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By Richard F. Sanford

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ABSTRACT

During parts of the Jurassic and Triassic Periods, fluvial-lacustrine sediments were deposited in the area of the Colorado Plateau, and tabular sandstone (tabular-type) uranium deposits formed at a density-stratified ground-water interface in areas of regional ground-water discharge. The typical effects of topographic, geologic, and compositional controls on ground-water flow, together with modern ground-water analogs, can be used to reconstruct ground-water flow during and shortly after sedimentation. Diagenetic effects of the passage of ground water can also provide further constraints. In the Upper Jurassic Morrison Formation and lower part of the Upper Triassic Chinle Formation, tabular sandstone uranium deposits are in lenticular, arkosic, fluvial, channel sandstone overlain by tuffaceous overbank and lacustrine mudstone and underlain by marine rocks, especially evaporites. The thin, subhorizontal, tabular-shaped bodies float in the sandstone with no apparent lithologic control. They are in reduced sandstone within dominantly redbed sequences of sandstone and mudstone. The deposits favor transitional facies of interbedded sandstone and mudstone between dominantly fluvial sandstone and dominantly overbank and lacustrine mudstone. They tend to be concentrated in syndepositional synclines. Organic matter, either as detrital coalified plant fragments or structureless impregnations, is closely associated with uranium ore. Decreases in paleotopographic slope are indicated by lithofacies changes, typically from distal alluvial plain to mudflat or floodplain. Geologic controls focused discharge in zones of abrupt thinning and pinching out of Lower Jurassic and upper Paleozoic aquifer systems. Tabular sandstone uranium deposits formed where topographic controls favored mixed local and regional discharge. Transient, depression-focused recharge of humic-acid-bearing ground water at wetlands in paleotopographic depressions may have provided a mechanism for downward and downdip transport of humic acid that precipitated at a subhorizontal, density-stabilized interface between relatively fresh, shallow ground water and discharging, saline regional flow. Uranium was precipitated during and after humate precipitation.

INTRODUCTION

Previous studies suggest that tabular sandstone (tabular-type) uranium deposits formed in areas of ground-water discharge (Sanford, 1982, 1988, 1990a, b, 1992), and quantitative models for selected areas support the hypothesis (Sanford, 1982, 1990a, 1994). In this study, I reconstruct the hydrogeology of the Colorado Plateau during parts of the Jurassic and Triassic Periods when fluvial-lacustrine sediments and tabular bodies of uranium ore were being deposited. I examine additional evidence pertaining to ground-water flow, extend the earlier studies to other areas of uranium deposits on the Colorado Plateau, and reconcile evidence for ground-water paleodischarge and evidence of ground-water paleorecharge at the site of uranium deposition.

Hydrologic principles, observation of modern ground-water-flow systems, and results of quantitative modeling help predict the flow of ancient ground water. Hydrologic controls are then combined with stratigraphic, sedimentologic, paleoenvironmental, and structural data from the Colorado Plateau to construct conceptual models. The effects of the passage of ground water based on diagenetic evidence further constrain the model.

Previous hydrogeologic work on the Colorado Plateau typically focused on surface water or shallow ground water but neglected the large-scale flow of ground water in the basin as a whole. Paleotopography was not fully utilized in paleohydrogeologic reconstruction. In this paper, I incorporate concepts previously proposed to provide an integrated model for basin- and local-scale ground-water flow in the Colorado Plateau as a whole.

DESCRIPTION OF TABULAR SANDSTONE URANIUM DEPOSITS

Tabular sandstone uranium deposits are tabular, originally subhorizontal bodies entirely within reduced fluvial sandstone of Late Silurian age or younger. Tabular sandstone uranium deposits constitute the largest uranium resource type in the United States. They account for approximately 65 percent of the total United States production and reserves of uranium (Chenoweth and McLemore, 1989). Throughout this paper, the terms "reduced" and "oxidized" refer to iron unless otherwise noted.

The general features of tabular sandstone uranium deposits are summarized elsewhere (Finch, 1967; Fischer, 1974; Adams and Saucier, 1981; Nash and others, 1981; Thamm and others, 1981; Finch and Davis, 1985; Granger and Finch, 1988; Shawe and others, 1991; Sanford, 1992). Typically, tabular sandstone uranium deposits are in lenticular, arkosic, fluvial, channel sandstone overlain by tuffaceous overbank and lacustrine mudstone and underlain by marine rocks, especially evaporites. The thin, subhorizontal, tabular-shaped bodies "float" in the sandstone with no apparent lithologic control. They are in reduced sandstone within dominantly redbed sequences of sandstone and mudstone. The deposits favor transitional facies of interbedded sandstone and mudstone between dominantly fluvial sandstone and dominantly overbank and lacustrine mudstone. They tend to be concentrated in syndepositional synclines. Organic matter, either as detrital coalified plant fragments or structureless impregnations, is closely associated with uranium ore. The age of the host rocks ranges from Late Silurian to Tertiary, the older age limit corresponding to the first appearance of woody land plants. The deposits probably formed shortly after deposition of the host sandstone. In the Colorado Plateau, the largest tabular sandstone uranium deposits are in sandstone of the Upper Jurassic Morrison Formation and Upper Triassic Chinle Formation.

HYDROGEOLOGICAL PRINCIPLES USED IN RECONSTRUCTION

Here I consider both the controls that govern the flow of ground water and the effects of the passage of ground water. The controls are described by the general principles of physical hydrogeology, and they lead to predictions that can be tested by looking for evidence of the effects of the passage of ground water.

CONTROLS ON GROUND-WATER FLOW

Controls on ground water flow are topographic, geologic, and compositional. Topographic controls are imposed by the configuration of the water table and, indirectly, the ground surface. Geologic controls are imposed by the distribution of permeability and thickness of units in the saturated zone. Compositional controls are imposed by masses of water having different density due to salinity. Darcy's Law provides a framework for classifying these controls (fig. 1) (Hitchon, 1969; Winter, 1988). The volumetric flow rate (Q) in saturated porous media is the product of three parameters: hydraulic conductivity (K), cross-sectional area normal to flow (A), and gradient in hydraulic potential (dh/dl) (Hubbert, 1940, 1953, 1956).

Although distinguishable conceptually, ground-water controls may be correlated. Finer sediments commonly are associated with both lower topographic slope and lower permeability. Thinning of aquifers may be accompanied by a decrease in permeability owing to an increase in the proportion of fine-grained sediments.

TOPOGRAPHY

In mature, topographically uplifted basins, such as those of the Colorado Plateau, gravity-driven flow predominates; recharge occurs at higher elevations, whereas discharge occurs at lower elevations (Kreitler, 1989). For an unconfined aquifer at the surface, a decrease in the slope of the water table results in a lower potential gradient and smaller flow rate (Q) through the downstream end of the medium, which causes discharge at the decrease in slope. The most common expression of this case is at decreases or breaks in slope, typically where an alluvial fan or plain meets an almost flat valley bottom (Freeze and Witherspoon, 1967; McLean, 1970; Habermehl, 1980; Allison and Barnes, 1985; Duffy and Al-Hassan, 1988; Straw and others, 1990; Winter and Woo, 1990). A special case of a concave break in slope that focuses discharge is at the shoreline where the water table meets a standing body of water (see, for example, Pfannkuch and Winter, 1985; Cherkauer and Nader, 1989). Wetlands typically are present in areas of perennial discharge.

In this study, I assume that paleotopographic highs were recharge areas, that paleotopographic depressions were discharge areas, and that discharge occurred at major decreases in slope due to a decrease in dh/dl (fig. 1). Thus, the largest scale topographic controls on ground-water flow are indicated by the major highs in orogenic zones and the major depressions in sedimentary basins. Following the theory of Toth (1962, 1963), it is assumed that the deepest regional flow discharges at the lowest elevations and that shallower flow discharges farther upslope. The distal edge of the alluvial plain, or transition from alluvial plain to mudflat, is expected to be a zone of discharge and mixing of shallow local and deeper regional ground water (McLean, 1970; Duffy and Al-Hassan, 1988; Straw and others, 1990).

GEOLOGY

Both a facies change resulting in lower permeability and a thinning of hydrostratigraphic units in the downstream direction favor discharge of ground water and the presence of wetlands (fig. 1) (Freeze and Witherspoon, 1966, 1967; Garven and Freeze, 1984a, b; Bethke, 1989; Kreitler, 1989). The thinning may involve just one aquifer within a basin or

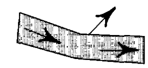
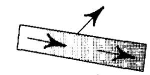
GROUND-WATER CONTROLS	FAVORABLE FOR DISCHARGE	DARCY'S LAW: $Q = KA\, \mathrm{d}h/\mathrm{d}l$	
		Decrease in:	
Topography	Concave change in slope	**d*h*/d*l***	
Geology	Decrease in transmissivity		
Permeability	Decrease in permeability	*K*	
Thickness	Thinning of aquifer	*A*	
Composition	Thinning of fresh-water lens	*A*	

Figure 1. Classification of topographic, geologic, and compositional controls on ground water showing conditions favorable for discharge. *Q* is volumetric flow rate; *K* is hydraulic conductivity; *A* is cross-sectional area normal to flow; d*h*/d*l* is gradient of hydraulic potential (head) with distance.

the basin as a whole. For the Colorado Plateau in Mesozoic time, geologic controls on ground-water flow are reconstructed from permeability data and stratigraphic evidence.

AQUIFERS AND CONFINING UNITS

Ground water in horizontally stratified sedimentary basins tends to flow laterally through aquifers and vertically through confining units (Hubbert, 1940; Toth, 1978; Kreitler, 1989). The notion that fine-grained or clay-rich units are impermeable continues to be expressed by some geologists, even though it was understood more than 90 years ago to be a "time-honored delusion" (Munn, 1909). Flux across confining units can be significant; the lower permeability (*K*, fig. 1) of a confining unit is compensated by the cross-sectional area (*A*), which is orders of magnitude greater when flow is perpendicular to bedding, and by a higher potential gradient (d*h*/d*l*) that may exist across the confining unit. For example, upward flux through the bed of Lake Frome, Australia, is 170–180 mm/yr (Allison and Barnes, 1985).

COMPOSITION

A gravitationally stable body of saline water may force fresher water flowing over it to discharge (fig. 1). (By definition, saline water has 1,000–35,000 mg/L total dissolved solids, and brine has >35,000 mg/L total dissolved solids (Robinove and others, 1958).) Some surface water and much ground water is saline (Hanor, 1983; Hammer, 1986; Kreitler, 1989). Saline bodies of water, including salt lakes and the oceans, typically receive inflow from more dilute surface and ground water. Buoyancy forces cause less dense fresher water to overlie more dense salt water in the subsurface. At equilibrium, the fresh water-salt water interface is horizontal. When the upper fluid is moving, the interface slopes upward in the direction of movement (Cooper and others, 1964). The salt-water wedge acts as a barrier to the flow of relatively fresh water, which tends to discharge at the surface more or less at a shoreline or other break in slope (McLean, 1970; Duffy and Al-Hassan, 1988; Dutton and others, 1989; Fee and others, 1992; Herczeg and others, 1992; Hines and others, 1992; Long and others, 1992; Macumber, 1992). In topographic depressions where the water table slopes inward and ground-water flow converges, the hydraulic potential for shallow ground water is least at the depression (Hubbert, 1940). The salt water-fresh water interface must therefore rise toward the depression, even if salt water fails to discharge at the surface.

Compositional controls on ground-water flow cannot be reconstructed in ancient basins with as much certainty as topographic and geologic controls because the original fluids have disappeared. The chemical evolution of the ground water can be inferred, however, from the composition of the rocks through which the water passes. Because evaporite minerals dissolve rapidly, ground water that passes through evaporites or evaporite-cemented sediments becomes saline, as demonstrated by salinities as high as 439,000 ppm in modern basins, including the Paradox Basin (Mayhew and Heylman, 1965; Hanor, 1983; Kreitler, 1989). The contribution of evaporites to saline ground water is well documented (Gallaher and Price, 1966; Boswell and others, 1968; van Everdingen, 1971; Anderson and Kirkland, 1980; Johnson, 1981; Fisher and Kreitler, 1987; Banner and others, 1989; Dutton and others, 1989). Evaporites are not required, however, for the presence of brines; brines can evolve by interaction of rock and normal or evaporatively concentrated sea water originally trapped during sedimentation (Fisher and Kreitler, 1987; Dutton, 1987) or by reverse chemical osmosis (Bredehoeft and others, 1963; Coplen and Hanshaw, 1973; Graf, 1982). Thus, in reconstructing ancient ground-water flow, the fact that ground water flowed through or around evaporitic horizons is strong evidence for saline ground water, but flow through marginal-marine rocks deposited in an arid or sabkha environment also suggests saline water. A close modern analog to ancient saline water movement is the dissolution of the Middle Jurassic Carmel Formation evaporites, transport of saline water downdip in the underlying Lower Jurassic Navajo Sandstone, and upward discharge from the Navajo (Taylor and Hood, 1988).

FEATURES OF GROUND-WATER FLOW

The features discussed here are commonly observed characteristics of ground-water flow in sedimentary basins analogous to ancient basins such as those of the Colorado Plateau.

SCALE OF GROUND-WATER-FLOW SYSTEMS

The features of ground-water-flow systems vary with the scale of the system, which is generally classified as regional, intermediate, or local (Toth, 1962, 1963). Regional flow recharges at major drainage divides and discharges at basin floors. Intermediate flow recharges and discharges in areas that are separated by one or more local topographic highs and lows.

COMPOSITIONAL VARIATIONS

Toth (1962, 1963) predicted that chemical contrasts would be greatest across the boundaries between flow systems of different magnitude as a result of the different flow paths. In fact, numerous modern examples demonstrate that diverse types of ground water from local, intermediate, and regional flow systems converge in mixed discharge zones (Counts, 1957; Toth, 1963; Freeze and Witherspoon, 1966; Gallaher and Price, 1966; Boswell and others, 1968; van Everdingen, 1971; Foreman and Sharp, 1981; Mono Basin Ecosystem Study Committee, 1987; Sharp, 1988; Swanson and others, 1988; Banner and others, 1989; Dutton and others, 1989; Whittemore and others, 1989; Huff, 1990; Fee and others, 1992; Herczeg and others, 1992; Hines and others, 1992; Long and others, 1992; Macumber, 1992; Strobel, 1992). The local flow system typically discharges dilute water, whereas the intermediate and regional flow systems discharge saline water of diverse compositions, commonly within a relatively small area. For example, in the Cascade Range, north-central Oregon, two springs only meters apart vary from less than 100 to 8,000 mg/L total dissolved solids (Ingebritsen and others, in press). Both springs are in a regional discharge area, but the saline spring is fed by the regional flow, and the fresh-water spring is fed by local flow. Such compositional contrasts at the surface clearly indicate the presence of steep compositional gradients, or ground-water interfaces, in the subsurface. Such interfaces may be widespread in the shallow subsurface (Runnells, 1969) and are observed in modern coastal environments (Cooper and others, 1964), in geothermal areas (Williams and McKibben, 1989) in unconsolidated alluvium beneath large rivers (Counts, 1957; Gallaher and Price, 1966; Boswell and others, 1968; Foreman and Sharp, 1981; Sharp, 1988), and where rivers erode exposed evaporites (Warner and others, 1985).

A variety of diagenetic reactions occur at such interfaces, including precipitation of humate (Swanson and Palacas, 1965; Hair and Bassett, 1973; Sholkovitz, 1976; Ortiz and others, 1980; Fox, 1983; Thurman, 1985, p. 26ff and 394ff), precipitation of dolomite (Ward and Halley, 1985), precipitation of calcite (Mono Basin Ecosystem Study Committee, 1987), dissolution of calcite (Plummer, 1975), and other reactions (Magaritz and Luzier, 1985; Randazzo and Bloom, 1985; Hines and others, 1992). In the Colorado Plateau, tabular layers of humate, uranium, and dolomite suggest former interfaces (Fischer, 1947, 1974; Shawe, 1955, 1962, 1966, 1976; Granger and others, 1961; Granger, 1968; Wood, 1968; Melvin, 1976; Sanford, 1982, 1990a, b, 1992; Granger and Santos, 1986; Northrop and Goldhaber, 1990; Wanty and others, 1990; Hansley and Spirakis, 1992).

RECHARGE AND DISCHARGE IN FLUVIAL-LACUSTRINE ENVIRONMENTS

Recharge and discharge in complex present-day lake-groundwater systems (Meyboom, 1967; Lissey, 1971; Stephenson, 1971; Winter, 1976, 1978, 1986, 1988) are likely analogs for such systems in the ancient Colorado Plateau. Lakes always are in topographic depressions, and the water table normally slopes toward the lake, causing discharge of ground water to the lake. Lakes at higher elevation may recharge the ground-water system, but the lake at the lowest elevation typically only receives ground-water discharge and contributes no recharge (Winter, 1976). A flow-through lake may have discharge on the upgradient side and recharge on the downgradient side. Greater width of the lake relative to the thickness of the underlying aquifer favors increased focusing of ground-water discharge around the lake margins (Pfannkuch and Winter, 1984). At playa lakes, relatively fresh water discharges around the shoreline, and saline water recharges or discharges in the center (Friedman and others, 1982; Allison and Barnes, 1985; Spencer and others, 1985; Duffy and Al-Hassan, 1988; Winter and Woo, 1990).

TRANSIENT EFFECTS AND WATER-TABLE VARIATIONS

The water-table level fluctuates as a result of fluctuations in precipitation (Lissey, 1971; Winter, 1983). Three zones are distinguishable: (1) the permanently saturated zone beneath the steady-state position of the water table, (2) the transiently saturated zone above the steady-state water-table level but below the permanently unsaturated zone, and (3) the permanently unsaturated zone. Water-table fluctuations leave traces in the authigenic mineralogy of the sediments. The most conspicuous and easily mappable feature in ancient sedimentary rocks is color variation due to the oxidation state of iron. Red, yellow, and buff indicate oxidized iron, whereas green, gray, and black indicate reduced iron. Oxidized and reduced sedimentary rocks have been related to paleo-water-table level in the Colorado Plateau and elsewhere (Walker, 1967; Reading, 1978, p. 48–49; Dodson and others, 1980; Huber, 1980; Dubiel, 1983, 1989; Davis, 1988; Ghiorse and Wilson, 1988; Dubiel and others, 1991). Water-table level has been related to redox conditions in analogous modern systems (Jackson and Paterson, 1982; Fee and others, 1992; Hines and others, 1992; Long and others, 1992; Macumber, 1992). In this study, I assume by analogy that most of the permanently saturated zone tends to be reducing where organic matter was deposited, the transiently saturated zone and upper part of the permanently saturated zone have mottled or variegated sediments, and the permanently unsaturated zone has oxidized sediments.

Transient, depression-focused recharge to the ground-water system may occur during high-water periods and may constitute a major source of shallow, relatively fresh ground water at topographic depressions (Gallaher and Price, 1966; Lissey, 1971; Winter, 1983; Wood and Petraitis, 1984; Fetter, 1988, p. 45ff; Logan and Rudolph, 1992). During periods of high water, topographic depressions fill with surface water that then migrates into unsaturated, porous sediments of the stream bank or lake shore. This newly infiltrated ground water is slowly released to the ground-water system. In the Southern High Plains of Texas, for example, most of the recharge is focused at such topographic depressions (Wood and Petraitis, 1984). In the coastal plain of Argentina, fresh water recharges in marshes that are only 0.5–1.0 m below the surrounding land surface and overlies regional saline ground water (Logan and Rudolph, 1992). This phenomenon provides an explanation for apparent downward flow of ground water in areas of regional discharge in the ancient Colorado Plateau, as discussed following.

PALEOHYDROGEOLOGY IN THE COLORADO PLATEAU

MAJOR CONTROLS ON LATE JURASSIC GROUND WATER

TOPOGRAPHY

The drainage divides marking the southern and western margins of the drainage basin (Mogollon and Elko highlands, respectively, fig. 2) (Peterson, 1984, 1986, 1988a, in press; Thorman and others, 1990, 1991) during deposition of the Morrison Formation must have been beyond the present-day margins of the Colorado Plateau, perhaps in southern Arizona or northern Mexico (Billodeau, 1986) and Nevada. Paleocurrent directions of streams in the Morrison Formation (Craig and others, 1955; Mullens and Freeman, 1957; Young, 1978; Dodson and others, 1980; Tyler and Ethridge, 1983; Peterson, 1984, 1986, in press; Turner-Peterson, 1986) indicate that the regional topographic slope, and probably the regional ground-water flow, was mainly northeastward. Intermediate and local flow systems were undoubtedly affected by tectonically active structures within the Colorado Plateau. Throughout deposition of the Morrison Formation, the Elko and Mogollon highlands probably were regional recharge areas (fig. 2).

GEOLOGY

The most important geologic controls on ground-water flow in the Late Jurassic were buried Precambrian blocks and Phanerozoic eolian sandstone and carbonate aquifers (fig. 3) (Jobin, 1962; Sanford, 1982, 1990a; Stone and others, 1983; Freethey and Cordy, 1991; Geldon, in press). Northeastward from the middle of the Colorado Plateau, in the direction of ground-water flow, sedimentary rocks beneath the Morrison Formation thin from as much as 5,000 m (15,000 ft) to a thin veneer over the Uncompahgre and San Luis blocks, remnants of the Pennsylvanian-Permian ancestral Rocky Mountains, which formed a hydrologic barrier. Northeast of these blocks, sediments again thicken in the Eagle and Piceance Basins. The ancestral Front Range block formed a second barrier behind these basins. Ground water must have been forced around the ends and over the top of the barriers where it discharged. Similar flow of ground water around the Uncompahgre block takes place today in Devonian and Mississippian carbonate rocks (Taylor and Hood, 1988).

Major aquifer systems in the Colorado Plateau are the lower Paleozoic, upper Paleozoic, and Lower Jurassic aquifer systems (fig. 3) (Jobin, 1962, 1986; Sanford, 1982, 1990a; Taylor and others, 1986; Freethey and Cordy, 1991; Geldon, in press). The lower Paleozoic aquifer system includes the karstic Mississippian Leadville Limestone and correlative Redwall Limestone. The upper Paleozoic aquifer system includes the eolian Cedar Mesa Sandstone Member of the Cutler Formation, Coconino Sandstone, De Chelly Sandstone, Glorieta Sandstone, Meseta Blanca Sandstone Member of the Yeso Formation, Weber Sandstone, and White Rim Sandstone Member of the Cutler Formation. The Cedar Mesa Sandstone Member is the most transmissive of these units, and the arkosic Cutler Formation, with which the eolian sandstone units intertongue, is only an aquifer locally (Geldon, in press). The Lower Jurassic aquifer system includes the eolian Lower Jurassic Wingate and Navajo Sandstones. In general, the eolian sandstone aquifers thin and the percentage and thickness of confining units thicken to the northeast. Of the eolian sandstones, the thickest parts of Lower Jurassic Navajo Sandstone were the most transmissive and most variable hydrostratigraphic unit on the

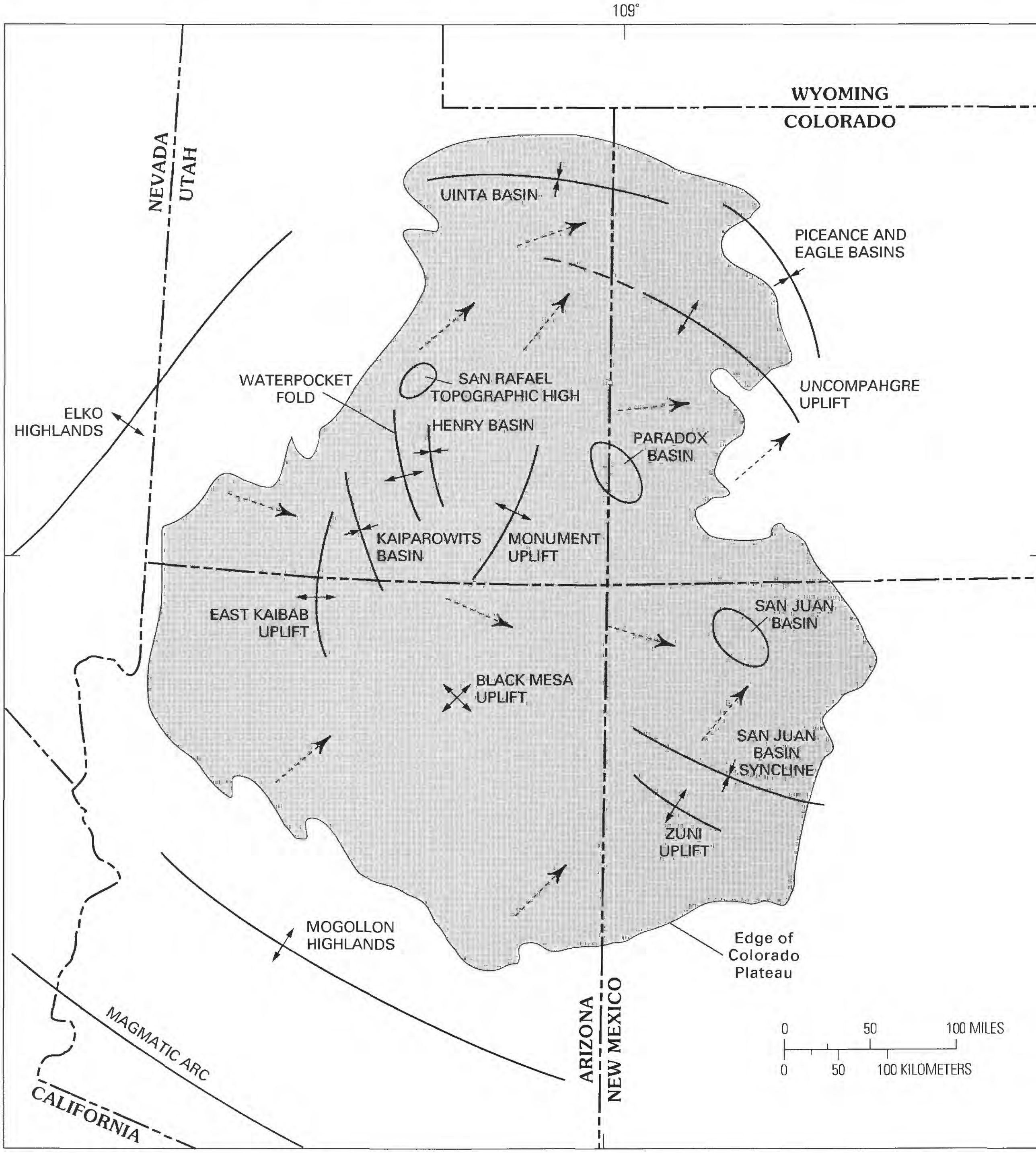


Figure 2. Map showing major geologic features, both active tectonic structures and topographic nonstructural features, that influenced ground-water flow in the Late Jurassic in the Colorado Plateau region. Shaded area is area of present-day Colorado Plateau. Outward-pointing arrows are anticlines, inward-pointing arrows are synclines, and dashed arrows indicate generalized direction of surface- and ground-water flow. Modified from Craig and others (1955), Mallory (1972), Peterson (1984, 1986, 1988a, in press), and Turner-Peterson (1986).

Colorado Plateau. The decrease in thickness of the Navajo Sandstone from more than 600 m (2,000 ft) to a feather edge across the Colorado Plateau (Jobin, 1962; Blakey and others, 1988) probably determined the major discharge zone during Late Jurassic time. The pinchout of the Navajo Sandstone, from 150 m (500 ft) to zero (Jobin, 1962; Blakey and others, 1988), forms an arcuate band with its main axis oriented north-south and bowed to the east (fig. 3). The underlying Wingate Sandstone and overlying Entrada Sandstone also tend to thin to the northeast; however, the change in their thicknesses is much less than that of the Navajo Sandstone (Jobin, 1962; Blakey and others, 1988). The upper Paleozoic aquifer system pinches out west of the Navajo pinchout in the Paradox Basin area but not in the San Juan Basin area, where the Navajo is absent. The highly transmissive Leadville and Redwall Limestones probably were important for regional flow but may have been too deeply buried under confining units to influence near-surface ground-water flow in Triassic and Jurassic time.

Thickness variations suggest that northeast-flowing regional ground water generally flowed from the upper Paleozoic aquifer system upward into the base of the Lower Jurassic aquifer system (fig. 3). This flow then discharged upward from the Lower Jurassic aquifer system where it thinned to the northeast. Because the Navajo Sandstone thins so dramatically, it probably was a major source of upward ground-water discharge. Thinning of the Wingate and Entrada Sandstones, as well as thinning of the whole sedimentary section over the buried Uncompahgre block, contributed to discharge beyond the pinchout of the Navajo Sandstone. North and east of the Uncompahgre block, the eolian Middle and Upper Pennsylvanian and Lower Permian Weber Sandstone of the upper Paleozoic aquifer system favored recharge and focusing of ground water in a northerly direction around the Front Range block into central Wyoming.

COMPOSITION

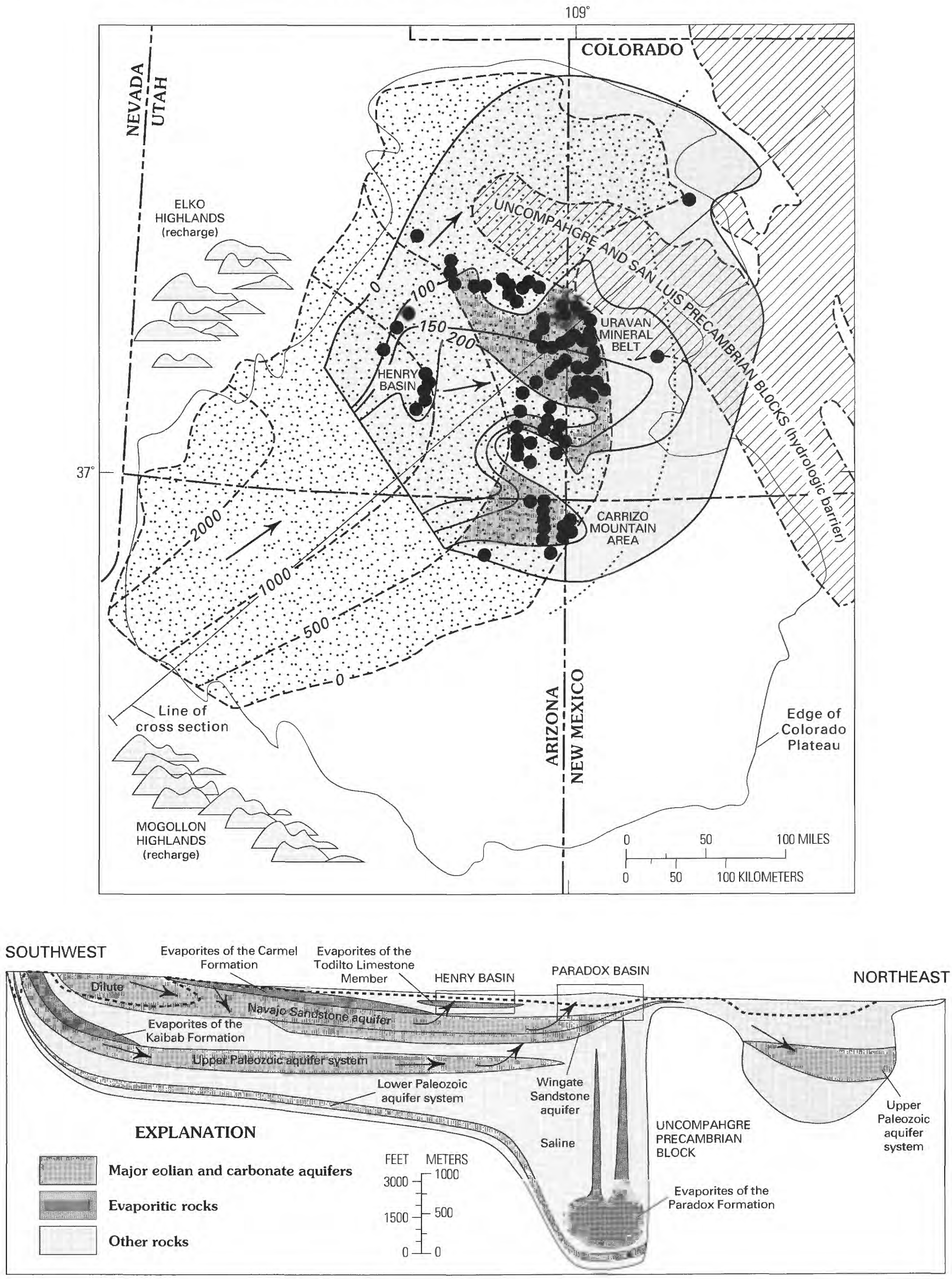
Judging from the widespread distribution of evaporites and evaporitic clastic rocks throughout the Colorado Plateau (fig. 4), regional and intermediate ground water was probably saline toward the distal ends of flow paths. The deepest regional flow penetrated Pennsylvanian and Permian evaporites. This ground water probably approached halite saturation and contained significant Na^+, K^+, Ca^{2+}, Cl^-, and SO_4^{2-} from the dissolution of halite, sylvite, anhydrite, and gypsum. Analysis of modern ground water whose solutes came from these evaporites indicates that the ancient brines were probably Na^+-Cl^- type (Hanshaw and Hill, 1969; Thackston and others, 1981; Sanford, 1990a). Sulfur isotopes from authigenic barite cement are consistent with the transport of Pennsylvanian sulfate up to the Upper Jurassic Morrison Formation (Breit and others, 1990). Ground water at intermediate depths flowed through Jurassic and Triassic evaporites (fig. 4). Gypsum in the Lower and Middle(?) Triassic Moenkopi Formation (Blakey, 1974), Middle Jurassic Curtis Formation (Peterson, 1988a), Middle Jurassic Todilto Limestone Member of the Wanakah Formation (Ridgley, 1989), and Upper Jurassic Tidwell Member of the Morrison Formation (Peterson, 1988a) suggests that intermediate ground water below and in the lower part of the Morrison Formation was saline.

Local ground water that remained in the uppermost layer of alluvium was probably a dilute Na^+-Ca^{2+}-HCO_3– solution, judging from analysis of modern ground water in the Colorado Plateau and elsewhere (Hanshaw and Hill, 1969; Thackston and others, 1981; Davis, 1988; Sanford, 1990a). This relatively fresh water probably rested on the saline water formed by passage through Mesozoic and older evaporites and marine sediments.

SALT WASH SANDSTONE MEMBER OF THE MORRISON FORMATION

Owing mainly to local paleotopographic variations, the different members of the Morrison Formation exhibited distinct differences in ground-water flow. The Salt Wash Sandstone Member was deposited on a broad fan-shaped alluvial plain that included, from southwest to northeast, dominantly low sinuosity, sand-dominated stream deposits; high-sinuosity, mud-dominated, floodplain deposits; and lacustrine mudstone-limestone deposits in the undifferentiated Morrison Formation (fig. 3) (Craig and others, 1955, Mullens and Freeman, 1957; Young, 1978; Galloway, 1979; Dodson and others, 1980; L.C. Craig, U.S. Geological Survey, unpublished data, 1982; Tyler and Ethridge, 1983; Peterson, 1984, 1986, in press; Peterson and Tyler, 1985; Peterson and Turner-Peterson, 1987). L.C. Craig (unpublished data, 1982) estimated the slope of the alluvial plain at from 1:1,000 to 1:2,000.

During deposition of the Salt Wash Sandstone Member, ground water probably discharged at wetlands in topographic depressions in the Henry Basin, Uravan mineral belt, and Carrizo Mountains area (figs. 3, 5). A variety of evidence, including the transition from low- to high-sinuosity channels, decrease in thickness of sandstone, decrease in sandstone as a percent of total thickness, increase in mudstone thickness and percentage, transition from sandstone-mudstone to claystone-limestone facies, and transition from fluvial sheet gravels to mudflat-lake muds (Craig and others, 1955; Mullens and Freeman, 1957; Peterson and Tyler, 1985), suggests a major decrease in topographic slope at the distal edge of the alluvial plain. The greatest concentration of uranium deposits in the Salt Wash Member is where stream deposits in the Salt Wash Member thin from 60 to 30 m (200–90 ft) (Craig and others, 1955) and where the Navajo Sandstone thins from 150 m (500 ft) to zero (fig. 3).


109°
COLORADO
NEVADA
UTAH
ELKO
HIGHLANDS
(recharge)
UNCOMPAHGRE AND SAN LUIS PRECAMBRIAN BLOCKS (hydrologic barrier)
0
100
150
200
URAVAN
MINERAL
BELT
HENRY
BASIN
37°
CARRIZO
MOUNTAIN
AREA
2000
1000
500
0
Line of
cross section
ARIZONA
NEW MEXICO
Edge of
Colorado
Plateau
MOGOLLON
HIGHLANDS
(recharge)
0 50 100 MILES
0 50 100 KILOMETERS
SOUTHWEST
Evaporites of the Carmel Formation
Evaporites of the Todilto Limestone Member
HENRY BASIN
PARADOX BASIN
NORTHEAST
Dilute
Navajo Sandstone aquifer
Evaporites of the Kaibab Formation
Upper Paleozoic aquifer system
Lower Paleozoic aquifer system
Wingate Sandstone aquifer
Saline
UNCOMPAHGRE PRECAMBRIAN BLOCK
Upper Paleozoic aquifer system
Evaporites of the Paradox Formation
EXPLANATION
Major eolian and carbonate aquifers
Evaporitic rocks
Other rocks
FEET METERS
3000 1000
1500 500
0 0

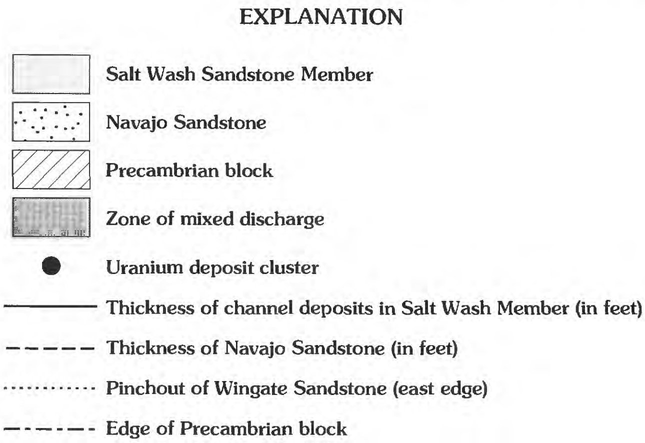


Figure 3 (above and facing page). Simplified map and cross section of the Colorado Plateau for Late Jurassic time at end of deposition of the Salt Wash Sandstone Member of the Morrison Formation. Thickness of stream deposits in the Salt Wash Member, total thickness of the underlying Lower Jurassic Navajo Sandstone, and location of buried Precambrian blocks indicate areas of ground-water discharge. Arrows on map and cross section show direction of ground-water flow. Areas in cross section delineated by boxes are shown in detail in figure 5. Dotted line in cross section is dilute-saline interface. The Lower Jurassic aquifer system is composed of the Wingate and Navajo Sandstone aquifers. Modified from Craig and others (1955), Baars (1962), Jobin (1962), Mallory (1972), Peterson (1984, 1986, 1988a, in press), and Blakey and others (1988).

The Henry Basin was an area of decreased topographic slope as indicated by thicker sediments, more channel sandstone, higher sinuosity channels, increased upper flow regime horizontal laminations, and lacustrine mudstone (Peterson, 1984, 1986). Topographic depressions within the Henry Basin are suggested by thick sediments, evaporite deposits, lacustrine deposits, repetition of facies, and coincidence of synclines with present-day synclines (F. Peterson, 1980, 1984). Tabular sandstone uranium-vanadium deposits are associated with topographic depressions, actively subsiding synclines, and reduced, carbon-bearing lake deposits, and they slope upward stratigraphically in the downstream flow direction of surface water (F. Peterson, 1980; Northrop and Goldhaber, 1990). The tabular ore layers and diagenetic alterations have been interpreted as suggesting two fluids with a mixing zone between them (Northrop and Goldhaber, 1990; Wanty and others, 1990). Although some of the specific reactions proposed by Northrop and Goldhaber (1990) and Wanty and others (1990) are questionable (Spirakis, 1991; Hansley and Spirakis, 1992), the tabular nature of the uranium-vanadium bodies strongly suggests a density-stabilized interface. The tabular shape, upward slope, and association with paleotopographic depressions are consistent with a saline water interface that arches upward at the topographic depression (fig. 5*A*).

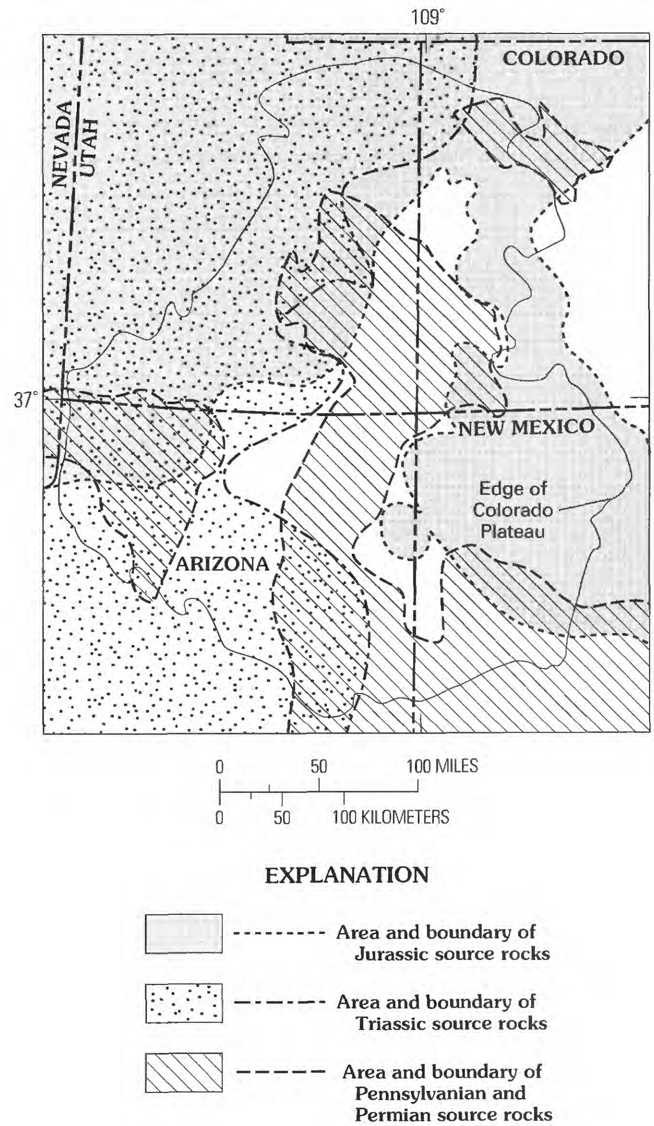


Figure 4. Generalized map showing source rocks for solutes in ground water in the Colorado Plateau region. Source rocks include halite-sylvite-bearing evaporites, anhydrite-gypsum evaporites, and clastic rocks containing anhydrite-gypsum beds. Pennsylvanian and Permian source rocks include Paradox Formation, Supai Formation, Cedar Mesa Sandstone Member of the Cutler Formation, San Andres Limestone, and Yeso Formation. Triassic source rocks include Moenkopi Formation. Jurassic source rocks include Carmel Formation, Todilto Limestone Member of the Wanakah Formation, and Tidwell Member of the Morrison Formation. Data from Baars (1962), Mallory (1972), Blakey (1974, 1980), J.A. Peterson (1980), F. Peterson (1984, 1988a), and Ridgley (1989).

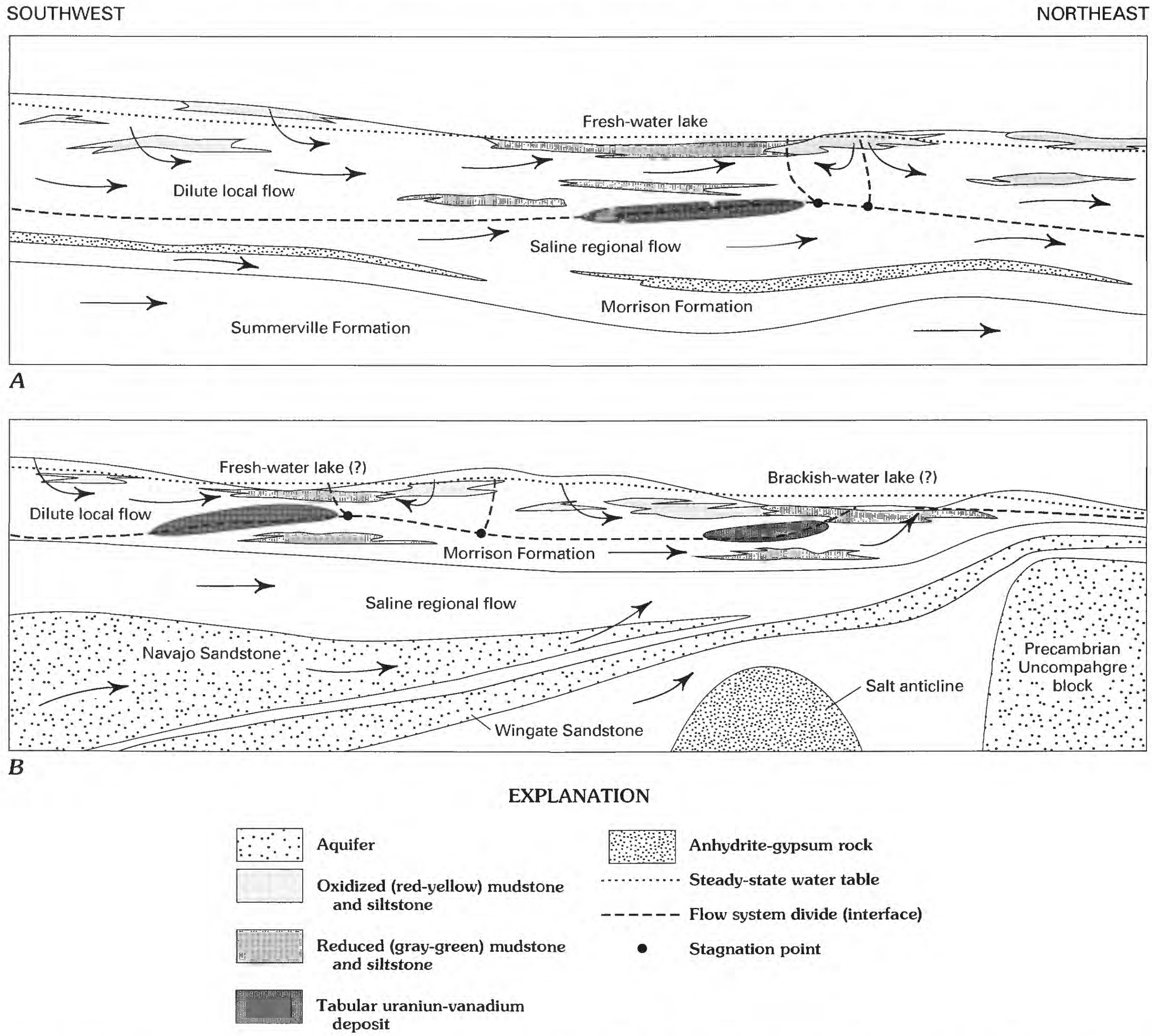


Figure 5. Schematic cross section showing influences on ground-water flow in the Colorado Plateau region during the Late Jurassic at the end of deposition of the Salt Wash Sandstone Member of the Morrison Formation (not to scale). Location of areas are delineated by boxes on cross section of figure 3. No vertical scale implied. Flow lines, flow-system divides, and stagnation points drawn according to the theory of Toth (1962), Hitchon (1969), Winter (1976, 1983, 1988), and others, as constrained by oxidized and reduced rocks suggestive of recharge and discharge. Principle sources of dissolved solids are evaporitic rocks. *A*, Henry Basin. *B*, Paradox Basin.

In the Uravan mineral belt, tabular sandstone uranium deposits are associated with distributary channels, thick host sandstone, higher sandstone to mudstone ratio, lenticular rather than flatbedded sandstone, scour-and-fill bedding, and overlying conglomeratic sandstone (Weir, 1952; Phoenix, 1958; Shawe, 1962; Motica, 1968; Thamm and others, 1981), all of which suggest topographic depressions. The deposits typically are within gray reduced sandstone that contains carbonized wood and overlies a green reduced mudstone bed (fig. 6) (McKay, 1955). As in the Henry Basin, the shape, upward slope, and associated reduced rocks are consistent with a saline water-fresh water interface inclined upward toward an area of perennial discharge (fig. 5*B*).

An absence of uranium deposits in the Four Corners area between the Uravan mineral belt and the Carrizo Mountains deposits coincides with an inferred local recharge area (fig. 3). This area, characterized by an abundance of eolian sandstone (Bluff Sandstone Member of the Morrison Formation) and a lack of channel sandstone, has been interpreted as a local topographic high (Peterson and Tyler, 1985; Blakey and others, 1988; Peterson, 1988b, in press).

South of the recharge area, in the Carrizo Mountains and vicinity (fig. 3), uranium deposits are in a relatively thick part of the Salt Wash Sandstone Member where the sedimentary structures and thickness data indicate an eastward-trending, syndepositional structural depression (Hilpert, 1969). This area also is characterized by an abrupt decrease in the sandstone to mudstone ratio and by abrupt changes in rock color (Chenoweth and Malan, 1973).

Modeling of regional ground-water flow in the Colorado Plateau during Late Jurassic-Early Cretaceous time indicates that local dilute ground water and regional saline fluids converged at the topographically and geologically controlled discharge zones (Sanford, 1982, 1994). Recharge was in highland areas to the southwest, and deep regional flow gained solutes through interaction with evaporites and other rocks along the flow path (fig. 3). At the more local scale, hydrologic theory and modern analogs suggest the presence of an interface that would have been near the surface in topographic depressions (fig. 5). In some areas, such as the Henry Basin, the saline water interface may have remained at shallow depth and not reached the surface (fig. 5*A*). In other areas, such as the Uravan mineral belt, the interface may have reached the surface, allowing relatively fresh water and saline water to discharge together (fig. 5*B*).

RECAPTURE MEMBER OF THE MORRISON FORMATION

Similar to the Salt Wash Sandstone Member, the Recapture Member of the Morrison Formation was deposited on a broad, roughly fan shaped alluvial plain sloping to the northeast (fig. 7) (Craig and others, 1955; L.C. Craig, unpublished data, 1982; Peterson and Turner-Peterson, 1987; Peterson, in press).

A sandstone facies between conglomeratic and claystone-sandstone facies (Craig and others, 1955; L.C. Craig, unpublished data, 1982) marks a decrease in paleotopographic slope where local and regional ground-water systems probably discharged. Syndepositional subsidence (Hilpert, 1969) favored local and regional ground-water discharge.

Geologic controls favoring discharge from the Recapture Member include thinning of the Lower Jurassic and upper Paleozoic aquifer systems. Dramatic thinning of the Navajo Sandstone favored discharge beneath the northwestern part of the Recapture. The Wingate Sandstone, which is the major aquifer east of the pinchout of the Navajo Sandstone, is thickest in the Four Corners area and thins from there toward the northeast (Jobin, 1962; Blakey and others, 1988). Thinning of the Wingate to the northeast also favored discharge. The Entrada Sandstone has a relatively constant thickness (Jobin, 1962; Blakey and others, 1988).

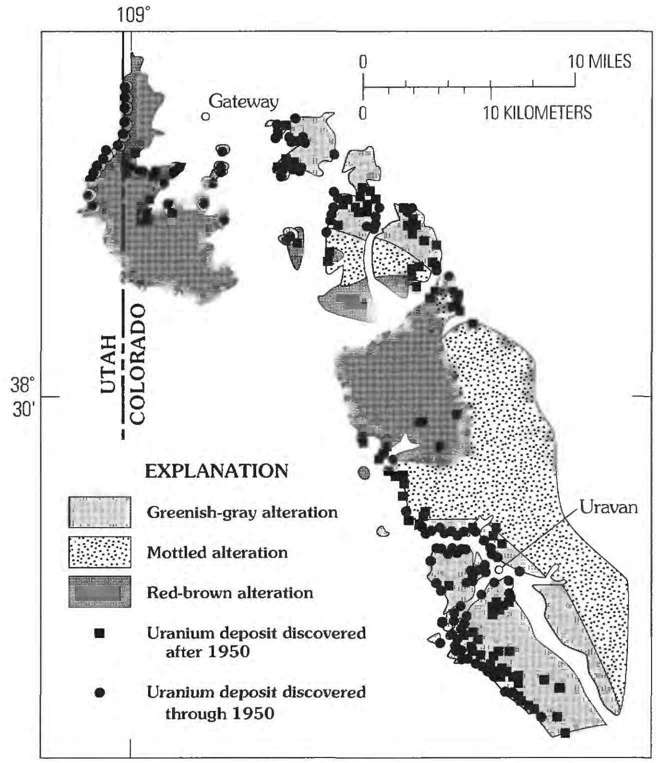


Figure 6. Map showing areas of alteration in mudstone underlying uranium-bearing sandstone and location of uranium deposits in the northern end of the Uravan mineral belt. Uranium deposits are closely associated with reduced mudstone in areas of inferred ground-water discharge. Mudstone alteration and uranium deposits discovered through 1950 from McKay (1955); deposits discovered after 1950 from Umetco Company (unpublished map, 1976).

The Lower Permian Glorieta Sandstone, Meseta Blanca Sandstone Member of the Yeso Formation, San Andres Limestone, and De Chelly Sandstone are today the major upper Paleozoic aquifers in the San Juan Basin (Stone and others, 1983). The sandstone aquifers thin and pinch out toward the north and east (Baars and Stevenson, 1977; Blakey and others, 1988), but, because the present transmissivity of the San Andres Limestone is related to dissolution near the outcrop, it may not have been an aquifer in Jurassic time.

Tabular sandstone uranium deposits in the Recapture Member in northwest New Mexico (Hilpert, 1969) are at the transition between the conglomeratic and sandstone faces and near the pinchout of the Navajo and Wingate Sandstones. An eastward-trending troughlike structure traverses the main part of the mining district (Hilpert, 1969). Anhydrite cement in the Recapture Member (Hansley, 1990) and the upper part of the underlying Middle Jurassic Wanakah Formation (Ridgley, 1989) suggests a source of saline water in the underlying Middle Jurassic Todilto Limestone Member of the Wanakah Formation or the Permian evaporitic rocks of the Black Mesa uplift (figs. 2, 4).

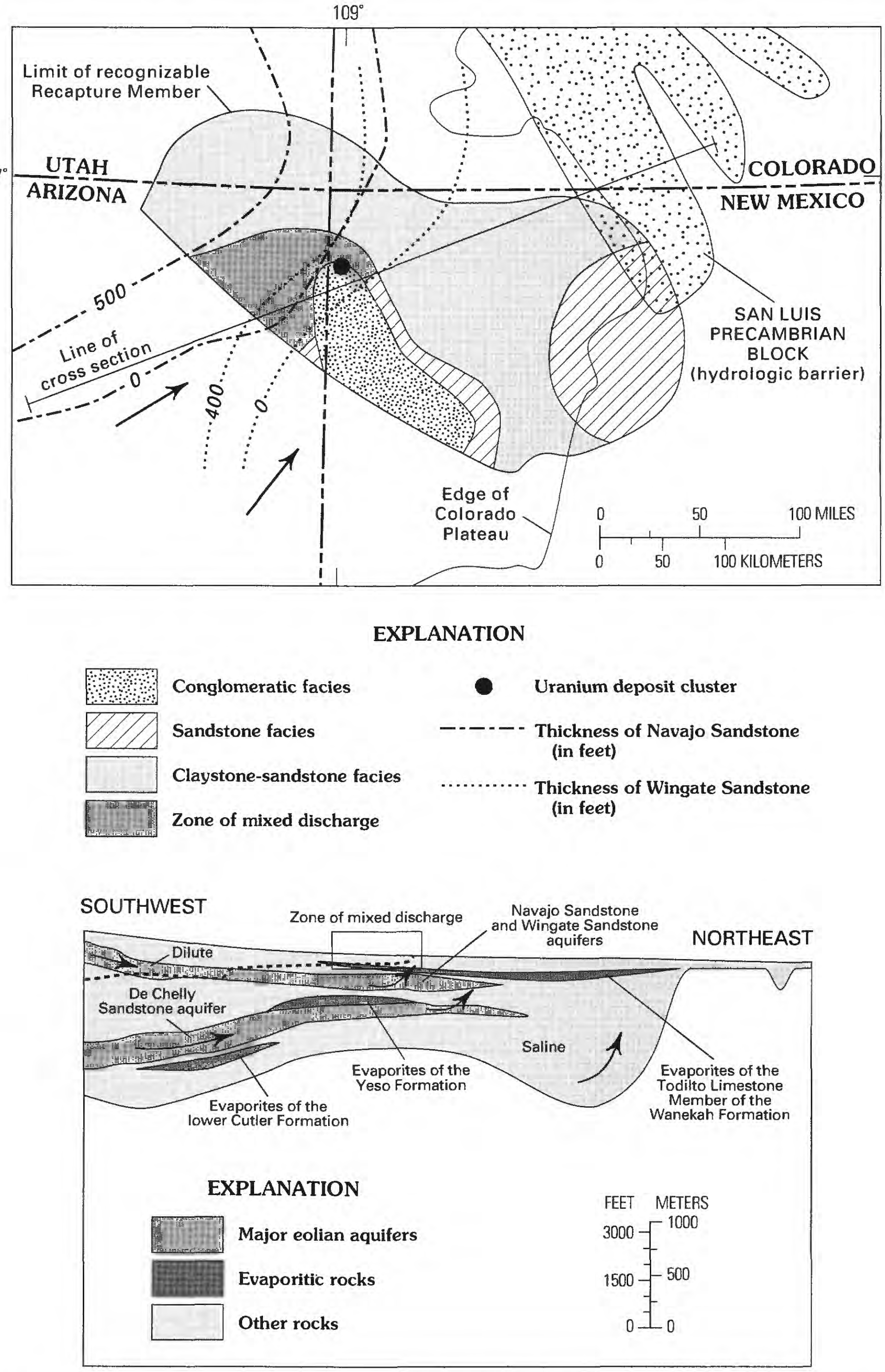


Figure 7. Simplified map and cross section of the San Juan Basin for Late Jurassic time at the end of deposition of the Recapture Member of the Morrison Formation. Discharge is favored by decrease in topographic slope in sandstone facies and by pinchout of the Navajo Sandstone and Wingate Sandstone aquifers. The De Chelly Sandstone (not shown) also thins abruptly just east of the pinchout of the Wingate Sandstone. Arrows on map and cross section show direction of ground-water flow. Dotted line in cross section is dilute-saline interface. Data from Craig and others (1955), Baars (1962), Jobin (1962), Mallory (1972), Baars and Stevenson (1977), and Blakey and others (1988).

WESTWATER CANYON MEMBER OF THE MORRISON FORMATION

The Westwater Canyon Member was deposited on a fan-shaped alluvial plain traversed by braided streams flowing generally toward the northeast and locally to the east and southeast (Craig and others, 1955; Hilpert, 1969; L.C. Craig, unpublished data, 1982; Condon and Huffman, 1984; Condon and Peterson, 1986; Turner-Peterson, 1986; Peterson and Turner-Peterson, 1987).

Local and regional ground-water discharge in the Westwater Canyon Member probably occurred along a northwest-trending zone where a transition from an alluvial-plain facies to a mudflat facies suggests a major change in slope (figs. 8, 9). A map of sandstone to mudstone ratio indicates the regional paleotopographic slope (fig. 8). Sandstone to mudstone ratios vary from 300:1 in the southwest to 0.5:1 in the northeast (Robert Lupe, U.S. Geological Survey, unpublished data, 1982; Kirk and Condon, 1986). Discharge probably occurred in a zone of major decrease in topographic slope, approximately from the >10:1 to 4:1 contours of sandstone to mudstone ratio (fig. 8). Tectonic activity affected the distribution of facies and the paleoslope on a more local scale, as indicated by locally thick sediments, high sandstone to mudstone ratios, and smaller numbers of sandstone-mudstone interbeds (Kirk and Condon, 1986). Stream channels were concentrated in subsiding structures, whereas overbank muds were deposited on paleohighs. Thus, local ground-water flow tended to recharge in the local highs dominated by overbank mudstone and discharge in the depressions dominated by channel sandstone.

The most significant geologic control on ground-water flow in the San Juan Basin probably was the thinning of the De Chelly Sandstone and the Meseta Blanca Member of the Yeso Formation (fig. 9). The De Chelly Sandstone thins abruptly from 240 to 100 m (800–300 ft) and then pinches out gradually toward the east (Baars and Stevenson, 1977). The Meseta Blanca Member thins abruptly from 150 to 100 m (500–300 ft) and then pinches out gradually toward the north (Baars and Stevenson, 1977). Because the change in thickness (rather than the thickness itself) is the critical geological control on ground-water flow, the region of abrupt thinning (rather than the pinchout) was most likely the zone of maximum geologically controlled discharge for regional ground water.

Tabular sandstone uranium-humate deposits in the western part of the Grants uranium region were a major source of uranium (Kelley, 1963; Hilpert, 1969; Rautman, 1980; Adams and Saucier, 1981; Turner-Peterson, Santos, and Fishman, 1986; Finch and McLemore, 1989). The deposits are in the Westwater Canyon Member and cluster in a belt from just upslope of the 10:1 contour of sandstone to mudstone ratio to the 4:1 contour, in the zone of abrupt thinning of the Meseta Blanca Member (fig. 9). The uranium region itself consists locally of two or more local belts of deposits that are 3–5 km (2–3 mi) apart (Granger and others, 1961). The main deposits tend to be in the centers of the thickest sandstone masses, which are in syndepositional synclines (Hilpert and Moench, 1960; Hilpert, 1969; Kirk and Condon, 1986). The general position of the Grants uranium region probably was controlled by ground-water discharge at the maximum change in topographic slope, indicated by the major facies change, and by the zone of maximum thinning of the Meseta Blanca Member. Local clusters of uranium deposits within the region were probably controlled by local paleotopographic depressions.

Discharging regional ground water was probably saline owing to dissolution of anhydrite-bearing evaporites of the Middle Jurassic Todilto Limestone Member of the Wanakah Formation (figs. 4, 10). Dissolution is shown by the numerous breccia pipes that terminate downward in the Todilto (Moench and Schlee, 1967; Hilpert, 1969; Hunter and others, 1992).

The oxidation state of iron in the sedimentary rocks suggests local recharge and discharge areas within the general area favorable for ground-water discharge in the Grants uranium region. For example, a syndepositional syncline contains reduced rock and uranium deposits, whereas the adjacent paleohighs contain oxidized rock and lack uranium deposits (Turner-Peterson, 1985). The combination of paleotopographic lows and reduced rock suggests that high water table, ground-water discharge, and preservation of organic matter are associated with the deposits.

Detrital ilmenite and titaniferous magnetite in sandstone of the Westwater Canyon Member show variable degrees of alteration to anatase, leucoxene, hematite, and pyrite (Adams and others, 1974; Adams and Saucier, 1981; Reynolds and others, 1986). Alteration probably occurred by incongruent dissolution of detrital iron-titanium oxide minerals by ground water that was reducing, neutral to weakly acid, and humic acid rich (Adams and others, 1974). Dissolution of iron-titanium oxide minerals is diagenetic evidence for shallow, relatively fresh, ground water, and the pattern of alteration indicates the extent of the shallow ground-water system (figs. 10, 11). In general, the intensity of iron-titanium oxide dissolution decreases downward and from southwest to northeast (Adams and others, 1974; Adams and Saucier, 1981; Turner-Peterson, 1985, 1986; Reynolds and others, 1986). Some authors (Adams and Saucier, 1981; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986) have plotted the total thickness of the zone of iron-titanium oxide dissolution. This measure does not truly represent the intensity of iron-titanium oxide mineral alteration because the thickness of the host Westwater Canyon Member also decreases to the southwest. Plotting the same data in terms of the percentage of the Westwater Canyon Member that is altered better indicates

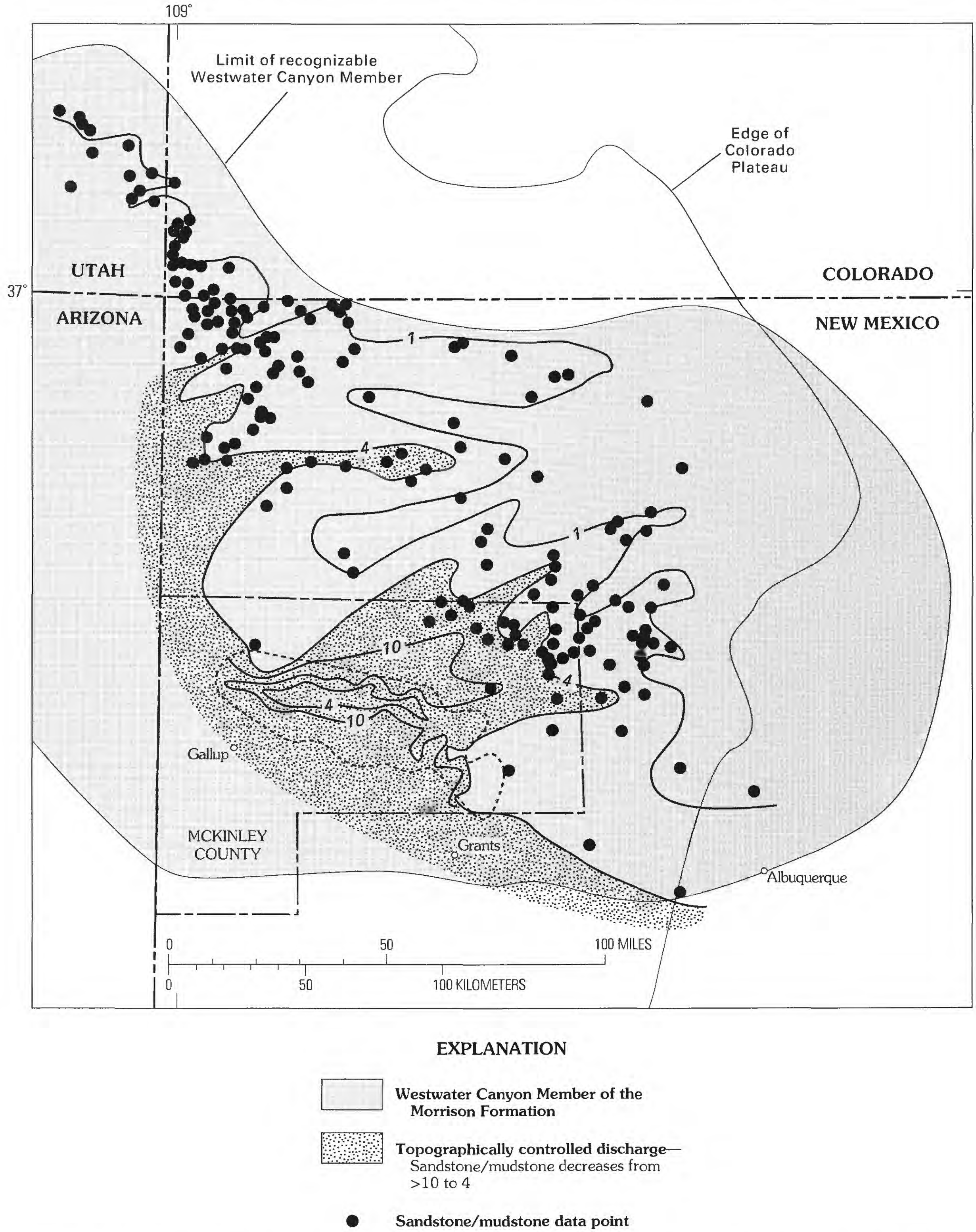


Figure 8. Map showing contours of sandstone to mudstone thickness ratio in the Westwater Canyon Member of the Morrison Formation. Decrease in ratio from southwest to northeast indicates decrease in topographic slope. Ground-water discharge and mixing is favored where sandstone to mudstone ratio is from >10 to 4. Data from Kirk and Condon (1986; area in New Mexico outlined by dotted curve) and from Robert Lupe (U.S. Geological Survey, unpublished data, 1982; data points shown by solid circles).

the intensity of alteration in the Westwater Canyon (fig. 11). The contours indicate a wedge-shaped lens of alteration that includes the entire Westwater Canyon Member in parts of the south and west (100 percent alteration) and thins to a feather edge toward the northeast. Pockets of less alteration are present in the middle of the southern edge of the Westwater Canyon Member but probably are secondary effects superimposed on the regional trend. Although considerable latitude is possible in contouring the data, there is no reason to interpret a pinching-out of the alteration zone to the south, as indicated by previous authors (Adams and Saucier, 1981; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). The pattern of iron-titanium oxide alteration has been interpreted to indicate downward flow of fluid and is a major argument in support of the "lacustrine-humate model" of uranium ore formation (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). This evidence alone is not compelling because the alteration pattern can equally well be interpreted as a result of downdip flow of dilute ground water that tended to be confined to the upper part of the sandstone by saline ground water.

BRUSHY BASIN MEMBER OF THE MORRISON FORMATION

The Brushy Basin Member and the lithologically similar undifferentiated Morrison Formation consist of discontinuous sandstone beds in a predominantly mudstone and claystone matrix with limestone beds and nodules (Craig and others, 1955; Dodson and others, 1980; Bell, 1983, 1986; Turner-Peterson, 1985, 1987; Lockley and others, 1986; Peterson and Turner-Peterson, 1987; Turner and Fishman, 1991). Lithofacies suggest a low-gradient alluvial plain and scattered lakes or playas. A large lake having well-developed diagenetic facies similar to those in modern playas such as Searles Lake (Smith, 1979) is thought to have covered 150,000 km^2 mainly in northwest New Mexico and southwest Colorado (figs. 12–14) (Bell, 1983, 1986; Turner-Peterson, 1985, 1987; Turner and Fishman, 1991). The general direction of streams was northeastward.

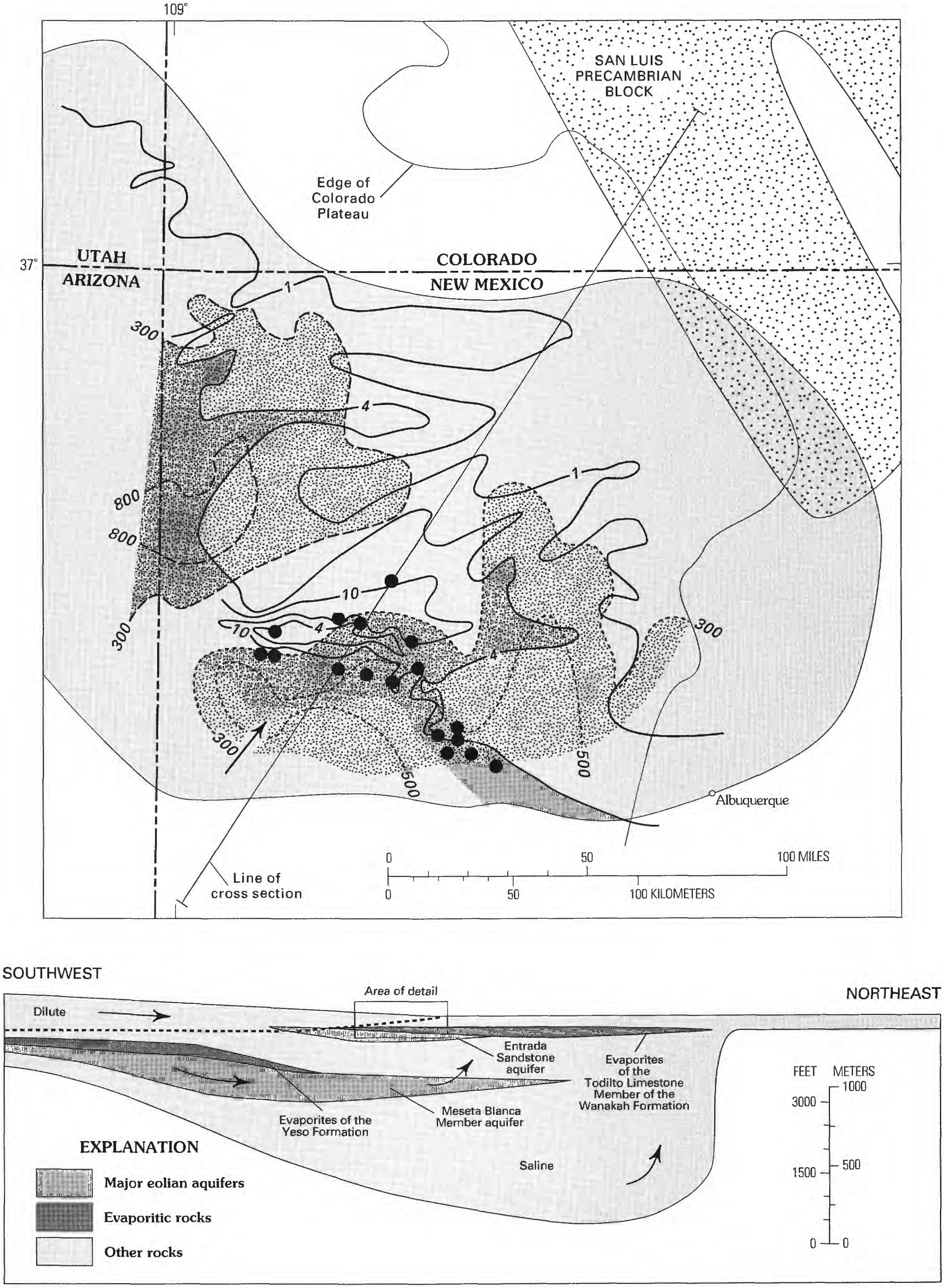
The generally fine grain size of the Brushy Basin Member suggests a low and uniform topographic slope that would not have favored significant recharge or discharge over much of the area. Lithofacies vary from continuous sandstone (sandstone to mudstone >1.0), to discontinuous sandstone (sandstone to mudstone <1.0 and >0.6), to dominantly mudstone (sandstone to mudstone <0.6) (fig. 12*A*) (Bell, 1983, 1986). The main change in topographic slope was probably in the southern part of the depositional area of the Brushy Basin Member in northwest New Mexico where mostly sandstone was deposited (continuous sandstone, fig. 12*A*, and sandstone, fig. 12*B*).

Quantitative modeling of ground-water flow during deposition of the Brushy Basin Member indicates that discharge occurred throughout a large topographic depression (Sanford, 1990b, 1994). A lake in the depression would have focused ground-water discharge at the shoreline. Most of this discharge presumably took place on the upstream or southwest side of the lake because of the regional hydraulic gradient (fig. 13). Both regional and local ground-water systems probably discharged around the playa. In the absence of a lake, ground water probably discharged in the topographically lowest parts of the closed depression.

The low permeability of the Brushy Basin Member, compared to the Westwater Canyon Member, suggests that ground-water flow through the Brushy Basin Member may have been mainly vertical. Geologic controls on ground-water flow during deposition of the Brushy Basin Member were similar to those for the rest of the Morrison Formation, as discussed above (figs. 3, 7, 9). Deep, saline ground water discharged where Jurassic and upper Paleozoic aquifer systems thinned abruptly in the subsurface. The Uncompahgre and San Luis blocks forced most of the remaining ground water to discharge or flow around the blocks.

Diagenetic studies of the Brushy Basin Member have focused on the alteration associated with a large alkaline-saline playa lake (figs. 12, 13) (Bell, 1983, 1986; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986; Turner and Fishman, 1991). Turner and Fishman proposed well-defined facies boundaries. T.E. Bell (oral commun., 1989) considered the facies boundaries too poorly defined to allow identification of discrete boundaries. A calcite facies (Bell, 1983, 1986) is important evidence for fluid mixing. The marginal mudflat of the Brushy Basin playa corresponds to the smectite-discontinuous sandstone and calcite facies (figs. 12*A*, 14) (Bell, 1983, 1986), alternatively termed the smectite facies (fig. 12*B*) (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986; Turner and Fishman, 1991). The smectite-discontinuous sandstone facies contains isolated limestone nodules, and the calcite facies contains abundant laterally continuous limestone beds (Bell, 1983, 1986). By analogy with modern playas and saline lakes (Eugster and Hardie, 1978; Mono Basin Ecosystem Study Committee, 1987; Duffy and Al-Hassan, 1988), this carbonate formed as a result of discharge of bicarbonate-bearing ground water at the edge of the playa. The increasing amount of carbonate going from smectite to calcite facies suggests increasing carbonate concentration and deeper flow depth of the discharging ground water.

Diagenetic minerals such as analcime, zeolites, and potassium feldspar occupy the central part of the playa and are interpreted as evidence for an alkaline-saline brine (fig. 12) (Bell, 1983, 1986; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986; Turner and Fishman, 1991). Other diagenetic indicators are more difficult to interpret.


109°
SAN LUIS
PRECAMBRIAN
BLOCK
Edge of
Colorado
Plateau
37°
UTAH
ARIZONA
COLORADO
NEW MEXICO
300
800
800
300
1
4
1
10
10
4
4
300
300
500
500
Albuquerque
Line of
cross section
0
50
100 MILES
0
50
100 KILOMETERS
SOUTHWEST
NORTHEAST
Area of detail
Dilute
Entrada
Sandstone
aquifer
Evaporites
of the
Todilto Limestone
Member of the
Wanakah Formation
Evaporites of the
Yeso Formation
Meseta Blanca
Member aquifer
Saline
FEET
METERS
3000
1000
1500
500
0
0
EXPLANATION
Major eolian aquifers
Evaporitic rocks
Other rocks

For example, the alteration of smectite to illite, which increases downdip toward the center of the basin, has been interpreted as evidence both for upward flow of deep ground water (Whitney and Northrop, 1987) and for downward flow of playa lake water (Owen and others, 1989; Turner and Fishman, 1991).

Modern playa analogs (Allison and Barnes, 1985; Duffy and Al-Hassan, 1988) and computer modeling (Sanford, 1990b, 1994) show that flow can be downward or upward depending on hydrodynamic conditions. If the ground water had a constant density throughout, it would discharge at a topographic depression; however, in a playa setting where surface water is highly concentrated, buoyancy may cause ground water to sink beneath the playa and recirculate by convection back updip to discharge near the shoreline or margin of the playa (Duffy and Al-Hassan, 1988). Downward flow of playa lake water is suggested by zeolite alteration in the Westwater Canyon Member beneath the Brushy Basin Member (Hansley, 1986, 1990). One possible interpretation that is consistent with hydrologic theory, modern analogs, model predictions, and diagenetic alteration is shown in figure 14. Although the flow of shallow ground water in the alluvial plain probably was consistently downdip, the flow of ground water in the playa probably varied with time, alternately moving downward or upward as the density of the lake and pore fluid varied.

According to one version of the lacustrine-humate model, uranium deposits in the Westwater Canyon Member and Jackpile Sandstone Member are genetically related to the mudflat (smectite) facies of the Brushy Basin Member (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). Although a fair correspondence between deposits and the mudflat facies exists in the San Juan Basin, the correspondence completely breaks down for other parts of the Colorado Plateau (fig. 13). In the Uravan mineral belt, most deposits in the Salt Wash Member are beneath the analcime-potassium feldspar facies of the Brushy Basin Member. Furthermore, the Salt Wash Sandstone Member may be separated from the upper part of the Brushy Basin Member by an unmineralized lower part that has been interpreted as equivalent to the Recapture Member (Turner and Fishman, 1991). In the Henry Basin, uranium deposits are beneath the alluvial or continuous-sandstone facies. Thus, the correspondence of Brushy Basin mudflat with tabular sandstone uranium deposits is probably a fortuitous coincidence limited to the San Juan Basin rather than a general characteristic having genetic significance.

EXPLANATION

Westwater Canyon Member of Morrison Formation

Upper Paleozoic aquifers >300 feet

Precambrian block

Zone of mixed discharge

Uranium deposit cluster

Thickness of De Chelly Sandstone (in feet)

Thickness of Meseta Blanca Member of Yeso Formation (in feet)

Contour of sandstone to mudstone ratio in Westwater Canyon Member of Morrison Formation

Figure 9 (above and facing page). Simplified map and cross section of the San Juan Basin for Late Jurassic time at the end of deposition of the Westwater Canyon Member of the Morrison Formation. Transition in sandstone to mudstone ratio from >10 to 4 indicates topographically controlled discharge. Abrupt thinning of the De Chelly Sandstone and Meseta Blanca Sandstone Member aquifers indicates geologically controlled discharge. Where both coincide is an inferred zone of mixed local and regional discharge. Arrows on map and cross section show principle direction of ground-water flow. Area in cross section delineated by box is shown in more detail in figure 10. Dotted line in cross section is dilute-saline interface. Data from Craig and others (1955), Baars (1962), Jobin (1962), Peterson and others (1965), Mallory (1972), Baars and Stevenson (1977), and Blakey and others (1988).

JACKPILE SANDSTONE MEMBER OF THE MORRISON FORMATION

The Jackpile Sandstone Member overlies and interfingers with the Brushy Basin Member in the southeastern part of the San Juan Basin (Moench and Schlee, 1967; Owen and others, 1984). It consists mostly of fluvial sandstone deposited in an active northeast-trending syncline. The upper part of the Jackpile Member was removed in places by erosion prior to deposition of the Upper Cretaceous Dakota Sandstone (Moench and Schlee, 1967; Adams and others, 1978).

The presence of zeolite facies mudstone of the Brushy Basin Member beneath the thickest part of the Jackpile Sandstone Member indicates that a low area existed prior to Jackpile deposition (Bell, 1983). Isopachs and interfingering relations with the Brushy Basin Member indicate active subsidence during deposition (Moench and Schlee, 1967). Preservation of the Jackpile Member suggests that low topography persisted while surrounding areas were uplifted and eroded.

Paleocurrent directions and isopachs of the Jackpile Sandstone Member (Moench and Schlee, 1967; Adams and others, 1978) suggest that shallow, relatively fresh ground water flowed northeast along the axis of the syndepositional syncline (fig. 15). Because the area was a topographic depression, deeper ground water probably discharged into the base of the unit (Sanford, 1990b, 1994).

Diagenetic evidence indicates the timing, relative extent, and movement of the shallow and deeper ground water. Iron-titanium oxide minerals were extensively

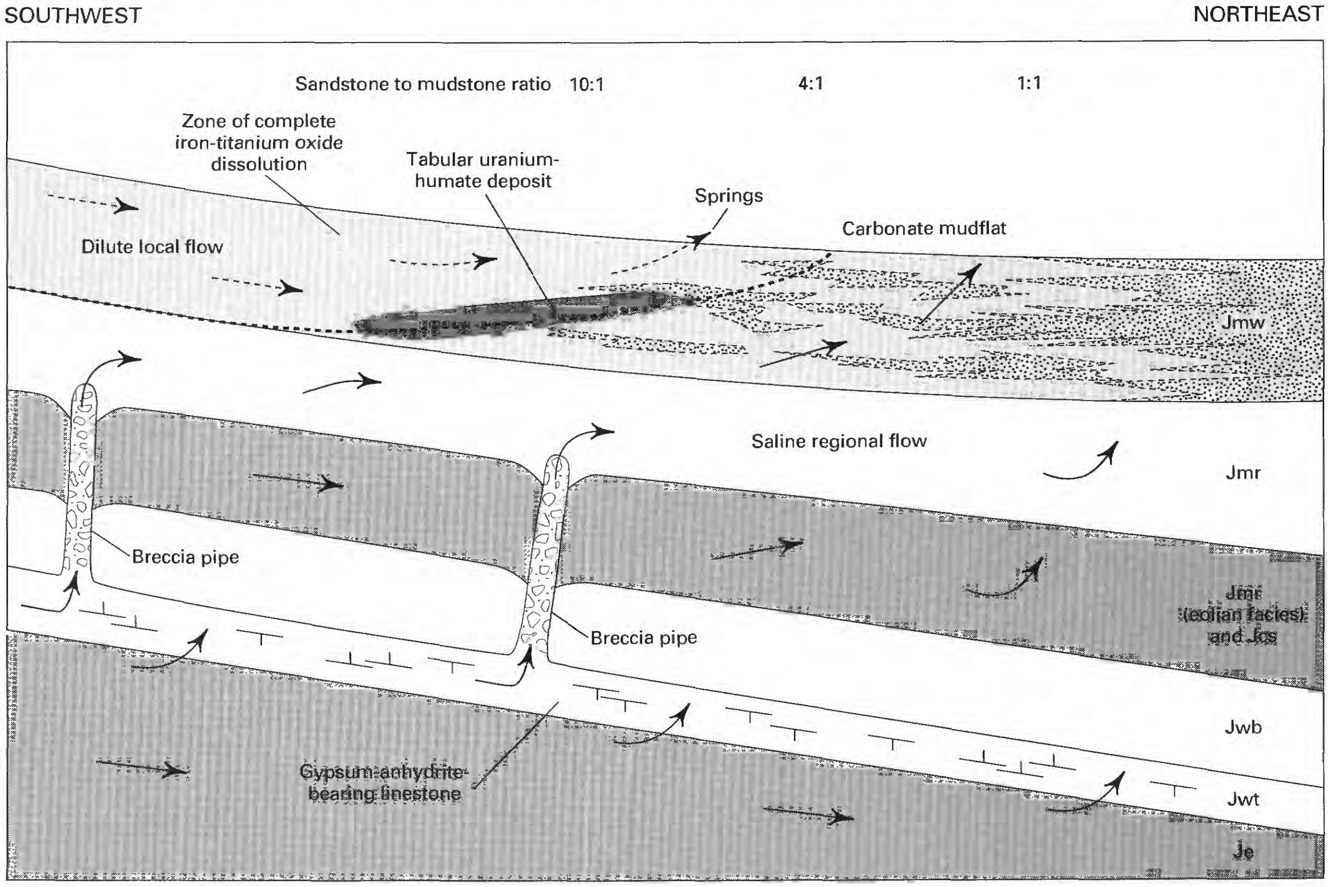


Figure 10. Detailed schematic cross section of the Westwater Canyon Member of the Morrison Formation and underlying units for Late Jurassic time at the end of Westwater Canyon deposition. Location of area of cross section is delineated by box on cross section of figure 9. No vertical scale implied. Arrows show direction of ground-water flow. Dotted line is dilute-saline interface. Flow is primarily gravity driven and downdip. Discharge occurs where topographic surface has decrease in slope. Breccia pipes, formed by dissolution of anhydrite-bearing Todilto Limestone Member of the Wanakah Formation, were conduits for upward flow of saline water. Shallow fresh water forms a lens resting upon deeper regional saline water. Unit abbreviations: Je, Entrada Sandstone; Jwt, Todilto Limestone Member of the Wanakah Formation; Jwb, Beclabito Member of the Wanakah Formation; Jcs, Cow Springs Sandstone; Jmr, Recapture Member of the Morrison Formation; Jmw, Westwater Canyon Member of the Morrison Formation.

dissolved in "hydrologically continuous" sandstone of the Jackpile Sandstone Member (Adams and Saucier, 1981). This alteration was paragenetically very early and probably occurred during or shortly after deposition (Adams and others, 1978). As discussed earlier for the Westwater Canyon Member, iron-titanium oxide dissolution suggests alteration by dilute, reducing, humic-acid-bearing ground water.

Other alteration suggests later incursion of brackish or saline ground water from the underlying Brushy Basin Member or lower units into the deepest parts of the syncline (Adams and others, 1978; Bell, 1983). Albitization of feldspar, which decreases in intensity upward, suggests that the later ground water was sodium-rich fluid similar to that inferred for pore water in the zeolite facies of the Brushy Basin Member directly beneath the Jackpile Member (Bell, 1983). Alternatively, saline ground water may have discharged upward from units such as the Todilto Limestone Member of the Wanakah Formation. Tabular uranium-humate deposits suggest deposition at an interface between relatively fresh and saline ground water within the Jackpile Sandstone Member. The presence of the deposits in the thickest part of the sandstone above the deepest part of the structure is consistent with ponding of saline water at depressions within the sandbody (Bell, 1983).

Breccia pipes that extend up from the Todilto Limestone Member and to the Jackpile Sandstone Member (Moench and Schlee, 1967; Hilpert, 1969; Hunter and others, 1992) may have been conduits through the Brushy Basin Member for the upward-moving, deep regional ground water. Although such conduits may have aided upward ground-water flow, they would not have been necessary for significant upward flow. Discharge through modern playa lakebeds is a common phenomenon (Meyboom, 1967; Lissey, 1971; Stephenson, 1971; Winter, 1976, 1978, 1986, 1988; Friedman and others, 1982; Allison and Barnes, 1985; Spencer and others, 1985; Duffy

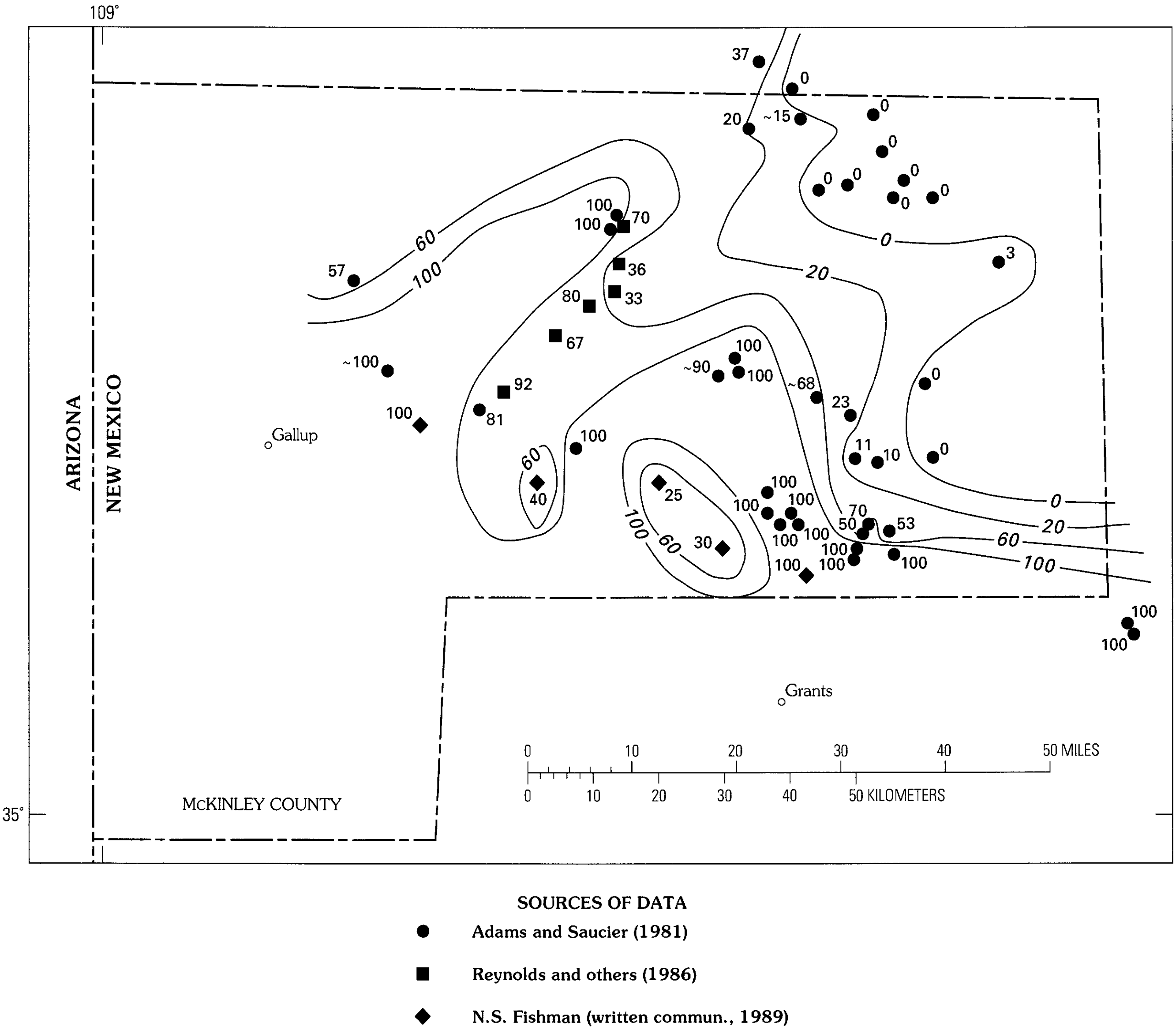


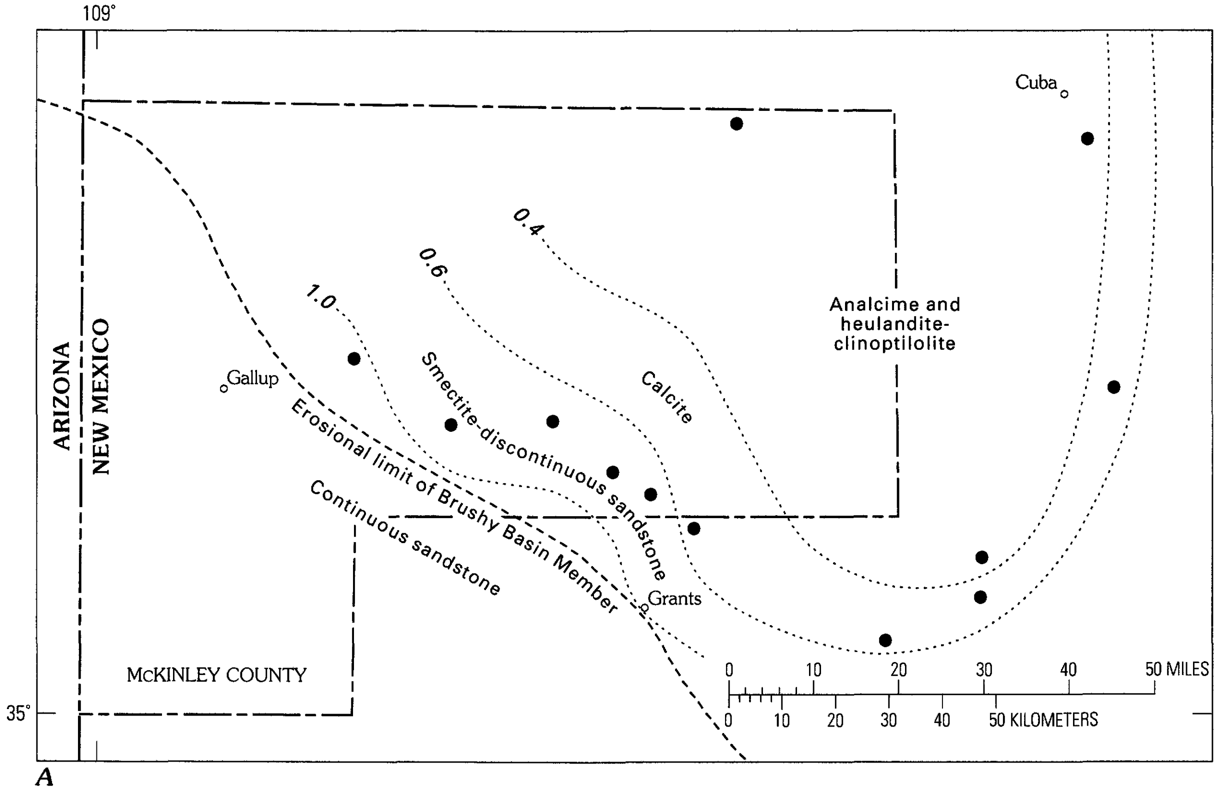
Figure 11. Map showing contours of the interval of total ilmenite-magnetite dissolution in the upper part of the Westwater Canyon Member of the Morrison Formation. The thickness of the altered interval is plotted as a percentage normalized to the total thickness of the Westwater Canyon Member. The normalized thickness indicates the intensity of alteration. Compare with maps of the unnormalized thickness of the same interval shown in Adams and Saucier (1981), Turner-Peterson (1985), and Turner-Peterson and Fishman (1986).

and Al-Hassan, 1988; Winter and Woo, 1990), and computer modeling of Late Jurassic-Early Cretaceous groundwater flow in the San Juan Basin shows that Brushy Basin Member mudstone could have been sufficiently permeable to yield significant discharge, approximately 15±10 mm/yr (Sanford, 1994).

Thus, the diagenetic and paragenetic relations indicate that the Jackpile Sandstone Member was altered mostly by shallow, relatively dilute ground water early in its history and, later in its history, by alkaline-saline ground water moving upward from the underlying Brushy Basin Member and (or) by saline water moving upward from deeper units such as the Todilto Limestone Member. Alkaline-saline and (or) saline ground water probably ponded in deeper parts of the basin and formed an interface with fresher water above along which tabular sandstone uranium deposits formed.

LOWER PART OF THE CHINLE FORMATION

The lower part of the Upper Triassic Chinle Formation consists of continental deposits of fluvial and lacustrine origin (Stewart and others, 1972; Blakey and Gubitosa, 1983; Dubiel, 1987, 1989; Dubiel and others, 1991). Clastic sediments were shed from the Uncompahgre highlands on the northeast and from the Mogollon highlands on the southwest.



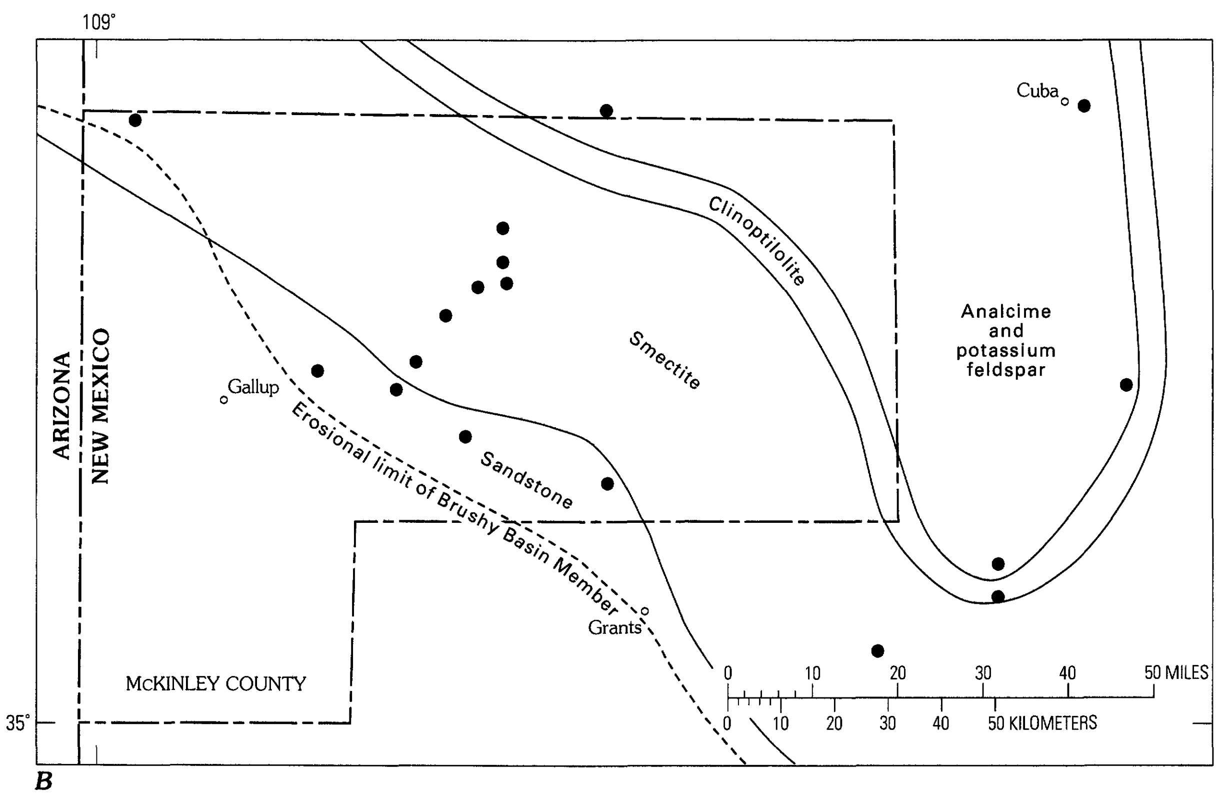


Figure 12. Maps showing interpretations of the diagenetic patterns in the Brushy Basin Member of the Morrison Formation. Both show transition from alluvial plain to playa, but they differ on choice of diagnostic minerals and nature of facies boundaries. *A*, Drawn from data and interpretation of Bell (1983, 1986). Dotted lines are contours of sandstone to mudstone ratio. Facies boundaries in *A* are dotted to indicate Bell's view that facies boundaries cannot be clearly identified. *B*, Drawn from Turner-Peterson (1985) and Turner-Peterson and Fishman (1986). Note that calcite facies in *A* are omitted from *B*.

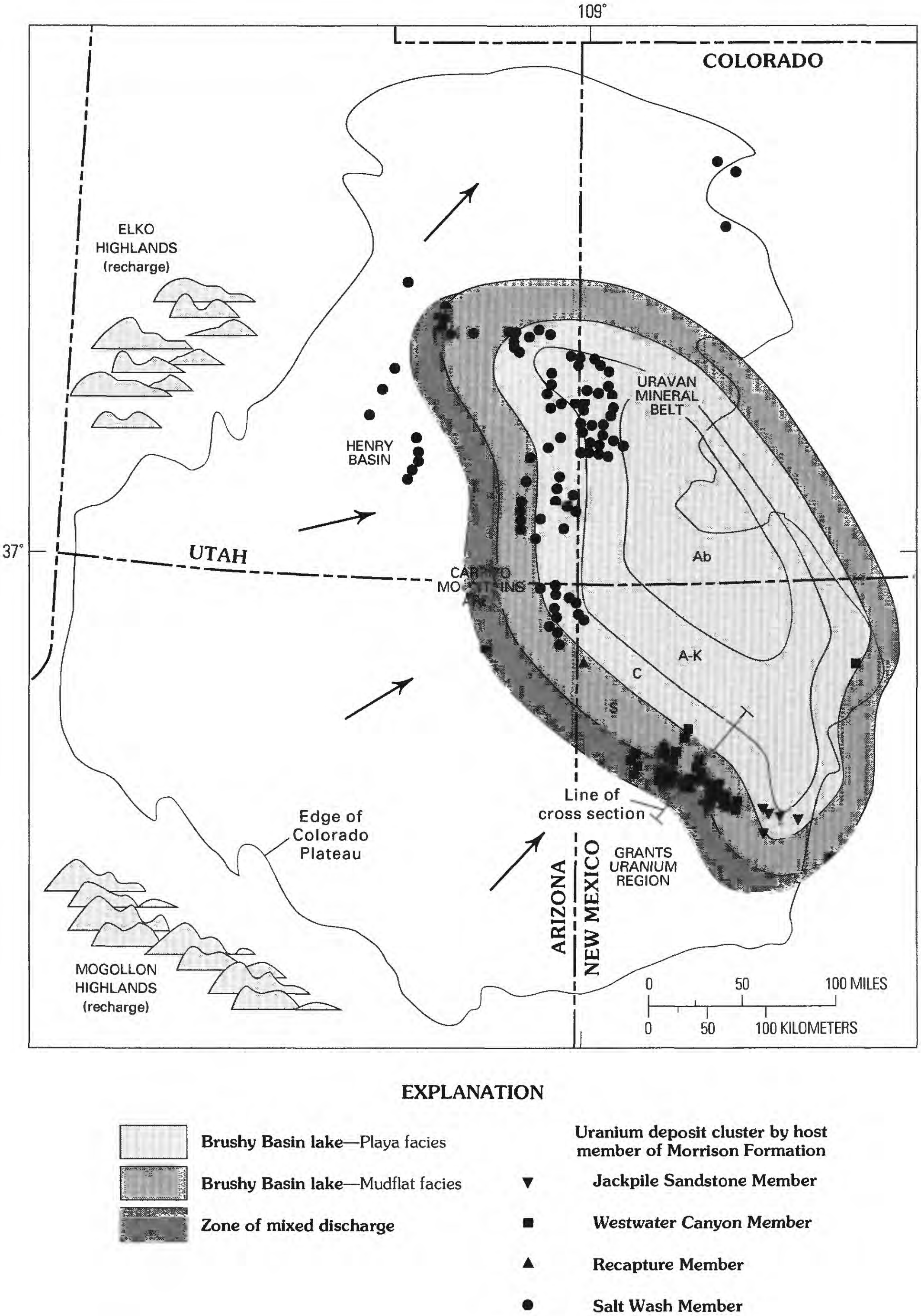


Figure 13. Schematic map of Colorado Plateau area showing diagenetic alteration in the Brushy Basin Member of the Morrison Formation, zone of mixed local and regional discharge at distal edge of alluvial plain, and location of tabular sandstone uranium deposit clusters in the Morrison Formation. Facies: S, smectite mudflat, C, clinoptilolite; A–K, analcime-potassium feldspar; Ab, albite. Arrows show general direction of surface- and ground-water flow. Brushy Basin facies from Turner and Fishman (1991); uranium deposit clusters from Finch (1991).

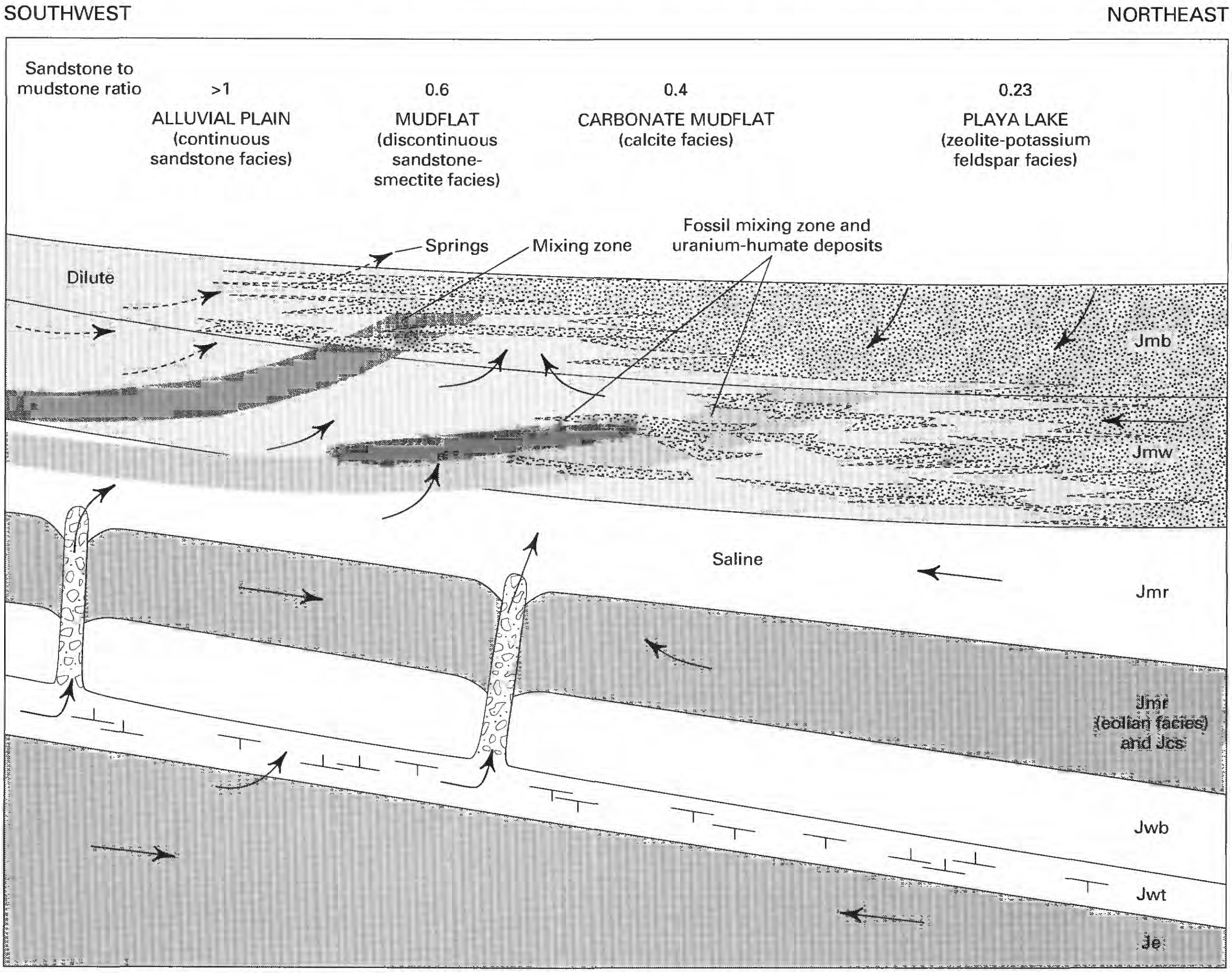


Figure 14. Detailed schematic cross section of the Brushy Basin Member of the Morrison Formation and underlying units for Late Jurassic time at the end of Brushy Basin deposition in the Colorado Plateau area along line of section shown in figure 13. Arrows show general direction of ground-water flow. Gravity-driven downdip flow from southwest meets updip density-driven local flow from playa and regional flow from deep basin. Discharge occurs where the topographic surface has decrease in slope, as indicated by transition from alluvial plain to mudflat. Facies and average sandstone to mudstone ratios for the Brushy Basin Member are from Bell (1983, 1986). Unit abbreviations: Je, Entrada Sandstone; Jwt, Todilto Limestone Member of the Wanakah Formation; Jwb, Beclabito Member of the Wanakah Formation; Jcs, Cow Springs Sandstone; Jmr, Recapture Member of the Morrison Formation; Jmw, Westwater Canyon Member of the Morrison Formation; Jmb, Brushy Basin Member of the Morrison Formation.

Major rivers flowed northwestward from northwestern New Mexico to northwestern Utah, and tributaries flowed northward from the Mogollon highlands and westward from the Uncompahgre highlands (figs. 2, 16).

The lower part of the Chinle Formation consists of the Shinarump, Monitor Butte, Moss Back, and Petrified Forest Members (Stewart and others, 1972; Blakey and Gubitosa, 1983; Dubiel, 1987, 1989). The basal Shinarump Member, characterized by conglomerate and sandstone deposited in braided stream channels, fills valleys and scours in the underlying marine Kaibab Limestone, the marine-marginal Moenkopi Formation, and the eolian De Chelly and Coconino Sandstones. The overlying Monitor Butte Member shows the same transport directions as the Shinarump Member but consists of tuffaceous, bentonitic mudstone, siltstone, sandstone, and limestone deposited in lacustrine and fluvial environments. The next higher unit, the Moss Back Member, similar to the Shinarump Member, consists mainly of fluvial sandstone and conglomerate. Locally, the Moss Back Member is the basal unit and rests on the Permian Cutler Formation (Wood, 1968). At the top of the Chinle, the Petrified Forest Member consists of variegated mudstone and lenticular sandstone deposited on a low-gradient alluvial plain having high- and low-sinuosity fluvial channel systems, overbank and floodplain environments, and scattered lakes and marshes. Lithofacies and fossils indicate that precipitation and surface water were abundant, streams and lakes were fresh and perennial, and the water table was typically high; however, paleosols and ichnofossils indicate that water tables and lake levels fluctuated episodically owing to a tropical monsoonal climate (Dubiel and others, 1989, 1991).

TOPOGRAPHIC CONTROLS ON GROUND-WATER FLOW

Based on lithofacies data (Stewart and others, 1972; Blakey and Gubitosa, 1983; Dubiel, 1987, 1989), topographic control caused ground water to flow dominantly northwestward following the main channel systems of the Shinarump and Moss Back Members (fig. 16). Flow in the margins of the depositional area was along the tributary streams toward the main northwest-trending fluvial axis. Active structural features affected ground-water flow at regional and local scales. A large, actively rising highland apparently controlled the distribution of lithofacies in the White Canyon and Monument Valley areas (Young, 1964; Malan, 1968; Fisher, 1972). In the Paradox Basin, particularly in the Lisbon Valley area, active anticlines were associated with salt diapirism (Wood, 1968; Fisher, 1972).

The topographic gradient and probably the rates of ground-water flow probably changed systematically with time, as shown by the variations in mean grain size of the different members. The coarse-grained, fluvial channel sandstone of the Shinarump Member suggests a relatively steep gradient. The change to fine-grained rocks of the Monitor Butte Member that were deposited in lacustrine, deltaic, and marsh environments implies a shallower gradient and slower ground-water flow. Low-gradient conditions were locally interrupted during deposition of the dominantly coarser grained Moss Back Member but returned during deposition of the fine-grained Petrified Forest Member.

GEOLOGIC CONTROLS ON GROUND-WATER FLOW

Geologic control on ground water was dominated by complex variations in thickness and facies of the upper Paleozoic aquifers (fig. 16). Southwestward along the flow path from the ancient Uncompahgre highlands, the upper Paleozoic aquifer system thickens abruptly into the Paradox Basin and from there it thins (Baars, 1962; Jobin, 1962; Blakey and others, 1988; Geldon, in press and unpublished data). Also in a southwest direction, arkosic rocks decrease in thickness, whereas eolian sandstone, particularly the Cedar Mesa Sandstone and White Rim Sandstone Members of the Cutler Formation, increases in thickness. Regional thinning of the Paleozoic section westward from the axis of the Paradox Basin suggests decreasing transmissivity and therefore discharge, but more eolian sandstone relative to arkose favors recharge because of increased transmissivity. Farther from the Paradox Basin, depositional and tectonic variations are important locally. The net effect of the various influences is unclear, at least locally; however, in the area between the Uncompahgre highlands and the main lower Chinle fluvial

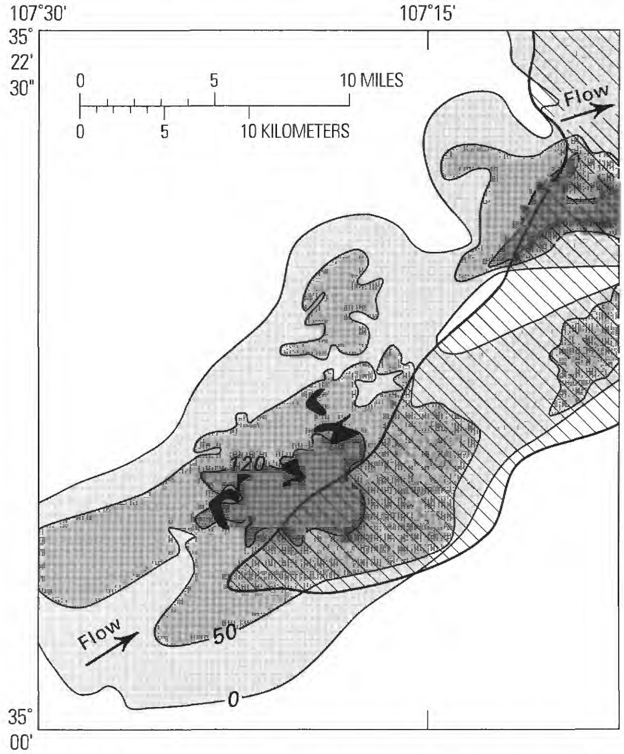


Figure 15. Isopach map of the thickness (in feet) of the Jackpile Sandstone Member of the Morrison Formation showing facies of underlying Brushy Basin Member, location of uranium deposits (solid black), and directions of paleoflow. Area of calcareous facies of Brushy Basin Member is unpatterned; area of zeolite facies of Brushy Basin Member is diagonal-lined. Modified from Moench and Schlee (1967), Adams and others (1978), and Bell (1983).

channel, there may have been three general ground-water zones. Next to the uplift, where the topographic slope was greatest and the upper Paleozoic sediments were dominantly arkosic, recharge probably was dominant. Southwestward from this zone, where the slope was more gradual and thinner sediments (favoring discharge) competed with thicker eolian sandstone (favoring recharge), recharge gradually gave way to discharge. Finally, as ground water neared the main Chinle channel axis, where the topographic slope was minimal, ground water probably discharged.

A similar zonation may have been present northward from the Mogollon highlands, although thickness and facies changes were less extreme. From the Mogollon highlands northward almost to the Utah State line, the upper Paleozoic section gradually thins, whereas eolian sandstone units, particularly the De Chelly (Blakey and others, 1988), gradually thicken. Based on the isopachs of total sandstone thickness, the net effect was probably a slight increase in transmissivity. In the vicinity of the Arizona-Utah State line, the thickness of Permian sandstone abruptly decreases mainly due to thinning of the De Chelly Sandstone, but, farther to the north, Permian sandstone units thicken again owing to the Cedar Mesa Sandstone and White Rim Sandstone Members (Blakey and others, 1988).

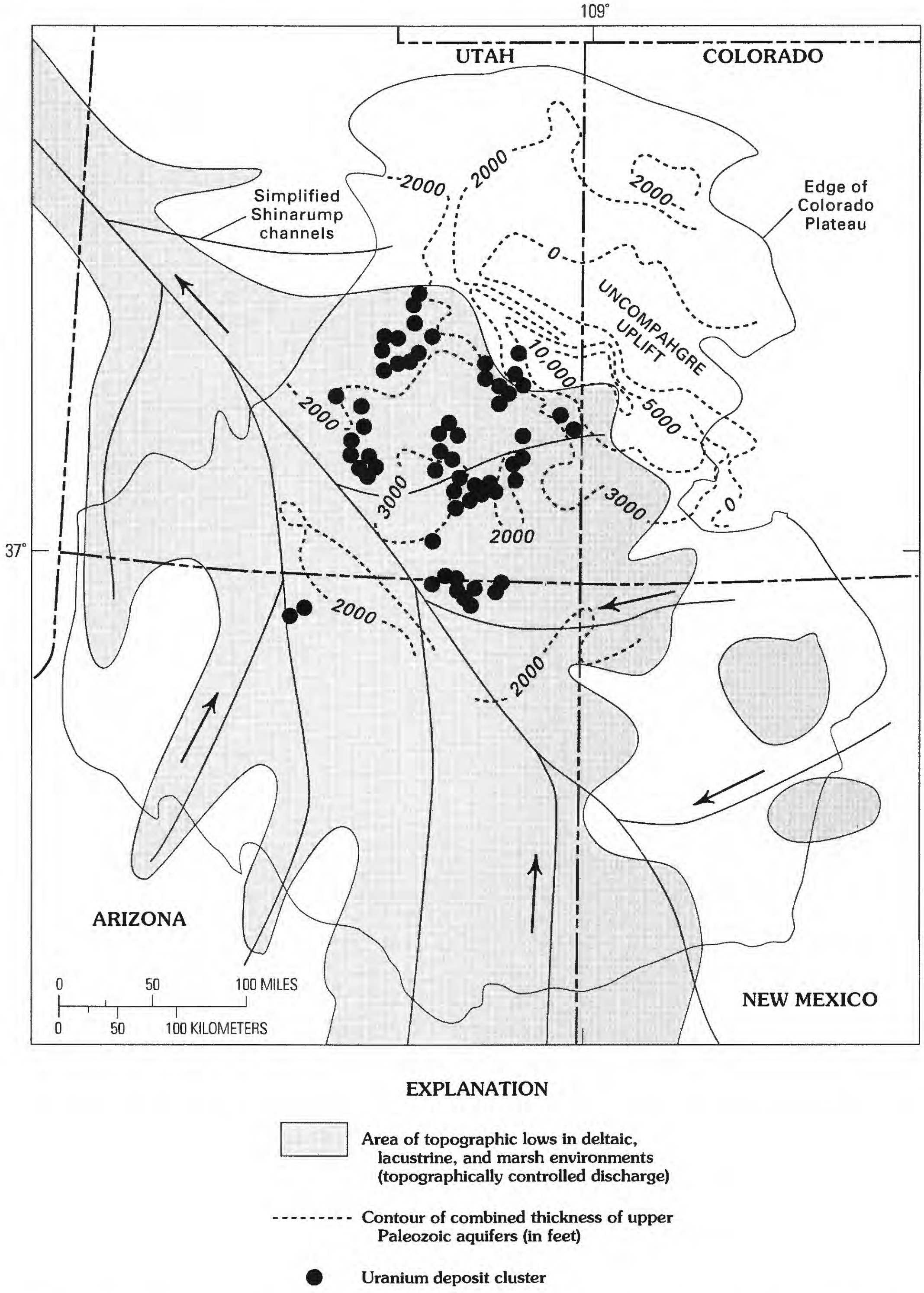


Figure 16. Map showing relationship between uranium deposit clusters and ground-water discharge in the Colorado Plateau during deposition of the lower part of the Triassic Chinle Formation. Channels in Shinarump and Moss Back Members indicate north-, west-, and northwestward surface- and ground-water flow (indicated by arrows). Discharge of local and regional ground water was in topographically low areas marked by deltaic, lacustrine, and marsh environments of the Monitor Butte Member. Paleogeographic data simplified from Dubiel (1989); thickness of upper Paleozoic aquifers from A.L. Gelden (unpublished data, 1992); uranium deposit clusters from Finch (1991).

Thus, the overall pattern of geologic control on ground-water flow suggests a transition from dominantly recharge to dominantly discharge from basin margin to central fluvial channels. Unlike the Morrison Formation, geologic and topographic controls in the Chinle Formation did not clearly combine to favor discharge, but, instead, topographic control of discharge was partly counteracted by geologic controls that favored recharge.

DIAGENESIS AND URANIUM DEPOSITION

The distribution of oxidized and reduced rocks aids in identifying recharge and discharge zones and accumulations of organic matter. Green and gray mudstone and sandstone coincide with Shinarump and Moss Back channels (Wood, 1968; Dubiel, 1989), supporting the inference that the Chinle fluvial channels were zones of persistent ground-water discharge throughout deposition of the lower part of the Chinle Formation. The green mudstone facies of the Monitor Butte Member (Dubiel, 1989) also suggests reducing conditions, a constant high water table, and perennial ground-water discharge. Preserved organic carbon and reduced sandstone and mudstone elsewhere in the Chinle Formation (Dubiel, 1989) further indicate areas of persistent ground-water discharge.

The inferred ground-water-flow pattern would have caused zones of mixing between relatively fresh, local ground water and more saline, regional ground water in areas of discharge (fig. 16). The gypsiferous Moenkopi Formation (Blakey, 1974) and evaporites in Pennsylvanian and Permian rocks probably contributed to the salinity of deeper ground water that tended to discharge upward into the Chinle Formation in areas marginal to and within floodplain, lacustrine, and marsh environments.

Tabular sandstone uranium-vanadium and uranium-copper deposits in the Chinle Formation are associated with transitional lithofacies, channel sandstone, syndepositional synclines, and reduced lacustrine mudstone in the Shinarump and Moss Back Members (Johnson, 1957; Finch, 1959; Witkind and Thaden, 1963; Thaden and others, 1964; Malan, 1968; Wood, 1968; Lupe, 1977; Huber, 1980; Dubiel, 1983). Almost all of the deposits are in areas of inferred topographically controlled discharge, as shown by deltaic, marsh, and lacustrine deposits of the Monitor Butter Member (fig. 16). Ore deposits are further localized at transitional lithofacies in the Shinarump and Moss Back Members where fluvial channel sandstone pinches out and where distal braided stream deposits grade into floodplain deposits (Finch, 1959; Lupe, 1977). Many of the Chinle-hosted deposits are in a belt 4.8–19 km (3–12 mi) wide and 209 km (130 mi) long that corresponds to a major facies change from dominantly sandstone to dominantly mudstone on the flanks of a large uplift approximately in the area of the present Monument uplift (Young, 1964; Malan, 1968; Fisher, 1972).

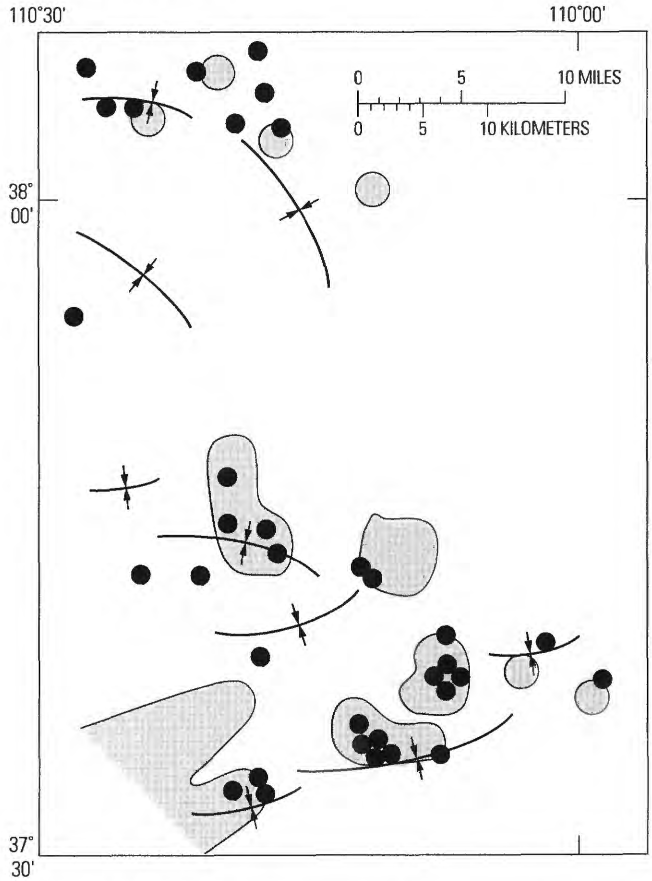


Figure 17. Map showing relationship between uranium deposits (solid circles), syndepositional synclines, and organic-rich lacustrine mudstone (shaded areas) in part of the Chinle Formation in southeast Utah. Modified from Dubiel (1983).

In the Lisbon Valley area, on a smaller scale, uranium deposits are on the flanks of a rising salt-cored anticline (Wood, 1968; Fisher, 1972). In addition to transitional lithofacies, uranium deposits are closely associated with black, organic-rich, lacustrine-marsh mudstone that was deposited where the water table was high (fig. 17) (Dubiel, 1983). Generally, the uranium deposits are below or, less commonly, beside the lacustrine mudstone (R.F. Dubiel, oral commun., 1992). In addition, approximately 90 percent of uranium deposits in this area are within 3.2 km (2 mi) of the axis of a syndepositional syncline (fig. 17). In the Lisbon Valley area, a density-stratified interface was proposed as a mechanism for ore-deposit formation, based on the occurrence of the deposits at a particular horizon within the Chinle Formation (Wood, 1968; Fischer, 1974; Huber, 1980). Minor uranium deposits and concentrations are in the Petrified Forest Member of the Chinle Formation. These are associated with thicker than normal sediments that are interpreted to indicate greater subsidence and a high water table that helped preserve organic matter (Spirakis, 1980).

ORIGIN OF TABULAR SANDSTONE URANIUM DEPOSITS

In summary, the tabular shape, transitional sedimentary lithofacies, syndepositional synclines, and reduced channel sandstone and mudstone associated with tabular sandstone uranium deposits in the Morrison and Chinle Formations on the Colorado Plateau suggest that deposits formed where decreasing topographic slope and topographic depressions caused shallow, relatively fresh ground water and deeper, more saline ground water to discharge and mix at a density-stratified interface. The next step is to integrate these conclusions with the other types of evidence for this ore-deposit type and to reconcile divergent opinions on diagenesis and ore formation.

ROLE OF HUMATE

The location of tabular sandstone uranium deposits in the San Juan Basin likely is closely controlled by the prior deposition of pore-filling amorphous organic matter that is generally thought to be humate precipitated as a gel from a humic-acid-bearing solution (Granger and others, 1961; Moench and Schlee, 1967; Granger, 1968; Nash, 1968; Schmidt-Collerus, 1969; Squyres, 1970, 1980; Haji-Vassiliou and Kerr, 1973; Hatcher and others, 1986; Turner-Peterson, Fishman, and others, 1986). Uranium-vanadium deposits elsewhere in the Morrison Formation are poor in pore-filling organic matter, but humate may have been essential in uranium ore-formation and subsequently destroyed (Hansley and Spirakis, 1992). Humate in uranium deposits in the Chinle Formation has been postulated to exist (Huber, 1980), but studies necessary to determine its presence have not been performed. Thus, the role of humate is critical to the origin of the uranium deposits in the San Juan Basin and possibly elsewhere.

Previous workers have suggested that humate came (1) from the overlying Upper Cretaceous Dakota Sandstone and moved downdip in the Westwater Canyon Member ("Dakota source hypothesis") (Granger and others, 1961), (2) from the host sandstone and moved laterally downdip ("internal source hypothesis") (Granger and others, 1961; Squyres, 1970, 1980), (3) from the mudstone beds overlying and interbedded with sandstone and moved downward and upward perpendicular to bedding or laterally outward ("lacustrine-humate model") (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986), or (4) from surface water flowing downdip during deposition of the host sands ("syngenetic source hypothesis") (Granger and others, 1961). None of these interpretations can be ruled out based on availability of organic material. Organic "trash" is available in the host sandstone, and the former presence of organic matter in mudstone is suggested by the fact that the mudstone is reduced today. Alteration patterns of iron-titanium oxide mineral and feldspar dissolution are interpreted as indicating downward flow from the mudflat of the Brushy Basin Member (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986); however, replotting of the iron-titanium oxide data shows that downdip flow was significant (fig. 11). The downdip flow only has to remain in the upper part of the Westwater Canyon Member, which is normal for a dilute ground water overlying a slightly more saline ground water. The lacustrine-humate model would predict symmetric humate layers above and below mudstone layers; however, lacustrine mudstone beds generally are above the host sandstone, and humate layers do not wrap around the ends of mudstone beds. The Dakota source hypothesis would require that humate move from shoreline marshes downdip and seaward, which would only allow humate to accumulate within a short distance downdip from the Late Cretaceous outcrop of the Westwater Canyon Member. Deposits far downdip in the Westwater Canyon Member are difficult to explain by this mechanism.

Both the Dakota source hypothesis and lacustrine-humate model imply that humate was introduced significantly later than sedimentation. Paragenetic relations suggest that humate precipitation and associated iron-titanium oxide dissolution were early, but a variety of interpretations are possible (Adams and others, 1974; Adams and Saucier, 1981; Hansley, 1986). Channels that scoured into slightly older humate- and uranium-impregnated channels (Fitch, 1980; Squyres, 1980) suggest humate precipitation almost immediately after sedimentation; however, humate impregnation may have been later, controlled by permeability variations. These types of evidence for a very early age favor the syngenetic source hypothesis.

Spatial and chemical evidence tends to favor a syngenetic source in muds deposited very shortly after the host sand. Perhaps the strongest geologic evidence for a specific source is the close spatial association of organic-rich lacustrine mudstone typically above the uranium deposits (F. Peterson, 1980; Peterson and Turner-Peterson, 1980; Dubiel, 1983; Turner-Peterson, 1985). In addition, analyses of modern dissolved organic carbon suggest that lakes and wetlands were a more likely source of humic acid than ground water. Natural ground water has low dissolved organic carbon (median concentration, 0.7 mg/L), almost equal to that of sea water (mean, 0.5 mg/L); in contrast, oligotrophic and eutrophic lakes have mean dissolved organic carbon of 2.2 and 12 mg/L, respectively, and bogs have a mean dissolved organic carbon of 33 mg/L (Thurman, 1985, p. 8ff). The low dissolved organic carbon values in ground water suggest that dissolved organic carbon cannot be transported in large amounts for great distances and that nearby sources of dissolved organic carbon, especially lakes and bogs, are more likely.

ONE OR TWO SOLUTIONS?

Some workers have suggested that tabular humate layers formed by the action of one solution (Squyres, 1980; Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986). According to one version of the lacustrine-humate model (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986), humic acid from pore water in mudstone is expelled vertically upward or downward into the adjacent sandstone. The expelled fluid dissolves iron, vanadium, and aluminum from detrital grains and clays. As these cations increase in concentration along the flow path, they cause humate to precipitate. Once precipitation begins, flocculation, van der Waals forces, "herding instinct," or "the affinity of organics for each other" (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986) is supposed to account for the tabular shape.

This mechanism is unrealistic on spatial, chemical, and hydrologic grounds and is not supported by a plausible mechanism, modern analogs, or experimental evidence. Flocculation and van der Waals forces act on a very small scale, not over the thousands of meters typical of tabular sandstone uranium deposits. They result in small clumps because the forces act radially from numerous centers. How flocculation or van der Waals forces would yield an extensive, subhorizontal layer is not explained. Chemically, the proposed mechanism is implausible because the amount of water from compaction is too small to dissolve and transport the observed amounts of humate precipitated or cations leached. For example, humic acid in ground water is typically 0.5–1.0 mg/L and locally as much as 15 mg/L (Thurman, 1985); however, humate can constitute more than 5 percent of the rock in a uranium deposit (Levanthal, 1980). To achieve such high concentrations, a much higher water to rock ratio is required than can be provided by pore water from compaction (Hilpert, 1969). In addition, it is improbable that the pore water in the mudstone would be so different from that in the sandstone that humic acid would dissolve from the first and precipitate in the second. Hydrologically, the model neglects gravity-driven flow, which would have been orders of magnitude greater than compaction-driven flow. Flow in transmissive fluvial sandstone is normally parallel with stratification, not perpendicular as depicted by the lacustrine-humate model. Downdip flow of one fluid would not result in the observed tabular layers but would probably create podlike or roll-shaped deposits as, for example, in the roll sandstone uranium deposits of Wyoming (Harshman, 1972). The proposed mechanism appears to be loosely based on the process of podzolization; however, podzolization occurs today at the ground surface under boreal forests in areas of high rainfall and ground-water recharge (Petersen, 1976; Mokma and Buurman, 1982; Birkeland, 1984, p. 120ff), an environment very different from the arid to semiarid conditions during deposition of the Morrison Formation. Further, "M. Thurman, 1981, oral communication," is the only reference to experiments showing the formation of tabular humate layers from one solution. Thurman today states that there are no experiments showing the formation of tabular humate layers from one solution (Michael Thurman, U.S. Geological Survey, oral commun., 1992).

On the other hand, field, theoretical, and laboratory evidence for formation of tabular humate layers at a saline water interface between two solutions is abundant. The subhorizontal attitude, gently crosscutting relationships, and lack of small-scale lithologic control are strong evidence for a density-stratified interface (Fischer, 1947, 1974; Shawe, 1955, 1962, 1966; Granger, 1968; Wood, 1968; Melvin, 1976; Sanford, 1982, 1990a, b; Granger and Santos, 1986; Northrop and Goldhaber, 1990). On theoretical grounds, a density-stratified interface provides a laterally extensive, subhorizontal site for humate deposition and other reactions. The solutes in the lower fluid also provide a mechanism for humate precipitation, as demonstrated by experimental and field studies (Swanson and Palacas, 1965; Hair and Bassett, 1973; Sholkovitz, 1976; Ortiz and others, 1980; Fox, 1983; Thurman, 1985, p. 26ff and 394ff). The maximum amount of humate removal is at salinities between 15,000 and 20,000 mg/L. Therefore, although models of uranium and humate precipitation based on a density-stratified interface are commonly called "brine-interface" models, the term "brine" is misleading because the denser ground water need only be saline. As discussed above, topographic depressions associated with the uranium deposits are favorable for discharge of saline ground water, and the abundant evaporitic rocks in the subsurface are likely sources for saline water. Modern analogs of mixing between discharging, saline ground water overlain by relatively fresh water are common (Counts, 1957; Toth, 1963; Freeze and Witherspoon, 1966; Gallaher and Price, 1966; Boswell and others, 1968; van Everdingen, 1971; Foreman and Sharp, 1981; Mono Basin Ecosystem Study Committee, 1987; Sharp, 1988; Swanson and others, 1988; Banner and others, 1989; Dutton and others, 1989; Huff, 1990; Fee and others, 1992; Herczeg and others, 1992; Hines and others, 1992; Long and others, 1992; Macumber, 1992; Strobel, 1992). Thus, the saline water interface or two-solution model is the only plausible explanation for the precipitation of tabular humate layers.

SEEPAGE, COMPACTION, AND DENSITY

Seepage, compaction, and density have been proposed to account for the movement of humic-acid-bearing ground water from the presumed source (lacustrine mudstone) to the presumed site of humate deposition (adjacent sandstone). An early version of the lacustrine-humate model calls on downward seepage or compaction to transport humic acid from lacustrine mudstone to sites of deposition in adjacent sandstone (Peterson and Turner-Peterson, 1980). Later versions of the model rely on compaction and density for moving humic acid (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986). All the proposed mechanisms have serious difficulties.

Downward seepage is proposed as a mechanism; however, no hydrologic reason is given for downward seepage as opposed to upward seepage. As discussed above, each of the regions of uranium ore formation in the Colorado Plateau is dominated by evidence for upward flow of ground water. Syndepositional synclines, decreases in slope, topographic depressions, lacustrine sediments, and reduced rocks suggest a high water table, preservation of organic matter in the saturated zone, and the discharge of ground water from local and regional flow systems. Under these conditions, seepage is normally upward into lakes and wetlands (Meyboom, 1967; Lissey, 1971; Stephenson, 1971; Winter, 1976, 1978, 1986, 1988; Friedman and others, 1982; Allison and Barnes, 1985; Spencer and others, 1985; Duffy and Al-Hassan, 1988; Winter and Woo, 1990). Transient, depression-focused recharge has not previously been mentioned as having a role in uranium ore formation.

Compaction has been suggested as a significant mechanism for downward or lateral flow of ground water in the Morrison Formation (Shawe, 1976; Wood, 1980; Adams and Saucier, 1981; Turner-Peterson, 1985; Adams, 1986; Hansley, 1986; Turner-Peterson and Fishman, 1986; Northrop and Goldhaber, 1990; Wanty and others, 1990). Compaction is unlikely, however, to cause flow in the proper direction, is a minor ground-water control compared to gravity-driven flow, and cannot account for significant humate transport or diagenetic alteration (Hilpert, 1969; Sanford, 1990a, 1994). Compaction-driven flow is generally directed upward, especially near the top of a thick section of sediments (Bethke, 1986), as was present below the Morrison Formation. In the center of a large alkaline-saline playa, downward flow is possible, but more as a result of density than compaction. The marginal mudflat of a large playa lake, which is inferred to have downward ground-water flow (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986), is the least likely area for downward flow. The mudflat is at a lower elevation than the surrounding alluvial plain, so gravity-driven flow is directed upward and discharges in the mudflat. Ground water in the mudflat is less dense than that in the central part of the playa, so density drives ground water from the central playa outward toward the mudflat, where it discharges, as shown for modern examples (Allison and Barnes, 1985; Spencer and others, 1985; Duffy and Al-Hassan, 1988; Winter and Woo, 1990). The mudflat of a large playa lake can therefore be expected typically to have ground-water discharge.

Second, simple calculations show that compaction is a minor influence as compared to gravity-driven flow (Sanford, 1990a, 1994). The Brushy Basin Member would contribute an average of 0.0035 mm/yr of ground-water flow from expulsion of pore water in 5 m.y., whereas gravity-driven flow would contribute approximately 15 mm/yr. The dominance of gravity-driven flow over compaction-driven flow in this type of basin is further demonstrated by more elaborate calculations (Bethke, 1986; Person and others, 1992; Garven and others, 1993). For example, Bethke (1986) estimated that maximum compaction-driven flow in the Illinois Basin is 2 mm/yr, whereas the maximum gravity-driven flow is 11,000 mm/year. Thus, available evidence indicates that gravity-driven flow in these settings exceeds compaction-driven flow by some two to four orders of magnitude.

Finally, compaction cannot account for the observed humate accumulation and diagenetic alteration of detrital minerals. As discussed above, humate accumulation requires a higher water to rock ratio than can be achieved by expulsion of pore water. Iron-titanium oxide minerals are locally 100 percent altered from the top to the base of the Westwater Canyon Member. It is doubtful that enough pore water would have been expelled from the Brushy Basin Member to displace all the pore water in the Westwater Canyon Member, much less cause the intense alteration. Again, a higher water to rock ratio would be required than was available from compaction of the Brushy Basin Member. Further, there is no petrographic evidence for compaction. In the playa facies of the Brushy Basin, relict shard textures are perfectly preserved by replacement minerals such as chalcedony and clinoptilolite; in the mudflat facies, original shard textures are destroyed (Turner and Fishman, 1991).

Density of ground water has also been suggested as a mechanism for downward movement of ground water (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986; Turner-Peterson and Fishman, 1986). The references cited by the authors of the lacustrine-humate model for downward flow of ground water pertain to playa lake water in the *center* of the playa where solutes are highly concentrated and abundant evidence shows that dense brines can move downward. The lacustrine-humate model depends, however, on ground water descending in the *mudflat*, not in the central playa. An argument that demonstrates that ground water can descend in the central part of a playa does not demonstrate that it descends in the mudflat. As shown by diagenetic facies in the Brushy Basin Member, the mudflat has relatively fresh water, and the concentration of solutes increases toward the center of the lake. The density is therefore less in the mudflat than in the playa center. All other factors being equal, density would cause ground water to flow downward in the playa center, then outward, and finally *upward* in the mudflat. Modeling of modern environments confirms this pattern (Duffy and Al-Hassan, 1988).

Another difficulty with the density argument is that it is incompatible with transport of humic acid. Humic acid precipitates in concentrated solutions (Swanson and Palacas, 1965; Hair and Bassett, 1973; Sholkovitz, 1976; Ortiz and others, 1980; Fox, 1983; Thurman, 1985, p. 26ff and 394ff), a fact acknowledged by the authors of the lacustrine-humate model. To rely on a dense solution to move humic-acid-bearing ground water is to contradict the assumed chemistry of the humic-acid-transporting solution, which is thought to be dilute and mildly alkaline. The solution cannot be both dense and dilute.

A third difficulty is that a dense solution cannot explain the upward movement of ground water, which the authors of the lacustrine-humate model consider necessary for ore deposits in sandstone above mudstone, such as in the Jackpile Sandstone Member and locally in the Westwater Canyon Member. Much emphasis is placed on an apparent "mirror image" alteration pattern, where the intensity of alteration in sandstone decreases away from the Brushy Basin Member, both down into the Westwater Canyon Member and up into the Jackpile Member. This pattern cannot be explained, however, by density-driven flow. Although density-driven flow probably was a significant mechanism in certain situations, it is incompatible with the lacustrine-humate model.

TRANSIENT, DEPRESSION-FOCUSED GROUND-WATER RECHARGE

The above discussion raises two critical questions. If there was a saline water interface, why was humate only precipitated in certain places along the interface? If humic acid came from lacustrine muds, how did it move downward, apparently against the prevailing hydrologic gradient?

Transient, depression-focused recharge during periods of high runoff is a common phenomenon in modern wetland environments and appears to be the only solution to the dilemma (fig. 18). A stream that normally gains water from ground-water discharge may, during flood stage, lose water to the banks of the channel (Gallaher and Price, 1966; Speer and others, 1966; Fetter, 1988, p. 47; Jacobson and others, 1989). Ground-water flow, which normally is toward the channel, is reversed away from the channel. Similarly, during periods of high runoff, lakes that normally have ground-water discharge into them may recharge the ground-water system (Meyboom, 1967; Lissey, 1971; Winter, 1976, 1983, 1986; Wood and Petraitis, 1984; Allison and Barnes, 1985; Fetter, 1988, p. 45ff; Logan and Rudolph, 1992). Water-table "mounds" build up temporarily in the ground surrounding the lake, and the direction of ground-water flow is reversed. More water infiltrates the ground around the temporarily deepened lakes than infiltrates the ground over the intervening hills. Thus, the wetland temporarily becomes an area of ground-water recharge. The time period between such events may range from days to decades.

For the ancient environment relevant to uranium ore formation, transient, depression-focused recharge in wetlands can explain the apparent downward transport of humic matter in zones of normally upward discharge (fig. 18). Dissolved organic matter probably was concentrated in the bottom water of lakes and in the pore water of lacustrine and fluvial sediments that were deposited at topographic depressions. A perennially high water table, which favors the preservation of organic matter, accounts for the observed reduced rocks. During baseline or steady-state flow, ground water discharged upward into the channel or lake sediments. Depending on the prevailing climate, discharge consisted of saline ground water (fig. 18*A*, baseline stage–dry) or saline ground water overlain by fresher ground water (fig. 18*B*, baseline stage–wet). During periods of high water, surface water probably rose and ponded in topographic depressions. The organic-acid-bearing pore water in the sediments may have been flushed downward and outward along the channel. Judging from analyses of modern water (Thurman, 1985), dissolved organic carbon in the descending pore water may have been 2–33 mg/L, in contrast to 0.5–1.0 mg/L in the underlying saline ground water. The relatively fresh water formed a lens that spread out on top of the underlying saline ground water. The underlying saline fluid was displaced slightly downward owing to the increased pressure of the relatively fresh water on top. The fresh-water lens occupied the upper part of the zone formerly occupied by saline ground water. The less soluble, humic part of the dissolved organic carbon precipitated in the mixing zone.

The localization of humate and uranium only at certain places along the interface can be explained by the localization of humate sources and depression-focused recharge. The humic-acid-rich water descended from specific locations on the surface where organic-rich sediments preferentially accumulated and transient recharge was focused; that is, at topographic depressions. Wetlands may have been the only sites of appreciable accumulation of organic matter because grasses had not yet evolved and the major low-growing plants were ferns and related vegetation that require an abundant and constant water supply. Further, topographic depressions were favorable for accumulation of detrital organic matter, which is widely associated with the uranium deposits. Although an interface between shallow fresher water and deeper more saline water may have been widespread, precipitation of humate apparently only occurred at the interface hydrologically downgradient from sources of humic acid at local topographic depressions. Ground-water flow downdip along the channels would account for the commonly observed elongation of deposits.

Fluctuations in the position of the interface due to intermittent, seasonal, climatic, and tectonic variations can explain the thickness and multiple positions of uranium-humate bodies. Small fluctuations in the position of the interface (on the scale of meters) can explain thickness variations by means of dispersion. During periods of high water, shallow, relatively fresh ground water displaced saline water below. In the zone of displacement, the humic acids would have been transported in the interconnected pores, whereas saline water would have remained in the less connected pores. Humate precipitation may have taken

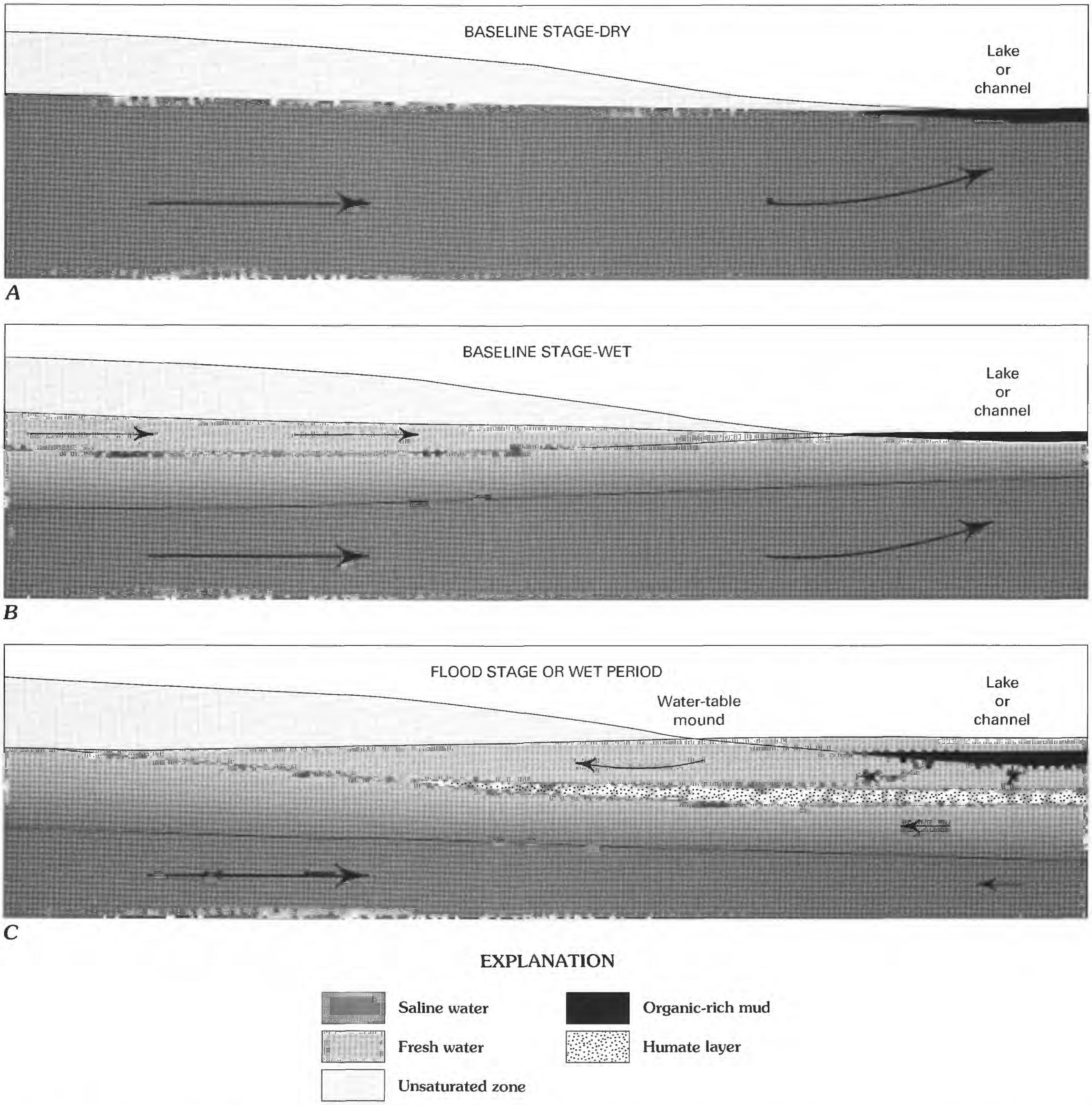


Figure 18. Schematic cross section across a topographic depression occupied by a channel or lake showing relationships of hydrology and humate. Ground water normally discharges at topographic depressions, but, during high-water conditions, recharge of relatively fresh water can take place. Gravity-driven, transient, downward-flowing ground water carries humic acids from wetlands, and humate precipitates in an interface zone of mixing between relatively fresh water and displaced saline water. *A*, Possible baseline or steady-state discharge of saline ground water under dry conditions. no fresh-water discharge. *B*, Possible baseline or steady-state discharge under wetter conditions, relatively fresh and saline ground water discharge. Modified from Dutton and others (1989). *C*, Transient recharge during high-water stage or period. Modified from Winter (1976, 1986) and Fetter (1988, p. 47).

place by dispersive mixing of humic-acid-bearing ground water in the interconnected pores with saline ground water in the less connected pores. Multiple positions of tabular humate bodies are explained by larger scale variations of the interface, which may have been controlled by longer term fluctuations of climate or by tectonic adjustments that affected the steady-state or baseline position of the water table. Because humate can be redissolved and reprecipitated by dilute water (Swanson and Palacas, 1965), downward movement of the interface could have moved the humate downward, but upward movement of the interface would have left the humate in place. Thus, a single layer of humate could be concentrated by repeated downward excursions of the interface.

Whereas compaction is a one-time occurrence involving small amounts of ground water, transient flushing can involve large ground-water fluxes and thus account for intense alteration. The widespread alteration of iron-titanium oxide minerals probably can only be explained by many pore volumes passing through the sediments. The pattern of dissolution of iron-titanium oxide minerals in the San Juan Basin and the elongation of tabular uranium bodies along the channels throughout the Colorado Plateau are consistent with a combination of transient, depression-focused recharge and lateral flow down the channels.

Variability in precipitation is necessary for reversals in ground-water flow. In Triassic and Jurassic times, precipitation fluctuated in time periods that varied from single-event storms to seasonal and longer term climatic cycles. Paleoclimatic, sedimentologic, and, paleontologic evidence (Dubiel, 1989; Dubiel and others, 1991) indicates a monsoonal climate in the Late Triassic. Generally abundant water supply was punctuated by periods of dry conditions. A generally drier climate prevailed during the Late Jurassic (Peterson and Turner-Peterson, 1987). Lithofacies in the Brushy Basin Member are similar to those of the Lake Eyre region of central Australia, where major flooding occurs every 5–10 years (Bell, 1986). Conglomeratic layers in the otherwise fine-grained Brushy Basin Member (Phoenix, 1958) are evidence for episodic flooding. During both Late Triassic and Late Jurassic time, variegated red and green mudstone suggests fluctuating water tables.

SUMMARY AND CONCLUSIONS

Reconstruction of ground-water-flow directions in Jurassic and Triassic fluvial-lacustrine rocks of the Colorado Plateau strengthens the conclusions of previous studies (Sanford, 1982, 1990b, 1992, 1994) that tabular sandstone uranium deposits formed in zones of inferred regional ground-water discharge. On the scale of the Colorado Plateau, the deposits are commonly associated with transitional lithofacies that indicate topographic controls on ground-water flow. Commonly arcuate zones of transitional lithofacies indicate a decrease in paleotopographic slope and favor discharge and mixing of local and regional ground-water-flow systems in wetland environments. For example, such facies changes in the Salt Wash Sandstone Member of the Jurassic Morrison Formation include the sandstone-mudstone facies, transitional between conglomeratic sandstone facies and claystone-limestone facies (Craig and others, 1955), and the fluvial sheet-sand facies, transitional between the fluvial sheet gravels and mudflat-lake muds (Peterson and Tyler, 1985). In the Triassic Chinle Formation, decreasing topographic slope is indicated by a transition from distal braided stream to floodplain deposits (Finch, 1959; Young, 1964; Malan, 1968; Lupe, 1977). Tabular sandstone uranium deposits are closely associated with these facies changes, typically where the distal edge of the alluvial plain merges into mudflat. Measurable parameters that indicate a decrease in slope on a regional scale include an increase from low- to high-sinuosity channels, a decrease in thickness of sandstone, a decrease in sandstone as a percent of total thickness, and an increase in mudstone thickness and percentage (Craig and others, 1955; Mullens and Freeman, 1957; Peterson and Tyler, 1985). On a more local scale, the deposits are commonly associated with syndepositional synclines, possibly controlled by basement faulting. Such structural control has been inferred for the Henry Basin (Peterson, 1984, 1986), Uravan mineral belt, Grants uranium region (Kirk and Condon, 1986), Jackpile Sandstone Member of the Morrison (Moench and Schlee, 1967), and Chinle strata (Spirakis, 1980; Dubiel, 1983). The topographic depressions associated with these structural downwarps were favorable for ground-water discharge and wetlands. Sedimentologic evidence for structural downwarps includes, in the Henry Basin, thicker sediments, more channel sandstone, higher sinuosity channels, increased upper flow regime horizontal laminations, and lacustrine mudstone (Peterson, 1984, 1986); in the Uravan mineral belt, distributary channels, thick host sandstone, higher sandstone to mudstone ratios, lenticular rather than flatbedded sandstone, scour-and-fill bedding, and overlying conglomeratic sandstone (Weir, 1952; Phoenix, 1958; Shawe, 1962; Motica, 1968; Thamm and others, 1981); and, in the Grants uranium region, locally thick sediments, high sandstone to mudstone ratios, and smaller numbers of sandstone-mudstone interbeds (Kirk and Condon, 1986). Lacustrine mudstone is associated with uranium deposits in the Henry Basin (Peterson, 1984, 1986), Grants uranium region (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986), and Chinle strata (Dubiel, 1983). As evidence for closed topographic depressions, lacustrine deposits strongly suggest low hydraulic potential and ground-water discharge during sedimentation.

The only generally consistent association between uranium deposits and lithofacies is between lithofacies in the host sandstone and uranium deposits. Lithofacies in overlying units are not consistently associated with uranium deposits. For example, a proposed association between tabular sandstone uranium deposits and the mudflat facies of the Brushy Basin Member of the Morrison Formation (Turner-Peterson and Fishman, 1986) breaks down for deposits in the Uravan mineral belt and Henry Basin, where uranium deposits are associated with analcime-potassium feldspar and alluvial-plain facies of the Brushy Basin Member, respectively, not the mudflat facies (fig. 13). Other workers noted the relationship between tabular sandstone uranium deposits and lithofacies of the host sandstone but failed to explain the relationship. For example, Craig and others (1955) noted that deposits cluster where the Salt Wash Sandstone Member of the Morrison is more than 73 m (240 ft) thick and stream channel sandstone makes up 40–55 percent of the thickness of the member; the deposits are between 27 and 60 m (90 and 200 ft) thick and have a percentage mean deviation of between 5 and 18 percent. They noted that the permeability of these rocks is intermediate between more sandstone rich facies and more mudstone rich facies, and they hypothesized that intermediate flow rates were optimum for uranium and vanadium supply. I suggest that the intermediate lithologic facies represents paleotopographic conditions that are hydrologically favorable for humate and uranium deposition. The facies changes are concomitant with hydrologic changes that controlled the transport and deposition of organic matter and uranium.

The scale of the observation and the influence of local tectonic structures must be accounted for in interpreting the paleotopographic slope. On the scale of the Colorado Plateau, sedimentary facies, total thickness, sandstone to mudstone ratio, and other parameters change systematically in the direction of flow. For example, facies of the Salt Wash Sandstone Member of the Morrison Formation change from conglomeratic sandstone to sandstone and mudstone to claystone (Craig and others, 1955) or from fluvial sheet gravels to fluvial sheet sands to mudflat and lake muds (Peterson and Tyler, 1985). In addition, there are regional changes such as decrease in total thickness and sandstone to mudstone ratio. At this regional scale, coarser facies, thicker sandstone, and higher sandstone to mudstone ratio suggest greater topographic slope closer to the source. Local tectonic activity can, however, significantly affect these overall trends (Peterson, 1984; Kirk and Condon, 1986). On a more local scale, for example in the Henry Basin, local tectonic activity affected stream gradients, and the deposition of more channel sandstone in synclines may have resulted from combing back and forth of streams and winnowing out of finer material (Peterson, 1984). At this scale, coarser facies, greater thickness, and higher sandstone to mudstone ratio are associated with streams that were slightly lower in elevation than the surrounding overbank deposits.

Geologic controls on ground-water flow favored discharge of generally northeast flowing ground water everywhere in the Morrison Formation and especially in arcuate zones of abrupt aquifer thinning. Thinning and pinching out of the Lower Jurassic and upper Paleozoic aquifer systems favored geologically controlled discharge. Within these aquifer systems, northward and eastward thinning of the Navajo Sandstone, Wingate Sandstone, Cedar Mesa Sandstone Member of the Cutler Formation, De Chelly Sandstone, and Meseta Blanca Sandstone Member of the Yeso Formation most favored deep ground-water discharge. Thinning of the section over the Uncompahgre and San Luis Precambrian basement blocks probably contributed to deep ground-water discharge. For deposits in the Chinle Formation, westward and northward flow was in the direction of a thinner Paleozoic section but a thicker eolian aquifer, and the net effect of geologic controls is unclear.

Within the major discharge zones where topographic and geologic controls generally favored local and regional ground-water discharge, specific areas of discharge are marked by reduced rocks such as green and gray mudstone. A close association between reduced mudstone and channel sandstone and tabular sandstone uranium deposits has been noted for the Henry Basin (Peterson, 1984, 1986), Paradox Basin (McKay, 1955), San Juan Basin (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986), and Chinle Formation (Wood, 1968; Dubiel, 1983). Reduced rocks in dominantly redbed sequences suggest perennially high water table conditions (Walker, 1967; Reading, 1978, p. 48–49; Dodson and others, 1980; Dubiel, 1983, 1989; Davis, 1988; Ghiorse and Wilson, 1988; Dubiel and others, 1991) and reducing conditions owing to bacterial degradation of organic matter, both of which are most likely in areas of perennial ground-water discharge.

The composition of the discharging ground water may be inferred from the types of rocks through which the ground water passed. Shallow, local ground water was probably dilute meteoric water. As it passed downdip through the aquifer, it reacted with detrital material and any bacterially degraded organic matter. Judging from modern ground water in shallow aquifers in arid environments, the water was probably a dilute Na^{+}-Ca^{2+}-HCO_3^{-}- type (Hanshaw and Hill, 1969; Thackston and others, 1981; Davis, 1988; Sanford, 1990a). Recharging, depression-focused ground water was probably relatively fresh, neutral to slightly acidic, reducing, and humic acid rich.

In contrast to the dilute, local ground water, deeper, regional ground water was probably saline owing to the widespread presence of evaporites and evaporitic clastic rocks. Shallow source rocks included the Curtis Formation, Todilto Limestone Member of the Wanakah Formation, and Tidwell Member of the Morrison Formation. Deeper sources included gypsum beds in the Triassic marginal-marine Moenkopi Formation. Still deeper Pennsylvanian and Permian sources of saline water were especially abundant and included all or parts of the Paradox Formation, Kaibab Limestone, Cutler Formation, and Yeso Formation. Dissolution of salts and migration of saline water has modern-day analogs. For example, Carmel Formation evaporites are dissolved by descending relatively fresh water, which then becomes saline; this saline water moves downdip in the underlying Navajo Sandstone and finally discharges upward from the Navajo (Taylor and Hood, 1988). Modern ground water in the Colorado Plateau today is locally highly saline owing to dissolution of evaporites (Mayhew and Heylman, 1965; Hanshaw and Hill, 1969; Thackston and others, 1981; Sanford, 1990a). Evidence for an interface between regional saline and local fresher ground water is shown by tabular layers of humate, uranium, and dolomite in the Colorado Plateau (Fischer, 1947, 1974; Shawe, 1955, 1962, 1966; Granger, 1968; Wood, 1968; Melvin, 1976; Sanford, 1982, 1990a, b; Granger and Santos, 1986; Northrop and Goldhaber, 1990) and by experimental evidence and modern analogs, as discussed above. Many uranium-humate and uranium-vanadium deposits are elongated along the channels and rise stratigraphically toward the basin (Reinhardt, 1963; Moench and Schlee, 1967; Granger, 1968; Hilpert, 1969; Fischer, 1974; Melvin, 1976; Northrop and Goldhaber, 1990), which would be expected at an interface where an upper dilute ground water flowed over a lower brine and discharged.

Thus, abundant evidence exists for an association between tabular sandstone uranium deposits and regional ground-water discharge during ore formation. Further, the discharging ground water included dilute local and saline regional fluids that probably interacted at a density-stabilized interface.

The fact that a consistent set of characteristics is associated with uranium deposits in Jurassic and Triassic deposits throughout the Colorado Plateau indicates that the deposit type can be described by one general genetic model. The recurrent deposit characteristics including geometry, channel sandstone host rock, elongation and stratigraphic rise in the direction of paleoflow, association with reduced rocks, and presence in structurally controlled paleotopographic depressions suggest common physical and chemical controls in which wetlands played a critical role. Humate-rich and vanadium-rich deposits probably are variations on a general theme rather than distinct deposit types (Sanford, 1992). Chemical changes among these variations can be attributed to post-ore diagenesis (Hansley and Spirakis, 1992).

The conclusion that tabular sandstone uranium deposits are closely associated with a particular hydrologic environment implies that the ore, or at least the humate, was deposited very soon after deposition of the sediments, perhaps after only meters or tens of meters of burial. Many prior estimates could narrow the age only to "shortly after deposition" of the host sediments, which could mean anything from days to tens of millions of years. For example, ore deposits in the Westwater Canyon Member of the Morrison Formation are thought to have formed during compaction of the overlying Brushy Basin Member (Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986). The present analysis suggests that ore formed even earlier. In a zone of regional ground-water discharge, depression-focused recharge would only displace the uppermost ground water. Humic acid from wetlands would only be transported to shallow depths. Once the humate layer was deposited, uranium may have accumulated later as a result of the reducing conditions generated by bacterial degradation of humate. A very early age for humate precipitation is supported by channel scours into humate-impregnated sandstone (Fitch, 1980; Squyres, 1980).

The associations among channel sandstone, transitional lithofacies, decrease in topographic slope, thinning of aquifers, syndepositional synclines, paleotopographic depressions, interbedded sandstone and mudstone, underlying marine rocks especially evaporites, reduced mudstone, and tabular sandstone uranium deposits are so significant that any model of uranium deposition must account for them. The only unifying phenomenon yet proposed that is consistent with these observations is the regional discharge of deep gravity-driven ground water that mixed with shallow dilute ground water during and shortly after deposition of the host sediments in a wetland environment. Depression-focused transient recharge can explain the apparent downward transport of humic matter in areas of normally discharging, saline, regional ground water.

The present analysis suggests that exploration for new districts and belts of tabular sandstone uranium deposits should be guided by features that indicate areas of regional ground-water discharge and transient, depression-focused, local recharge during and shortly after sedimentation. Major uranium belts can be expected where coarse-grained, alluvial-plain facies merge into finer grained, lower gradient facies. Areas where aquifers also thin in the direction of flow are still more favorable. Within these broad areas, local structural, sedimentologic, and diagenetic features such as syndepositional synclines, fluvial channels, and reducing conditions that indicate ancient wetlands are most favorable.

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