash Member of the Morrison Formation.*

The Salt Wash succession in the study-area can be separated into three lithologic units : (1) lower and (2) upper sandstone-dominated intervals separated by (3) an interval of variable mudstone content interbedded with 3-7 sandstone ledges. The Salt Wash is interpreted as having been deposited in a complex fluvial system that contained a range of co-existing channel-types. Sandstone facies recognized in outcrop, core, and electric logs are interpreted as follows : large-scale, cross-bedded sandstone facies deposited by low-sinuosity streams; fining-upward, medium-to-small-scale, trough-cross-bedded sandstone facies deposited during the lateral migration of mixed-load, sinuous streams; and an upward-coarsening sandstone facies with variable sedimentary structures deposited as crevasse-channels and -splays. These sandstone facies have distinctive internal organizations and three-dimensional geometries. These and other characteristics are compared and contrasted in Table 1. The non-framework component of the Salt Wash is collectively assigned to the interbedded mudstone, siltstone, and thin sandstone facies.

Poor exposure of the non-framework sediments of the Salt Wash makes mapping of individual depositional units impossible. For this reason the geometry and distribution of these sediments are discussed only in relation to the distribution of the framework sandstones of the Salt Wash. Subenvironments of deposition observed in these floodplain sediments are fully discussed elsewhere (Tyler, 1981; Tyler and Ethridge, in preparation).

Table 1 : Depositional Characteristics of the Three Major Sandstone Facies of the Salt Wash Member

	Large-Scale Crossbedded Facies	Medium-to-Small-Scale Trough-Crossbedded Facies	Thin, Upward-Coarsening Facies
Nature of Contacts	lower: erosional upper: abrupt, locally gradational	lower: erosional upper: transitional	lower: planar, only locally erosive upper: sharp-to-gradational
Primary Sedimentary Structures	giant trough-crossbeds at base overlain by gently-dipping, high-w/d trough-crossbeds; planar crossbeds, ripple and horizontal stratification are accessory	low-w/d, steeply-dipping, trough-crossbeds dominant; grade vertically into ripple and horizontal lamination	extremely variable; often an upward increase in scale of structures
Vertical Profiles	blocky; thin fining-upward zone locally developed in upper part of facies; average thickness 10 m.	upward-fining; average thickness 5 m.	generally upward-coarsening; locally highly variable; average thickness 1 m.
Geometry of Depositional Units	strike: lensoid, base concave dip: elongate lateral amalgamation results in sheet geometry	strike: lensoid dip: lensoid	strike: } lobate; dip: } planar base, convex upper surface
Isolith Pattern	broad, straight channels; eastwards-oriented	beaded or ribbon-like thicker sands, oriented obliquely to paleodip	not recognized; inferred lobate- or fan-shaped
Electric-Log Pattern	thick, blocky	hemi-conical, often stacked	thin, inverted Christmas tree
Interpretation	Low-Sinuosity Streams	Meandering Streams	Crevasse-Channel and -Splay

w/d : ratio of width to depth

FACIES AND GEOMETRY OF THE FRAMEWORK SANDSTONES

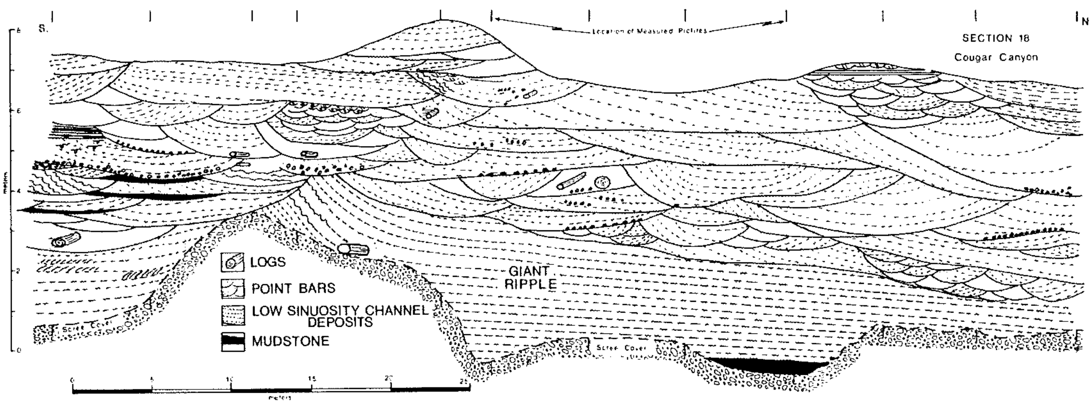
Low-Sinuosity Channel Sandstones

Internal Organization

Low-sinuosity channel sandstones represented by the large-scale crossbedded sandstone facies are the most common sandstone deposits in the Salt Wash. The facies generally rests on a marked erosion-surface (with relief of up to 4 m) along which intraformational mudclast conglomerates are abundant. Large-scale trough-crossbedding, up to a metre thick, with gently-dipping foresets that have tangential bases is the dominant stratification-type. These crossbed sets are characterized by high width-to-depth ratios and an absence of topsets. Foresets are locally accentuated by heavy minerals or mudflakes. The sandstones are dominantly fine-grained and poorly-to-moderately sorted. Fragmental plant material, large logs (without root systems), bones, and bone fragments are common, as are pedogenic limestone nodules reworked out of the adjacent floodplain deposits.

Minor components of this sandstone facies are planar crossbeds, ripple-laminated and horizontally-laminated sandstone and siltstone, and thin mud stringers (Table 1).

A striking feature of the large-scale crossbedded sandstone facies is very large (giant) trough-crossbedding up to 60 m wide and 4 m thick. Foresets on the lateral margins of these giant crossbeds dip steeply (Figure 3) and are commonly contorted. Towards the axes of the troughs, foresets become gently inclined. Foreset intrasets (Collinson, 1968) oriented obliquely to the masterset are common. The giant trough-crossbeds, which average 10-15 m wide, occur as erosive, multilateral structures.



<u>Figure 3</u> : Detailed cross-section through the upper sandstone interval of the Salt Wash, illustrating the lateral variability of the large-scale-crossbedded sandstone facies. Giant trough-crossbeds with contorted lateral margins occur at the base of the facies, which is dominated by large-scale trough-crossbeds. Thin, asymmetric, lensoid point-bar cycles are interbedded within this facies.

Detailed mapping and numerous measured sections through the large-scale crossbedded facies did not reveal any regular vertical arrangement of sedimentary structures or grain-size. Rather, vertical and lateral variability in vertical sequences is characteristic of the facies and is well illustrated in the detailed cross-section through the upper-sandstone interval of the Salt Wash (Figure 3). However, it was observed in the field that the largest of the giant crossbeds occurred near or on the erosional surface at the base of this facies (Figure 3) and that there is an occasional progressive decrease in the scale of sedimentary structures in the upper 50 cm of individual depositional units.

Paleocurrent analysis revealed that the streams responsible for deposition of this facies flowed towards the east and northeast.

Geometry of Sandstone Units

The large-scale crossbedded sandstone facies is characterized by abrupt lower and upper contacts, which are easily recognizable, both in electric logs and in outcrop. The lack of a regular variation in grain-size and sharp contacts of the facies result in a distinctive cylindrical pattern on electric logs. An erosion-surface marks the base of the assemblage; mudstones rest directly upon ripple- or horizontally-laminated sandstones at the upper contact. Facies thickness averages 10 m, but it varies greatly, and a maximum thickness of 25 m has been recorded.

Two distinct cross-sectional geometries are recognized in this facies. In the lower and upper sandstone-dominated intervals of the Salt Wash, amalgamation of individual depositional units resulted in a multilateral, sheet-like geometry. Due to truncation and reworking of individual depositional units, it is difficult to estimate the pristine dimensions of the paleochannels. However, in one instance, a lenticular, asymmetric channel-fill sequence near the top of the lower sandstone unit was 250 m wide and 15 m deep. Superposition and amalgamation of these individual depositional units created sand-belts more than 20 km wide (Figure 4).

The geometry of the large-scale crossbedded facies in the flood-plain-dominated middle interval differs from that of the sand-dominated intervals. Channel sequences here exhibit a multistoried geometry. Lateral margins of the sand-bodies interfinger with adjacent floodplain deposits. Laterally- and vertically-truncated tabular mudstones within these sandstones suggest that superposition of depositional units occurred. The widths of these amalgamated sand-belts vary between hundreds of metres and several kilometres, as compared to the tens of kilometres in the sand-dominated intervals.

The plan geometry of this facies is illustrated in the isopach maps of the upper-sandstone interval. Two broad, slightly sinuous, increased thicknesses of sand traverse the district from west to east (Figure 5). These dip-oriented zones of higher-sandstone content are considered to represent the plan-morphology of the large-scale crossbedded facies. On dip-oriented cross-sections, the sandstone units comprise laterally-persistent layers (Figure 4) that bifurcate towards the east (Tyler, 1981).

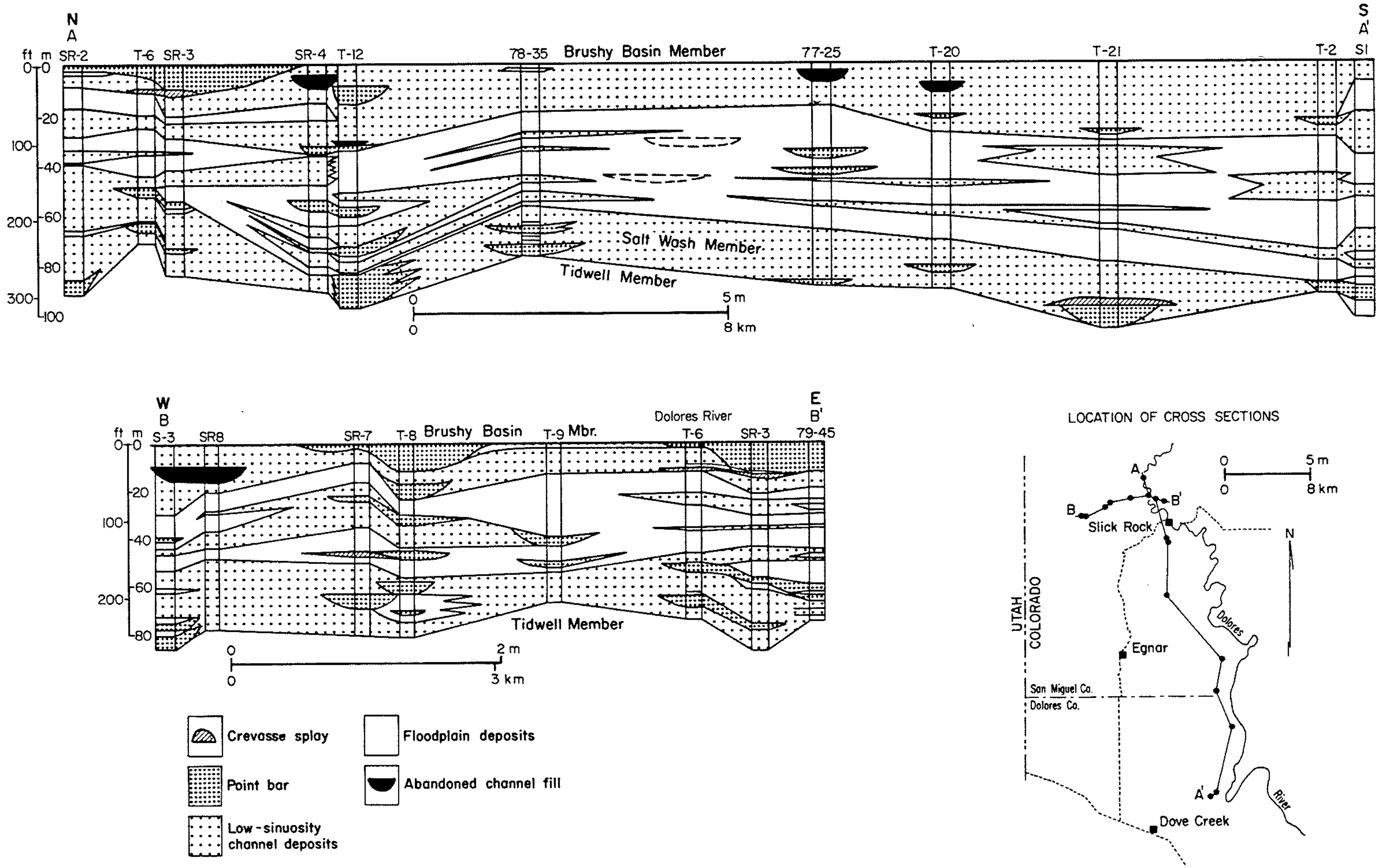


Figure 4 : *Strike (A-A')- and dip (B-B')-oriented cross-sections through the Salt Wash Member. Amalgamation and superposition of dip-elongated, low-sinuosity channel deposits created sand-belts in the lower and upper intervals of the Salt Wash. Point-bar and crevasse-splay depositional units exhibit lenticular geometries.*

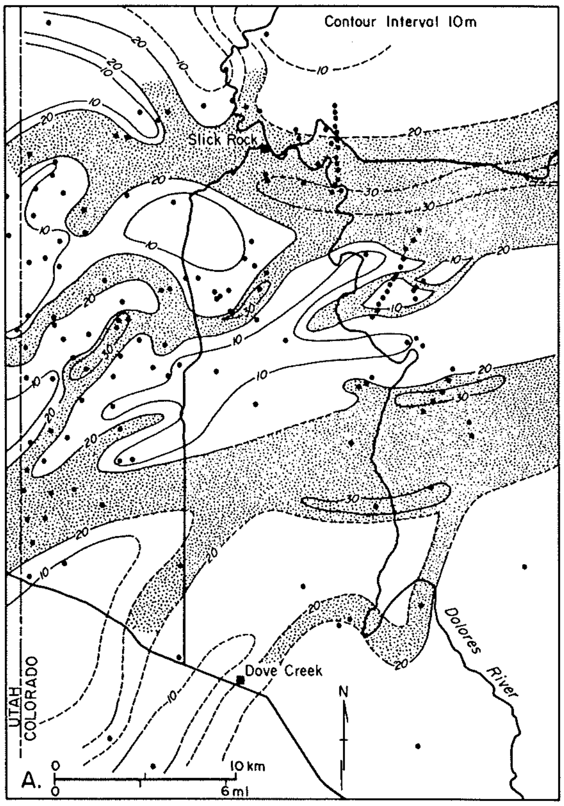


Figure 5 : *Isopachous map of the upper sandstone-dominated interval of the Salt Wash. Eastwards-oriented thicker developments of sand represent the amalgamated deposits of low-sinuosity channel streams, while sinuous ribbons, aligned obliquely to the paleoslope, are inferred to be the deposits of a meandering tributary system.*

Interpretation

The laterally-persistent, paleodip-oriented, large-scale-crossbedded facies is interpreted to represent deposition in deep, slightly-sinuous, bed-load channels that traversed the district from west to east. Modern analogues are parts of the Niger-Benue system (NEDECO, 1959) and, possibly, parts of the Red River (Schwartz, 1978). Course-change was accomplished by avulsion of streams that had aggraded above the adjacent floodplain, rather than by lateral migration.

The multilateral, giant, trough-crossbeds that consistently occur at the base of the facies represent the deposits of giant ripples. An alternative interpretation is that the troughs are channel-fill deposits. However, their location in the facies, the laterally-truncated boundaries with contiguous giant crossbeds, and their internal structure all indicate deposition by downstream-migrating giant ripples. Primary bedforms of a similar magnitude have been reported from monsoonal-belt rivers that experience high seasonal floods, for example, the Yamuna River (Singh and Kumar, 1974). The scale of these giant crossbeds and comparison with modern analogues suggest that the Salt Wash fluvial system was subjected to periodic flooding. Avulsion of channels took place during these possibly-seasonal flood-events. Early erosion was followed by deposition of giant crossbeds upon the basal erosional surface.

The broad, but relatively shallow, trough-crossbeds that comprise the majority of the structures originated under conditions of base ("normal") flow. High width-to-depth ratios, the absence of topsets, the low amplitude of the basal erosion-surface, and the low angle of dip of the foreset of most trough-crossbeds indicate that these structures are the erosional remnants of larger mega-ripples that were truncated by subsequent bedforms migrating down the paleochannel. Small-scale planar crossbeds were probably produced by the downstream migration of straight-crested dunes. The size of the planar crossbeds suggests deposition during low flow. The upward thinning of sedimentary structures in the upper parts of individual sandstone units reflects waning current-strengths following avulsion and channel-abandonment.

High-Sinuosity Channel Sandstones

Internal Organization

High-sinuosity channel sandstones, as represented by the medium- to small-scale trough-crossbedded sandstone facies, are characterized by a progressive vertical decrease in grain-size (Table 1) and scale of sedimentary structures. The facies overlies an erosion-surface along which mud-clasts are common. Trough-crossbedding is the dominant sedimentary structures. Locally, planar crossbeds and horizontal- and ripple-stratification are present. Trough-crossbeds of this facies have low width-to-depth ratios and steeply-dipping foresets. The erosion-surface of individual crossbed-sets has a greater relief than in the afore-mentioned facies. Grain-size varies from medium- to fine-grained sandstone at the base to very fine-grained sandstone and siltstone at the top of the sequence. The upper part of the facies contains planar-, ripple-, and climbing-ripple stratification and abundant burrows. This fining- and thinning-upward sequence is occasionally associated with lateral-accretion surfaces.

The thickness of the medium-to-small-scale trough-crossbedded sandstone facies varies between four and nine metres. The shape basal contact and upward-fining grain-size impart a "Christmas-tree" pattern to electric logs.

Paleocurrent vectors of this facies are highly variable. They have low consistency-ratios and are oriented towards the northeast or southeast (Tyler, 1981). The streams that deposited these sediments flowed obliquely across the paleoslope.

Geometry of Depositional Units

Individual depositional units of this facies are distinctly lensoid (Table 1) and, from detailed mapping, appear to be asymmetrical in shape (Figure 3). On a larger scale, superimposed and amalgamated depositional units retain their lensoid geometry, both in strike- and dip-oriented sections (Figure 4).

Isolith maps of the upper sandstone interval of the Salt Wash illustrate narrow sinuous zones of high sandstone that converge with the broad sheet-sandstones of the low-sinuosity channel facies (Figure 5). These narrow "beaded" or "ribbon" sands are considered to represent the plan-morphology of the lensoid, medium-to-small-scale, trough-crossbedded sandstone facies.

Interpretation

Lenticular, fining- and thinning-upward sandstone packages are interpreted to represent point-bar deposits. The meandering pattern exhibited by the "ribbon-sands" in Figure 5 and the presence of epsilon units confirm this interpretation; other researchers have reached a similar conclusion. In an early study, Stokes (1954) mapped curving sedimentary trends (interpreted as old river bends) and their relation to ore-deposits west of the present study-area. Exploratory drilling has revealed sinuous sandstone ribbons in the subsurface (P. Rubick, personal communication, 1980).

Crevasse-Channel and -Splay Sandstones

Internal Organization

The coarsening-upward sandstone facies, representing crevasse-channel and -splay sandstones, is the most variable of the three facies. The internal organization of sedimentary structures varies laterally within individual depositional units, but varies even more dramatically between depositional units. Although vertical increases in grain-size with height in the column are common, other profiles (blocky, fining-upward) have also been observed. Unifying characteristics that identify a sandstone package as part of this facies are the distinctive geometry of the depositional units, the variability of sedimentary structures, facies thickness, and facies association.

The base of the facies is generally planar and is only locally erosive into underlying assemblages. A variety of cross-stratification structures rests on the basal contact; these include stacked cosets of planar crossbeds of variable thickness (10-50 cm), trough-crossbeds with low width-to-depth ratios, single planar crossbeds (up to one metre thick) resting upon a thin ripple-laminated zone, and interstratified trough- and planar-crossbeds. Upward-coarsening cycles are concomitant with an increase in the scale of sedimentary structures.

Both single and composite depositional units are recognized in the facies. Single units comprise upward-coarsening profiles overlain either by a thin transitional zone or by siltstone or mudstone. These simple profiles attain a maximum thickness of 2 metres. Composite profiles contain thin interbedded mudstones (between a few centimetres and 30 cm thick) that terminate minor upward-fining cycles within the broad, upward-coarsening sandstone progradational unit. Reactivation- and truncation-surfaces are common in these units. Composite depositional units are 1-2 metres thick. Depositional units of this facies are thinner than the two other sandstone facies recognized in the Salt Wash.

Geometry of Depositional Units

Lensoid cross-sectional geometries in both dip- and strike-section suggest a lobate geometry (Table 1). A sharp planar surface that is only locally erosive marks the base of the facies. The upper contact is convex (Figure 6), and both abrupt and gradational boundaries have been observed. This distinctive geometry is best preserved when the unit is interbedded within fine-grained floodplain clastics. In the sand-dominated parts of the Salt Wash, geometries are largely destroyed by truncation and amalgamation of adjacent sandstone bodies. Individual depositional units vary from less than ten to a few hundreds of metres wide. Upward coarsening of this sandstone facies imparts a funnel-shaped pattern to electric logs.

Figure 6 : *Distinctive geometry of a crevasse-splay deposit (C.S.) viewed obliquely to the paleoslope (towards the north-east). Basal contact is planar, non-erosive. Upper contact is abrupt and convex. Slick Rock Hill.*

Interpretation

Lobate, coarsening-upward, sandstone cycles are interpreted to be crevasse-splay deposits. Crevasse-splays are fan- or tongue-shaped sandstone bodies introduced into the floodplain by crevassing of a levee during flooding (Collinson, 1978). Geometries and the internal organization of crevasse-splays deposited on modern alluvial plains have not been well documented. However, crevasse-splays in the interdistributary areas of delta-plains have received considerable attention. In the deltaic setting, splays can comprise semi-permanent, prograding, and upward-coarsening minor mouth-bar/crevasse-channel couplets, or they may be deposited by single, sudden incursions of sediment-laden waters into the bay, producing locally-wide levee-aprons (Elliott, 1978). Numerous, small anastomosing streams comprise the crevasse-channels in the latter case, and the resultant deposits take the form of isolated, small channel-lenses, each separated by a thin mud-drape. Alternatively, rather than being confined to channels, the flow may develop into a density-current and deposit an erosive-based sand-lobe (Elliott, 1978).

The variability of crevasse-splay deposits in the Salt Wash is therefore a function of the diverse processes active at the river-floodplain interface. The composite crevasse-splays were probably semi-permanent features that were active during high-river-stage and were temporarily abandoned at low-stage when suspension-sedimentation dominated. Subsequent flooding of the river resulted in truncation of the mudstones and the formation of reactivation-surfaces in the sandstones. The vertical increase in grain-size is the result of successive flood-events aggrading increasingly-coarser-grained sand over the fan-shaped crevasse-splay surface. The larger, abruptly-based and convex-topped, simple lenses commonly observed in the Salt Wash probably resulted from deposition by single-pulse, unconfined, density-currents. Smaller isolated lenses represent the deposits of anastomosing crevasse-streams on the river flanks.

The lateral variation in sedimentary structures probably represents proximal-distal relations. In the proximal parts of the splays, stacked cosets of trough-crossbeds resting on an erosive base are inferred to represent deposition in crevasse-channels that scoured into the underlying floodplain assemblage. In the distal parts of the splay, isolated or stacked sets of planar crossbeds that rest on a planar, non-erosive base were probably formed by the avalanching of sediment-laden water over the edge of the crevasse-fan under conditions of unconfined flow.

DEGREE OF INTERCONNECTION OF SANDSTONE DEPOSITIONAL UNITS

The degree of interconnection of depositional units is a complex attribute dependent on their packing, the frequency and extent to which they touch, and the degree to which they are in mutual communication (Allen, 1978). In the Salt Wash, the degree of interconnection is further dependent on vertical and horizontal location in the assemblage and environments of deposition. In the sandstone-dominated lower and upper intervals of the Salt Wash (Figure 4), the degree of interconnection of individual depositional units with adjacent and under- and overlying depositional units is well developed. All three sandstone facies are interbedded in these zones, and contacts between sandstone bodies are mutually erosive. Sandstones in the floodplain-dominated middle interval are generally isolated; therefore, the degree of interconnection is poor (Figure 4). Exceptions occur near Slick Rock and Dove Creek, where stacking of depositional units results in partial vertical interconnection of sandstone bodies.

The superposition and amalgamation of depositional units in the lower and upper intervals of the Salt Wash destroyed the original geometry of sandstone facies. This merging of sand-bodies reduced the importance of geometry with respect to the degree of connection of depositional units. However, in the middle floodplain-dominated interval the initial degree of interconnection (or lack of connection) of individual depositional units is preserved. In strike-section, lensoid, point-bar and tabular, low-sinuosity, channel deposits occur as isolated pods in a "matrix" of floodplain sediments (Figure 4). The degree of interconnection is poor. In paleodip section, point-bar deposits retain their isolated, lenticular geometry. Low-sinuousity channel deposits comprise laterally-persistent sand-sheets that pinch and swell, bifurcate, and merge down the paleoslope (Tyler, 1981). The degree of interconnection between adjacent deposits is high. These highly-interconnected, low-sinuousity channel deposits comprise the major conduits of groundwater flow in the Salt Wash.

In general, the fan-shaped geometry and restricted areal extent of the crevasse-splay sandstones cause these deposits to have a low degree of interconnection.

SANDSTONE DISTRIBUTION

In addition to the preferred vertical location of sandstones in the lower and upper intervals of the Salt Wash, the coarser clastics exhibit a preferential areal distribution. Total sandstone content varies from less than 40% to more than 70% of the Salt Wash column. Thicker developments of sandstone comprise two paleodip-aligned, eastward-trending linear belts (illustrated by the percent-sand isolith map of the Salt Wash, Figure 7) separated by intermediate sandstone contents. Increases in the thickness of the sandstone-dominated lower and upper intervals of the Salt Wash (Figures 8A and 5, respectively) and an increase in the sandstone content of the middle interval (Figure 8B) account for the dip-aligned increases in sand-thickness reflected in the isolith map of the member.

Comparison of isopach and sand-percent maps of the three intervals (Figures 5 and 8A and B) reveals that the northern (Slick Rock) thick-sand belt remained static throughout deposition of the Salt Wash and was probably localized by the rising Gypsum Valley salt ridge (Tyler, 1981). The Dove Creek belt was unaffected by local salt tectonics and shifted its position and orientation through time (Figures 5, 8A, and 8B). For this reason, the Slike Rock belt is more sharply defined and contains a higher percentage of sandstone than does the Dove Creek belt.

Isolith and isopach maps illustrate that the Salt Wash in the study-area was deposited in a zone of confluence of smaller streams into major or trunk drainages and the merging of tributaries into these trunk streams. The broad fluvial pattern was one of convergence (Figures 5 and 8) and can be described as dendritic. East-trending, dip-oriented, increased thicknesses of sand are inferred to be the deposits of the trunk streams of this dendritic system.

DEPOSITIONAL SETTING OF THE FRAMEWORK SANDSTONES

Framework sandstones of the Salt Wash in the Slick Rock District were deposited by a range of coexisting channel-types. Channel arrangement

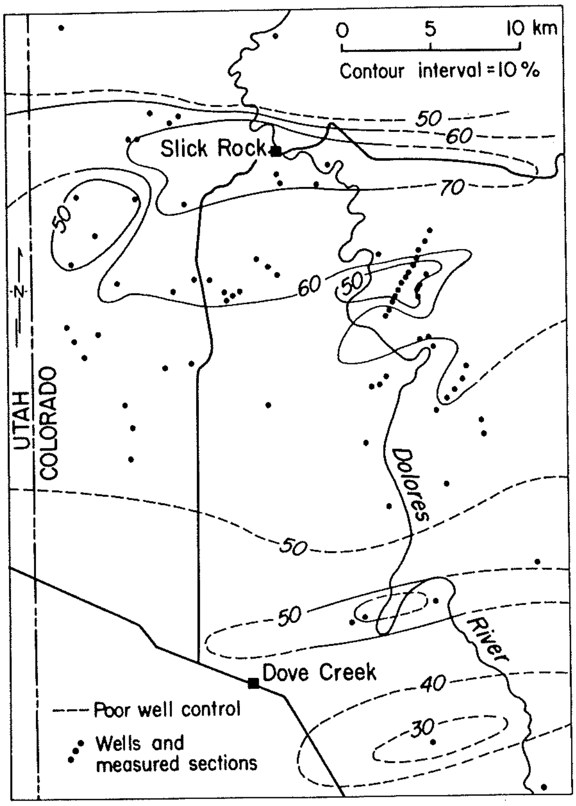


Figure 7 : *Sandstone-percent map of the Salt Wash Member, illustrating two paleo-dip-oriented belts of high-sandstone content.*

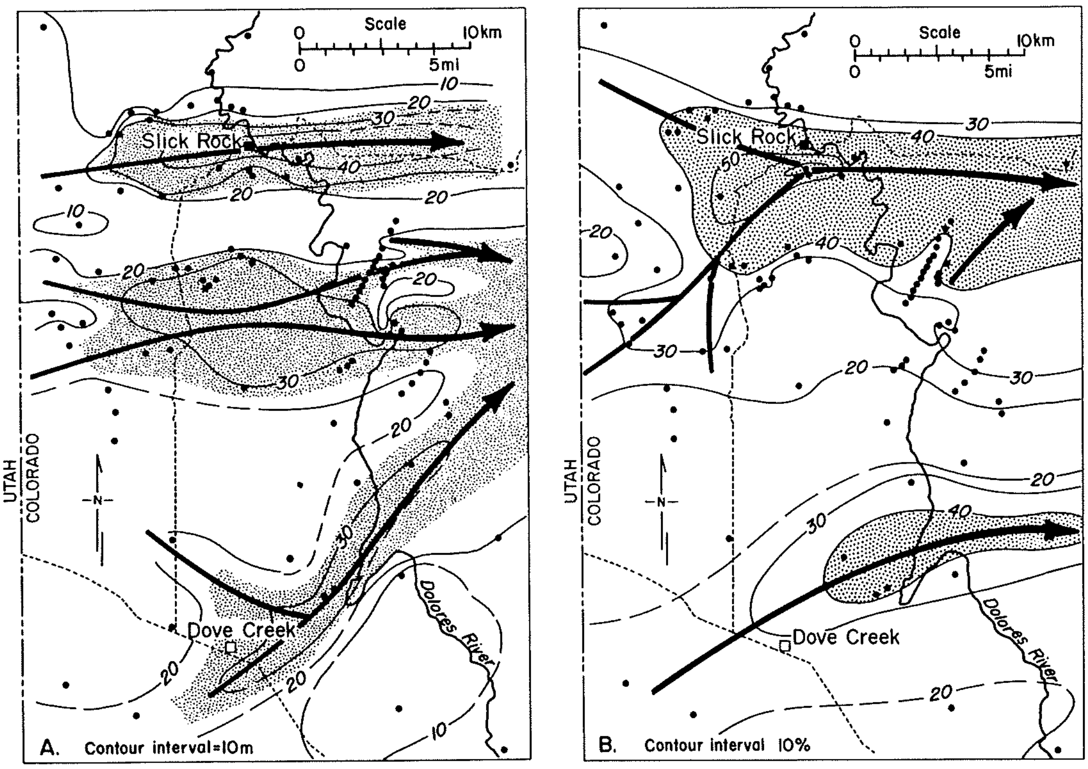


Figure 8 : *Isopach map of the lower interval of the Salt Wash Member (A) and percent-sand isolith map of the middle interval (B), illustrating eastwards-trending thicker developments of sand that transect the district. Arrows emphasize the directions of flow and the convergence of streams into trunk systems.*

was dendritic. Broad and deep low-sinuosity streams that were seasonally subjected to major floods flowed across the district from west to east. Meandering streams which, according to their paleocurrent and isopach and isolith patterns, were tributaries of the major low-sinuosity streams rose on the adjacent well-drained floodplain. This tributary system recycled sediment deposited on the floodplain by crevasse-channels and -splays during flood-events. Sandstones of the Salt Wash were thus deposited by a dynamic system of aggrading channel-types that deposited and recycled sediment continually.

Convergence of smaller streams and tributaries into major or trunk streams gave rise to thicker accumulations of sandstone in two east-trending belts. Local salt tectonics in the form of the rising Gypsum Valley anticline localized the northern belt by restricting migration of the trunk stream. The less-well-defined southern belt, which was apparently unaffected by local salt tectonics, shifted its orientation and position during the deposition of the Salt Wash.

FLUVIAL ARCHITECTURE AND ORE-DEPOSITS

Epigenetic uranium deposits in sandstone host-rocks account for 95 per cent of the past production of uranium in the United States. These deposits constitute at least 95 per cent of the reserves and 79 per cent of the potential United States uranium resources (Young, 1978). The importance of the Colorado Plateau as a uranium-producing province is underscored by the fact that it has accounted for 70 per cent of past uranium production in the United States (Young, 1978). Uranium ore is contained in 28 sedimentary formations ranging in age from Pennsylvanian to Pliocene (Wood, 1956). Twenty-four of these formations are terrigenous clastic deposits, three are carbonates, and one is coal (Young, 1978). The most important uranium-producing formations are the Triassic Chinle Formation, the aeolian Entrada Sandstone (Jurassic), and the fluvial Morrison Formation (Jurassic).

In the Slick Rock District, most of the ore-production is derived from the Salt Wash Member of the Morrison Formation. Ninety per cent of the vanadium-uranium ore mined comes from the upper sand-dominated interval (Chenoweth, 1978). Uranium deposits range in size from a few tons of ore, produced from one-man surface workings, to cumulative productions exceeding 1 000 000 kg U_3O_8 produced by large-scale underground operations (e.g. Deremo Mine, Figures 1 and 9). Ore deposits are confined to the northern half of the district, and their distribution is apparently random, if the sizes of the ore deposits are not considered. However, a contour map of cumulative uranium-production through 1971 illustrates that the larger ore-deposits are aligned along distinct trends (Figure 9) that are east-west oriented in the northern part of the study-area and northeast-oriented in the west central part of the district. This alignment of ore-deposits parallels the depositional fabric of the framework sandstones of the Salt Wash Member (Figures 5 and 7).

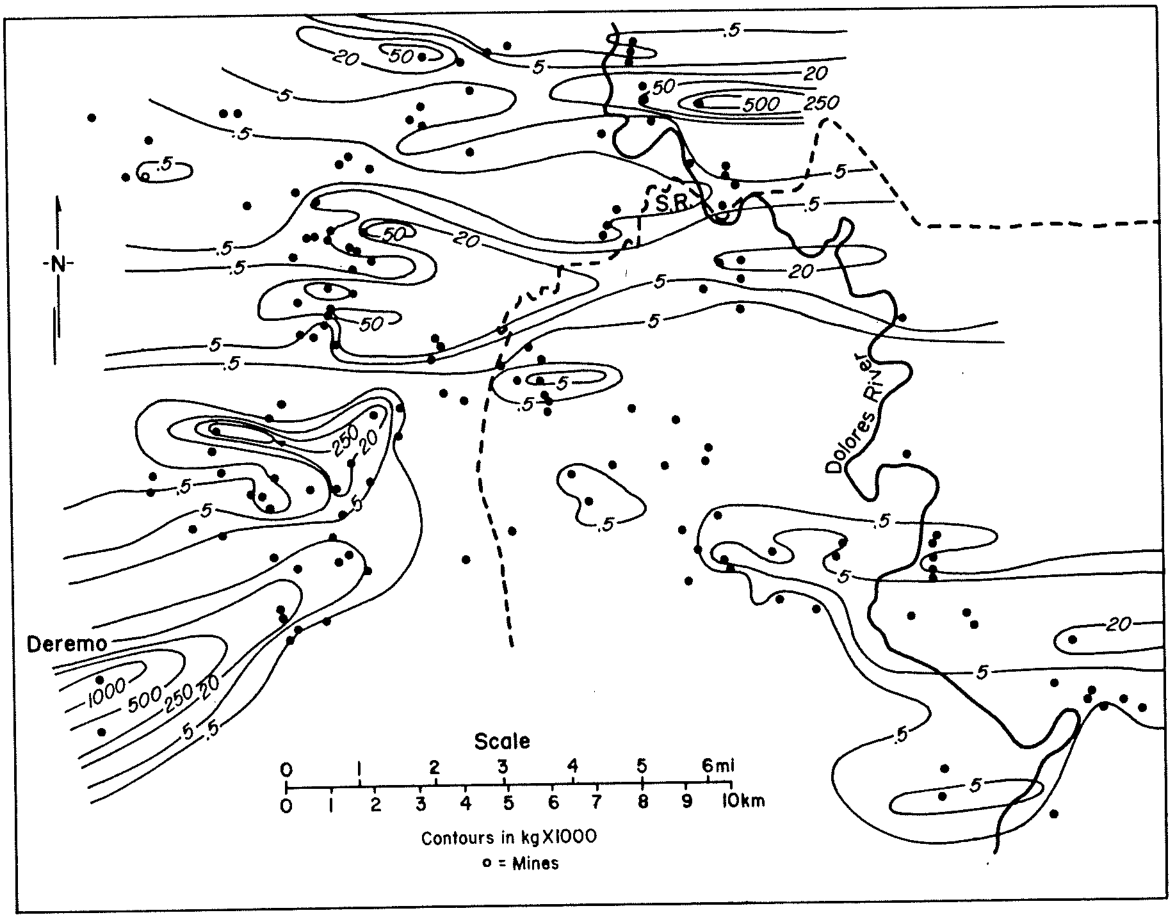


Figure 9 : *Isopleth map of cumulative uranium-production from the Slick Rock District prior to 1971 (data obtained from Nelson-Moore, Collins, and Hornbaker, 1978). The larger ore-deposits align along west-east and northeast trends parallel to the depositional fabric of the host-sandstones.*

Comparison of the production isopleth map with the isopach map of the upper sandstone interval (the source of much of the ore mined before 1971) reveals that the larger ore-deposits are preferentially contained within sandstone of intermediate thickness (Figure 10). Furthermore, the most important ore-deposits (with pre-1971 productions of 50 000 kg of U_3O_8) tend to occur within and along the lateral margins of the Slick Rock trunk stream or within the meandering tributaries near their confluence with the trunk stream (Figure 10). Less significant deposits (more than 5 000 Kg U_3O_8 produced) have a more-widespread distribution, being located within the Slick Rock trunk stream, along the margins of both trunk streams, and within the tributary systems (Figure 10).

The influence of fluvial architecture on the location of uranium deposits on a local scale is illustrated by the fact that ore-bodies most commonly occur within the dip-elongated, highly-interconnected, low-sinuosity,

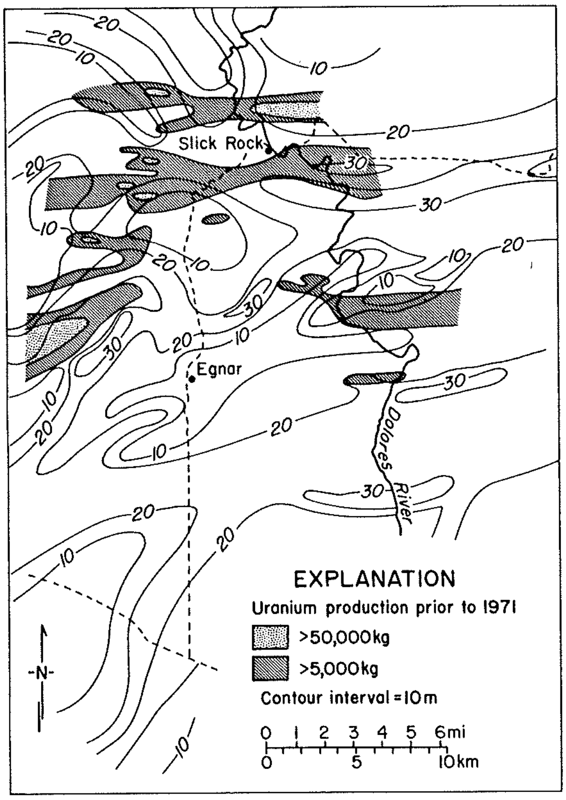


Figure 10 : *Combined production-isopleth/upper-sandstone-interval-isopach map. Major ore-deposits of the district (with cumulative productions greater than 50 000 kg U_3O_8) occur within or along the margins of the Slick Rock trunk stream, or within the tributary system near confluences with the trunk. Smaller ore-deposits have a more widespread distribution.*

channel sandstones. The uranium ore occurs as stratabound tabular bodies that are thin compared to their lengths. Long axes of the ore-deposits are parallel or subparallel to the local sedimentary fabric. Boundaries are diffuse and are defined by economic limits rather than by abrupt changes in ore-grade. Locally, the vertical degree of interconnection between low-sinuosity channel sandstones results in stacked ore-bodies.

Point-bar sequences are less-commonly mineralized. Less than one-quarter of the 43 ore-bodies observed occur in lower point-bar sequences; these ore-bodies are smaller than the vanadium-uranium ore-deposits in low-sinuosity channel sandstones. Boundaries of the ore-zones in this sandstone facies are more abrupt, occasionally being defined by epsilon-crossbedding. The ore often takes the form of a massive replacement of the host-sandstone, obliterating the primary sedimentary structures, whereas ore-zones in low-sinuosity channel sandstones are characterized by mineralization localized along foresets.

Mineralization is rarely observed in upper point-bar, or crevasse-channel and -splay sandstones. A significant site of minor, patchily-developed ore-bodies is at permeability-barriers associated with abrupt changes in lithology (e.g. at the base and upper contacts of sandstone sequences). Six of the 43 ore-bodies examined are associated with permeability-barriers; this relationship is independent of facies.

The close association between ore-deposits and low-sinuosity channel sandstones indicates that these paleodip-elongated, highly-interconnected sandstones acted as the major conduits for the migration of uranium-bearing groundwater. The source of uranium is generally considered to lie in the diagenetic destruction of volcanic detritus contained within the Salt Wash and the overlying Brushy Basin Member. Uranium-bearing groundwaters migrated downdip along transmissive conduits until encountering reductants in the form of vanadium (III)-bearing organic complexes contained within stagnant groundwater (Granger and Warren, 1981), and locally, fossil plant-debris. Reduction and precipitation of uranium resulted in tabular bodies aligned parallel to the sedimentary fabric. (For a more detailed description of the genesis of ore-bodies, see Rackley, 1976; Nash, Granger and Adams, 1981; Thamm, Kovschak, and Adams, 1981; Tyler, 1981; and others). Although the ore-bodies have a distinct dip-orientation, they are also concentrated into an elongated strike-parallel belt, the Uravan Mineral Belt (Fischer and Hilpert, 1952) roughly concentric with the truncated proximal portion of the Salt Wash, as well as the outer limits of the Salt Wash Member (Figure 1). The Slick Rock District is located in the southern part of this belt. It is considered significant, although possibly fortuitous, that this clustering or ore-deposits coincides with the zone of convergence of streams (see Figures 5 and 8) midway down the paleoslope of the Member.

Ore-bodies within low-sinuosity channel sandstones are larger, but are less concentrated, as indicated by alteration and scintillometer-readings, than the ore-bodies in point-bar sequences. This suggests that the geometry of depositional units influenced, not only paths of fluid-migration, but also ore-grade. It has not yet been determined whether the higher-grade ore in point-bar sequences is a consequence of (1) a higher concentration of reductants in the stagnant groundwaters in these lenticular units; or (2) facies-boundaries of the sinuous-channel sandstones having confined and concentrated the movement of the uranium-bearing mineralizing solutions; or (3) a combination of both of these factors.

The close association between the major ore-deposits of the Slick Rock Uranium District and the Slick Rock trunk stream suggests that this trunk (or fluvial axis) was the principal zone of movement of the mineralized groundwaters. It has been shown that the less-well-defined Dove Creek trunk was characterized by changes in position and orientation during Salt Wash sedimentation. This instability is reflected in the paucity of mineralization associated with the trunk stream. The Slick Rock trunk stream, stabilized by local salt tectonics, experienced only minor changes in position and, therefore, comprises an axis of highly-interconnected, multistoried, dip-elongated depositional units that contain relatively abundant deposits. Recognition of trunk-stream elements, such as the Slick Rock trunk stream, within a potentially-mineralized fluvial sequence may prove to be a useful exploration tool.

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REFERENCES

Allen, J.R.L. (1978) — Studies in Fluviatile Sedimentation: an Exploration Quantitative Model for the Architecture of Avulsion-Controlled Alluvial Suites — Sedim. Geol., 21, 129-147.

Bridge, J.S., and Leeder, M.R. (1979) — A Simulation Model of Alluvial Stratigraphy — Sedimentology, 26, 617-644.

Campbell, C.V. (1976) — Reservoir Geometry of a Fluvial Sheet Sandstone — Bull, Am. Ass. Petrol. Geol., 60, 1009-1020.

Chenoweth, W.L. (1978) — Uranium in Western Colorado — The Mountain Geologist, 14, 89-96.

Collinson, J.D. (1968) — The Sedimentology of the Grindslow Shales and the Kinderscout Grit: a Deltaic Complex in the Namurian of Northern England — J. Sedim. Petrol., 39, 194-221.

Collinson, J.D. (1978) — Alluvial Sediments — *in* M.G. Reading (ed.), Sediments and Facies, Elsevier Publishing Co., New York, 15-60

Craig, L.E., Holmes, C.N., Cadigan, R.A., Freeman, V.L., Mullens, T.E., and Weir, G.W. (1955) — Stratigraphy of the Morrison and Related Formations, Colorado Plateau Region : a Preliminary Report — Bull. 1009E, U.S. Geol. Surv., 125-166.

Elliott, T. (1978) — Deltas — *in* M.G. Reading (ed.), Sediments and Facies, Elsevier Publishing Co., New York, 97-142.

Ethridge, F.G., Ortiz, N.V., Sunada, D.K., and Tyler, N. (1980) — Laboratory, Field and Computer Flow Study of the Origin of Colorado Plateau Type Uranium Deposits : Second Interim Report — Open File Report, U.S. Geol. Surv., 800-805.

Fischer, R.P., and Hilpert, L.S. (1952) — Geology of the Uravan Mineral Belt — Bull. 988-A, U.S. Geol. Surv., 1-13.

Granger, H.C., and Watten, C.G. (1981) — Genetic Implications of the Geochemistry of Vanadium-Uranium Deposits in the Colorado Plateau Region — Programme with Abstracts, Rocky Mountain Section, Am. Ass. Petrol. Geol., 29th Ann. Meeting, Albuquerque, 24.

Miall, A.D. (1978) — Fluvial Sedimentology: an Historical Review — *in* A.D. Miall (ed.), Fluvial Sedimentology, Mem. 5, Can. Soc. Petrol. Geol., 1-48.

Miall, A.D. (1978) — Fluvial Sedimentology — Mem. 5, Can. Soc. Petrol. Geol.

Moody-Stuart, M. (1966) — High and Low Sinuosity Stream Deposits, with Examples from the Devonian of Spitzbergen — J. Sedim. Petrol., 36, 1102-1117.

Mullens, T.E., and Freeman, V.L. (1957) — Lithofacies of the Salt Wash Member of the Morrison Formation, Colorado Plateau — Bull., Geol. Soc. Am., 68, 505-526.

NEDECO (1959) — River Studies and Recommendations on Improvement of Niger and Benue — North Holland Publishing Co, Amsterdam.

Nash, J.T., Granger, H.C., and Adams, S.S. (1981) — Geology and Concepts of Genesis of Important Types of Uranium Deposits — Econ. Geol., 75th Anniversary Volume, 63-116.

Nelson-Moore, J.L., Collins, D.B., and Hornbaker, A.L. (1978) — Radioactive Mineral Occurrences of Colorado and Bibliography — Bull. 40, Colorado Geol. Surv.

Peterson, F. (1980) — Sedimentology of the Uranium-Bearing Salt Wash Member and Tidwell Unit of the Morrison Formation in the Henry and Kaiparowits Basins, Utah — U.G.A. - 1980 Henry Mountains Symposium, 305-322.

Rackley, R.I. (1976) — Origin of Western-States Type Uranium Mineralization — *in* K.H. Wolf (ed.), Handbook of Stratabound and Stratiform Ore Deposits II, 7, Elsevier Publishing Co., New York, 89-156.

Schwartz, D.E. (1978) — Sedimentary Facies, Structures, and Grain-Size Distribution: the Red River in Oklahoma and Texas — Trans., Gulf Coast Ass. Geol. Soc., 28, 473-491.

Shawe, D.R., Simmons, G.C., and Archbold, N.L. (1968) — Stratigraphy of the Slick Rock District and Vicinity, San Miguel and Dolores Counties, Colorado — Prof. Pap. 576A, U.S. Geol. Surv.

Singh, I.B., and Kumar, S. (1974) — Mega- and Giant-Ripples in the Ganga, Yamuna, and Son Rivers, Uttar Pradesh, India — Sedim. Geol., 12, 53-66.

Stokes, W.L. (1954) — Some Stratigraphic, Sedimentary, and Structural Relations of Uranium Deposits in the Salt Wash Sandstone — U.S. Atomic Energy Comm., RME-3102.

Thamm, J.K., Kovschak, A.A., and Adams, S.S. (1981) — Geology and Recognition Criteria for Sandstone Uranium Deposits of the Salt Wash Type, Colorado Plateau Province — Final Report GJBX-6(81), Bendix Field Eng. Corp., Grand Junction.

Tyler, N. (1981) — Jurassic Depositional History and Vanadium-Uranium Deposits, Slick Rock District, Colorado Plateau — Unpublished Ph.D. Thesis, Colorado State University, Fort Collins, Colorado.

Wood, H.B. (1956) — Relations of the Origin of the Host-Rocks to Uranium Deposits and Ore Production in the Western United States — Prof. Pap. 300, U.S. Geol. Surv., 522-541.

Young, R.G. (1978) — Depositional Systems and Dispersal Patterns in Uraniferous Sandstones of the Colorado Plateau — Utah Geol., 5, 85-102.

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