UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

FIELD, MODEL, AND COMPUTER SIMULATION OF SOME ASPECTS OF THE ORIGIN AND DISTRIBUTION OF COLORADO PLATEAU-TYPE URANIUM DEPOSITS

by

Frank G. Ethridge, Daniel K. Sunada, Noel Tyler and Sarah Andrews

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FINAL REPORT

For U.S. Geological Survey Project No. 14-18-001-G-429

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Frank G. Ethridge, Daniel K. Sunada, Noel Tyler and Sarah Andrews

Department of Earth Resources
and
Department of Civil Engineering
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ABSTRACT

Numerous hypotheses have been proposed to account for the nature and distribution of tabular uranium and vanadium-uranium deposits of the Colorado Plateau. In one of these hypotheses it is suggested that the deposits resulted from geochemical reactions at the interface between a relatively stagnant groundwater solution and a dynamic, ore-carrying groundwater solution which permeated the host sandstones (Shawe, 1956; Granger, et al., 1961; Granger, 1968, 1976; and Granger and Warren, 1979). The study described here was designed to investigate some aspects of this hypothesis, particularly the nature of fluid flow in sands and sandstones, the nature and distribution of deposits, and the relations between the deposits and the host sandstones.

The investigation, which was divided into three phases, involved physical model, field, and computer simulation studies. During the initial phase of the investigation, physical model studies were conducted in porous-media flumes. These studies verified the fact that humic acid precipitates could form at the interface between a humic acid solution and a

potassium aluminum sulfate solution and that the nature and distribution of these precipitates were related to flow phenomena and to the nature and distribution of the host porous-media.

During the second phase of the investigation field studies of permeability and porosity patterns in Holocene stream deposits were investigated and the data obtained were used to design more realistic porous media models. These model studies, which simulated actual stream deposits, demonstrated that precipitates possess many characteristics, in terms of their nature and relation to host sandstones, that are similar to ore deposits of the Colorado Plateau.

The final phase of the investigation involved field studies of actual deposits, additional model studies in a large indoor flume, and computer simulation studies. The field investigations provided an up-to-date interpretation of the depositional environments of the host sandstones in the Slick Rock District and data on the nature and distribution of the ore deposits which are found to be directly related to the architecture of the host sandstones which acted as conduits for the transport of mineralized groundwaters. Large-scale model studies, designed to simulate Grants Mineral Belt deposits, demonstrated that precipitates had characteristics similar to those of actual uranium deposits and data obtained from these studies strongly supported the hypothesis that the ores formed soon after deposition of the host sandstones and that their distribution was largely controlled by permeability and porosity patterns established at the time of deposition of the host sandstones.

A numerical model was developed during the second and third stages of the investigation that can predict favorable locations for mineralization

given sufficient data on porosity, hydraulic conductivity, the distribution and thickness of sandstone hosts, and an estimate of the initial hydrologic conditions. The model was successfully tested using data from the Slick Rock District.

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James A. Ferentchak and Nestor Ortiz did most of the model studies associated with Phases 1 and 2 of the investigation. Their important efforts are acknowledged by several references to their published work. They were admirably assisted by John A. Brookman. Fred Peterson introduced us to the Salt Wash and spent valuable time with two of us in the field. Union Carbide Corporation, Cotter Corporation, Plateau Resources, Marathon Resources, Mineral Recovery Corporation and Energy Reserves Group provided access to company information or mines. Stimulating and informative discussions were held with numerous company geologists involved with the day-to-day exploration for uranium. John Vanderpool, Jim Whetstine, Terry Gulliver, Mike LeBaron, Bill Thompson, Bob Nylund, Dick White, Patty Rubick, Mark Stephen, Robert A. Brooks and Robert V. Perry were all extremely helpful. W. Chenoweth and A. Girdley of the Dept. of Energy and Dan Shawe, Terry Offield, Morris Green, Marty Goldhaber, John Campbell, Allen Kirk and Dave Macke of the U.S.G.S. are also thanked for their interest and advice.

Ellen Winder and Cheryl Knapp assisted Noel Tyler in the field. Field and/or laboratory data on textures, permeability, and porosity of Holocene river sediments was obtained by Van Leighton, Richard Johnson, Sunji Ouchi, Adam Burnett, and Paul Zuirblis. Pam Turner, Steve Savig, Lisa Reining and M. Martinez assisted in obtaining data from the large indoor flume. Terri Bostedt typed this report and many of the other manuscripts listed in the reference section. Her invaluable service in keeping up with all the paper work and budgets on a project of this complexity is also greatly appreciated. An earlier version of this manuscript was reviewed by Harry Granger, Dick Grauch, Morris Green, Curt Huffman, Joel Leventhal and Rick Sanford. Their comments and suggestions are greatly appreciated.

INTRODUCTION AND OBJECTIVES

This research project, which extended over a period of three and one-half years, has involved several different avenues of research into the origin and distribution of certain Colorado Plateau type uranium deposits. In the first phase of this research project, the penetration and precipitation of a humic acid solution into a porous-media flume saturated with aluminum potassium sulfate solution was studied to evaluate one of several hypotheses concerning the origin of the peneconcordant type uranium deposits of the Colorado Plateau.

During the second phase, data on textural and permeability-porosity patterns in Holocene braided streams were collected and used in conjunction with published data from other Holocene stream deposits to design realistic models of these types of sedimentary deposits for use in the porous media flume and computer experiments. Additional laboratory experiments were then conducted to evaluate the effects of porous media layering, density difference, and mineral precipitation on the formation of uranium deposits. The final investigation during this second phase of the project involved the modification of an existing computer program and the use of this program to predict the shape and distribution of laboratory precipitates.

The third phase of the investigation involved field studies in the Colorado Plateau, physical model studies, and computer simulation studies. Field studies involved an investigation of the San Rafael Group and the Tidwell and Salt Wash Members of the Morrison Formation in the Slick Rock vanadium-uranium District of southwest Colorado. A computer model was developed for the Salt Wash Member of the Morrison Formation in the Slick Rock District. The development of this model was a direct outgrowth of the computer program used in the second phase to predict the location and distribution of precipitates generated during laboratory studies. Data for the model were generated from thin section and field geologic investigations. An area of approximately 25 square miles (65 sq. km) in the northern portion of the district was modeled in detail. The location of simulated uranium deposits as predicted by the model were compared to actual uranium deposits in the Slick Rock District. The final aspect of the third phase of the investigation involved physical model studies in a large indoor flume measuring 2.0 m by 2.5 m by 0.4m deep. In this flume, alluvial fan deposits similar to those described for the Westwater Canyon Member of the Morrison Formation, Grants Mineral Belt, New Mexico were constructed. Several different hypotheses for the origin of the contained uranium deposits were evaluated during the conduct of these physical model studies.

Numerous manuscripts and abstracts have already been published or are in press or preparation as a direct result of the various efforts undertaken during this investigation. These publications are reviewed in the next section of this report. In the final sections, results obtained during the various investigations undertaken during this research project are reviewed. It is not, however, our intent to present all of the data generated during these various investigations in this summary report. Readers who are interested in the details of our investigations are referred to the various theses, reports, and publications mentioned in the following sections.

REPORTS, PUBLICATIONS AND ABSTRACTS

As a direct result of this research project, two M.S. Theses (Ferentchak, 1979 and Andrews, 1981) and one Doctoral Dissertation (Tyler, 1981); three project reports (Ortiz, et al., 1978; Andrews and Ethridge, 1979; and Ethridge, et al., 1980a; this last report was published as an open file report of the U.S.G.S.); two refereed publications (Ethridge, et al., 1980b; and Ortiz, et al., 1980a); and four abstracts of oral presentations (Ethridge, et al., 1979; Tyler and Ethridge, 1980; Ortiz, et al., 1980b; and Tyler and Ethridge, 1981) have been published.

In addition, three seminars were given to U.S.G.S. personnel in Golden, Colorado; two manuscripts are in final preparation (Tyler and Ethridge, in prep., (a&b)) for submission to journals; a portion of the short course notes for the Fluvial System Short Course held at Colorado State University in 1981 (Ethridge, 1981) contains results from this project; and an abstract has been submitted (Andrews and Ethridge, in review) for the 1982 AAPG meeting in Calgary.

The following sections of this report consist mainly of reviews of the results presented in detail in these publications. In addition, some new results not previously published will be presented. These reviews will be subdivided in accordance with the three phases described above in the introduction.

INITIAL POROUS-MEDIA FLUME STUDIES

Initial laboratory experiments were designed to evaluate one of several hypotheses concerning the origin of certain Colorado Plateau-type sandstone uranim deposits. This hypothesis (Shawe, 1965; Granger, et al., 1961; and Granger, 1968 and 1976) emphasizes the differences between the predominantly tabular (peneconcordant) deposits of the Colorado Plateau and the roll front deposits of other sedimentary basins and proposes that physical and chemical reactions at the interface between two groundwater solutions were instrumental in depositing much of the uranium in the Colorado Plateau region.

To evaluate this hypothesis, experiments were conducted in two similar porous media flumes (Figs. 1 and 2) filled with glass beads and/or one of several different types of natural sands (Ortiz, et al., 1978, Table 1; also see caption Fig. 3, this report). Humic acid and aluminum potassium sulfate solutions were used in all experiments throughout the project. In the experiments conducted during this initial phase of the project, the porous-media flume was saturated with the aluminum solution and the humic acid solution was injected from a point source. These solutions were used because the resulting humate precipitates formed quickly, were dark colored and easy to see against the light background of the porous-media, did not react with the quartz sand media, and the reactions were easily reversible so that precipitate could be dissolved and another test conducted without disturbing the flume.

The use of physical models such as those described here and later in this report have become increasingly commonplace in the earth sciences

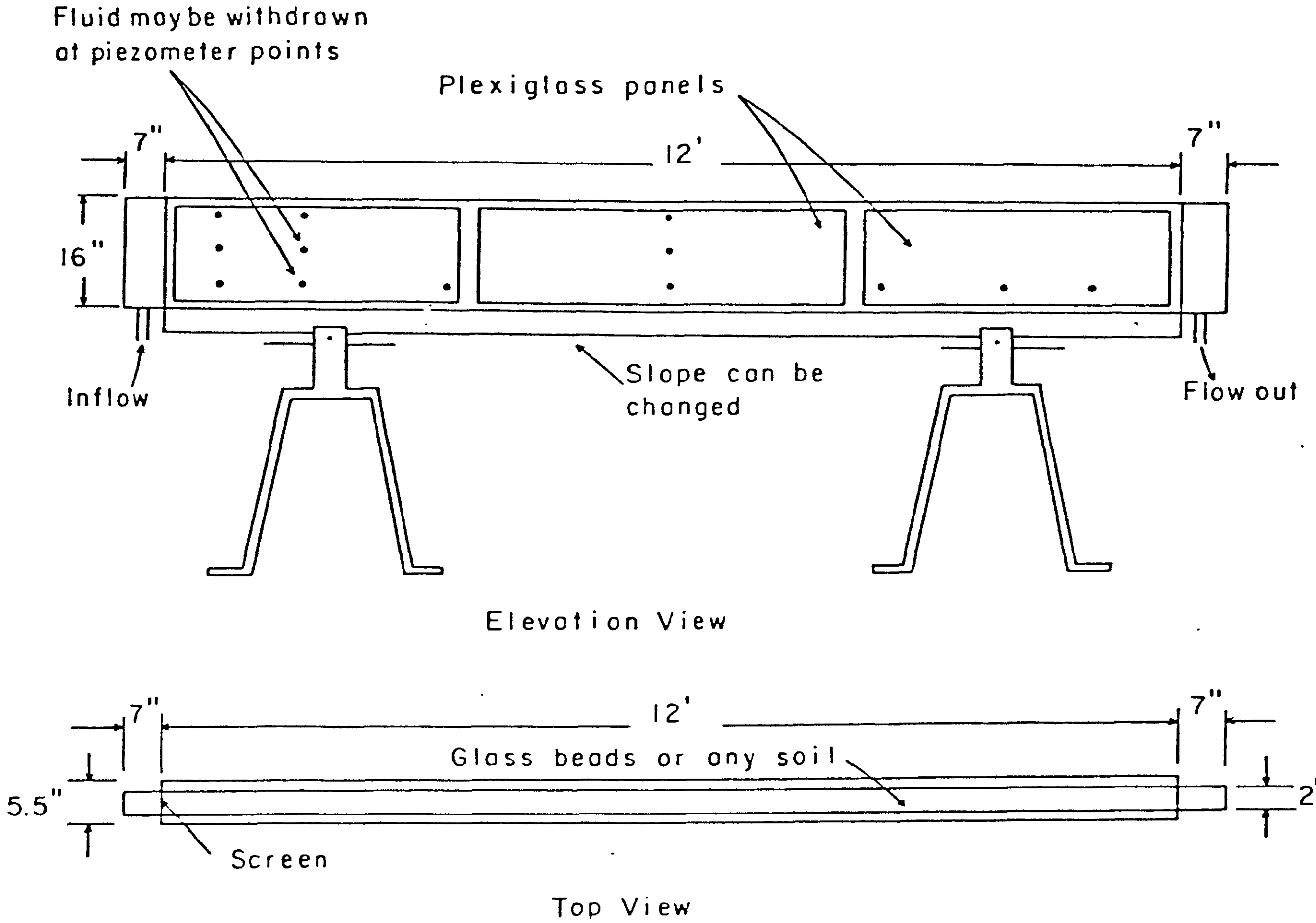

Figure 1. Large porous-media flume. (From Ferentchak, 1979).

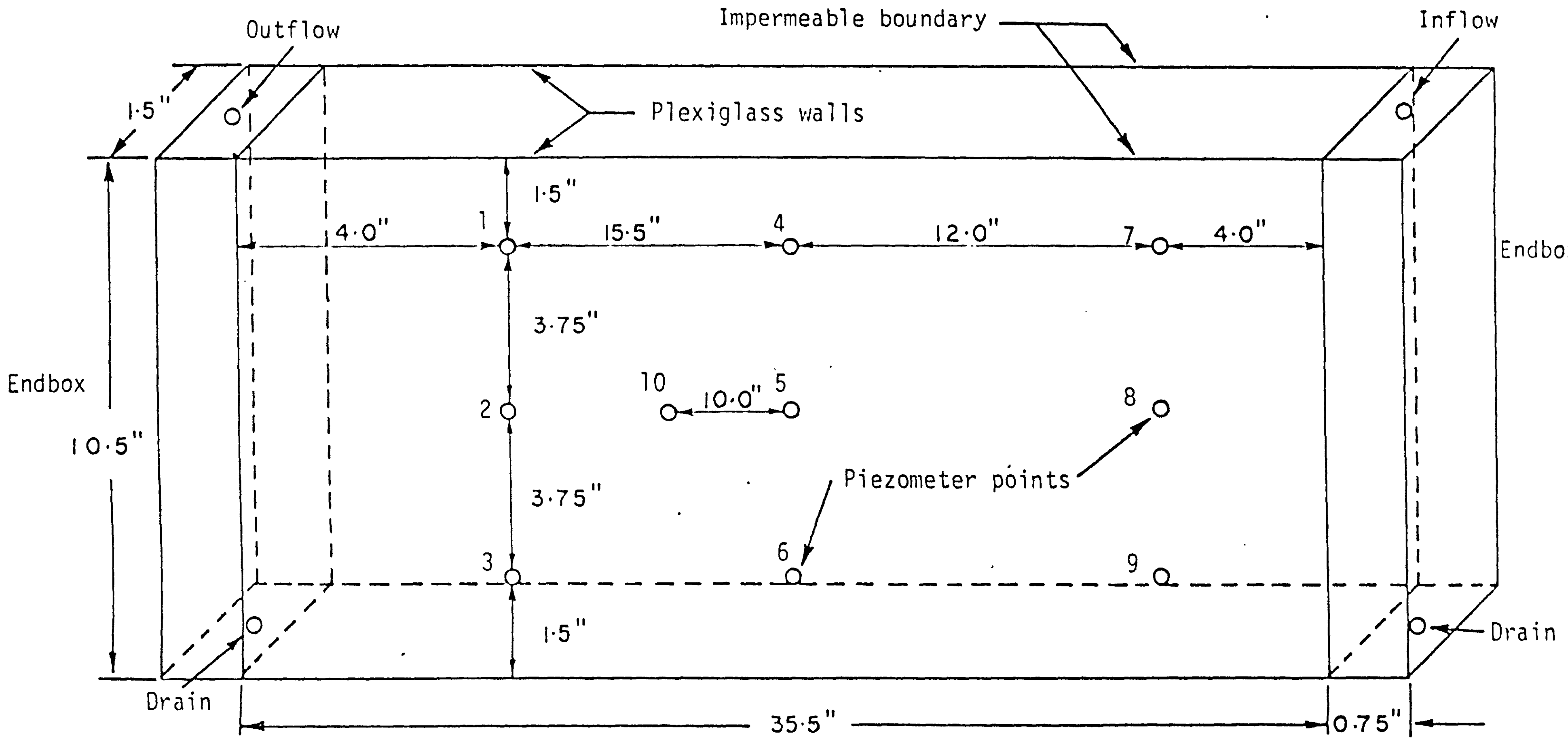

Figure 2. Diagrammatic view of small porous media flume used in experimental runs for Phase 2 of study. (From Ferentchak, 1979).

in recent years. The advantages of such model studies are that close control of variables can be maintained and precise measurements can be readily obtained. Disadvantages include the problems of scaling ratios, initial conditions and boundary conditions. Physical models have been used successfully to generate and test hypotheses and for predictive and descriptive purposes, however, the inherent uncertainties in the relationships between the model and its prototype require independent evaluation before the results can be considered valid (Harvey, 1980).

In the initial series of experiments the effects of variable flow rates, porous-media layering, mudstone lenses (baffles), fluid density differences, and geochemical reactions on the flow phenomenon were evaluated to provide some possible insight into the deposition of uranium ore. A complete review of the experimental procedures and results are given in Ortiz, et al. (1978) and in Ferentchak (1979). Only the major results are reviewed here.

During these initial experiments it was found that a distinct band of precipitate did, in fact, form at the interface between the two solutions within the porous-media flume. The characteristics of these precipitate bands and their relation to experimental conditions were as follows:

1) The precipitates filled the pores of the porous media and reduced hydraulic conductivity.
2) They formed both parallel and perpendicular to the flow and were thicker where the contact time between solutions was large (e.g., parallel to the flow path).

3) Under conditions where the flow of humic acid was increased, relative to the aluminum potassium sulfate solution, the precipitate was dissolved back into solution and redeposited at a new interface.

4) When the flow of humic acid was decreased, the original precipitate remained and a new precipitate formed.

5) Under conditions characterized by multiple porous-media layers, the precipitate was thicker and darker in the more permeable layers and flow lines tended to converge toward these layers.

6) The effect of the baffles was to change the flow configuration, and thus the location of the precipitate band (no precipitate was detected in the porous media immediately adjacent to a baffle).

7) Density differences between the two solutions had the obvious effect of changing the location of the interface between the two solutions but had no effect on the width or sharpness of the resulting precipitate band.

8) No significant diffusion effects were observed. This lack of diffusion effects may be related to the relatively high flow rates utilized in the experiments as compared to flow rates in natural groundwater systems.

These experiments provided a visual record of the flow dynamics of solutions in simple porous media systems and of the reactions and resulting precipitates at the interface between two solutions.

TEXTURAL AND PERMEABILITY-POROSITY STUDIES OF HOLOCENE DEPOSITS

Field and laboratory investigations of the texture and permeability-porosity patterns in Holocene braided stream deposits were initiated in phase two of this investigation and have continued into phase three. These studies were designed to compare data collected from braided stream deposits with data from other Holocene deposits (Pryor, 1973) and from laboratory studies (Beard and Weyl, 1973). Data obtained were then utilized in designing more realistic porous-media flume experiments involving simulated braided and meandering stream deposits. Data collected from longitudinal bar deposits in the South Platte River were compared with published data from other Holocene deposits (Ethridge, et al., 1980a). Additional data on transverse bar deposits in the South Platte were collected during phase three and are reported here for the first time. Table 1 is a summary of textural and permeability-porosity data from Holocene sand bodies including the longitudinal and transverse bar deposits of the South Platte River. The relatively low average values reported for permeability in the transverse bar deposits, when compared with the longitudinal bar data, are probably a function of operator variation (different investigators were responsible for each bar type). However, since relationships are only evaluated within each sand body type, the conclusions discussed below are considered valid. Relationships between permeability-porosity and textural parameters are reported in Table 2. The only consistent relationships are between grain size and permeability and between grain sorting and porosity. In the first case, permeability increases as grain size increases and in the second case, porosity increases as sorting improves. There appears to be no consistent

Table 1. Range of values for mean grain size, sorting, permeability and porosity for Holocene sand bodies.

	MEAN GRAIN SIZE Φ (Phi)	SORTING	PERMEABILITY (darcys)	POROSITY (percent)
LONGITUDINAL BARS[1]	2.618 to -1.484 Fine sand to granule	.60 to 2.55 moderately well sorted to very poorly sorted	1.42 to 202.23 (avg. = 66.14)	27.1 to 53.6 (avg. = 41.81)
TRANSVERSE BARS[2]	2.49 to 1.42 Fine sand to medium sand	.41 to 1.06 well sorted to poorly sorted	7.60 to 75.75 (avg. = 33.23)	38.76 to 48.60 (avg. = 44.39)
POINT BARS[3]	3.5 to 0.0 Very fine sand to very coarse sand	.31 to .87 very well sorted to poorly sorted	40.0×10^{-3} to 500 (avg. = 93)	17.0 to 52.0 (avg. = 41)
BEACHES[3]	2.18 to 0.74 Fine sand to medium sand	0.18 to 0.68 very well sorted to moderately well sorted	3.6 to 166.0 (avg. = 68.0)	39.0 to 56.0 (avg. = 49.0)
DUNES[3]	2.83 to 1.32 Fine sand to medium sand	0.23 to 0.48 very well sorted to well sorted	5.0 to 104.0 (avg. = 54.0)	42.0 to 55.0 (avg. = 49.0)

1. Data from Ethridge et al. (1980)
2. Data from Ouchi, Burnett, and Zuirblis (1980)
3. Data from Pryor (1973)

Table 2. Relations of permeability and porosity to textural parameters and depositional environments.

	POINT BARS[1]		BEACH[1]		DUNE[1]	
	Permeability	Porosity	Permeability	Porosity	Permeability	Porosity
Grain size increase	Increase	Increase	Increase	Decrease	Increase	Decrease
Sorting increase	Increase	Increase	Decrease	Increase	Decrease	Increase

	EXPERIMENTAL DATA[2]		LONGITUDINAL BARS[3]		TRANSVERSE BAR[4]	
	Permeability	Porosity	Permeability	Porosity	Permeability	Porosity
Grain size increase	Increase	Independent	Increase	Decrease	Increase	Independent
Sorting increase	Increase	Increase	Independent	Increase	Decrease	Increase

[1] Data from Pryor (1973)

[2] Data from Beard and Weyl (1973)

[3] Data from Ethridge et al. (1980)

[4] Data from Ouchi, Burnett and Zuirblis (1980)

relationship between grain size and porosity or between grain sorting and permeability. The relationship between permeability and sorting expressed in Table 2 require further explanation. For artificially packed sand, permeability increases as sorting increases (improves) for a given grain size and as mean grain size increases for a given sorting (Beard and Weyl, 1973). In natural sand bodies, however, grain size and sorting may be highly correlated. Depending upon the nature and degree of this correlation, permeability could increase, decrease or show no change with an increase in sorting as demonstrated by the data used in the construction of Table 2. In general, permeability is much more variable than porosity. Sand bodies from different depositional environments exhibit well organized, but different patterns of permeability variations (Pryor, 1973). This statement is equally valid when the data from longitudinal and transverse bars are added to the data from point bars, beaches, and dunes which were collected by Pryor (1973).

In point bar deposits, clay laminae are common between crossbedded units. The zones of lower permeability decrease the effective permeability and hence, the ultimate groundwater through-flow capabilities in these sand bodies (Pryor, 1973). This decrease in effective permeability in point bar deposits is a direct result of the fact that maximum permeability gradients parallel the inclined foreset beds of cross stratified units. These inclined foreset beds generally intersect clay laminae at a high angle (Pryor, 1973, p. 181). In contrast, longitudinal and transverse bar deposits of braided streams have fewer and less continuous clay laminae (low permeability units) and hence, the relative groundwater through-flow capabilities in these sand bodies would be greater than in point bar sand bodies. The presence of widespread clay and silt units in trough cross-stratified point bar deposits results in a high degree of anisotropic permeability. Permeability is highest parallel to the length of these cross-stratified units and in the direction of dip of the units. This tendency for significant anisotropic permeability in trough cross-stratified point bar deposits was not observed in planar cross-stratified units of transverse bar deposits (Ouchi, Burnett and Zuirblis, 1980).

ADDITIONAL POROUS-MEDIA FLUME STUDIES

In an effort to design more realistic models of river deposits and to examine the relations between precipitate bands and enclosing sediments, data on sedimentary structures, textures and permeability-porosity patterns in the Holocene stream deposits were used to construct simple and more complex fluvial deposit models in the small porous-media flume (Figs. 3 and 4). Both braided stream (Fig. 3) and point bar deposits (Fig. 4) were modeled. Similarities between the modeled sediment-precipitate relationships and actual sediment-uranium ore relationships found in many Colorado Plateau deposits suggest that the processes operating in both cases may be similar. These similarities include:

1) The tendency for the location and distribution of precipitate bands to be influenced by directional permeability gradients (Pryor, 1973) in cross-stratified units (Fig. 5). Tyler (1981; p. 150) noted this same tendency in uranium-vanadium deposits of the Slick Rock District. In several instances the orientation of individual cross-stratified units played an important role in the mineralization history of these deposits. In these instances, small tabular ore deposits are confined to individual cross-stratified units while the overlying and underlying units are barren. In most case the orientation of the mineralized unit differs from barren units.

2) The effect of discontinuous mudstone layers that disrupt flow patterns. The effect of this disruption is an offsetting of precipitate bands (Fig. 6). Similar offset ore deposits associated with clay

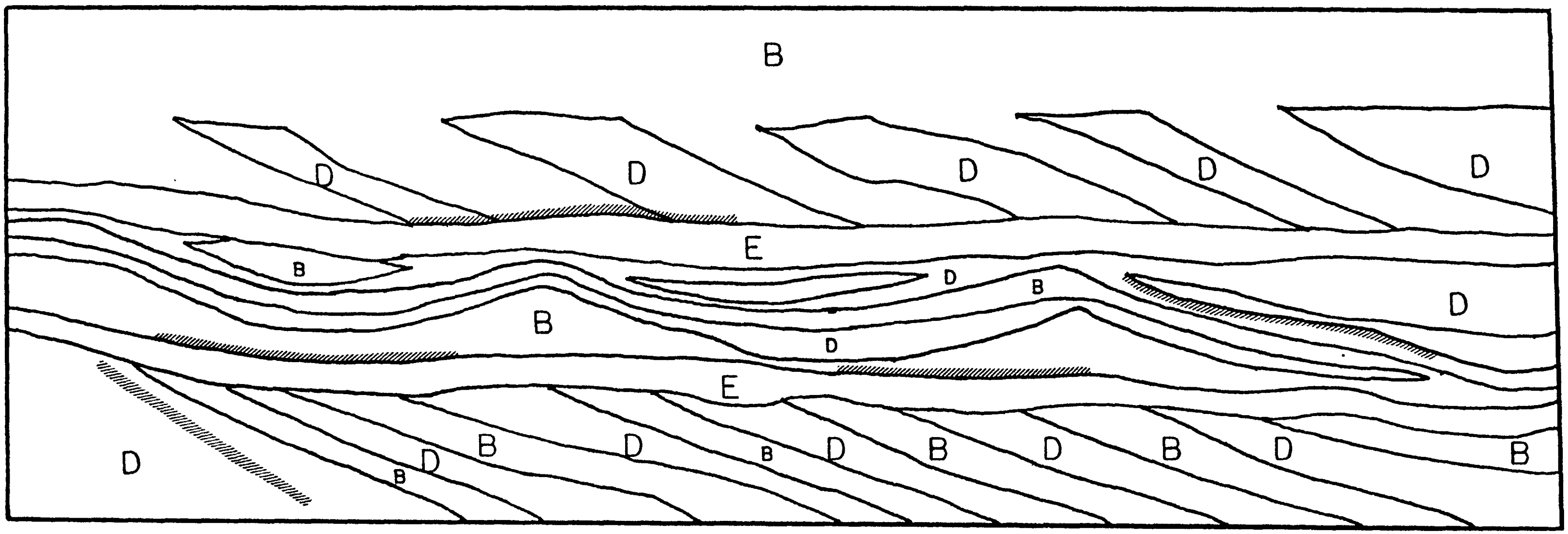

Figure 3. Cross section of simulated Platte River braided stream deposit in small porous media flume. Letters refer to different types of porous media as follows: A = very fine sand (o.15 to 0.3mm); B = fine sand (0.15 to 0.6mm); C = fine Ottawa sand (0.42 to 0.59mm); D = Ottawa sand (0.5 to 0.84mm); and E - small glass beads (1.60mm). Small hachured bands are impermeable layers.

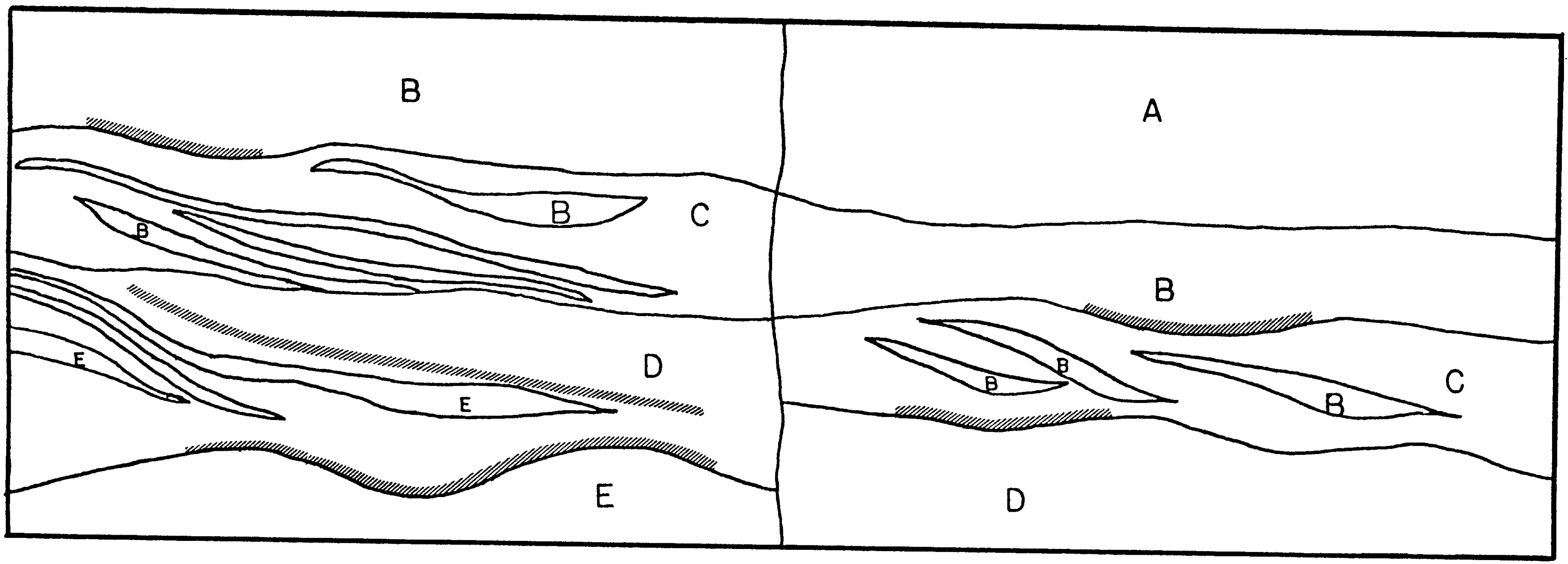

Figure 4. Cross section view of simulated complex point bar deposit in small porous media flume. Letters refer to different types of porous media as described in caption to Figure 3 on previous page. Small hachured bands are impermeable layers.

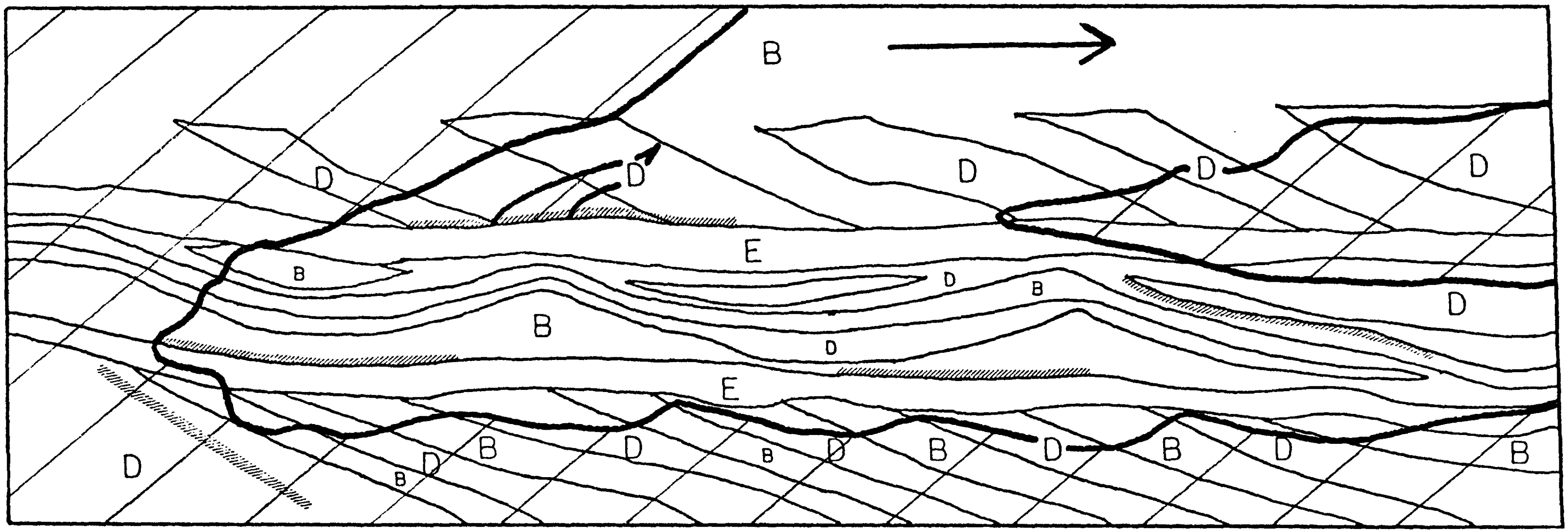

Figure 5. Cross section of simulated Platte River braided stream deposit in small porous media flume. Letters refer to different types of porous media as described in caption to Figure 3. Dark band equal location of precipitate band. Arrow indicates flow direction. Thickness of precipitate band is exaggerated for illustrative purposes. Hachured areas equal areas that contain humate solution not displaced by potassium aluminum sulfate solution.

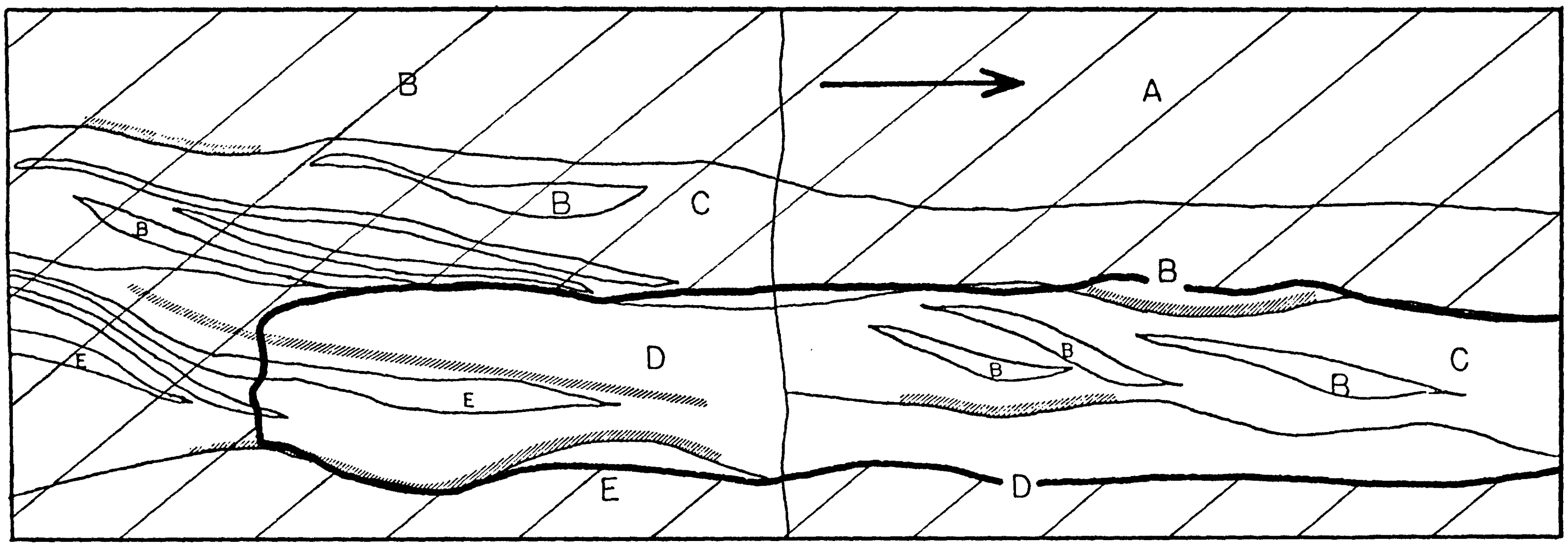

Figure 6. Cross section view of simulated complex point bar deposit in small porous media flume. Letters refer to different types of porous media as described in caption to Figure 3. Dark band represents location of precipitate band. Arrow indicates flow direction. Hachured area equals area of humate solution not displaced by potassium aluminum sulfate solution. (Note: Redrafted from photograph; Figure 17B, p. 106, Ethridge, et al., 1980).

layers were observed by Shawe, et al. (1959, p. 412) in the Slick Rock District.

3) The presence of fine bands of precipitate that parallel the cross-laminations above the final precipitate. Similar relations have been noted by Squyres (1963) in the Ann Lee Mine of the Grants Mineral Belt.

4) The intertonguing relations between sedimentary layers with precipitate bands and those without precipitate bands observed in model studies have also been observed in ore-bearing sandstones of the Slick Rock District (Ethridge, et al., 1980, p. 62; and Shawe, 1976, p. D25). These intertonguing relationships are especially apparent in point bar deposits and are not unexpected based on data from modern point bars (Pryor, 1973. In the modern point bars examined by Pryor, large variations in texture and permeability patterns are the rule.

If, as some researchers suggest (Brookins, 1977 and 1979; Galloway, 1979, 1980), the ore forming processes were early in the post-depositional history of the deposits, then the geometry and distribution of the ore deposits would have been controlled, in large part, by the initial texture, porosity, permeability, and sedimentary structure patterns within the host sandstones as is certainly the case in the laboratory models. Detailed discussions of the experimental results and the similarities between the modeled deposits and actual ore bodies is found in Ethridge, et al. (1980a and b) and in Ortiz, et al. (1980a).

FIELD STUDIES IN THE SLICK ROCK DISTRICT, S.W. COLORADO

Field studies of Jurassic sedimentary rocks and contained vanadium-uranium ore deposits in the Slick Rock District of the Uravan Mineral Belt, southwest Colorado (Fig. 7) were initiated during the second phase of this investigation and completed during the third and final phase.

The field studies involved the detailed examination of some 31 surface exposures, 80 subsurface geophysical logs, four borehole cores, underground exposures in seven mines, and 95 thin sections of surface and subsurface samples. The principal objective of these studies was to develop an understanding of the depositional and diagenetic histories of the ore-bearing Salt Wash Member of the Morrison Formation and related upper Jurassic sedimentary rocks (Fig. 8). A second, but no less important objective was to examine the relationships between depositional sedimentary environments and the contained vanadium-uranium deposits. The third and final objective was to provide data for the development of a computer simulation model for the Salt Wash Member that would predict favorable locations for ore deposits. Data and results obtained for the first two objectives are described in detail by Tyler (1981) and are summarized below. Methods and results for objective three are described later in this report.

The inferred Late Jurassic depositional environments of the Slick Rock District are schematically illustrated in Figure 9. During the deposition of the Entrada Sandstone, much of western Colorado and eastern Utah, including the Slick Rock District, was arid and covered by migrating sand dunes. A decrease in the amount of sand supplied to the area possibly coupled with a rise in the level of the water table facilitated

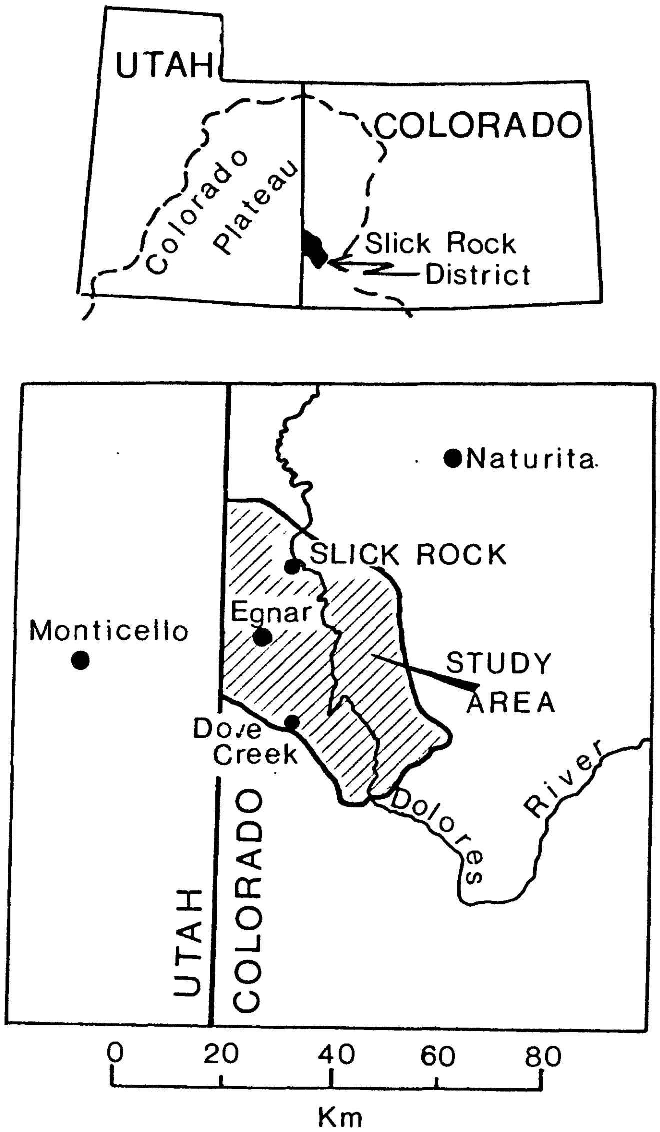

Figure 7. Location of the Slick Rock District, southwestern Colorado (Modified from Shawe, et al., 1968).

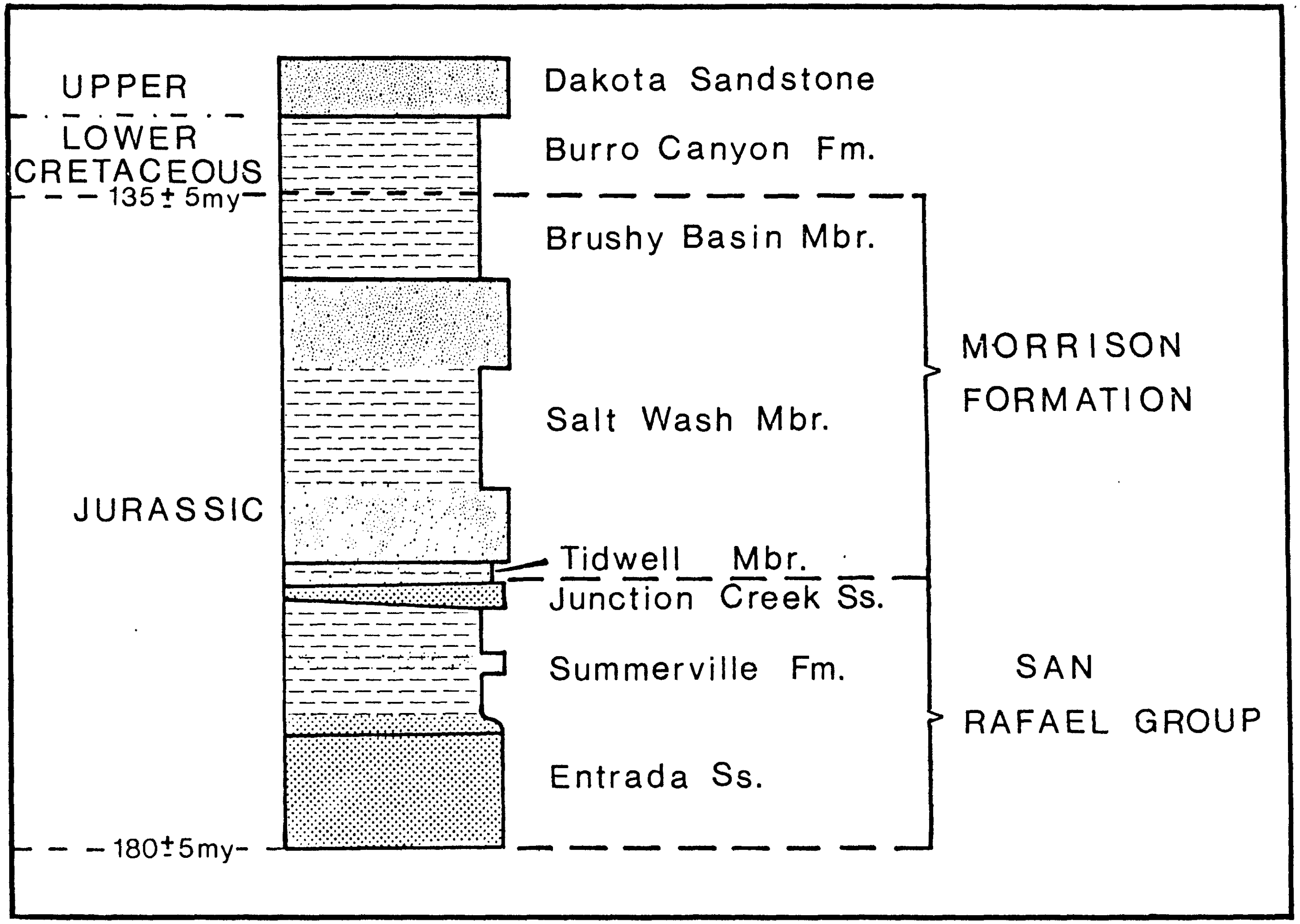

Figure 8. Upper Jurassic and Lower Cretaceous stratigraphic column, Slick Rock District, San Miguel and Dolores Counties, Colorado (From Tyler, 1981).

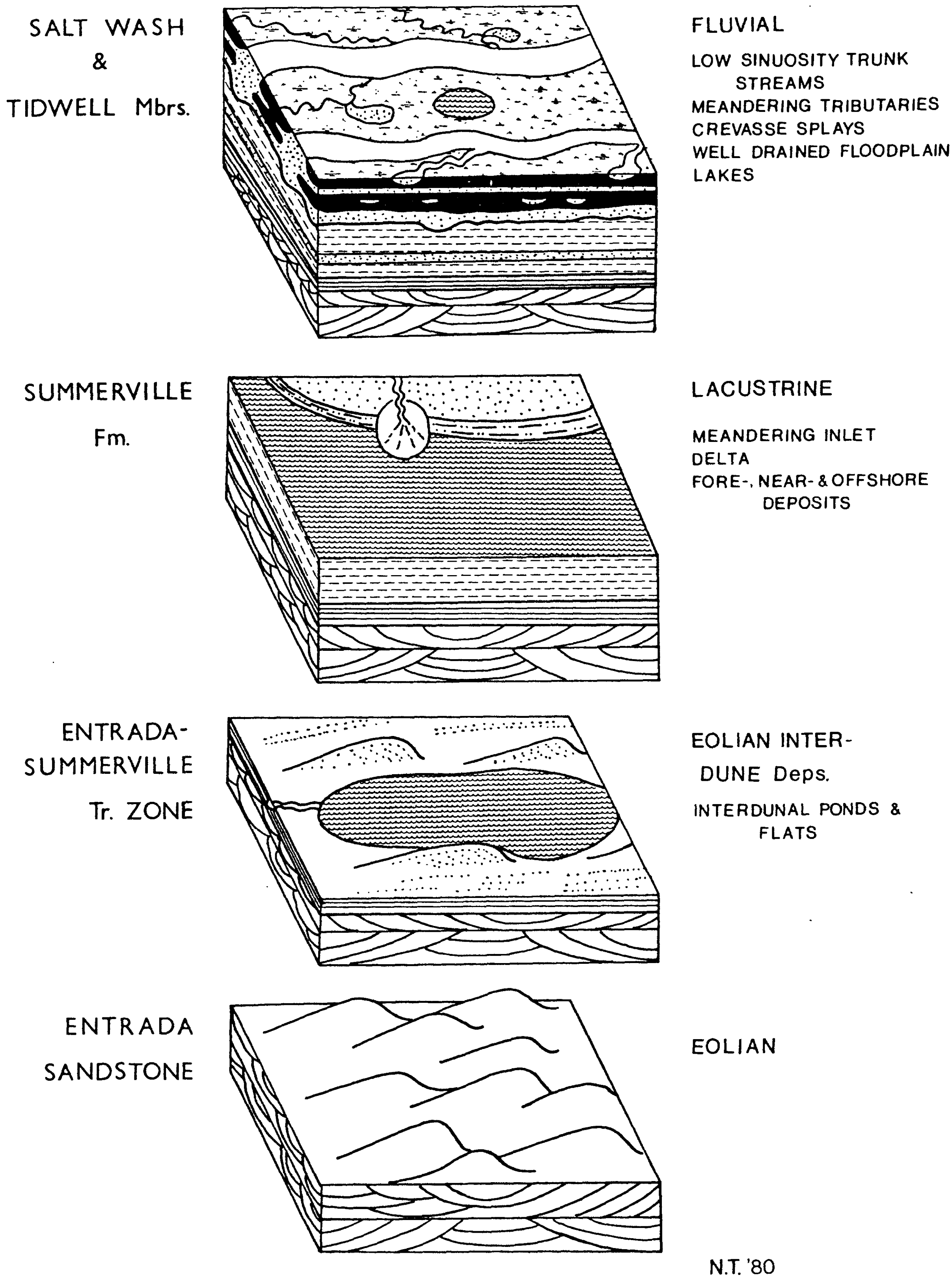

Figure 9. Late Jurassic genetic stratigraphy in the Slick Rock District, southwestern Colorado (From Tyler, 1981).

the formation of the extensive interdune deposits characteristic of the Entrada-Summerville transition zone. During Summerville time the Four Corners region had been broadly downwarped. Low rates of sediment influx and a high water table level resulted in the development of a large, relatively shallow lake. The Summerville Formation in the Slick Rock District is considered to be the nearshore lacustrine equivalent of the Todilto Limestone and associated units south of the study area. Periodic minor fluctuations in the water level were common. A major regression took place during early- to mid-Summerville time resulting in the extensive shoreface and foreshore lacustrine deposits of the mid-Summerville ledge. Gypsum beds overlying the Todilto Limestone Formation to the south of the district probably formed during this lacustrine regression. In the Slick Rock District, evidence that the nearshore lacustrine sands were subaerially exposed is present in the form of mudcracks. Abundant salt casts in these sedimentary rocks suggest that the lacustrine waters were saline. Small meandering streams flowed into the Summerville lake from the north, and deposited their loads in lacustrine deltas. As the Summerville lake dried up, sand dunes migrated across the lacustrine plain. These eolian sands are now preserved as the Junction Creek Sandstone in the southern part of the Slick Rock District. A major period of fluvial activity followed the final regression of the Summerville lake. The initial fluvial sediments in the district were largely deposited in a flood plain setting (the Tidwell Member). Following this initial period fluvial activity, large, low sinuosity streams flowed across the area from the west. These wide and deep, slightly sinuous streams are suggested to be transitional between the braided streams of the proximal Salt Wash and the meandering streams of the distal Salt Wash.

Small meandering tributaries entered the larger low sinuosity channels from both margins. Greater accumulations of sandstone deposited by these aggrading low sinuosity streams are located in two eastward trending zones of higher sandstone contents in the vicinity of Slick Rock and Dove Creek, respectively (Fig. 10). These zones of high sandstone content are inferred to represent the location of two major trunk streams of the Salt Wash distributary system. Reasons for the localization of the major trunk streams are not well understood, but the Slick Rock axis may have been controlled, in part, by the Gypsum Valley salt anticline which was active during deposition of the Salt Wash. Local tectonism, thus, may have been an important factor in shaping the architecture (trend, distribution, and inter-connectedness) of the Salt Wash fluvial deposits.

The Slick Rock vanadium-uranium District is localized within the braided-to-meandering transition zone of the Salt Wash fluvial system. Migration of ore-bearing solutions was probably restricted by decreasing transmissivities in this zone. Ore deposits in the district are divided into two broad categories: (1) small, patchily distributed, relatively high grade pseudomorphic replacements of organic debris (logs and wood fragments) and (2) ore deposits that have no direct relations with organic debris. In this second category, deposits are relatively large and low grade. The source of the vanadium in the district and the larger Uravan belt has been satisfactorily demonstrated to lie in the epigenetic destruction of the opaque accessory minerals of the Salt Wash and associated sediments (Shawe, et al., 1959; Shawe, 1976). The source of the uranium is more difficult to identify. Tyler (1981) believes that the conclusions of Finch (1967) and Brooks, et al. (1978) are most compatible

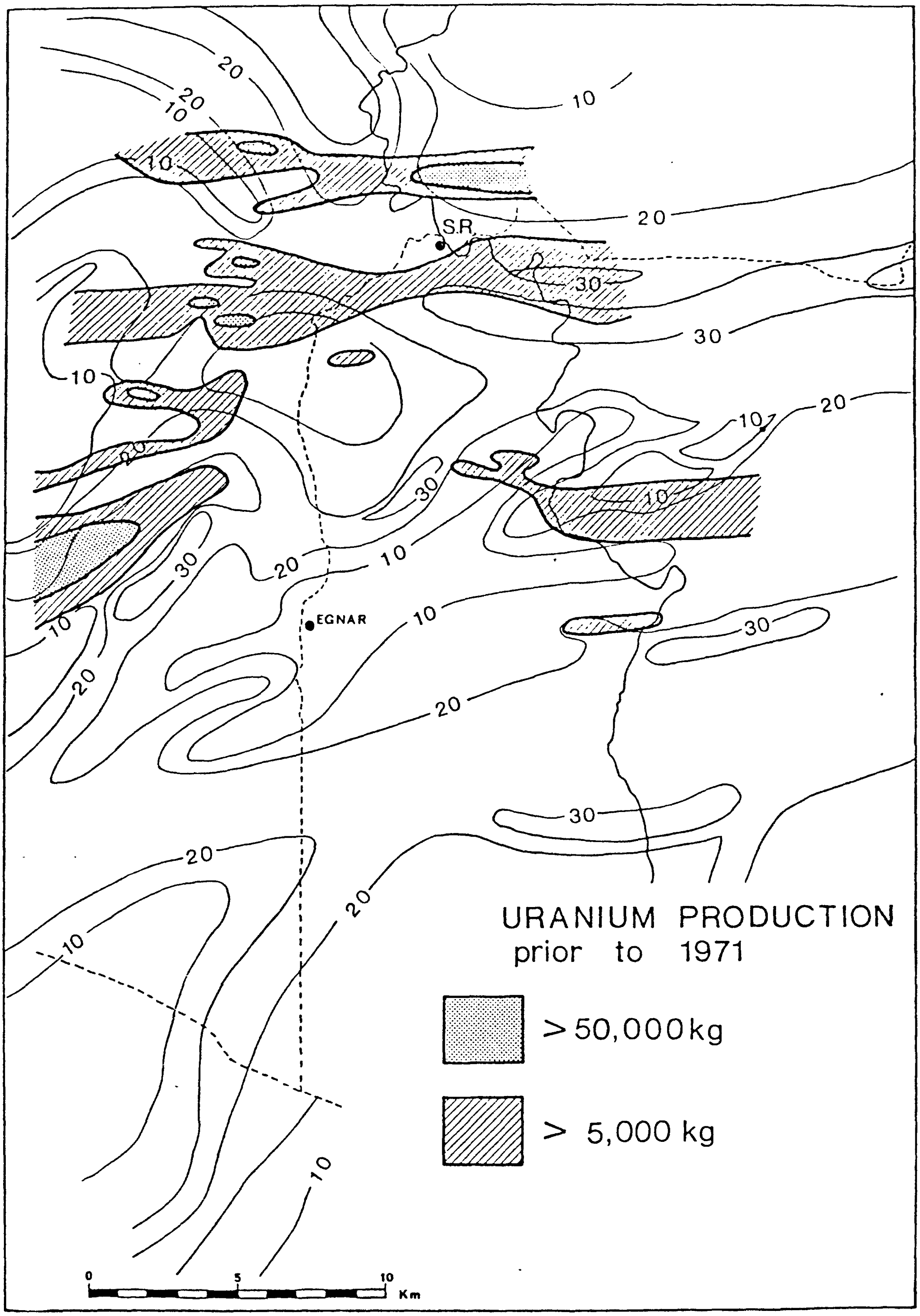

Figure 10. Composite isopach-uranium production isopleth map of the upper Salt Wash, Slick Rock District, Southwest Colorado (S.R. stands for Slick Rock; Contour interval for isopach is 10 meters: from Tyler, 1981).

with existing data. These authors believe that the source of the uranium lies in the diagenetic destruction of volcanic and granitic detritus in the Salt Wash and Brushy Basin Members

The nature of the reductants required for the precipitation of the uranium out of solution has received considerable attention. The most recent theory proposed by Granger and Warren (1981) suggests that vanadium (III), which is a powerful reducing agent, may have been responsible for the precipitation of the uranium. In this theory it is postulated that vanadium and aluminum were released during diagenesis of the sediments and that they formed soluble organic complexes. Later the aluminum and vanadium were forced out of solution by ion exchange and formed hydroxide gels which subsequently crystallized as clay minerals. The uranium (VI) was reduced and precipitated principally by vanadium (III) obtained from these organic complexes. Based on a detailed petrographic study, Tyler (1981) suggests that mineralization took place at moderate depths of burial during the later eogenetic or early mesogenetic stage of diagenesis. Precipitation of ore minerals was accompanied by alteration and replacement of diagenetic minerals and corrosion and replacement of framework grains. Petrographically, the ore zones are most easily distinguishable by the abundance of vanadium-bearing phyllosilicate minerals, notably chlorite.

On a district wide scale the larger, low grade vanadium-uranium deposits are directly related to the architecture of the host sandstones. Production isopleth maps of uranium (Fig. 10) and vanadium yields prior to 1971 reveal that these larger ore bodies are oriented along E-W or E-NE trends parallel to the sediment depositional axes. These ore bodies are preferentially found within and along the margins of the major low sinuosity stream deposits of the Slick Rock axis and within the meadering tributary deposits near their confluence with the trunk stream deposits. The importance of the architecture of these deposits is illustrated by the fact that the ore bodies most commonly occur in the laterally continuous low sinuosity channel deposits. The generally isolated point bar deposits less commonly contain ore and usually only where the deposits are interconnected with the low sinuosity channel deposits. The lateral interconnectedness of the low sinuosity stream deposits is of prime importance in preferential ore deposition. These sheet sandstones probably acted as conduits for the transport of uranium-bearing ground waters which flowed from up-dip recharge areas.

On a local scale, textural and permeability patterns and the orientation of individual cross-stratification units played an important role in the history of ore deposition in the Salt Wash Member as previously discussed (see section on Additional Porous-Media Flume Studies).

PHYSICAL MODEL STUDIES OF ALLUVIAL FAN DEPOSITS

During phase three of the investigation into the origin of certain Colorado Plateau type deposits, seven physical models of alluvial fan deposits were constructed in a large 2.0m by 2.5m by 0.4m deep indoor flume (Fig. 11). These physical models were designed to simulate sedimentary deposits of the uranium-bearing Westwater Canyon Member of the Morrison Formation of the Grants Mineral Belt, New Mexico. Sediment used in the building of these fans was a mixture of coarse, very angular sand, medium-to-fine-grained subrounded fluvial sand, and commercial silica sand. This mixture provided a white deposit which contrasted with the darker humate deposit color and a bimodal grain size for better differentiation of coarse and fine layers within the model. The fans were allowed to build by natural processes with a recirculating humic acid solution. After the fans were built to a suitable level, an aluminum potassium sulfate solution was infiltrated from their apices to form a humate precipitate. During the seven runs that were completed, two different aquifer and tectonic conditions were modeled. In the first instance an unconfined aquifer was simulated and in the second instance a confined aquifer and post-depositional tilting were simulated. After each run the fans were dissected, photographed, any humate precipitate bands were accurately recorded as to their three-dimensional location within the fan, and samples were taken in small aluminum tubes. The grain size distribution, porosity, and permeability of the samples were determined. Details of the experimental precedures and the results obtained in the first five runs are described by Andrews (1981).

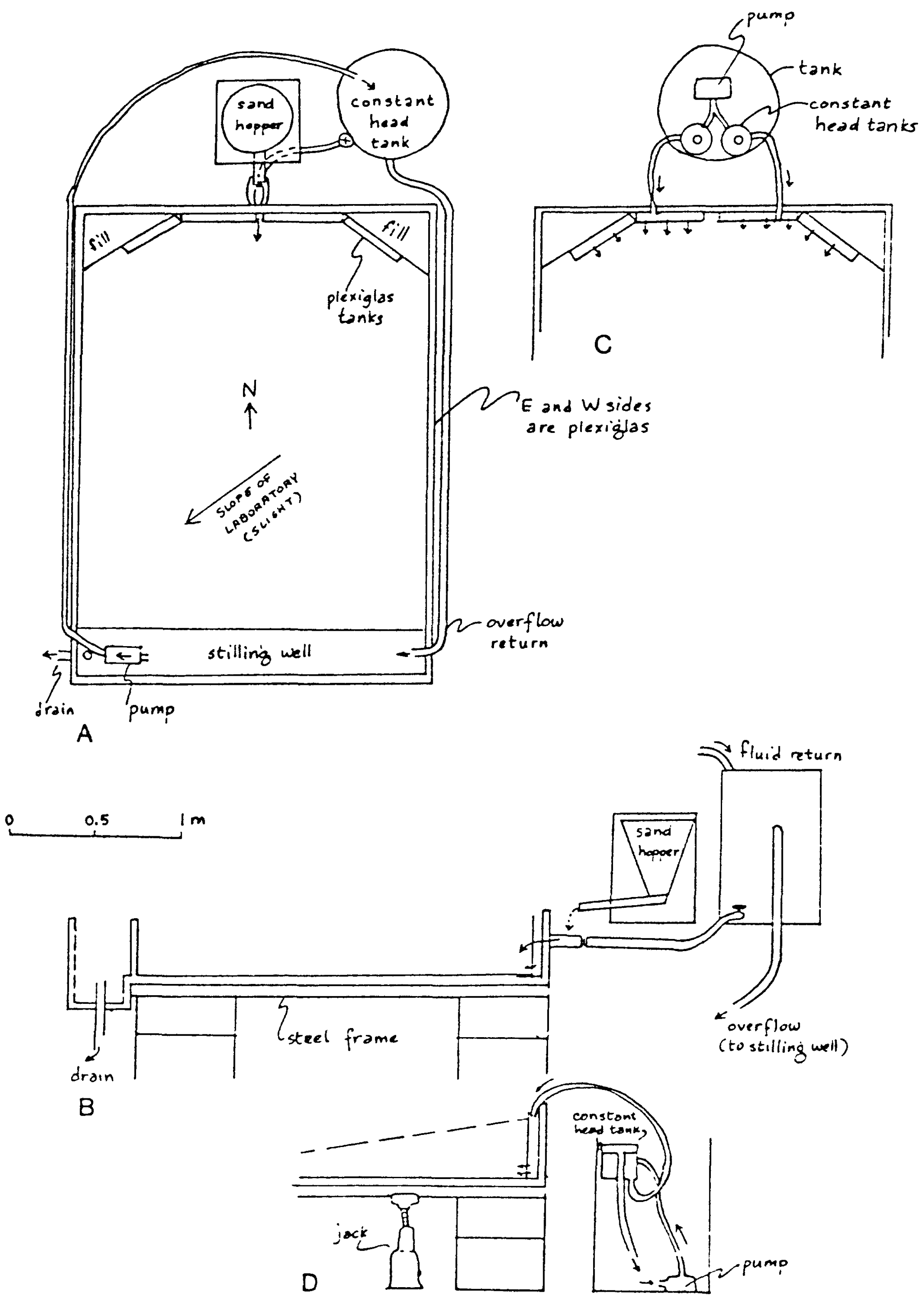

Figure 11. Plan and side view of large indoor flume (from Andrews, 1981).

The two different aquifer and tectonic conditions modeled were designed to simulate the conditions proposed in two different hypotheses concerning the origin of uranium deposits in the Westwater Canyon. The first hypothesis has been described as the sedimentary hypothesis (Brookins, 1977 and Galloway, 1979 and 1980). In this hypothesis it is proposed that groundwater flow patterns during and closely following deposition of the sediments controlled primary ore emplacement (Galloway, 1979). These flow patterns were controlled by the radiating pattern of the fan aquifer system. According to Galloway, humates necessary for uranium precipitation were derived from vegetation growing on the Westwater fan and uranium was derived from the overlying tuffaceous Brushy Basin Member. During the period of ore deposition the Westwater Canyon deposits represented a semi-confined aquifer underlying the less permeable Brushy Basin.

The second hypothesis tested has been termed the post-depositional tilting and erosion hypothesis (Granger, 1968; Melvin, 1976). In this hypothesis it is suggested that ore deposition took place during Early Cretaceous time. During this time period the Morrison deposits were uplifted to the south and truncated, resulting in a beveled outcrop exposure of the entire Morrison stratigraphic section. Both researchers note a correlation between this paleosurface and the positions of major ore bodies. This hypothesis proposes explanations for both the trend and the northerly stratigraphic rise of the ore bodies in the Grants Mineral Belt. The source of the humates is theorized to be swamps or bogs developed during Early Cretaceous time.

Humate precipitates formed under experimental conditions in the large indoor flume were similar to primary uranium deposits of the

Grants Mineral Belt in terms of geometry and distribution. Although scaling problems preclude the direct comparison of the physical models and the actual Westwater deposits, data was collected which help point out the strengths of each of the hypotheses reviewed above. The physical model which most closely simulates the actual situation that exists in the Grants Mineral Belt is the unconfined aquifer. Two aspects of the humate deposits in this model are important with regard to the hypotheses reviewed above: (1) reactions at the interface between two solutions did produce tabular-shaped precipitates similar in terms of geometry to those found in the Grants Mineral Belt; and (2) these precipitate bands comprise en echelon bodies, elongate parallel to drainage patterns, which tend to rise stratigraphically basinward (Figs. 12 and 13). The nature of the relationship between the precipitate bands and the enclosing sediments are thus similar to that observed for ore deposits in the Grants Mineral Belt (Santos, 1963; Granger, 1968; and Galloway, 1979 and 1980) and also in the Uravan mineral belt (Reinhardt, 1963 and Tyler, 1981).

Results of these physical model studies suggest that tabular, en echelon ore bodies that rise stratigraphically basinward can form without necessity of outside influences such as post-depositional tilting and erosion or volatiles and gases from nearby stocks (as proposed for the Uravan Mineral Belt; Rheinhardt, 1963). The simpler sedimentary hypothesis (Brookins, 1977 and Galloway, 1979 and 1980) is sufficient to account for the observable relations.

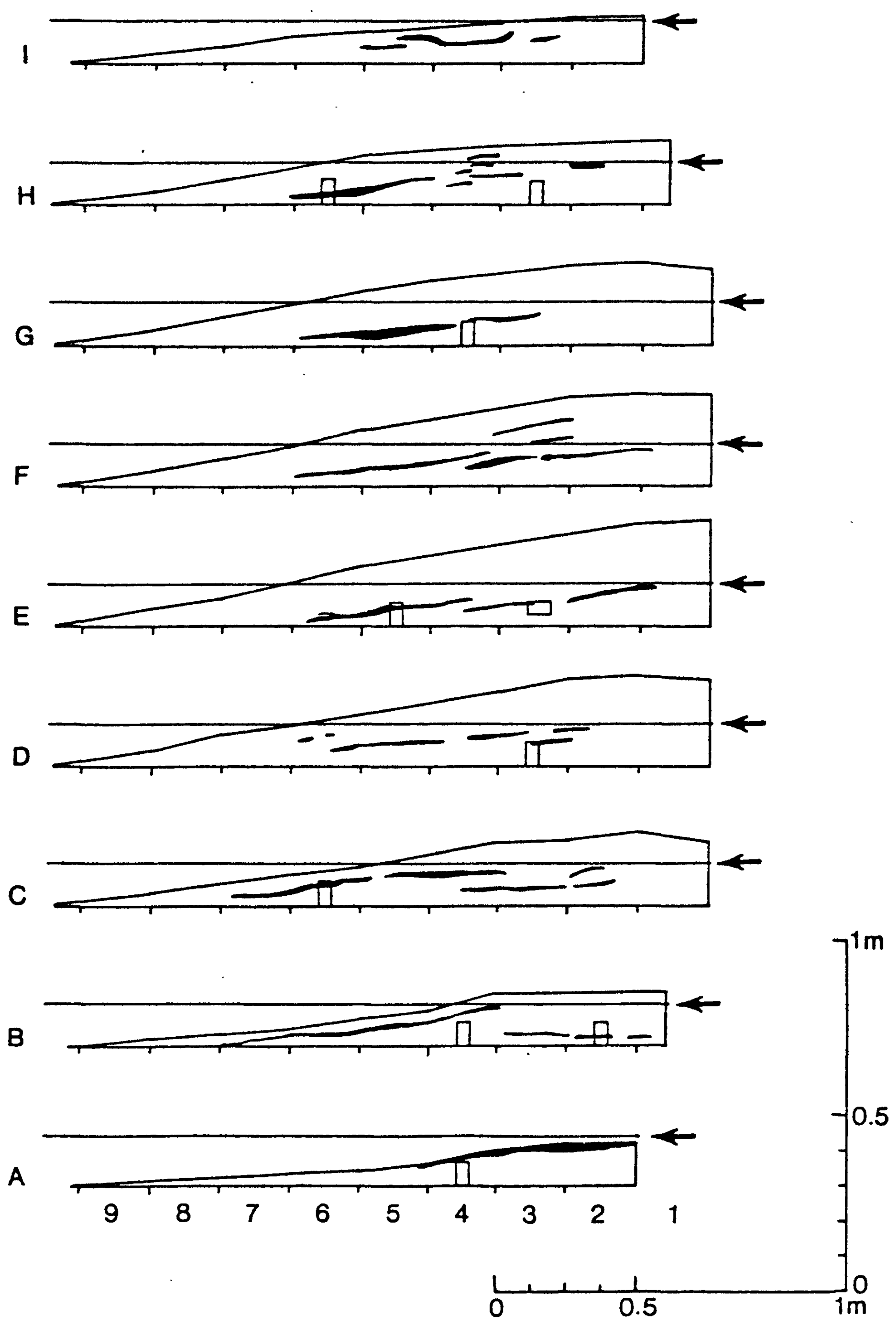

Figure 12. Locations of humate deposits in longitudinal sections of large indoor flume (Run #4). Arrows equal humate lake level (For details see Andrews, 1981). Dark irregular lines are humate deposits. Small rectangles show location of some of the small core tube samples.

Figure 13. Plan view reconstruction of humate deposits, in large indoor flume (Run #4).

INITIAL NUMERICAL MODEL STUDIES

A numerical computer modeling precedure was included in the investigation into the origin of Colorado Plateau type uranium deposits as a means whereby modeling of groundwater aquifers could be accomplished on a scale too large for physical modeling techniques. During the initial phase of the investigations, a numerical model was perfected which was capable of predicting the location and shape of the interface between solutions in a homogeneous porous medium. Details of the computer model and a comparison of numerical, analytical, and physical model results is given in Ferentchak (1979) and Ortiz, et al. (1980a). The excellent agreement between the three solutions (e.g. numerical, analytical, and physical; Fig. 14) is indicative of the adequacy of the numerical model in predicting the location and shape of the interface and, thus, the precipitate band.

Based on the excellent results obtained in these initial numerical modeling studies, the model was modified and used to predict favorable locations for mineral deposits in the Salt Wash Member in the Slick Rock District. Results of these studies, conducted in the final phase of the investigation are given in the next section of this report.

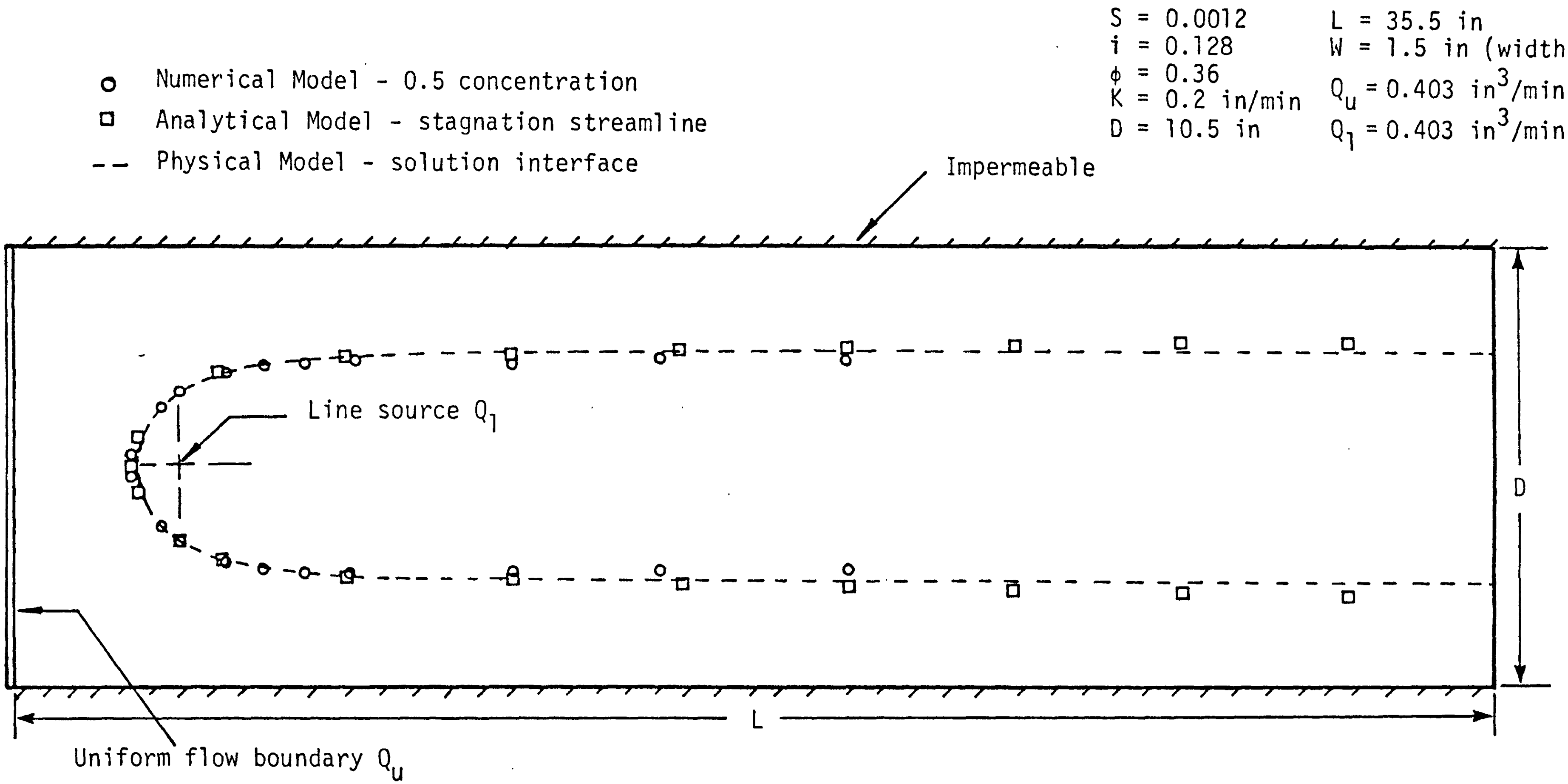

Figure 14. Comparison of three solutions for steady state conditions (From Farentchak, 1979).

THE NUMERICAL MODEL - THE SLICK ROCK DISTRICT

The numerical model developed in phase II was used to predict favorable locations of uranium deposits in the area around Slick Rock. Numerical models are complex and difficult to use properly. Numerous publications on groundwater modeling are available (McWhorter and Sunada, 1977; and Segerlind, 1976) and a description of the model used in these experiments is found in Ferentchak (1979).

For the Slick Rock District model, constant head boundaries on the east (column j; Fig. 15) and west (column A; Fig. 15) boundaries of the area were used. The north and south boundaries (row 1 and 10) were selected to be stream-lines (impermeable boundaries). The source areas for the uranium were selected on the basis of sedimentologic considerations concering the predicted location of the major axes of fluvial transport and hence, sand deposition (Tyler, 1981) to be in grid A2, A4 and A8 and were present until steady-state concentration was obtained in the model. This took approximately 1600 simulated years. Computer runs were made with other grids selected as source area to test the sensitivity of the model to the location of source areas. Results of these computer runs indicated that it is necessary to define source areas based on field and/or subsurface geologic evidence in order to get depositional patterns in the model to reflect depositional patterns in the field.

Basic data of aquifer thickness, hydraulic conductivity and porosity were obtained by field and laboratory studies. Aquifer thicknesses were obtained from studies by Tyler (1981) and are shown in Figure 15 for each grid. Values of hydraulic conductivity were computed from grain sizes and porosities through the use of the Fair-Hatch equation (McWhorter and

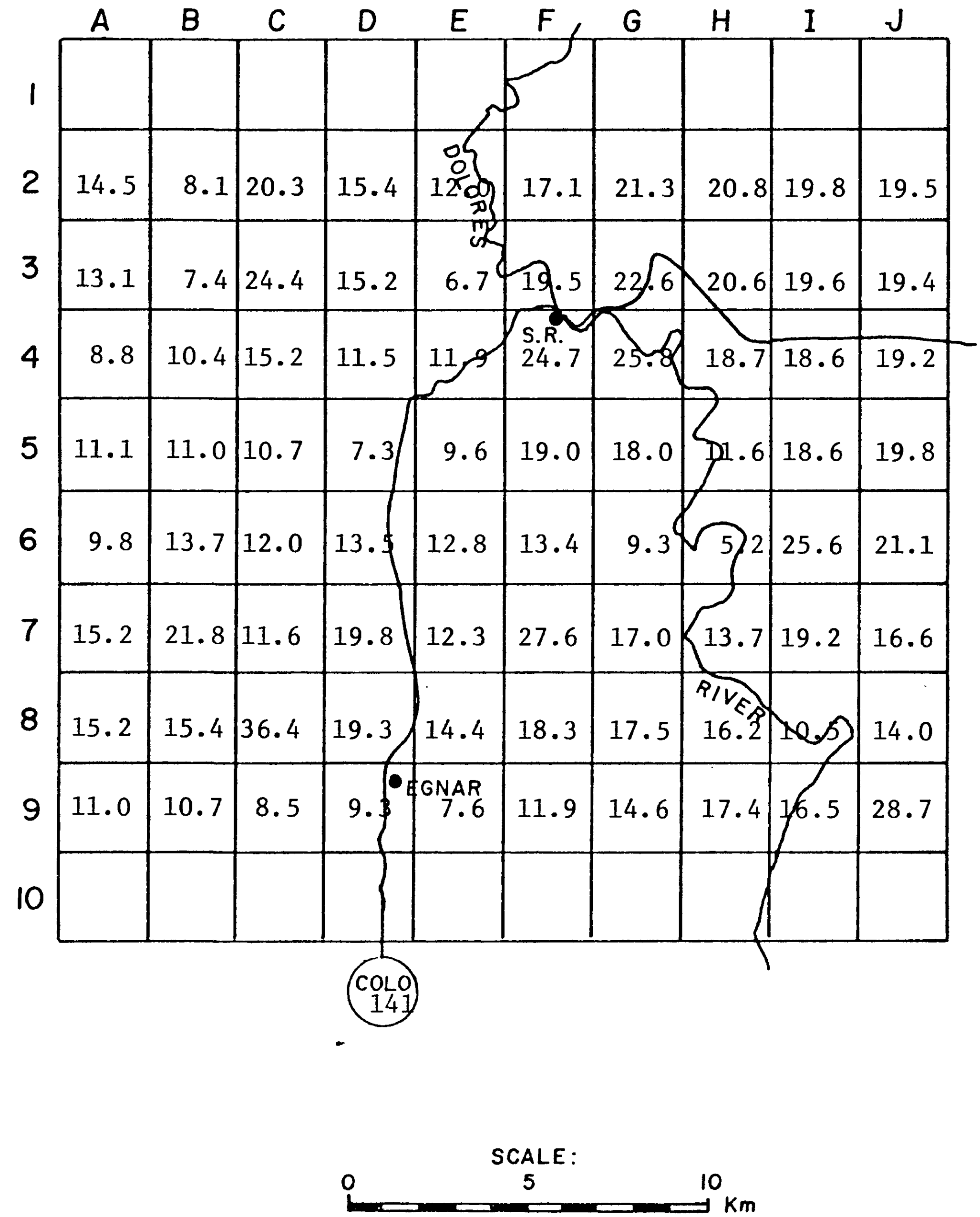

Figure 15. Aquifer thickness map for computer model (in feet)

Sunada, 1977). Grain sizes and an estimate of original porosity were obtained from analyses of available thin sections of aquifer samples from the area. To estimate original porosity, pore space and diagenetic cements were point counted and the two values were summed and converted to percentages. Values of hydraulic conductivities are given in Fig. 16 for each model grid.

The computer model was run until steady state concentrations of the uranium were obtained (approximately 1600 simulated years). Figure 17 shows the predicted location of the uranium deposits before any geologic change took place. The criteria used to predict precipitation of uranium is given by Ferentchak (1979). The computer results compare very favorably with the depositional pattern reported by Tyler (1981; Fig. 17). Predicted location of the uranium deposits through the use of the computer can be improved as more hydrologic data becomes available.

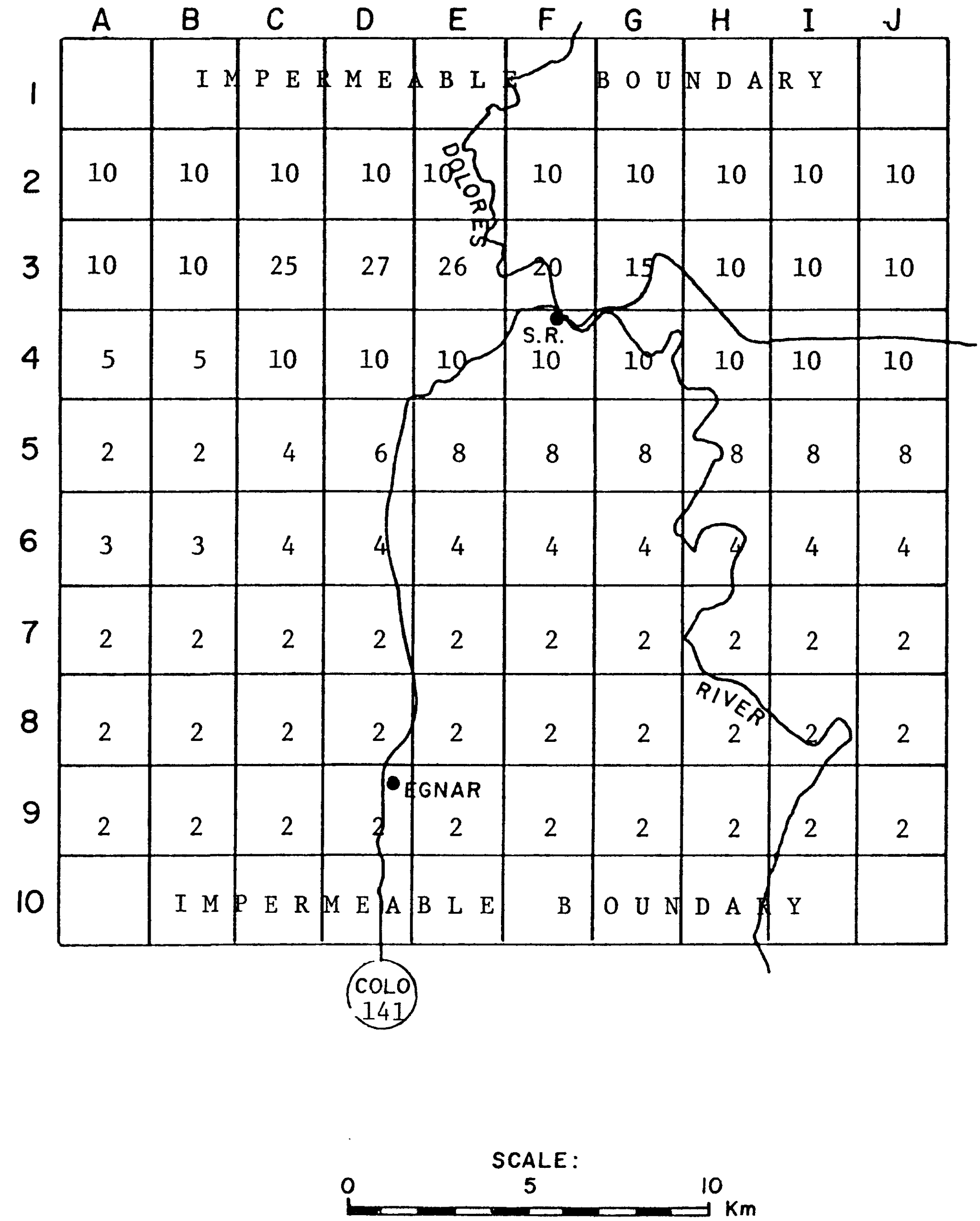

Figure 16 . Hydraulic conductivity map for computer model (in feet per day).

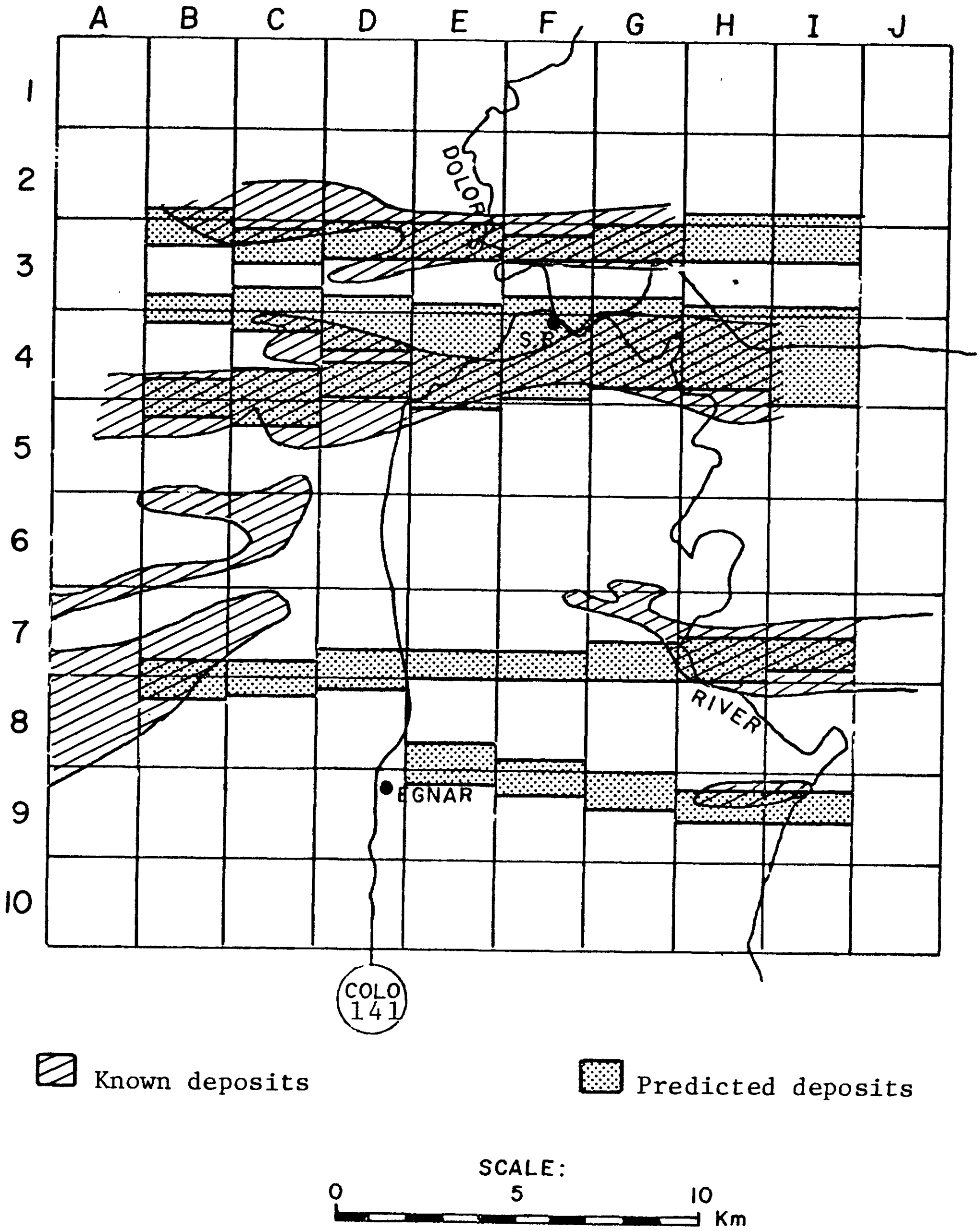

Figure 17 . Predicted and known uranium deposition .

SUMMARY

During this investigation into the origin and distribution of Colorado Plateau type uranium deposits, several different but related avenues of research have been undertaken. They include physical model, field, and numerical model studies. Data obtained during these studies support the contention that precipitates can form at the interface between two groundwater solutions and that the location and distribution of the precipitates are controlled by fluid flow phenomena and the texture and porosity-permeability patterns within the host media. Relationships observed in the physical models are similar to those recorded in some uranium mineral belts in the Colorado Plateau. These relationships include: (1) local phenomena such as the tendency for precipitates to be influenced by directional permeability gradients in cross-stratified units and the effect of low permeability layers in disrupting flow patterns and offsetting precipitate bands, and (2) regional phenomena such as the tendency for precipitates to form tabular, en echelon deposits, elongate parallel to original drainage patterns in the host sandstones that tend to rise stratigraphically basinward.

Field studies in the Slick Rock District of the Uravan Mineral Belt provided a modern interpretation of the depositional systems of the fluvial Salt Wash Member of the Morrison Formation. Data collected on the trend, distribution, and interconnectedness of the host sandstones and the relation between ore bodies and these sandstones revealed the importance of the sandstone architecture in controlling the movement of uranium-bearing ground waters and the localization of ore bodies.

Data obtained from the physical models of the Grants Mineral Belt strongly support the hypothesis (Galloway, 1979) that ore deposits in this belt were formed in the early post-depositional history of the host sandstones and that their shape and distribution was controlled, probably to a large extent, by the regional distribution and type of fluvial channel sandstone deposits and by local textural, porosity-permeability, and sedimentary structure patterns established at the time of deposition of the host sediments. Based on these assumptions, a numerical model was developed that can predict favorable locations for the development of mineral deposits. This model was tested successfully using data collected from the Slick Rock District.

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