

A New Model for Tabular-Type Uranium Deposits

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Abstract

Tabular-type uranium deposits occur as tabular, originally subhorizontal bodies entirely within reduced fluvial sandstones of Late Silurian age or younger. This paper proposes that belts of tabular-type uranium deposits formed in areas of mixed local and regional ground-water discharge shortly after deposition of the host sediments. The general characteristics of tabular-type uranium deposits, especially the most studied deposits, those in the Uravan mineral belt, Henry basin, and Grants uranium region, indicate that their essential feature was the formation at a density-stratified ground-water interface in areas of local and regional ground-water discharge. Reconstruction of the paleohydrogeology is the key to understanding the formation of these deposits. Gravity-driven ground water recharged in major highlands and discharged in lowlands at major concave changes in paleotopographic slope. Shallow local and deep regional ground-water systems were characterized by dilute and saline water, respectively. Typically, underlying marine rocks, especially evaporites, provided the solutes to the deep regional ground water. A density-stabilized interface existed at the ground-water divide between local and regional flow systems. Tabular-type uranium deposits formed where these divides or interfaces intersected pockets of reduction where organic matter accumulated. The precipitation of humate and uranium at an interface accounts for the tabular shape and the tendency of deposits to rise stratigraphically into the basin. Geologic ground-water controls that favor discharge, such as the pinch-out of major aquifers, are also favorable for uranium ore. The combination of topographic and geologic features that both cause discharge is most favorable for ore deposition.

Introduction

TABULAR-TYPE uranium deposits have been known since radioactivity was first discovered and have been studied intensely for 40 yr since the uranium boom of the 1950s (Finch, 1967). They account for approximately 65 percent of the total United States production and reserves of uranium (Chenoweth and McLemore, 1989). Despite their importance and history of study, there is no consensus on their formation; there is not even any consensus on what deposits constitute this type or on its definition. This paper presents a model that groups deposits according to general characteristics and offers a genetic explanation for those characteristics. It also provides exploration guidelines for new districts and belts of tabular-type uranium deposits. This paper should be considered as a brief outline of a model. A full description of the model and discussion of alternative models is in progress.

The deposits typical of this type include, among others, those in the Upper Jurassic Morrison Formation of the Uravan mineral belt, Henry basin, and Grants uranium region of the Colorado Plateau, United States (Fischer, 1947, 1974; Granger, 1968; Hilpert, 1969; Rautman, 1980; Turner-Peterson et al., 1986); Upper Triassic Chinle Formation in the White Canyon area and other parts of the Colorado

Plateau (Thaden et al., 1964; Young, 1964); Eocene Echo Park Alluvium in central Colorado (Chapin et al., 1982); Carboniferous and Permian rocks of the Maritime provinces of Canada (Prest et al., 1969; Dunsmore, 1977a and b); Eocene rocks near the Aquitaine basin of France (Meunier et al., 1989); Carboniferous and Permian rocks of eastern Europe (Barabash and Virag, 1966; Barthel and Hahn, 1985); Carboniferous to Jurassic rocks of the Arlit area of Niger (Bigotte and Obellianne, 1968; Cazoulat, 1985); Paleozoic to Tertiary rocks of Argentina (Belluco et al., 1985); and Tertiary rocks in the Lake Frome area of South Australia (Sanford, 1985).

Workers have described a number of important general characteristics and proven guides to exploration (e.g., Finch, 1967). They have also cited characteristics that only apply to deposits in particular local areas. The approach of this paper is to describe the deposit type according to only those characteristics that are generally present and to treat the local characteristics as variations or subtypes of the general model.

As discussed below, the essential feature or unifying element that explains the general characteristics of these deposits appears to be their formation at a density-stratified ground-water interface. This hypothesis, sometimes called the "brine-interface model," has been proposed in various forms by pre-

vious workers (Fischer, 1947, 1974; Shawe, 1955, 1966, 1976; Granger, 1968; Melvin, 1976; Sanford, 1982, 1990a and b; Granger and Santos, 1986; Northrop et al., 1990). However, this paper presents a new synthesis that incorporates observations previously not included in any comprehensive model, and it offers a genetic explanation for the existence of such an interface, and hence, for the formation of tabular-type uranium deposits.

This model differs fundamentally from the lacustrine-humate model for tabular-type uranium deposits (Peterson, 1980; Turner-Peterson, 1985; Adams, 1986; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986). According to the lacustrine-humate model, ground water was driven by compaction from lacustrine muds in the mud-flat facies of a large playa lake downward and outward into fluvial sands where humate and uranium precipitated as a result of the chemical evolution of the one fluid. According to the present model, ground-water flow is dominantly gravity driven, not compaction driven; ground water flowed down dip and discharged in the vicinity of the uranium deposits; a large playa lake was not involved in ore formation; and uranium concentrated as a result of humate precipitation at a gravitationally stable interface between two compositionally distinct types of ground water.

A definition for a tabular-type uranium deposit is a uranium deposit that occurs as a tabular, originally subhorizontal body entirely within reduced fluvial sandstones of Late Silurian age or younger. Throughout this paper, "reduced" and "oxidized" refer to iron unless otherwise noted. This definition is purely descriptive, yet it is consistent with an integrated genetic model. It incorporates the most striking feature of this deposit type, the tabular shape. It is necessary to include "originally subhorizontal" to allow for subsequent tectonic disruption. Types of deposits excluded by this definition are roll-type uranium deposits, such as those in Wyoming and south Texas (e.g., Harshman, 1972; Reynolds and Goldhaber, 1983) and sandstone-hosted unconformity-type deposits, such as those in northern Canada and Australia (Eupene, 1980; Hoeve and Quirt, 1984). Roll-type deposits occur as arcuate bodies that strongly cut across bedding and have oxidized rock on the updip side and reduced rock only on the down dip side. Unconformity-type deposits occur in late Proterozoic sandstones at unconformities, whereas tabular-type uranium deposits occur higher in the section, in rocks typically of Devonian to Jurassic age but locally as young as Eocene. Because organic material is ubiquitous and probably necessary for the formation of tabular-type uranium deposits, the age of the first woody land plants, Late Silurian, is probably a maximum age for this deposit type (Finch, 1967) and distinguishes

it from the Proterozoic unconformity type which lacks organic matter.

This definition groups deposit types that have sometimes been defined separately. For example, the vanadium-, humate-, and copper-rich deposits of the Uravan mineral belt, Grants uranium region, and White Canyon-Monument Valley area, respectively, are here grouped together. As discussed below, the mineralogic-diagenetic differences among these deposit types are best considered as chemical-mineralogic variations or subtypes within a more general type of deposit that shares their physical hydrology in common. The model is based on general characteristics of deposits. However, because the best documented examples are in the Colorado Plateau, most of the examples that follow are from this area.

General Characteristics of Tabular-Type Uranium Deposits

General features of tabular-type uranium deposits have been extensively described for deposits worldwide (e.g., Fischer, 1947, 1974; Thaden et al., 1964; Young, 1964; Barabash and Virag, 1966; Finch, 1967; Bigotte and Obellianne, 1968; Granger, 1968; Hilpert, 1969; Prest et al., 1969; Dunsmore, 1977a and b; Rautman, 1980; Chapin et al., 1982; Barthel and Hahn, 1985; Belluco et al., 1985; Cazoulat, 1985; Sanford, 1985; Turner-Peterson et al., 1986; Meunier et al., 1989; and others).

Geometry

Tabular-type uranium deposits that occur in essentially flat-lying sediments are typically subhorizontal, very extensive horizontally, and relatively thin vertically. For example, the Jackpile-Paguate deposit in the Grants uranium region has a lateral extent of 5,000 ft (1,515 m) long by 2,500 ft (757 m) wide, but a thickness of only 10 to 20 ft (3–7 m) and a total relief of only 40 ft (12 m; Adams et al., 1978). Where tabular-type uranium deposits cut across bedding, they commonly climb stratigraphically upward toward the basin (e.g., Hazlett and Kreek, 1963; Reinhardt, 1963; Moench and Schlee, 1967; Granger, 1968; Fischer, 1974; Melvin, 1976; Northrop and Goldhaber, 1990). Undulations or "rolls" in the deposits are associated with greater heterogeneity and abundance of mudstone layers.

Age of the deposits

Field and petrographic relations suggest that the deposits formed shortly after deposition of the sediments (Fischer, 1947, 1974; Young, 1964; Moench and Schlee, 1967; Granger, 1968; Hilpert, 1969). Limited, discordant U-Pb age determinations are consistent with this interpretation (Ludwig et al., 1984).

Association with fluvial continental sediments

Tabular-type uranium deposits typically occur in arkosic fluvial sediments and, within these units, they tend to be larger and more concentrated in the larger, more continuous stream paleochannels. They tend to be located within mixed sandstone-mudstone facies rather than in extremely sand- or mud-rich facies. Actively subsiding synclinal structures are more favorable than rising anticlinal structures (Peterson, 1980, 1984; Kirk and Condon, 1986). The sedimentary facies and tectonic factors are themselves related. Channel sands tend to accumulate preferentially in topographic lows that are controlled by actively subsiding structures, whereas overbank muds tend to accumulate preferentially at local topographic highs at actively rising structures (Peterson, 1980, 1984; Kirk and Condon, 1986). Thus tabular-type uranium deposits occur preferentially in actively subsiding structures where channel sands were preferentially deposited.

Association with overlying lacustrine mudstones

The ore-bearing fluvial channel sandstones are commonly overlain by lacustrine mudstones (Peterson, 1980, 1984; Peterson and Turner-Peterson, 1980; Dubiel, 1983; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). This association has only been noted in Jurassic and Triassic rocks of the Colorado Plateau, but the absence of similar observations elsewhere may be due to the lack of appropriate studies. At least in the Colorado Plateau, any model of tabular-type uranium deposit formation must incorporate the association with lacustrine deposits.

In the Grants uranium region in the San Juan basin of the Colorado Plateau, the mud-flat facies of a large playa lake overlies many of the uranium deposits. This association is the basis for one version of the lacustrine-humate model (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). However, the association of tabular-type uranium deposits and mud-flat facies of a large playa lake only holds for part of the Grants uranium region. The association has not been demonstrated for the Uravan mineral belt nor for deposits in the Chinle Formation. In fact, in the Uravan mineral belt, uranium ore underlies the analcime facies, not the mud-flat facies, of the playa (Keller, 1962). Thus, whereas an association with overlying lacustrine deposits is widespread and must be explained by any ore deposit model, an association with the mud-flat facies of a large playa lake is a local feature that may be more fortuitous than essential.

Association with reduced sediments

Tabular-type uranium deposits typically float as thin layers in gray to white, reduced sandstones. These sandstones typically overlie, underlie, or inter-

finger with gray to green mudstones that locally contain preserved organic matter and are often interpreted as lacustrine deposits in a reducing environment (McKay, 1955; Lupe, 1977; Peterson, 1980; Dubiel, 1983; Turner-Peterson, 1985). The reduced nature of these sandstone and mudstone beds contrasts sharply with the generally buff to reddish appearance of the red beds that dominate the Pennsylvanian to Jurassic rocks of the Colorado Plateau. The rocks in the immediate vicinity of the uranium deposits appear to have been first oxidized and later reduced by moving ground water. Commonly the sandstones are reduced, whereas adjacent mudstones are oxidized; but in many cases, the redox boundary is within the channel sandstone. The redox boundary commonly is parallel to the trend of the ore deposits which are typically elongated parallel to the paleochannels in which they occur (Thamm et al., 1981).

Association with underlying marine rocks

Ore-bearing fluvial sandstones are typically underlain by marine rocks, especially evaporites (Rose, 1976; Dunsmore, 1977a and b; Granger and Warren, 1981). Evaporite deposits include thin anhydrite-gypsum beds within clastic sequences (e.g., Tidwell Member of the Morrison Formation in the Henry basin), thick anhydrite-gypsum beds in limestone (e.g., Todilto Limestone Member of the Wanakah Formation in the San Juan basin), and massive halite-sylvite salt anticlines (e.g., Paradox Formation of the Hermosa Group in the Paradox basin). Instead of evaporites, some areas, such as the Arlit basin, Niger, are underlain by marine shales (Bigotte and Obellianne, 1968; Cazoulat, 1985). Rarely, marine rocks are absent beneath the ore-bearing unit, however saline ground water is associated with the deposits (Chapin, 1982). Thus, in most cases, a source of saline pore water is known beneath or up the paleohydrologic gradient from the tabular-type uranium deposits. Although known evaporites and marine rocks favor the occurrence of tabular-type uranium deposits, they are not essential, because ground water can be saline even without these rocks.

Association with underlying aquifers that thin toward the basin

Belts and regions of tabular-type uranium deposits tend to occur above aquifers that thin in the downdip or basinward direction (Sanford, 1982, and unpub. data). The most conspicuous example is the occurrence of the Uravan mineral belt updip from the pinch out of the underlying Navajo Sandstone, which is the major aquifer in the Paradox basin. In the Uravan mineral belt (Sanford, 1982, and unpub. data) and in the Tallahassee Creek district (Chapin et al., 1982), basement horst blocks controlled the location of tabular-type uranium deposits. In other uranium-

producing areas, the major underlying aquifer thins, but does not pinch out.

Mineralogical characteristics of ore

The generally reported mineralogical characteristics of tabular uranium ore are the presence of uranium minerals, typically uraninite or coffinite; some form of organic matter, either detrital woody or epigenetic amorphous organic matter; authigenic clays, principally smectite and illite-smectite; and pyrite. Other sulfides are present locally. The incongruent dissolution of detrital Fe-Ti oxides to Ti oxides has been well documented for the San Juan basin (Adams et al., 1974; Adams and Saucier, 1981; Reynolds et al., 1986) and has been reported elsewhere in the Colorado Plateau (Shawe et al., 1959; Shawe, 1976; Northrop et al., 1990). Altered volcanic ash is a common constituent of the host sandstones and associated mudstones of the Colorado Plateau, however, it is absent in other areas, such as at the Coutras deposit, France (Meunier et al., 1989). In detail, the mineralogy of tabular-type uranium deposits is highly complex and variable. Three major subtypes have been recognized on the basis of chemical differences. Although distinct end members exist, many deposits are transitional between subtypes.

Vanadium-rich subtype: Vanadium-rich uranium deposits occur in the Uravan mineral belt and Henry basin; Prince Edward Island, Canada; and Mecsek area, Hungary (Barabash and Virag, 1966; Prest et al., 1969; Granger and Warren, 1981; Northrop et al., 1990). Because vanadium commonly dominates over uranium, locally by as much as 20/1 by weight, the deposits are often called vanadium-uranium deposits (Granger and Warren, 1981). Vanadium occurs mainly as vanadium oxides and vanadium-rich clays such as roscoelite (chlorite-smectite). The copper content is minor. Organic matter is present as "trash," that is, fragments of detrital woody material. Amorphous, epigenetic matter, characteristic of the humate-rich subtype, is less common or absent. In the Henry basin, the vanadium-uranium layers are bounded above and below by dolomite-rich horizons that extend beyond the limits of the vanadium-uranium (Northrop et al., 1990).

Humate-rich subtype: Deposits associated with epigenetic, noncellular, optically amorphous organic matter, interpreted as humate (Hatcher et al., 1986), are known from the San Juan and Henry basins (Morrison Formation) and the Aquitaine basin, France (Granger et al., 1961; Moench and Schlee, 1967; Granger, 1968; Meunier et al., 1989; Northrop et al., 1990). In these deposits, vanadium and copper are concentrated but not as much as in the vanadium- and copper-rich subtypes.

Copper-rich subtype: Copper-rich uranium deposits are typified by those in the Chinle Formation

in the White Canyon-Monument Valley area of Utah (Thaden et al., 1964; Young, 1964). Copper/uranium ratios range from 1/1 to 18/1 by weight. Vanadium content is low. Uraninite is accompanied by a varied suite of minerals including pyrite, chalcopyrite, and sphalerite. As in the vanadium-rich uranium deposits, organic material consists mainly of carbonized wood fragments.

Examples of the Model

The major features of the model can be illustrated by examples from the most thoroughly studied areas, the Uravan mineral belt and the Henry basin deposits in the Salt Wash Member and the Grants uranium region in the Westwater Canyon Member of the Morrison Formation. Reconstruction of the paleohydrology at the time is the key to understanding ore formation (Sanford, 1982, 1990a and b).

Deposits in the Salt Wash Member

Uranium deposits in the Uravan mineral belt form an arcuate belt with its convex side facing east; uranium deposits in the Henry basin form a cluster approximately 100 mi (160 km) to the west (Fig. 1).

A zone of mixed local and regional discharge of ground water controlled the location of the Uravan mineral belt at the basin-wide scale. At the time of ore formation, inferred surface and ground water was dominantly gravity driven and flowed from Mogollon and Elko (formerly Sevier; Thorman et al., 1991) highlands in the west toward the northeast (Sanford, 1982, 1990a). Regional ground water recharged in the highlands and discharged in areas of major decrease in topographic slope and aquifer thickness. The major decrease in topographic slope was most likely at the facies change between areas having high sandstone/mudstone ratio, low sinuosity of streams, large total thickness of stream sediments, and other evidence of relatively high slope; and areas having low sandstone/mudstone ratio, high sinuosity of streams, small total thickness of stream deposits, and other evidence of relatively low slope. For example, in the Uravan mineral belt (Fig. 1), this zone of inferred topographically controlled discharge is shown between the 100- and 200-ft contours of total stream-deposit thickness. The exact choice of contours is somewhat arbitrary, but it indicates approximately the main facies transition. In the subsurface, discharge of ground water was focused by the thinning and pinch out of important aquifers, notably the Navajo Sandstone. The position of the Uravan mineral belt coincides with the intersection of the two discharge zones, the zone of topographically controlled discharge at the major concave change in slope and the zone of geologically controlled discharge at the pinch out of the Navajo Sandstone (crosshatch area of Fig. 1). The actively subsiding

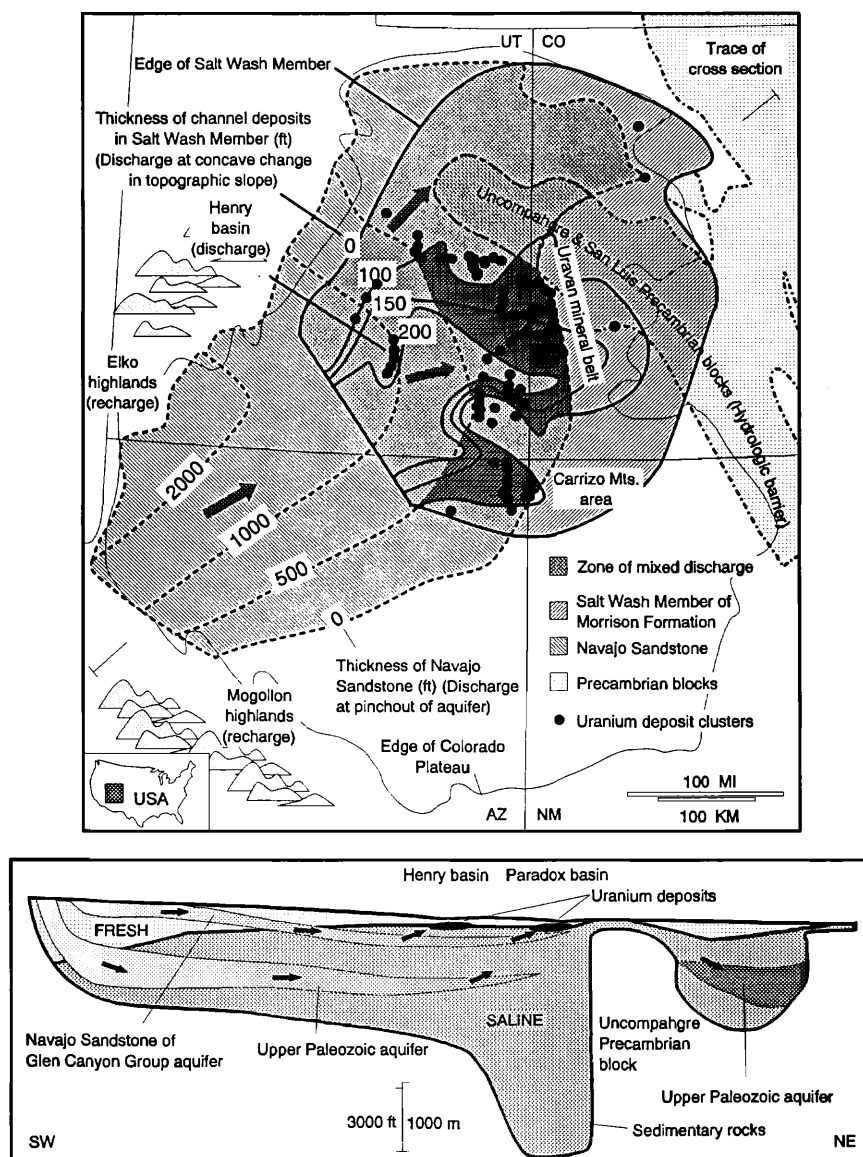


FIG. 1. Simplified map and cross section showing association of tabular uranium deposits (solid circles on map and ellipses on cross section) with zone of mixed local and regional ground-water discharge at concave change in topographic slope and pinchout of Navajo Sandstone aquifer, for Late Jurassic time at the end of deposition of the Salt Wash and beginning of deposition of the Brushy Basin Members of the Morrison Formation. Arrows show direction of ground-water flow. Geology adapted from Craig et al. (1955), Jobin (1962), Mallory (1972), Peterson and Tyler (1985), Blakey et al. (1988); ore deposit clusters from Finch (1991).

Henry basin (Peterson, 1980, 1984) caused local upward deflection of the regional flow system prior to its later discharge in the area of the Uravan mineral belt.

The interaction of this regional flow system with local flow systems in the area of the Uravan mineral belt explains the intermediate-scale features of tabular-type uranium deposits such as their associations with channel sandstone, reduced rocks, and lacustrine

deposits (Fig. 2). As demonstrated by numerous modern examples, regional discharge zones are characterized by the mixing of diverse types of ground water, ranging from relatively fresh to highly saline (Toth, 1963; van Everdingen, 1971; Johnson, 1981; Duffy and Al-Hassan, 1988; Swanson et al., 1988; Banner et al., 1989; Dutton et al., 1989). The presence of numerous evaporite horizons in Jurassic and older rocks of the Colorado Plateau, as well as highly

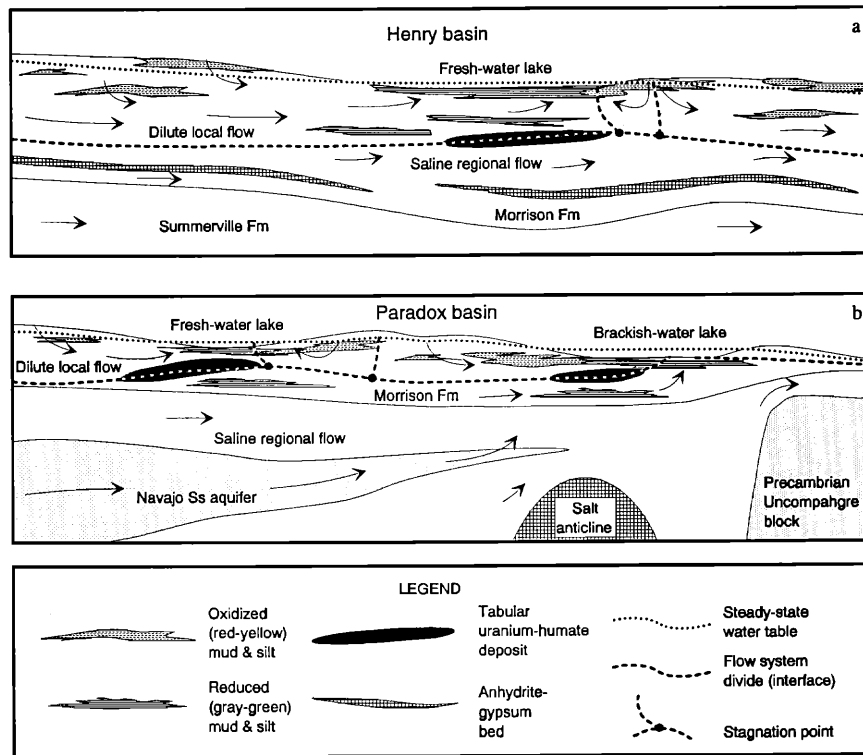


FIG. 2. Schematic cross section through Figure 1 showing environment of formation for tabular uranium deposits in the Henry basin (a) and Paradox basin (b) (not to scale). Recharge is at topographic highs, and discharge is at topographic lows. Recharge areas are indicated by oxidized rocks, particularly red and yellow mudstones, without preserved organic matter. Discharge areas are indicated by reduced rocks, particularly gray and green mudstones, locally with preserved organic matter. Principal sources of dissolved solids are evaporite (anhydrite-gypsum) beds in dominantly clastic units and massive evaporites (halite-sylvite-anhydrite-gypsum) in salt anticlines.

concentrated brines in the region today (as much as 439,000 ppm total dissolved solids; Mayhew and Heylman, 1965), and widespread authigenic minerals suggestive of a brine, such as barite, anhydrite, albite, and chlorite (e.g., Shawe, 1976; Breit et al., 1990), suggests that the Colorado Plateau region in Jurassic time resembled most continental basins today in having a deep, saline, regional flow system. The closest and most likely source of brine for the Henry basin deposits was gypsum beds in the Tidwell Member (Peterson, 1988) of the Morrison Formation, whereas that for the Uravan mineral belt was the anhydrite-halite-sylvite evaporites of the Middle Pennsylvanian Paradox Formation. The distribution of authigenic barite cement in the Salt Wash Member further suggests northeastward and upward migration of brine from the salt deposits of the Paradox Formation (Breit et al., 1990). Closer to the source area in the southwest, the Navajo Sandstone may have been recharged by downward-flowing brine from the evaporite-bearing Carmel Formation; this

brine then discharged as the Navajo pinched out to the northeast. This exact process occurs today (Taylor and Hood, 1988).

Specific areas of local recharge and discharge within the general area of mixed local and regional discharge are indicated by the distribution of oxidized and reduced rock (Fig. 2). In general, oxidized rocks are thought to indicate overbank deposits and other environments of subareal exposure and low water table, whereas reduced sediments formed in channels at topographic lows where the water table was essentially at the surface (Fischer, 1974; Reading, 1978, p. 48; Dodson et al., 1980; Peterson, 1980, 1984; Dubiel, 1983, 1989). Thus, within the zone of mixed local and regional discharge, oxidized rocks indicate local topographic highs and local recharge, whereas reduced rocks indicate local topographic lows and local, as well as regional, discharge.

The correspondence of reduced mudstone and uranium deposits therefore indicates that the deposits formed in discharge zones where saline regional and

fresh local flow systems mixed. As has been long recognized, the striking tabular horizontal geometry of the ore deposits and the lack of any obvious geologic control on a local scale is evidence for just such a stable interface between two density-stratified fluids (e.g., Fischer, 1947, 1974; Granger, 1968; Melvin, 1976; Sanford, 1982, 1990a and b; Granger and Santos, 1986; Northrop et al., 1990). Precipitation of diagenetic minerals such as chlorite, anhydrite, and barite and dissolution of authigenic minerals such as garnet (Hansley, 1986; Breit et al., 1990; Northrop et al., 1990; Hansley and Spirakis, 1992) also suggest the presence of a second fluid that was warm and/or saline. The presence of uranium-poor, tabular, dolomite-cemented layers extending beyond the tabular uranium bodies further demonstrates that the interface extended beyond the uranium orebodies (Northrop et al., 1990).

Paleohydrologic evidence provides an explanation for the location and geometry of these deposits. Hydrologic theory provides a framework for constructing ground-water flow systems (e.g., Hubbert, 1940, 1953; Toth, 1962, 1963; Cooper et al., 1964; Freeze and Witherspoon, 1966; Hitchon, 1969; Winter, 1976, 1983, 1988). The reduced and oxidized rocks, indicating areas of local recharge and discharge, and the tabular uranium deposits, indicating the position of a flow-system boundary, constrain the hydrodynamic model (Fig. 2). Flow-system divides separate local and regional flow systems. Stagnation points, or no-flow nodes, occur at the intersection of flow-system divides. The flow-system divides of greatest importance for uranium deposition are those between local and regional flow systems. The greatest focusing of flow lines and mixing of distinct fluid can be expected to occur at the flow-system divides beneath topographic lows. These divides are expected to be deeper below topographic highs and shallower beneath topographic lows.

In modern environments and in laboratory experiments, mixing at compositional interfaces causes the precipitation of humate, dolomite, and other phases (Swanson and Palacas, 1965; Ortiz et al., 1980; Randazzo and Bloom, 1985). The tabular uranium layers associated with humate and dolomite suggest that the same processes may have controlled the location of tabular-type uranium deposits. The brine need not be extremely saline; the salinity of sea water is sufficient for the precipitation of both humate and dolomite, for example. Stagnation points at the convergence of ground-water flow may have favored the concentration of precipitating solutes.

The tendency of uranium deposits to rise stratigraphically upward toward the basin center is explained by the deflection of the interface upward in the direction of flow and in areas of ground-water discharge

(Hubbert, 1940, 1953; Cooper et al., 1964). The theoretical reason for this rule is that the hydraulic potential in the upper, fresh water decreases in the direction of flow; the more slowly moving salt water below must therefore compensate for the lower potential by rising and thus increasing the hydraulic potential at a given depth. Modern examples are found at shorelines of oceans and saline lakes.

Uranium deposits formed at ground-water divides only where the divides intersected pockets of reduction where organic matter accumulated. Organic matter accumulated and pockets of reduction formed preferentially at discharge zones for several possible reasons: (1) detrital organic material, which was carried down from high elevations where precipitation was relatively high and large woody plants (cycads, ginkgoes, and conifers) flourished, accumulated in muds deposited in topographic lows, especially in standing water; the detrital organic matter then produced humic acids locally; (2) in basin centers where elevation and precipitation were low and large woody plants could not survive, and before development of angiosperms in the Late Cretaceous, the only plants were low-growing types, such as ferns, that required continually moist soil; thus, lush growth in basin centers existed only in areas of high water table and perennially saturated soil, such as those having persistent ground-water discharge; in situ accumulation of organic matter may have been another source for humic acid locally; (3) in the subsurface, low hydraulic potential at stagnation points may have favored the accumulation of humate precipitated from the moving ground water; (4) by analogy with reactions at a typical fresh water-sea water interface (Sanford and Konikow, 1989), maximum deposition of humate and uranium may have occurred near discharge zones where the crowding of flow lines was greatest; (6) later, preservation of organic material was best in areas of high water table, standing water, and discharge of reduced ground water.

The proposed hydrologic model is compatible with several different sources of uranium recognized by previous workers. Dilute, oxygen-rich water is an efficient carrier of oxidized hexavalent uranium (Langmuir, 1978). Thus the local fresh ground water is a likely medium of transport for uranium. Local fresh water may have leached uranium from rhyolitic volcanic ash (e.g., Zielinski, 1981, 1983) where it was present, as in the Morrison Formation, and/or from granitic basement where volcanic ash was absent (e.g., Meunier et al., 1989) updip and uphydrologic gradient from the ore deposits. Alternatively, residual, uranium-enriched brines from the evaporation of sea water could be a source of uranium from depth (Dunsmore, 1977a). The hydrologic model permits all of these possibilities but rules out the overlying

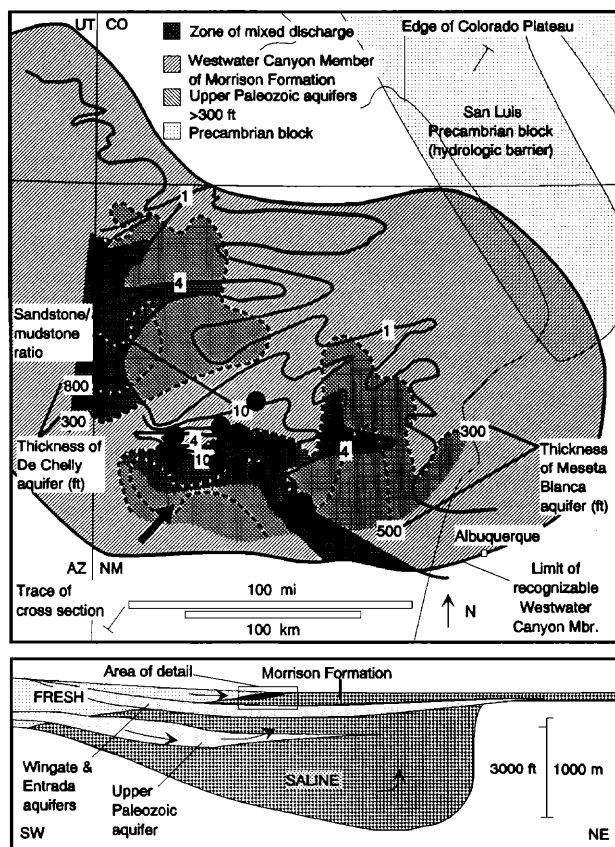


FIG. 3. Simplified map and cross section showing association of tabular uranium deposits (solid circles on map and ellipses on cross section) with zone of mixed local and regional ground-water discharge at concave change in topographic slope and abrupt thinning of Meseta Blanca Sandstone aquifer, for Late Jurassic time at the end of deposition of the Westwater Canyon Member and beginning of deposition of the Brushy Basin Members of the Morrison Formation. Arrow shows direction of ground-water flow. Sandstone/mudstone ratios from Lupe (Robert Lupe, U. S. Geol. Survey, unpub. data, 1982) and Kirk and Condon (1986); upper Paleozoic aquifer (DeChelly and Meseta Blanca Sandstones) thickness from Baars and Stevenson (1977); uranium deposit clusters from Finch (1991).

mudstones as a source of humate and uranium (Peterson, 1980; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986), because ground water flowed upward from the ore deposits to these mudstones.

Deposits in the Westwater Canyon Member

In terms of physical hydrology and early diagenesis, the formation of tabular-type uranium deposits in the Westwater Canyon Member is similar to that in the Salt Wash Member. The Grants uranium region comprises an elongate area of major deposits on the southeast margin of the San Juan basin (Fig. 3). These deposits also formed shortly after deposition of the host sediments (Fischer, 1947, 1974; Young, 1964;

Moench and Schlee, 1967; Granger, 1968; Hilpert, 1969; Ludwig et al., 1984).

Regional-scale discharge of ground water controlled the location of the Grants uranium region (Fig. 3). Surface and ground water was dominantly gravity driven and flowed northeast from the Mogollon highlands. Along the flow paths, the topographic slope and aquifer thicknesses gradually decreased. Facies changes from conglomerate to sandstone to mudstone, as well as decreasing sandstone/mudstone ratio, mark this concave change in topographic slope. The zone of greatest change in slope is indicated approximately by the decrease from >10 to 4 in sandstone/mudstone (Figs. 3 and 4). In the subsurface, the Wingate and Entrada aquifers have a relatively constant thickness, but the Meseta Blanca aquifer thins abruptly from 500 to 300 ft, then gradually pinches out. The abrupt thinning coincides with the main decrease in topographic slope, so both topographic and geologic controls on ground water favor discharge, with the greatest discharge located in a belt between the sandstone/mudstone contours >10 and 4. This zone coincides with the Grants uranium region.

The deep regional flow was probably saline. Flow paths pass through gypsum-anhydrite beds of the Todilto Member. Salinity of modern San Juan basin ground water is as much as 290,000 mg/l (J. Michael Kernodle, U. S. Geol. Survey, unpub. data, 1988).

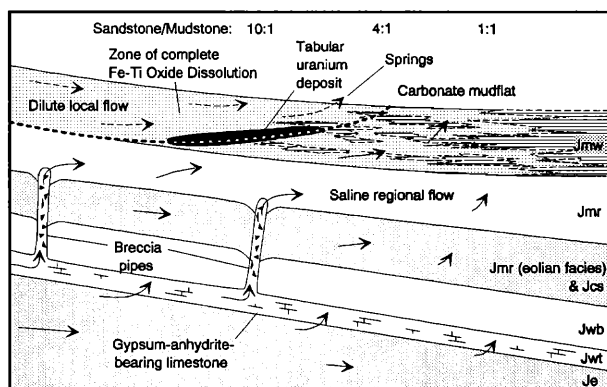


FIG. 4. Schematic cross section through Figure 3 showing environment of deposition for tabular uranium deposits in the San Juan basin (not to scale). Flow is primarily gravity driven and down-dip. Discharge and mixing occurs at concave change in slope, as indicated by sandstone/mudstone ratio from >10 to 4. Breccia pipes, formed by dissolution of gypsum-anhydrite-bearing Todilto Limestone Member of the Wanakah Formation, provide conduits for upward flow of brine. Fe-Ti oxides are completely destroyed within fresh-water lens. Abbreviations for units: Jcs = Cow Springs Sandstone; Je = Entrada Sandstone; Jmr = Recapture member of the Morrison Formation; Jmw = Westwater Canyon Member of the Morrison Formation; Jwb = Beclabito Member of the Wanakah Formation; Jwt = Todilto Limestone Member of the Wanakah Formation.

The evaporite beds have been extensively dissolved resulting in the formation of breccia pipes (Moench and Schlee, 1967; Hilpert, 1969), which further aided upward fluid transport by locally increasing the vertical hydraulic conductivity. Authigenic anhydrite cement in rocks from the Todilto Member up to and including the base of the Westwater Canyon Member (Hansley, 1986, 1990; Ridgely, 1989) indicates the passage of a brine. Etched garnets in the base of the Westwater Canyon Member (Hansley, 1986, 1990) and isotopic data on cogenetic illite-smectite and chlorite (Whitney and Northrop, 1987) also suggest that warm, saline deeper ground water moved updip through the member, although illite-smectite alteration has also been attributed to descending ground water from an overlying playa lake (Owen et al., 1989). These alterations followed a definite time sequence, as discussed below.

The shallow local ground water was probably dilute and either mildly acid or mildly alkaline (Adams et al., 1974; Hansley and Spirakis, 1992). The shallow ground water could have been made reducing by organic matter where the aquifer began to be confined by overlying mud and silt, as occurs today (Jackson and Patterson, 1982). The intensity of Fe-Ti oxide destruction decreases downward and toward the basin center to the northeast (Adams et al., 1974; Reynolds et al., 1986). The geometry of Fe-Ti oxide destruction corresponds with that expected for a fresh-water lens resting upon a denser brine (Sanford, 1990b). The carbonate mud-flat facies of the Brushy Basin Member of the Morrison Formation (Bell, 1983, 1986) probably represents the discharge zone where mixing of the two types of ground water caused precipitation of calcite, as observed today at the margins of alkaline-saline lakes (Garrels and MacKenzie, 1967).

Elsewhere in the Colorado Plateau, the uranium deposits tend to cluster in actively subsiding synclines where channel sands and reduced muds tended to accumulate, whereas deposits are smaller and less common where oxidized overbank muds were deposited at local topographic highs (Kirk and Condon, 1986). Where deposits systematically cut across bedding, they tend to rise stratigraphically upward toward the basin (Hazlett and Kreek, 1963; Melvin, 1976). Again, this is consistent with an association of uranium deposits with areas of discharge at topographic lows.

The timing and geometry of various diagenetic reactions are consistent with a stably stratified fluid interface that intermittently moved higher and southwestward. Fine-grained Brushy Basin-type facies transgressed over coarser grained Westwater Canyon-type facies. Sandstone-dominated alluvial facies of the Westwater Canyon Member interfinger with

fine-grained facies characteristic of the Brushy Basin Member deep in the San Juan basin. Higher in the section, the Brushy Basin-like mudstones interfinger with the Westwater Canyon Member at the outcrop (e.g., the "K" shale). At the top of the Morrison Formation, the Brushy Basin Member mudstones are dominant except for a small area of alluvial facies in the extreme southwest. At any one time, the interface would have approached the surface at the greatest change in hydraulic head gradient, especially at the shoreline of a lake or at the edge of a dry playa (Sanford, 1990b). Thus the transgression of fine-grained facies southwestward over coarser grained facies would have been accompanied by a corresponding movement of the interface.

Such a systematic shift in interface position is suggested by the sequence of alteration reactions and the repetition of ore trends. The generalized observed sequence of alteration with time and depth of burial is (1) dissolution of detrital Fe-Ti oxides and feldspar; (2) precipitation of pyrite, humate, uranium, and chlorite (rims); and (3) precipitation of chlorite (rosettes), potassium feldspar, albite, anhydrite, and silica, and dissolution of garnet and plagioclase (Adams and Saucier, 1981; Fishman and Reynolds, 1986; Hansley, 1986, 1990). In accordance with the diagenetic model of Hansley and Spirakis (1992), these reactions can be explained by reactions of rock with progressively deeper ground water, respectively: (1) dilute, local, mildly reducing, humic acid-bearing, mildly acidic ground water causing predominantly dissolution of detrital material, especially Fe-Ti oxide minerals and plagioclase; (2) dilute local ground water mixing with deeper warm, regional brine at an interface and precipitating a humate layer; and (3) deeper, warm, regional brine causing methanogenesis, organic acid production, and related diagenesis. Destruction of Fe-Ti oxides was caused by downdip flow of humic acid-bearing, dilute ground water. The alteration pattern of plagioclase, decreasing in intensity downward and toward the basin (Hansley, 1986) is also consistent with dissolution by dilute ground water. Cation loading and similar processes caused precipitation of humate at an interface with deeper brine. Humate precipitation at a brine interface has been documented in the field and experimentally (Swanson and Palacas, 1965; Ortiz et al., 1980). Subsequent biogenic sulfate reduction and degradation of humate, as the interface moved upward, caused precipitation of uranium and pyrite. As the deeper brine engulfed the former interface, humate and uranium precipitation ceased and deposition of minerals characteristic of deeper diagenesis began. Elevated levels of Na, K, Mg, and SO_4 caused the formation of albite, K feldspar, chlorite, and anhydrite, respectively; whereas organic

acids generated from diagenesis of the humate caused dissolution of garnet and other silicates (Hansley, 1986, 1990).

Further evidence of migrating interface position is exhibited locally by uranium deposits that form two or more parallel belts (e.g., Granger et al., 1961). The initial uranium-humate deposition probably occurred at the farthest extent of the fresh-water lens and corresponding zone of Fe-Ti oxide destruction. Later parallel belts represent successively higher and more southwesterly positions of the major discharge zone as the zone of maximum change in topographic slope moved southwestward.

Deposits elsewhere

Deposits in the Jackpile Sandstone Member of the Morrison Formation formed essentially like those in the Westwater Canyon Member. The Jackpile Member is a sandstone deposited on top of the Brushy Basin Member in an actively subsiding syncline (Moench and Schlee, 1967; Bell, 1983, 1986). Hence, it was a topographic low and an area of ground-water discharge. It differs from the Westwater Canyon Member in having the most intense feldspar dissolution at the bottom, instead of at the top, and complete Fe-Ti oxide dissolution throughout, instead of decreasing downward (Adams et al., 1978; Adams and Saucier, 1981). These relationships can be explained by the timing of diagenetic reactions, as discussed above. The feldspar and Fe-Ti oxides were dissolved by the early, shallow, dilute ground water which flowed down-dip through the more transmissive parts of the Jackpile Member. Later, as the interface moved up into the Jackpile Member with deeper burial, the uranium-humate body formed in the middle of the sands formerly saturated and leached by dilute ground water.

The fact that part of the zone of feldspar and Fe-Ti oxide dissolution is below the uranium-humate body is interpreted as evidence against the brine interface model (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986). They argue that the brine interface model requires that the dilute water which caused feldspar and Fe-Ti oxide dissolution must have been below the interface and denser brine must have been above—a gravitationally unstable configuration. The criticism of Turner-Peterson (1985) and Fishman and Turner-Peterson (1986) rests on a misinterpretation of the brine interface model, that Fe-Ti oxide dissolution, plagioclase dissolution, albitization, and humate precipitation all took place simultaneously. As discussed above, the diagenetic alterations occurred in a definite sequence, not simultaneously, and are consistent with a rising interface with a gravitationally stable brine below the dilute ground water. Plagioclase may have been dissolved early by dilute ground

water, and later the zone of plagioclase dissolution was engulfed by a brine from below. Of the alterations cited, only albitization has a distribution consistent with discharge from the Brushy Basin Member both downward into the Westwater Canyon Member and, later, upward into the Jackpile Member. The albitizing fluid was not necessarily the same fluid as that which precipitated humate.

Summary of the Model

As shown by the above examples, the proposed model explains the generally observed features of tabular-type uranium deposits in the Morrison Formation on the Colorado Plateau as well as the local variations. Less is known about deposits in other formations of the Colorado Plateau and in other parts of the world. However, the information that is available supports the model proposed here.

The striking tabular shape is due to an early, stable, density-stratified interface between a local dilute ground water and a regional saline ground water. Fluvial continental sediments overlying marine sediments, especially evaporites, are favorable for tabular-type uranium deposits, because they provide the fresh water and brine necessary for such an interface. Belts of uranium deposits form where the alluvial plain merges into mud flat, because this is the location of mixing and focusing of chemically contrasting types of ground water. Many deposits cut upward across stratigraphy toward the basin center, because the interface was forced upward in the direction of flow and in the discharge zone. Upward flow and mixing at an interface is also favored by topographic lows, which are indicated by reduced lacustrine mudstones or channel sandstones in actively subsiding synclines. Synclinal structures favor tabular-type uranium deposition because they cause focusing and mixing of ground-water flow and preferentially accumulate organic matter by several possible mechanisms. Belts of uranium are especially favored where subsurface aquifers thin or pinch out and force deep regional flow upward to interact with shallow dilute ground water. Different subtypes of tabular-type uranium deposits that are characterized by associations such as vanadium, humate, or copper share basically the same physical hydrology but differ in extent of postore diagenesis.

Discussion

One other model for deposits in the San Juan basin and elsewhere proposes that humic acid-bearing ground water was squeezed by compaction out of mudstones above, below, and interfingering with the host sandstones and moved outward to form humate deposits by cation loading as detrital minerals were dissolved; uranium precipitated during and after hu-

mate precipitation (Peterson, 1980; Turner-Peterson, 1985; Adams, 1986; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986). This model is partly compatible with the hydrologic model proposed here. Humic acid may have come from organic-rich muds interbedded with channel sands. Because channels were probably lower topographically than the surrounding overbank deposits, ground water that recharged locally adjacent to channels would have flowed laterally into the channels where it then moved downdip. Organic-rich muds interbedded with channel sands in synclines may have expelled humic acid-rich pore water into the much greater volume of gravity-driven, downdip-flowing, dilute ground water. The hydrology proposed here is therefore consistent with a source of humic acid in the fluvial sandstones updip from the ore deposits and in the organic-rich mudstones interbedded with channel sandstones.

A major difference between the models is the inferred direction and mechanism of ground-water flow. One version of the lacustrine-humate model proposes that humic acids mainly moved downward by compaction from the Brushy Basin Member into the underlying Westwater Canyon Member. It is difficult to imagine humic acid-rich pore water moving from overlying mudstones downward and updip by compaction against the much larger volume of gravity-driven, downdip flow. While pore water compacted out of organic-rich muds may have been rich in humic acid, it supplied little water compared to the gravity-driven, downdip flow. In modern basins, maximum velocities due to compaction are calculated to be about 0.2 cm/yr (Bethke, 1986) compared to gravity-driven flow rates of 1 to 11 m/yr (Habermehl, 1980; Bethke, 1986), or four orders of magnitude different. If compaction occurs, it is usually upward, not downward in the upper part of a typical basin (e.g., Bethke, 1986). In addition, organic matter is nearly absent from the Brushy Basin Member (Adams and Saucier, 1981). The Brushy Basin Member overlying and downdip from the ore deposits in the Westwater Canyon Member is thus an unlikely source of humic acid.

Another major difference is whether one fluid was involved or whether two fluids formed a density-stabilized interface. The lacustrine-humate model fails to explain important features of the tabular bodies. It attempts to explain the striking tabular geometry of the deposits by electrostatic forces or flocculation, however, it is difficult to envision how a radially symmetric force that diminishes as the square of the distance could form horizontal layers thousands of meters in breadth and only meters in thickness. No explanation is given for the tendency of many deposits to rise stratigraphically toward the basin. The

model fails to consider the influence of marine rocks, especially evaporites showing extensive dissolution, beneath tabular-type uranium deposits. Instead, it assumes that ground water related to ore deposition and diagenesis in the host sandstones was dilute water, in contradiction to extensive evidence for brines in most modern basins, including the modern San Juan basin and other basins—even those without evaporites.

The present model answers two arguments against a brine interface model given by Turner-Peterson and Fishman (1986). They assert that there is no evidence of a brine. First many modern basins, even those without evaporites, have brines. The San Juan basin today has concentrations as much as 290,000 mg/l (Michael J. Kernodle, U. S. Geol. Survey, pers. commun., 1990). During the Jurassic, there was a source of brine in the gypsiferous Todilto Limestone a small distance below the Morrison Formation. The gypsum beds have been extensively dissolved, and breccia pipes extend upward into the base of the Morrison Formation. The upward flow of deep basin ground water inferred in this study provides a means for the dissolved solids from the Todilto to be transported upward into the Morrison Formation. Finally, the tabular shape of the uranium-humate deposits is difficult to explain except by a density-stabilized fluid interface. Another objection to the brine interface model is that it cannot explain the relationship between sedimentary facies and uranium deposits. According to the present model, the sedimentary facies are closely related to the flow of ground water. The transition from alluvial plain to mud-flat facies indicates a concave change in topographic slope where different types of ground water are most likely to mix and discharge. Thus, sedimentary facies reflect the paleotopography, which controlled the flow of ground water, which in turn controlled the distribution of uranium deposits.

Diverse, mutually incompatible, geochemical-diagenetic models for uranium ore formation have been proposed (e.g., Granger and Warren, 1981; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986; Northrop et al., 1990; Hansley and Spirakis, 1992), however, that of Hansley and Spirakis (1992) is both comprehensive and consistent with hydrologic constraints (Sanford, 1982, 1990a and b). According to their model, dissolution of rhyolitic volcanic ash resulted in a dilute, mildly alkaline, U- and SiO₂-bearing shallow ground water. This alkaline ground water dissolved humic acids from terrestrial organic matter and leached iron from detrital Fe-Ti oxides in sandstones of the Morrison Formation while migrating through it. Tabular layers of chemically reactive humate precipitated at a brine interface by cation loading or other mechanisms. Sulfate from the

brine below was biogenically reduced causing precipitation of uranium, vanadium, pyrite, and calcite. For most organic-rich deposits of the Grants uranium region, this was the last significant diagenetic event, but, in parts of the Grants uranium region, Uravan mineral belt, and Henry basin, methanogenesis followed by organic acid generation caused various additional diagenetic reactions including dissolution of much of the humate and production of V-rich clay minerals. Thus, tabular humate-poor deposits today originally contained humate (Hansley and Spirakis, 1992). Analogues of the reactions at the brine interface exist today (Swanson and Palacas, 1965; Magaritz and Luzier, 1985; Randazzo and Bloom, 1985; Ward and Halley, 1985; Sanford and Konikow, 1989; Stoessell et al., 1991).

Conclusions

Reconstruction of the hydrogeology proves to be the key to understanding the formation of tabular-type uranium deposits. By answering the critical question, "Which way did the ground water flow?" hydrogeology narrows down the possible choices for sources of water and ore components, types of ore-forming and diagenetic reactions, and favorable locations and times for ore deposit formation.

The discovery of entire new districts and belts of uranium deposits worth \$100 million to \$1 billion is crucial for future uranium production in the United States (Fischer, 1974). Although current demand is constant, future increase in demand for safe, clean, efficient sources of energy by an expanding economy will require exploration for new sources of uranium. The model proposed here provides both general and detailed guidelines for uranium exploration. The key to finding new belts of tabular-type uranium deposits is to locate areas of regional ground-water discharge and favorable rock types. Necessary requirements are a continental basin having uranium-rich source rocks such as rhyolitic ash or granitic basement and having Upper Silurian or younger fluvial-lacustrine sedimentary rocks. Underlying marine rocks, especially evaporites, are favorable as sources of dissolved solids. Facies changes in fluvial-lacustrine sediments indicate the critical topographic controls on ground-water flow. Evidence of change from relatively high to low topographic gradient, i.e., concave change in slope, is favorable for uranium ore formation. Syndepositional synclines are favorable because they cause focusing and mixing of ground-water flow, and they favor accumulation of organic matter by several possible mechanisms. The concentration of organic matter, as humate, was critical for the reduction and precipitation of dissolved uranium. However, later diagenesis may have removed the humate and left the uranium, which is then commonly enriched in vanadium, copper, and other elements. Geologic controls

that favor ground-water flow discharge, such as the pinch out of major aquifers, are also favorable for uranium ore. The most favorable areas are those having both topographic and geologic features that focused regional and local ground-water discharge. Within such discharge zones, oxidized sediments indicate local recharge at topographic highs and are thus unfavorable, whereas reduced sediments indicate local discharge at topographic lows that are most favorable.

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