Fluid-Mineral Interactions: A Tribute to H. P. Eugster
© The Geochemical Society, Special Publication No. 2, 1990
Editors: R. J. Spencer and I-Ming Chou

Paleohydrogeology of the Colorado Plateau—background and conceptual models

RICHARD F. SANFORD
Mail Stop 905, U.S. Geological Survey, Denver Federal Center, Denver, CO 80225, U.S.A.

Abstract—Tectonic, stratigraphic, paleo-climatic, and hydrologic data are compiled for reconstructing regional paleogroundwater flow through the Phanerozoic in the Colorado Plateau. Following the early Paleozoic, which was characterized by a stable shelf environment, the Colorado Plateau underwent four major tectonic-sedimentary cycles: Pennsylvanian-Permian, Triassic, Jurassic-early Cretaceous, and late Cretaceous-Tertiary. Each cycle consisted of marine deposition, followed by uplift and fluvial-lacustrine-eolian deposition, followed by uplift and erosion. Seven principal aquifer systems and eight principal confining units controlled groundwater flow during these four cycles. During the same period, northward drift of the North American plate took the Colorado Plateau region from tropical equatorial through temperate mid-latitude climatic zones. These climatic changes profoundly affected groundwater flow and chemistry. Uplift of mountain ranges, principally the Pennsylvanian-Permian ancestral Rocky Mountains, the Triassic-Jurassic Mogollon highlands, and the Tertiary Rocky Mountains, profoundly affected climatic conditions and favored topographically controlled or gravity-driven groundwater flow. Repeated transgressions of shallow epeiric seas caused burial and compaction. Interfaces between fluids of contrasting composition formed as environments alternated among marine, evaporitic marginal marine, sabkha, fluvial, fresh lacustrine, saline lacustrine, and non-depositional environments. Mixing of fluids at such interfaces may have caused precipitation of uranium, vanadium, and copper. Variations in groundwater flow through time probably also influenced the distribution of hydrocarbon resources.

INTRODUCTION

THE COLORADO PLATEAU physiographic province of the western United States (Fig. 1) contains reserves of oil and gas, uranium, vanadium, copper, carbon dioxide, and evaporite (saline) minerals. Although the formation of these resources was controlled by the movement of groundwater, little is known about the paleohydrogeology. Diagenetic and mineralogical studies that have hydrogeologic implications have focused on parts of the San Juan, Paradox, and Henry Mountains basins in the Colorado Plateau (*e.g.* KELLER, 1962; NORTHROP, 1982; BELL, 1983, 1986; BREIT, 1986; TURNER-PETERSON and FISHMAN, 1986; HANSLEY, 1989). Regional hydrologic studies typically are limited to the present environment (*e.g.* BERRY, 1959; JOBIN, 1962; HANSHAW and HILL, 1969; LYFORD *et al.*, 1980; FREETHEY and CORDY, 1989; GELDON, 1989). As a step toward a synthesis of geologic and hydrologic data into a comprehensive paleohydrogeologic model, this paper presents a summary of the most important data and a conceptual model for groundwater flow through time in the Colorado Plateau. The data constitute input for quantitative hydrologic models that will test the speculative scenarios presented here (SANFORD, 1982, 1989).

The conceptual models are constructed by combining principles and data from observed stratigraphy, inferred paleoclimates and paleoenvironments, measured and derived hydrologic properties of rocks, hydrologic properties of modern sediment analogs, and groundwater flow in modern analog systems. First, the basin is reconstructed using modern stratigraphic thicknesses. The paleotopographic base level is restored using modern slopes in similar environments combined with paleo-slope indicators such as current directions and grain-size distribution. Then major factors affecting groundwater flow are evaluated based on basic hydrologic principles and modern groundwater systems (*e.g.* HUBBERT, 1940; FREEZE and CHERRY, 1979). Factors considered are gravity-driven flow down the topographic slope, outcrop pattern, evaporation of surface water, evapotranspiration by phreatophytes, compaction of sediments and accompanying overpressure, decompression due to erosional unloading, permeability and hydraulic conductivity variations, composition and density contrasts, temperature gradients, and fluid mixing. The flow paths are then constructed to be consistent with these factors. Finally, the flow paths are compared with mineral alteration and deposition patterns. In many cases, opposing hydrologic forces complicate the qualitative prediction of flow paths, and quantitative modeling is essential.

Mixing of different types of groundwater is given particular attention because of its potential to cause diagenetic changes and form certain types of ore deposits (BACK and HANSHAW, 1965; RUNNELS, 1969; PLUMMER, 1975). Because the thermodynamic saturation index is rarely a linear function of mixing between two fluids, precipitation can occur even when both end-member fluids are originally undersaturated with respect to a particular mineral (BACK and HANSHAW, 1965). Types of ore deposits linked to fluid interfaces include tabular-type uranium deposits, which will be used as an example in this paper.

Oil and gas migration and accumulation are also controlled by groundwater, and the location of hydrocarbons today may be as much a function of the history of groundwater flow as it is of the present flow (HUBBERT, 1953). Petroleum and natural gas are not specifically addressed in this paper, but the framework provided may be useful to petroleum geologists.

TECTONIC CYCLES AND GROUNDWATER CONTROLS

The Phanerozoic history of the Colorado Plateau was characterized by four major tectonic cycles: Pennsylvanian-Permian, Triassic, Jurassic, and Cretaceous-Tertiary. Each cycle lasted from 64 to 100 million years and consisted of marine-marginal marine deposition, fluvial-lacustrine-eolian deposition, and erosion (SANFORD, 1983; SANFORD, in GRANGER *et al.,* 1988). Many fluctuations occurred within individual cycles (Fig. 2). A diagram of deposition rate is shown instead of a stratigraphic column in order to show duration of events in proper proportion rather than relative thicknesses of stratigraphic units. Periods of erosion or non-deposition are just as important for understanding groundwater and spanned as much geologic time in the Colorado Plateau as periods of deposition.

Periods of deposition involve loading and expulsion of connate pore water that moves upward and outward from deeper parts of the basins (Fig. 3a) (MAGARA, 1976). The greater density of solids compared to groundwater, including saline groundwater, forces pore water upward with respect to the framework grains. Flow due to compaction is relatively slow and takes place over long periods of time in intracratonic basins (BETHKE, 1985). In the Colorado Plateau, Upper Cretaceous marine shales and abundant fluvial mudstones of all ages would be sources of expelled pore water. Fluvial, marine, and eolian sandstones compact less than mudstones, but can still expel large quantities of pore water. Compaction has the greatest influence on groundwater movement during rapid marine deposition, when topographic effects are minimal.

During fluvial deposition in general, gravity-driven flow probably outweighs compaction (BETHKE, 1985). Gravity-driven flow results from topographic variations and is characterized by flow from elevated areas toward topographic depressions (FREEZE and WITHERSPOON, 1967; HITCHON, 1969). Permeability variations in recharge areas tend to focus flow into aquifers; in discharge areas flow tends to be upward and out of aquifers (GARVEN and FREEZE, 1984). Lakes may be discharge areas or recharge areas, but large permanent lakes and lakes close to base level are nearly always discharge areas (WINTER, 1976; FREEZE and CHERRY, 1979, pp. 226–229).

Periods of nondeposition or erosion may have little compaction but much gravity-driven flow (Fig. 3b). In the Colorado Plateau, compaction due to tectonic compression was probably insignificant, except in the extreme northwest part of the region during the Sevier orogeny. During uplift and erosional downcutting, dilute meteoric water mixes with and may eventually flush out saline formation water in aquifers, although less permeable or very deep units may retain older water (ISSAR, 1981; DOMENICO and ROBBINS, 1985). In arid environments, much of the section above base level (*e.g.* sea level) may be underpressured or even unsaturated, and flow may be minimal (ORR and KREITLER, 1985; FREETHEY and CORDY, 1989).

Uplift and associated erosion also cause decompression, fracturing, and dissolution. Decompression can lower the hydrostatic head and tend to draw fluid into the region of unloading (NEUZIL and POLLOCK, 1983). Fracturing and dissolution of highly soluble minerals, such as halite and calcite, increases the hydraulic conductivity in uplifted areas (JOHNSON, K. S., 1981; FREETHEY and CORDY, 1989).

Pore water, originally sea water or meteoric water, is typically saline at depth owing to salt and carbonate dissolution, chemical equilibration with sediments, or membrane filtration (*e.g.* BREDEHOEFT *et al.,* 1963; HANSHAW and COPLEN, 1973; KREITLER, 1979). In all phases of the tectonic cycle, salinity variations in the fluid tend to cause the groundwater to move toward a state of gravitational equilibrium or steady state: when both fluids are stationary, the denser fluid lies below less dense fluid, and the interface is horizontal; when the upper, less dense fluid is flowing, the interface slopes upward in the direction of flow, (HUBBERT, 1940). Typically, salinity increases along the flow path from the basin margin to center, and a lens or wedge of fresh water rests upon saline water below (Fig. 3c). The meeting of dilute meteoric water moving down dip with saline pore water from below often creates a brine-fresh water interface (PAYNE, 1968, 1970,

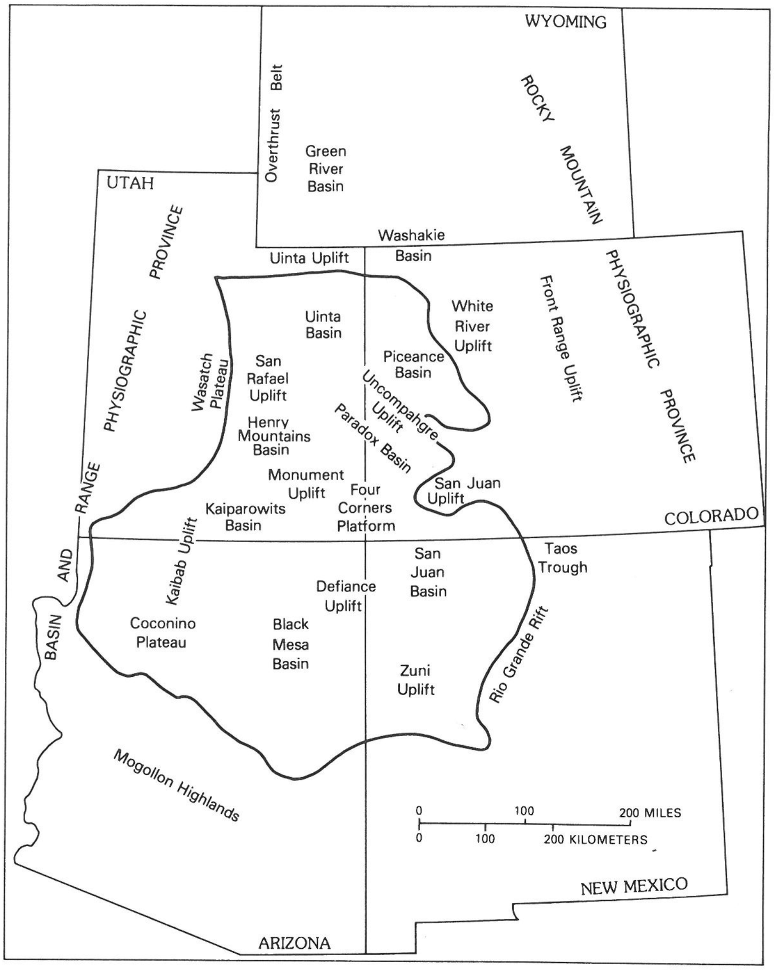

FIG. 1. Map of the Colorado Plateau physiographic province and surrounding area showing major structural features. From GROSE, 1972; GREEN, in GRANGER *et al.*, 1988.

1972, 1975; KREITLER, 1979; KREITLER *et al.*, 1977). Also, the meeting of meteoric, down-dip flow with intruding sea water or playa lake water often forms an interface (PERLMUTTER *et al.*, 1959; COOPER *et al.*, 1964; MCLEAN, 1970, 1975; CUSTODIO, 1981; KISHI *et al.*, 1982; MAGARITZ and LUZIER, 1985; RANDAZZO and BLOOM, 1985). Aquifers may be well mixed, whereas confining units may exhibit large compositional variations. Whenever the configuration of the basin changes due to tectonic forces or sedimentation, the relative flow rates of the different water types changes, or the groundwater changes density due to chemical effects, the bodies of groundwater and the positions of the interfaces must readjust to reestablish gravitational equilibrium. Salinity can also affect fluid flow by changing fluid viscosity and hydraulic conductivity.

Gradients in salinity across a low permeability layer can cause migration of water from the fresh water side toward the brine in response to the chemical potential gradient. This osmotic effect can explain certain abrupt changes in hydraulic head in the San Juan and Paradox basins (BERRY, 1959; HANSHAW and HILL, 1969). However, later workers found no osmotic membrane effects in the Paradox basin (THACKSTON *et al.*, 1981).

Temperature may affect groundwater flow at depth. The upward flux of geothermal energy tends to result in hotter, less dense water below cooler, denser water. Free convection may result, if the temperature effect overcomes the compositional effect on density (WOODING, 1962; WOOD and HEWETT, 1982). Compaction-driven flow is probably so slow that a normal geothermal gradient is maintained (BETHKE, 1985), but gravity-driven flow may

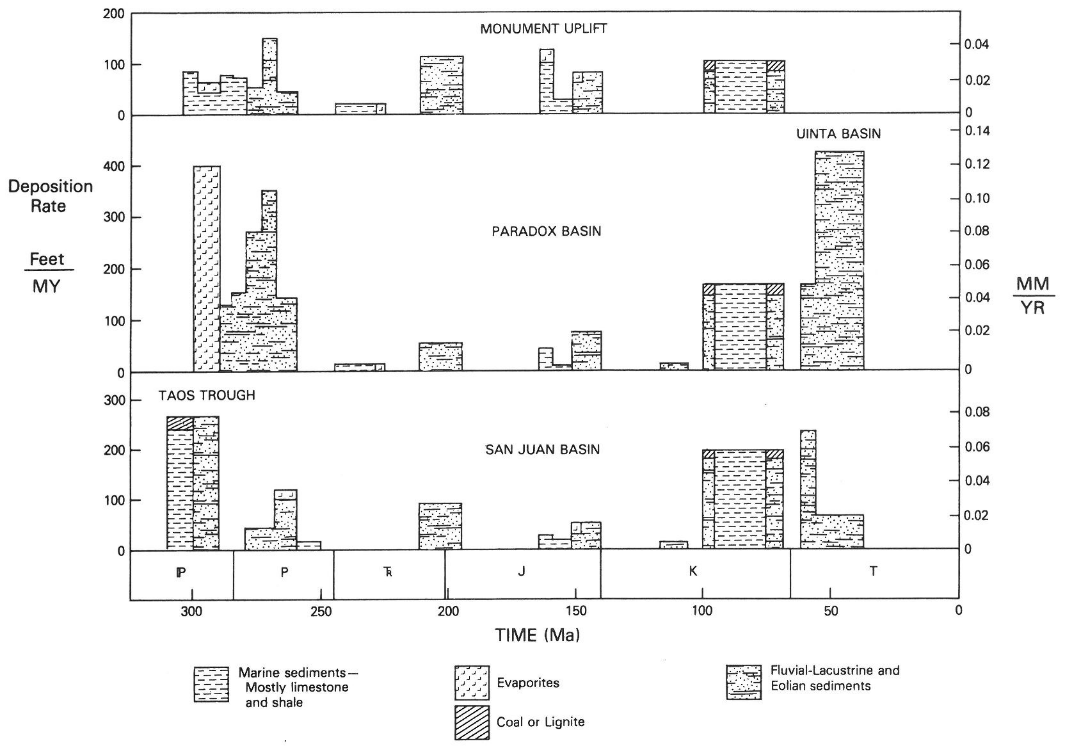

FIG. 2. Simplified deposition rate versus time for selected parts of the Colorado Plateau. Data primarily from MALLORY, 1972.

be large enough that the temperature is lowered in area of recharge and raised in areas of discharge (GARVEN and FREEZE, 1984). Because the salinity of groundwater in the Colorado Plateau ranges from fresh (<1000 mg/l TDS) to as much as 400,000 mg/l (*e.g.* HANSHAW and HILL, 1969), density variations due to salinity would typically outweigh those due to temperature, as suggested also for the Gulf Coast basin (RANGANATHAN and HANOR, 1988). However, temperature may be a major driving force locally in compositionally homogeneous aquifers (WOOD and HEWETT, 1982). Temperature also affects fluid viscosity and hydraulic conductivity.

The sequence of events determines which compositionally distinct types of pore water will mix and interact. Marine transgressions can be expected to cause sea water to mix with and displace interstitial fresh water and to cause the gravitationally unstable configuration of sea water overlying fresh water. Prograding fluvial deposits encroaching on regressing seas may lead to interstitial fresh water overlying sea water. When marine regressions occur during arid periods having evaporite deposition, fresh water can be expected to overlie hypersaline brine. Young fluvial sediments typically contain fresh groundwater, but associated lacustrine deposits may be either fresh or saline. Fluvial-lacustrine deposits therefore can have mixing of fresh and saline water in the near-surface as well as mixing of these types with other types at depth.

TECTONIC HISTORY AND PALEOCLIMATES

Plate-tectonic reconstructions and analysis of climatically sensitive deposits, such as coal and evaporites, show that the North American plate was drifting northward and rotating counterclockwise during most of the Paleozoic (*e.g.*, PARRISH *et al.*, 1982). A stable shelf environment existed in the Colorado Plateau region from Cambrian to Mississippian, while carbonates and clean sands were deposited (MALLORY, 1972; FOUCH and MAGATHAN, 1980). Gentle upwarping during late Mississippian and early Pennsylvanian caused karst formation in the Mississippian limestones. During the early Pennsylvanian, the Colorado Plateau was just north of the equator, and a shallow epeiric sea lay to the east. Warm trade winds from the northeast and cross-equatorial monsoon winds from the south provided a humid environment in coastal areas and

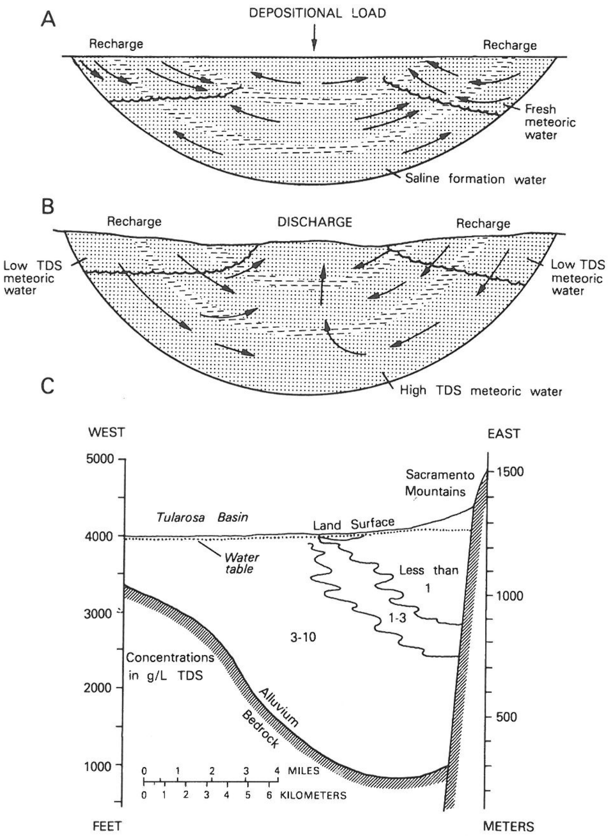

FIG. 3. Typical flow patterns and salinity variations in compacting and uplifted basins. A) Young basin undergoing active deposition and compaction. From KREITLER, 1979; B) Mature basin dominated by gravity-driven ground water flow. From KREITLER, 1979; C) Continental basin in arid climate showing water table and fresh water-brine interface. From MCLEAN, 1975.

inland as shown by "terra rosa" soils developed on exposed Mississippian carbonates (LESSENTINE, 1965) and by Morrowan lignite deposits in the Taos trough (CASEY, 1980). The environment was probably like that of east-facing (windward) coasts near the equator today, for example, in Indonesia.

By middle Pennsylvanian, the ancestral Rocky Mountains had created an extensive rain shadow inland where vast evaporite deposits began to form (Fig. 4a). By the Triassic, when the highlands were substantially reduced by erosion, the Carboniferous seas had retreated, and the vast Pangean continent lay to the northeast. A monsoon climate prevailed from the late Permian until the latest Triassic (Fig. 4c) (PARRISH *et al.*, 1982; DUBIEL, 1989). In winter months, cool, dry continental air masses would have come from the interior to the northeast. During the summer, the landmass would have drawn air from the Pacific Ocean. In the latest Triassic, conditions again became arid. The rising Mogollon highlands may have blocked the moist air from the southwest. Also, the Colorado Plateau region drifted north from equatorial latitudes into the trade-wind zone where winds tend to be from the northeast.

During the Triassic and Jurassic the ancestral Rocky Mountains were eroded to base level while the Mogollon volcanic arc and highlands rose to great height (Fig. 4d). Numerous transgressions and regressions of the sea from the northwest alternated with periods of dominantly fluvial-lacustrine-eolian sedimentation and non-deposition. Overall, a dominantly marine-marginal marine-evaporite period was followed by a dominantly fluvial-lacustrine-eolian phase in both the Triassic and Jurassic.

When the Four Corners had drifted to about 40°N, the Colorado Plateau region entered the temperate zone with dominantly westerly winds, cooler temperatures, and increased rainfall (Fig. 4e) (PARRISH *et al.*, 1982). In late Cretaceous, coal beds were widespread. An extensive epeiric sea that transgressed from the northeast covered much of the Colorado Plateau.

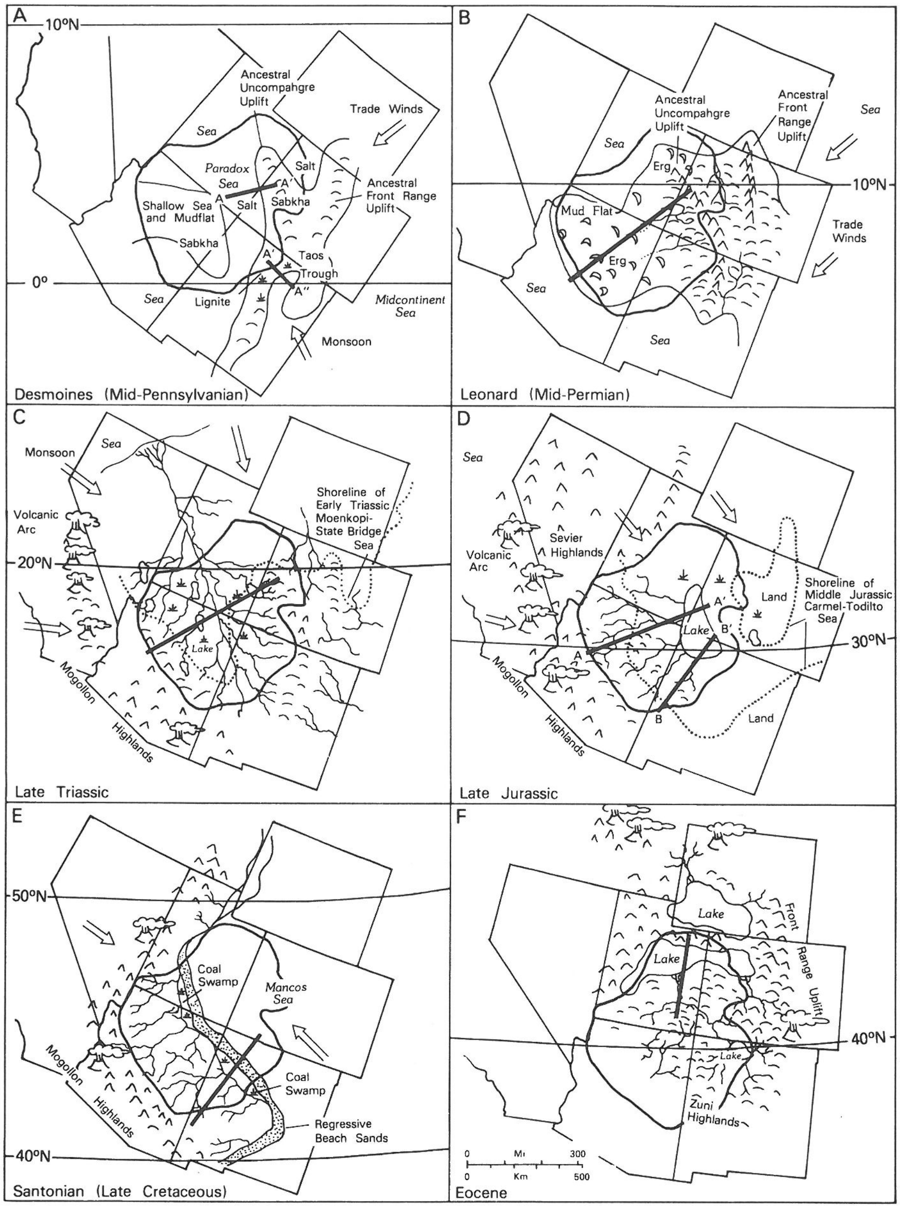

FIG. 4. Paleogeography and paleoclimate of the Colorado Plateau for selected periods in the Phanerozoic. Data from BLAKEY and GUBITOSA, 1983; PETERSON and HITE, 1969; MALLORY, 1972; BLAKEY, 1974; MACK *et al.*, 1979; CAMPBELL, 1980; CASEY, 1980; HECKEL, 1980; PETERSON, 1980; BLAKEY, 1980; PARRISH *et al.*, 1982; PARRISH and PETERSON, 1988; PETERSON, 1988a; DUBIEL, 1989.

Paleocene and Eocene uplift led to locally arid conditions controlled by orographic effects (Fig. 4f). Coal accumulation nearly ceased by the Paleocene (TREMAINE *et al.*, 1981), and alkaline-saline lakes became extensive by the Eocene (EUGSTER and HARDIE, 1978; JOHNSON and KEIGHIN, 1981). Late Tertiary uplift led to conditions much like those today.

HYDROLOGIC PROPERTIES AND HYDROSTRATIGRAPHIC UNITS

The wide range of sediment types and degrees of lithification in the sedimentary basins of the Colorado Plateau has resulted in extreme variation in hydrologic parameters. Horizontal hydraulic conductivity can range from 10^{-3} m/s for clean, uncemented littoral and eolian sand to 10^{-12} m/s for compacted, unfractured shale (FREEZE and CHERRY, 1979, p. 29). The actual range is probably less in general, because sandstones are commonly cemented by calcite or silica, lowering their hydraulic conductivity, and shales are commonly fractured and faulted, raising their hydraulic conductivity. Vertical hydraulic conductivity measurements are not available for most confining units in the Colorado Plateau, but estimates suggest modern values in the range 10^{-13}–10^{-10} m/s (FRENZEL and LYFORD, 1982).

Similarly, porosity is highly variable. In general, it decreases with increasing depth and lithostatic pressure. Argillaceous sediments may be deposited with 70–80% porosity but may only have 25–30% porosity after burial to 1000 m; sand typically has 35–45% porosity at the surface but 25–35% at 1000 m (HANOR, 1979; BOND and KOMINZ, 1984; BALDWIN and BUTLER, 1985). Most compaction data is from marine basins; sediments deposited subaerially may have only 40–50% porosity at the surface. Shales release relatively more of their pore water near the surface and are mostly compacted at relatively shallow depth, whereas sands compact gradually over a greater depth.

For analysis of groundwater flow, lithostratigraphic units are grouped into hydrostratigraphic units. Hydrostratigraphic units are parts of or groups of lithostratigraphic units that are similar in hydrologic properties and act as a single hydrologic unit. They typically do not correspond to individual formations or time-stratigraphic units. Aquifers are hydrostratigraphic units that have high transmissivity on a regional scale. Confining units are those that have generally low transmissivity.

Rocks of the Colorado Plateau can be grouped into seven aquifer systems and eight confining units (Table 1). Lithology and type of pore water included in the original sediment are shown for each lithostratigraphic unit. Permeabilities have been converted to hydraulic conductivities in meters per second (m/s) for pure water at 20°C. The highest hydraulic conductivities reflect fracturing at shallow depths (FREETHEY and CORDY, 1989; GELDON, 1989). Because this fracture permeability formed mainly during Tertiary uplift, values toward the lower end of the range probably should be used for pre-Tertiary basin reconstructions. Modern sediments that may serve as analogs for ancient environments have hydraulic conductivities comparable to the more permeable fractured sandstones.

The main aquifers are the Mississippian karstic limestones, Pennsylvanian-Permian eolian sandstones, Triassic-Jurassic eolian sandstones, Middle-Upper Jurassic eolian sandstones, and three Cretaceous fluvial-marine sandstones. Shales, siltstones, evaporites, and massive limestones form the confining units.

Faults have been variously interpreted as conduits and as barriers to groundwater flow (HANSHAW and HILL, 1969; THACKSTON *et al.*, 1981; HUNTOON, 1983; FREETHEY and CORDY, 1989).

GROUNDWATER CHEMISTRY

The past composition of groundwater can be inferred from analyses of existing water in the rocks of interest, analyses of water in analog modern environments, analyses of the original fluid trapped as inclusions in minerals, and thermodynamic stabilities of diagenetic minerals. Groundwater from the Colorado Plateau today indicates the types of water to be expected in the past when arid and semiarid climates prevailed, and when fresh water dissolved soluble constituents from the sediments. Modern analogs can suggest the types of water trapped in sediments when deposited. Fluid inclusions can provide evidence of paleo-temperatures and salinities, but usually only for atypically coarse-grained or high-temperature deposits. Thermodynamic calculations place constraints on fluid compositions, but kinetic effects and experimental uncertainty are limiting factors.

Modern groundwater in the Colorado Plateau ranges from fresh (<1000 mg/L TDS) to saline (>35,000 mg/L) (HANSHAW and HILL, 1969; IORNS *et al.*, 1965; PRICE and ARNOW, 1974; THACKSTON *et al.*, 1981; FREETHEY *et al.*, 1984; HOOD and PATTERSON, 1984; WARNER *et al.*, 1985; FREETHEY and CORDY, 1989; GELDON, 1989). Fresh water occurs at shallow depth near recharge areas. Dissolved solids increase with depth away from recharge areas (Fig. 3). The deeper basins typically contain highly saline to briny water; for example, more than 300,000 mg/L TDS occurs locally in the Leadville and Redwall Limestones (HANSHAW and HILL, 1969; GELDON, 1989), and 400,000 mg/L TDS is in the Paradox Member of the Hermosa Formation (THACKSTON *et al.*, 1981).

Major solutes in groundwater of the Colorado Plateau are sodium, calcium, magnesium, potassium, chloride, bicarbonate, carbonate, sulfate, and silica (FREETHEY and CORDY, 1989; GELDON, 1989). These constituents can usually be related to dissolution of soluble minerals such as calcite, gypsum, halite, sylvite, dolomite, and unstable silicates. The most common water types are calcium bicarbonate and sodium chloride. Major dissolved constituents in fresh water are typically calcium and bicarbonate. Brines (>35,000 mg/L) are commonly

Table 1. Primary lithostratigraphic and hydrostratigraphic units of the Colorado Plateau

Age	Primary lithostratigraphic units*	Lithologies	Original pore water	Hydrostratigraphic unit**	Hydraulic conductivity (m/s)†
Cambrian-Mississippian	Ignacio	Quartzite	Sea water	Lower Paleozoic aquifer	10^{-7} to 60
	Elbert	Dolomite, shale, sandstone	Sea water		
	Redwall	Limestone, orthoquartzite	Sea water		
	Leadville	Limestone, orthoquartzite	Sea water		
Pennsylvanian-Permian	Supai (lower)	Shale	Fresh-saline	Upper Paleozoic confining unit	10^{-6} to 3
	Molas	Paleosol	Fresh		
	Pinkerton Trail	Marine carbonate, shale	Sea water		
	Paradox	Halite, gypsum, shale	Hypersaline brine		
	Honaker Trail	Marine carbonate, shale	Sea water		
	Cutler	Arkose	Fresh		
	Halgaito	Shale	Fresh-saline		
	Abo	Shale, sandstone	Fresh-saline		
	Hermit	Shale	Fresh-saline		
	Organ Rock	Shale	Fresh-saline		
	Yeso	Shale, sandstone, carbonate	Fresh-saline		
Pennsylvanian-Permian	Supai (upper)	Eolian sandstone	Fresh-saline	Upper Paleozoic aquifer	10^{-5} to 60
	Weber	Eolian sandstone	Fresh-saline		
	Elephant Canyon	Marine limestone, sandstone	Sea water		
	Cedar Mesa	Eolian sandstone	Fresh-saline		
	De Chelly	Eolian sandstone	Fresh-saline		
	White Rim	Eolian sandstone	Fresh-saline		
	Coconino	Eolian sandstone	Fresh-saline		
	Glorieta	Eolian sandstone	Fresh-saline		
	Toroweap	Marine limestone, sandstone	Sea water		
	Kaibab	Marine limestone	Sea water		
	San Andres	Marine limestone	Sea water		
Triassic	Moenkopi	Marine siltstone, limestone, gypsum	Sea water, hypersaline brine	Triassic confining unit (Fluvial sandstone locally transmissive)	10^{-6} to 10^{-4}
	Chinle (lower)	Fluvial-lacustrine sandstone, mudstone	Fresh		
	Chinle (upper)	Bentonitic lacustrine mudstone, sandstone	Fresh-alkaline saline		
Triassic-Jurassic	Wingate	Eolian sandstone	Fresh-saline	Glenn Canyon Group aquifer	10^{-5} to 10^{-3} (Wingate) 10^{-3} to 0.1 (Navajo)
	Kayenta	Fluvial sandstone	Fresh		
	Navajo	Eolian sandstone	Fresh-saline		
	Nugget	Eolian sandstone	Fresh-saline		
	Page	Eolian sandstone	Fresh-saline		
Middle-Jurassic	Carmel	Marine siltstone, limestone	Sea water-hypersaline brine	Carmel confining unit	N.A.
	Entrada (lower)	Silty sandstone	Fresh-saline		
Middle-Late Jurassic	Entrada (upper)	Eolian sandstone	Fresh-saline	Entrada-Morrison aquifer	10^{-5} to 10^{-2}
	Cow Springs	Eolian sandstone	Fresh-saline		
	Bluff	Eolian sandstone	Fresh-saline		
	Salt Wash	Fluvial sandstone, mudstone	Fresh		
	Recapture	Fluvial sandstone, mudstone	Fresh-saline		
	Westwater Canyon	Fluvial sandstone, mudstone	Fresh		

Table 1. (Continued)

Age	Primary lithostratigraphic units*	Lithologies	Original pore water	Hydrostratigraphic unit**	Hydraulic conductivity (m/s)†
Middle-Late Jurassic	Curtis	Sandstone, mudstone, gypsum	Sea water-brine	Summerville-Curtis confining unit	N.A.
	Summerville	Mudstone, sandstone	Sea water-brine		
	Wanakah	Sandstone, siltstone, limestone, gypsum	Sea water-brine		
	Tidwell	Mudstone, gypsum	Sea water-brine		
Late Jurassic	Brushy Basin	Bentonitic lacustrine mudstone, sandstone	Fresh-alkaline saline	Brushy Basin confining unit	N.A.
Early-Late Cretaceous	Burro Canyon	Fluvial sandstone	Fresh	Dakota aquifer	10^{-3} to 10^{-2}
	Dakota	Fluvial-marine sandstone	Fresh-sea water		
Late Cretaceous	Mancos	Marine shale	Sea water	Mancos confining unit	N.A.
Late Cretaceous	Gallup	Fluvial-marine sandstone	Fresh-sea water	Mesaverde aquifer	0.01 to 1.0
	Mesaverde	Fluvial-marine sandstone	Fresh-sea water		
	Crevasse Canyon	Fluvial-marine sandstone	Fresh-sea water		
	Point Lookout	Coastal or marine sandstone	Fresh-sea water		
	Cliff House	Coastal or marine sandstone	Fresh-sea water		
Late Cretaceous	Lewis	Marine shale	Sea water	Lewis confining unit	N.A.
Late Cretaceous	Pictured Cliffs	Coastal or marine sandstone	Fresh-sea water	Pictured Cliffs aquifer	0.01 to 1.0
Late Cretaceous-Tertiary	Fruitland	Sandstone, shale, coal	Fresh-sea water	Tertiary confining unit	10^{-11} to 10^{-6} (Fluvial beds and fracturing enhance permeability locally)
	Kirtland	Fluvial-lacustrine shale	Fresh		
	Animas	Conglomerate, arkose, shale	Fresh		
	Nacimiento	Shale and arkose	Fresh		
	San Jose	Fluvial shale, sandstone	Fresh		
	Currant Creek	Conglomerate, sandstone, shale	Fresh		
	North Horn	Shale, limestone, sandstone	Fresh		
	Wasatch	Fluvial shale, sandstone	Fresh		
	Green River	Lacustrine shale, marl, evaporite	Fresh-alkaline-saline		
Holocene		Playa lake salt crust			10^{-3}
		Beach and dune sand			10^{-5} to 10^{-3}
		Fluvial sand			10^{-6} to 10^{-3}
		Clay			10^{-12} to 10^{-5}

Sources of data: JOBIN, 1962; WIT, 1967; COOLEY *et al.*, 1969; HANSHAW and HILL, 1969; PRYOR, 1973; TURK *et al.*, 1973; HOOD, 1976; FREEZE and CHERRY, 1979; ETHRIDGE *et al.*, 1980a and b; LYFORD *et al.*, 1980; THACKSTON *et al.*, 1981; BLAKEY *et al.*, 1988; CONDON and HUFFMAN, 1988; PETERSON, 1988b; FREETHEY and CORDY, 1989; GELDON, 1989.

* Listed in approximate stratigraphic order from oldest to youngest.

** Hydrostratigraphic units are named for purposes of discussion in this paper and are not official U.S. Geological Survey designations.

† N.A. stands for "not available."

sodium chloride-type. Intermediate saline water with TDS from 1000 to 35,000 mg/L has combinations of calcium, magnesium, sodium, sulfate, and bicarbonate as dominant ions.

Modern analogs to ancient surface water are sea water, river water, fresh lake water, and saline lake water. Variations in certain components of sea water, such as sulfur isotope ratios, can be useful in determining fluid sources (*e.g.* HOLSER and KAPLAN, 1966). Lake water varies from fresh to saline, oxidizing to reducing. Lake bottom sediments typically are reducing. Lake water compositions are highly variable and depend largely on the composition of rocks in the drainage basin (EUGSTER, 1980).

Alteration minerals reveal the chemistry of paleolake and surface water. Kaolinite typically forms from high flux of low-TDS water that may be acidic from the decomposition of organic matter. Analcime, potassium feldspar, and albite may indicate alkaline-saline alteration in a closed basin. Certain saline minerals such as gypsum, halite, and sylvite suggest arid environments where lake or sea water has evaporated; thick-bedded deposits of these minerals, as in the Paradox basin, suggest a restricted arm of the sea (HITE, 1968).

Fluid inclusions have been used to determine the temperature and salinity of breccia-pipe-hosted silver-base metal-uranium deposits in northern Arizona (WENRICH and SUTPHIN, 1989). Fluid inclusions yielded temperatures and salinities of fluids associated with veins of carbonate, sulfate, and copper-silver sulfide minerals in the Paradox Basin (MORRISON and PARRY, 1986).

GROUNDWATER FLOW THROUGH TIME

From Cambrian through Mississippian, stable marine shelf carbonates and sandstones accumulated on the flanks of the transcontinental arch which extended in a northeast-southwest direction through New Mexico and eastern Colorado (Figs. 4a and 5). Cambrian, Devonian, and Mississippian strata make up most of the section and thicken to the north and west away from the arch into Utah, Arizona, and Nevada. In late Mississippian and early Pennsylvanian, upwarping and regression of the sea exposed the limestones to weathering, karst formation, and soil development in a warm humid environment near the equator.

Groundwater would have consisted of connate sea water in submarine sediments and fresh water in exposed areas. The karst features may have formed on land and at the sea water-fresh water interface. In similar settings today, Florida and the Yucatan Peninsula, limestone is dissolved and dolomite is precipitated (WARD and HALLEY, 1985; BACK *et al.,* 1986).

After the lengthy stable period characterized by the marine shelf environment ended, the Colorado Plateau experienced four major cycles of marine deposition, subaerial deposition, and erosion.

Cycle 1: Pennsylvanian to Permian

In Morrowan time, shallow epeiric seas transgressed across the Mississippian limestone surface, and the ancestral Rocky Mountains began to emerge (Fig. 4a and 5). Winds from the east created a lush, humid environment, as indicated by lignite deposits in the Taos trough (CASEY, 1980). An arid climate prevailed on the lee side where vast evaporite deposits formed (OHLEN and MCINTYRE, 1965; BAARS *et al.,* 1967; PETERSON and HITE, 1969).

On the windward side, in the Taos trough, ample precipitation kept the water table near the ground surface, and debris shed from the emerging highlands was largely saturated with fresh water. In low-lying coastal areas, fresh to brackish water was locally acidified by decomposing organic matter. A mixing zone of brackish water between the fresh- and sea-water masses extended down and landward due to sea water intrusion. Because sediment loading was greatest adjacent to the highlands, expelled pore water tended to move updip and seaward toward the shallower parts of the trough (Fig. 5).

On the leeward side of the highlands, for example in the Paradox basin, sparse precipitation quickly percolated down through coarse clastic material of the alluvial fans. Because of the low recharge rate, high transmissivity, and steep slopes, the water table was probably only slightly above sea level. Discharge was at the toe of the alluvial fans and at the shoreline of the sea owing to decrease in topographic slope, decrease in grain size and transmissivity, and the presence of a salt water wedge. Gravity flow through the fan became increasingly more saline and alkaline due to evapotranspiration by phreatophytes, evaporative pumping by capillary action, and mixing with connate brine. Evaporation from shoreline pans or sabkhas drew brine from the basin shoreward. Compaction was greatest in muds interbedded with evaporites where deposition was most voluminous. Most of the water trapped during deposition of the evaporites and interbedded clay was probably lost very near the surface because of the high compressibility of the material; porosities of 1-2 percent are typical of evaporites at relatively shallow depths (GEVANTMAN, 1981). Fluid in the core of the Paradox Member evaporites probably

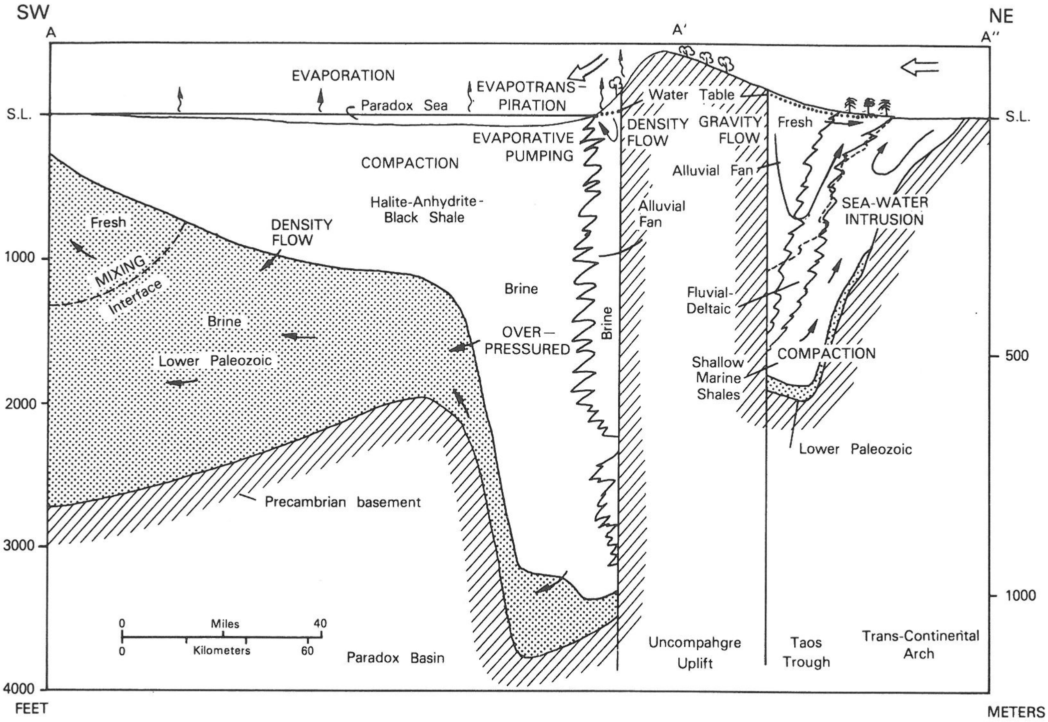

FIG. 5. Paleo ground water flow in Desmoinesian time (Middle Pennsylvanian). Line of section is shown in Fig. 4a; note offset in section at A'. S.L. stands for sea level. (Stratigraphy from OHLEN and MCINTYRE, 1965; BAARS *et al.,* 1967; PETERSON and HITE, 1969; HITE and CATER, 1972; SUTHERLAND, 1972; CASEY, 1980.

experienced overpressures, as observed today (SPENCER, 1975; THACKSTON *et al.,* 1981). Any groundwater that was forced out of the clastic sediments at the base of the section by compaction, density differences, or topographic forces probably moved through the lower Paleozoic aquifer rather than through the evaporites. Topography and compaction tended to force this deep groundwater up and out; however, the increased density due to salt dissolution tended to keep the most dense fluid in the deepest part of the basin. Any fresh water that had been trapped in the Mississippian aquifer from its previous subaerial environment would have been flushed out and replaced with brine at this time, as suggested by high-TDS water in the Leadville and Redwall Limestones today (HANSHAW and HILL, 1969; THACKSTON *et al.,* 1981; GELDON, 1989).

Toward the close of the Pennsylvanian, the shelf carbonate facies encroached on the evaporite facies, as subsidence of the Paradox basin and uplift of the Uncompahgre highlands slowed temporarily. In the Wolfcampian and Leonardian (early Permian), uplift and subsidence resumed at a greater rate, and large volumes of clastic material, fluvial arkosic sand and silt, and eolian sand and dust, spread southwestward from the Uncompahgre highlands over the Colorado Plateau (Fig. 4b and 6). Heterogeneous arkosic material next to the uplift grades into and intertongues with the fine-grained silt and eolian sand facies to the southwest. Toward the close of the early Permian, the sea, which had regressed far to the northwest, encroached on the western and southern parts of the Colorado Plateau.

Like west-facing shoreline areas in the trade-wind belt today, such as northern Chile, Namibia, and northwestern Australia, the climate was probably extremely arid. Precipitation mainly fell in the mountains. The water table at higher elevations probably was far below the ground surface due to low recharge, steep slopes, and high permeability of the coarse fan material. Evaporation and evapotranspiration would cause the fresh meteoric water to become alkaline and saline as it percolated through the fan and basin-fill sediments (*e.g.* MCLEAN, 1975; CARLISLE *et al.,* 1978; BRIOT, 1983). Ubiquitous calcite cement suggests that calcrete formed downstream at lower elevations as it does today in similar environments.

Where shallow groundwater and sea water met at the shoreline, a mixing zone would develop. Sea

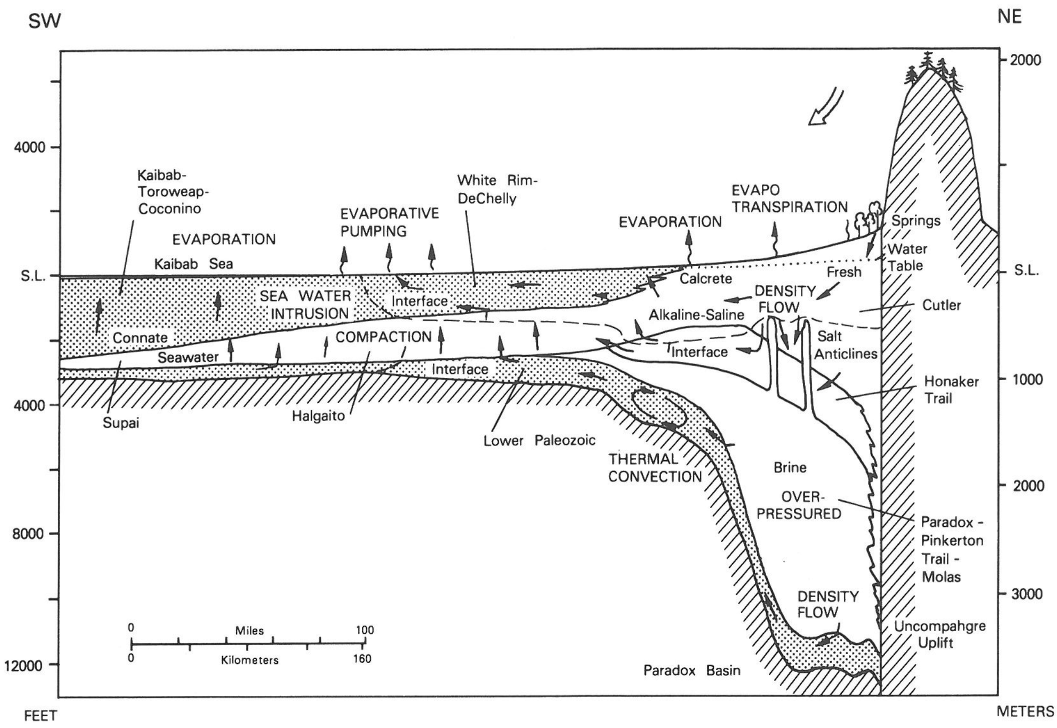

FIG. 6. Paleo ground water flow in Leonardian time (early Permian). Line of section is shown in Fig. 4b. S.L. stands for sea level. (Stratigraphy from BAARS, 1962; RASCOE and BAARS, 1972; CAMPBELL, 1980; PETERSON, 1980; and references cited for Fig. 5). Selected lithostratigraphic units labeled.

water is typically drawn landward by evaporation in similar sabkha environments. Because the shallow groundwater may have been less dense than sea water, the sea water probably intruded landward at depth and formed a sloping interface within the permeable sands and carbonate sediments.

Compaction continued to expel connate water from the deepest part of the basin adjacent to the Uncompahgre block. The black shale beds of the Paradox Member probably were a source of brine. Algal material and bacterial activity would lower the Eh of the brine. Expelled low-Eh brine then migrated into aquifers above and below. Brine expelled into the underlying Mississippian aquifer tended to accumulate in the deepest parts of the basin or to move updip toward the shoreline to the southwest and into thicker parts of the aquifer to the northwest (normal to the section of Fig. 6). In the core of the Paradox Member evaporites, overpressure probably developed as sediment loading occurred. Above the Paradox Member, the locally transmissive Honaker Trail Member of the Hermosa Formation was a conduit for expelled water of compaction from black shales in the Paradox and from clastic sediments in the upper part of the section.

Growth of salt anticlines began shortly after Paradox deposition (Fig. 4c of CATER, 1972). The bounding faults may have been favorable conduits for fluid flow. If descending fresh water encountered the salt, dissolution of salt and density-driven flow might have been important, as they are in the Gulf Coast today (*e.g.* RANGANATHAN and HANOR, 1988). Interfaces formed between connate brine, sea water, and fresh water in different parts of the basin. Gypsum, dolomite, and other minerals are evidence for such interfaces (RAUP, 1982; RANDAZZO and BLOOM, 1985). These interfaces would also be favorable zones for precipitation of copper, silver, and related metals. Gravity stratification of groundwater probably was taking place in the deepest Paleozoic sediments during the Pennsylvanian and Permian, and a stably stratified configuration may have persisted through the Mesozoic while these sediments remained deeply buried.

Cycle 2: Triassic

Tectonic uplift and deposition waned in the late Permian and earliest Triassic, and the topography became subdued. Hydrologically, conditions were like those in the early Permian except that com-

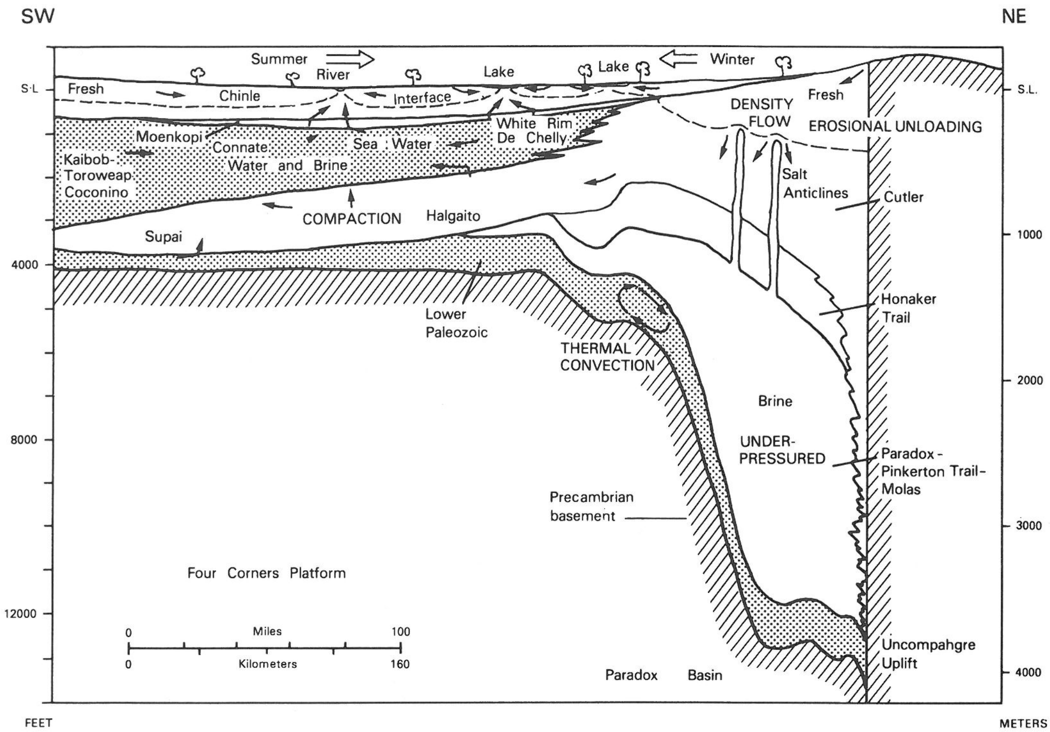

FIG. 7. Paleo ground water flow in Petrified Forest time (late Triassic). Line of section is shown in Fig. 4c. S.L. stands for sea level. (Stratigraphy from BLAKEY and GUBITOSA, 1983; BLAKEY, 1974; DUBIEL, 1987a, 1987b, 1989; and references cited for Fig. 6). Selected lithostratigraphic units labeled.

paction-driven expulsion of pore water ceased as active deposition came to an end. Groundwater flow was dominantly gravity-driven. Fresh water displaced brine in upper parts of the Permian section in the Paradox basin. Locally, especially in the Paradox basin, salt dissolution and resulting density-driven flow may have been important. Very little erosion at the top surface of the Kaibab Limestone and the Coconino and De Chelly Sandstones indicates a very gentle gradient over most of the Colorado Plateau area (BAARS, 1962). The lack of compaction, the gentle topographic gradient, and the presence of gravity stratification may have allowed evolved sea water at depth to occupy pore spaces of Permian sediments into Triassic time, although the upper part would have been recharged with fresh meteoric water.

During the early Triassic, the Moenkopi Formation was laid down during several episodes of regression and transgression of shallow epeiric seas (BLAKEY, 1974). The seas invaded from the northwest and formed a restricted bay surrounded by the Mogollon highlands, which were beginning to rise in the southwest, the Uncompahgre highlands, now largely eroded to the northeast, and the Defiance uplift, a subdued uplift to the southeast. Interstitial pore water trapped during deposition was dominantly sea water with pockets of hypersaline brine from marginal-marine evaporites and pockets of fresh water in areas of fluvial, subaerial deposition.

In late Triassic, a fluvial-deltaic-lacustrine system prograded over the marine deposits (Fig. 4c and 7) (BLAKEY and GUBITOSA, 1983; DUBIEL, 1987a, 1987b). An aggrading river system flowed northwestward toward the sea. A warm monsoon climate prevailed in which dry winters alternated with wet summers. Rising base level caused the formation of local but extensive lakes, deltas, and marshes. In these areas, green mudstones, well-preserved organic matter, and worm burrows indicate a water table close to the surface; away from these areas, red strata with poorly preserved organic matter and no worm burrows indicate a locally deep water table (DUBIEL, 1989). Abundant bentonitic beds indicate significant deposition of volcanic ash from a magmatic arc to the southwest.

Seasonally abundant precipitation provided fresh meteoric groundwater in the near-surface environment. Regional surface and groundwater flow was from highland areas marginal to the depositional basin toward the sea to the northwest. Complex local flow systems probably developed on the undulating ground surface, and topographic lows tended to be local discharge areas.

Topographic flow and compaction forced connate water upward from the Moenkopi and other underlying marine sediments. As deposition proceeded, fresh water in lower parts of the Chinle was replaced mainly by evolved sea water from below. The interface between fresh and saline water moved upwards as the newly deposited sediments subsided. Expelled saline water collected in areas of more active subsidence where compaction was greater and where downwarps tended to pool the denser fluid.

Erosional unloading could have had major effects on the regional groundwater flow (NEUZIL and POLLOCK, 1983). From late Permian through early Jurassic, the Uncompahgre highlands generally were eroding. As both the Precambrian core of the uplift and the upper strata of arkosic debris were stripped off, the release of stress caused underpressuring at depth and tended to draw fluid in from areas of higher pore pressure where erosional unloading was slower or where deposition was taking place. Groundwater in the permeable sandstones flowed relatively quickly in response to this change in stress, but less permeable units, particularly the Paradox evaporites remained underpressured for a significant length of time. At the same time, the depositional basin in the central and northwest parts of the Colorado Plateau was compacting and subsiding as the Moenkopi and Chinle were deposited. Deep ground-water expelled from beneath the central Colorado Plateau therefore tended to flow toward the areas of maximum decompression, *i.e.,* toward the Paradox basin. Determining whether this force overcame the opposing regional topographic slope would require a quantitative analysis.

Two types of ore deposits probably formed about this time (210 ± 10 Ma); sandstone-hosted, tabular uranium and breccia-pipe-hosted uranium-copper-silver-base metal deposits (WENRICH, 1985; LUDWIG *et al.,* 1986; GRANGER *et al.,* 1988; LUDWIG and SIMMONS, 1988). The role of groundwater was critical to the formation of both types, but exactly how is still uncertain.

Tabular uranium deposits in fluvial sandstones of the Chinle commonly are associated with complexly interbedded low-energy sediments and green lacustrine mudstones (LUPE, 1977; DUBIEL, 1983). Geometry and mineralogy of this deposit type in general (both Triassic and Jurassic) suggest formation at the interface between brine and fresh water (FISCHER, 1947; GRANGER and WARREN, 1981; NORTHROP, 1982; GRANGER and SANTOS, 1986).

A Triassic fresh water-brine interface first formed when fluvial sediments containing fresh interstitial water were deposited over marine sediments containing sea water and locally hypersaline brine. Gradually, the interface rose in response to sedimentation and subsidence. Topographic relief and compaction combined to force the brine toward topographic depressions, defined by thicker accumulation of sediments, lacustrine and generally finer-grained deposits, reducing conditions, and high water table. At the same time, fresh meteoric water was moving toward topographic lows as surface flow and groundwater. Abundant volcanic ash enriched this fresh water in uranium (ZIELINSKI, 1983). The two solutions met in the subsurface, and flow paths converged beneath the topographic depressions. Because discharge areas typically are much smaller than recharge areas (FREEZE and WITHERSPOON, 1967), and because fresh-water lenses narrow toward the discharge areas (HUBBERT, 1940), uranium-bearing groundwater and brine from depth were focused and were forced together near the discharge areas. Mixing of the two solutions caused uranium to precipitate (SWANSON *et al.,* 1966; ANDREWS, 1981). The topographic depression controlled the location of groundwater discharge and mixing, and the focusing of flow lines allowed a deposit, rather than disseminated low-grade concentrations, to form.

Breccia-pipe deposits are most abundant in the southwest part of the Colorado Plateau in northern Arizona (WENRICH, 1985). Fluid inclusions in the early carbonate and base-metal stages of mineralization have homogenization temperatures of 80–173°C and salinities typically more than 18 weight per cent equivalent NaCl (WENRICH and SUTPHIN, 1989). Groundwater having such salinities was probably widespread at depth in the Colorado Plateau, but a source for the high temperatures is more difficult to identify. Heated groundwater may have been associated with igneous activity in the magmatic are south and west of the Colorado Plateau, or it may have come from a deep basin. One source for a basinal brine of this temperature in the Colorado Plateau would have been the Paradox basin. The present reconstruction (Fig. 7) shows a maximum depth of 4000 m, which suggests temperatures of 100–150°C given a normal geothermal gradient (*e.g.* HANOR, 1979). However, the great distance from the Paradox basin to northern Arizona, the cooling that would have resulted from transport, and the unfavorable topographic slope in the Triassic-early Jurassic make the Paradox basin an unlikely source. A similar argument can be made for the Oquirrh basin on the northwest margin of the

Colorado Plateau. Thus the mineralizing fluid probably was not a basinal brine under a normal geothermal gradient. A magmatic heat source related to the magmatic arc to the southwest was a more likely source, because the transport distance would have been smaller and the topographic slope would have been more favorable.

Cycle 3: Jurassic to early Cretaceous

The climate changed from monsoon to arid in the latest Triassic, and arid conditions prevailed until the late Jurassic (CRAIG *et al.*, 1955; GREEN, 1975, 1980; BLAKEY *et al.*, 1983; KOCUREK and DOTT, 1983; DUBIEL, 1989). Sand seas or ergs covered much of the Colorado Plateau from latest Triassic to early Jurassic. The eolian Wingate and Navajo Sandstones were deposited and later became one of the principal aquifers in the region. Tectonically, the area was relatively quiet, and the topographic relief probably remained low. The central part of the Colorado Plateau was a topographic basin surrounded on three sides by the remnants of highlands that existed from the Permian through Triassic. The magmatic arc to the southwest was intermittently active through the latest Jurassic and early Cretaceous.

During the Middle Jurassic, the shallow restricted Carmel sea invaded from the northwest and covered much of the western and central Colorado Plateau region, while erg and coastal sabkha environments dominated in the southeastern part (BLAKEY *et al.*, 1983; KOCUREK and DOTT, 1983; CONDON and HUFFMAN, 1988; PETERSON, 1988b). Clastic, eolian, and evaporitic sediments were deposited.

Regression of the Carmel sea was accompanied by progradation of the Entrada erg. Another transgression of the sea from the northwest then deposited marine and evaporitic marginal-marine sediments of the Curtis Formation and Todilto Limestone Member of the Wanakah Formation. Transgressions and regressions resulted in complex intertonguing of marine, marginal-marine, evaporite, and sabkha facies characteristic of an arid climate from Middle to latest Jurassic.

Given the arid climate of the early Jurassic, shallow groundwater in the Colorado Plateau probably ranged from fresh to saline. Fresh meteoric water recharged in the highlands around the basin. As it moved toward lowland areas, groundwater may have become more saline and alkaline due to evaporation, evapotranspiration, and reaction with detrital material. Groundwater was mainly saline in the central, topographically low part of the area.

During transgressions of the Carmel and Curtis seas, groundwater flow in subaerial environments remained like that in the early Jurassic, but groundwater in strata beneath and adjacent to the seas was altered by sea-water intrusion and by compaction-driven flow upward and outward from deeper parts of the basin. Tidal and supratidal areas were dominated by landward flow driven by evaporation as in modern sabkha environments. Surficial fresh water tended to be displaced by sea water and hypersaline brine with each marine transgression, and fresh water tended to displace sea water and hypersaline brine as the seas retreated. With continued deposition and subsidence, however, fresh water lenses tended to remain on top of the denser saline groundwater, and eventually the entire column of sediments deposited from early Jurassic through middle late Jurassic was saturated by saline groundwater.

Uranium deposits in the Todilto Limestone are considered to have formed syngenetically in a sabkha environment where landward-migrating, low Eh-high pH sea water interacted with seaward-migrating, high Eh-low pH terrestrial water (RENFRO, 1974; RAWSON, 1980a, 1980b).

In the latest Jurassic, continued northward movement of the North American plate began to produce a cooler, less arid climate. Eolian sands, gypsum, and salt casts in the lower members of the Morrison Formation (GREEN, 1975; BLAKEY *et al.*, 1988; PETERSON, 1988b) suggest similarity to earlier arid conditions rather than to later Morrison conditions (GREEN, 1975), although the later fluvial sedimentation may have been the result of increased uplift in the source area rather a change in climate (FRED PETERSON, U.S.G.S., personal communication, 1989).

By the late Jurassic, the Uncompahgre uplift had eroded to base level so that sedimentation reached across and beyond to the present Central Plains region. The volcanic arc to the west and southwest of the Colorado Plateau resumed production of vast quantities of ash that are best preserved in lacustrine mudstones of the Brushy Basin Member at the top of the Morrison Formation. Because of lower base level to the northeast and rising highlands to the southwest, the axis of maximum deposition and subsidence migrated from the southwest Colorado Plateau in the Triassic to the central part by latest Jurassic.

The Upper Jurassic Morrison Formation consists of fluvial conglomerates and sandstones from sources in the southwest and south that grade into lacustrine mudstones in the Paradox and San Juan basins (Fig. 4d and 8) (CRAIG *et al.*, 1955; BELL, 1983, 1986; TURNER-PETERSON, 1985). Mineralogy

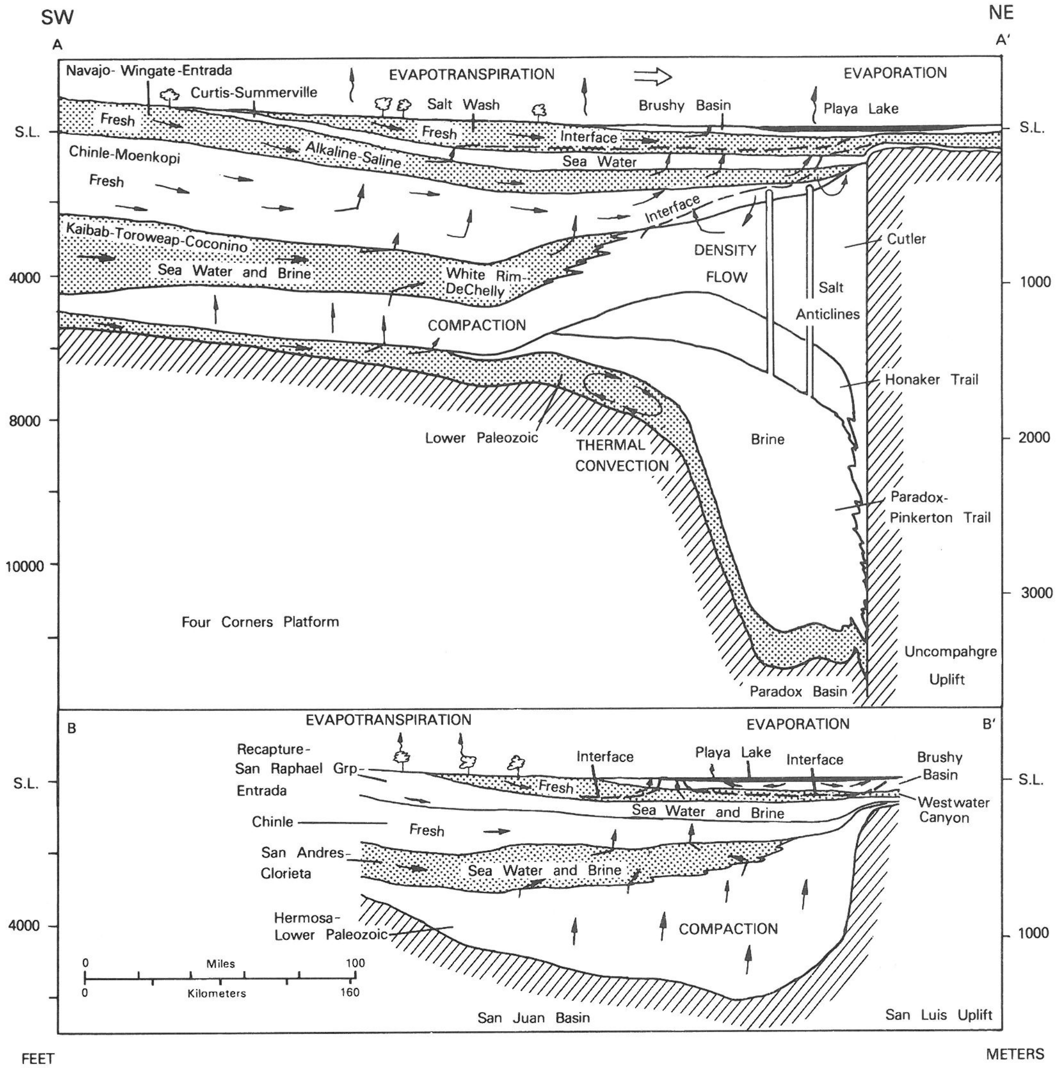

FIG. 8. Paleo ground water flow in Brushy Basin time (late Jurassic). Lines of section are shown in Fig. 4d. S.L. stands for sea level. (Stratigraphy from CRAIG *et al.*, 1955; PETERSON *et al.*, 1965; CONDON *et al.*, 1984; CONDON and PETERSON, 1986; CONDON and HUFFMAN, 1988; PETERSON, 1988b; and references cited for Fig. 7). Selected lithostratigraphic units labeled.

and facies in the Brushy Basin Member suggest that it was locally a playa lake. Carbonized logs and humic material in the fluvial sandstones indicate that the climate was humid enough for plant growth.

Because of the considerable uranium resources hosted by the fluvial sandstones of the Morrison Formation, much has been written about it over the past 40 years. Redistributed-type deposits are generally thought to be roll-type deposits that formed in the Tertiary by remobilization of older tabular-type deposits. However, there is still no general agreement on how Upper Jurassic-Lower Cretaceous tabular-type deposits formed. The following hydrologic model is believed to be consistent with the observed mineral parageneses and facies, but a complete discussion of ore formation is beyond the scope of this paper.

In response to the regional topographic slope, groundwater moved generally from the southwest and south toward the northeast (Fig. 8). Water that recharged in the highlands to the southwest preferentially flowed through fluvial sandstones of the Morrison Formation, the Middle Jurassic eolian sandstones, the Upper Permian sandstones and limestones, and the lower Paleozoic aquifer system. During downdip flow, evaporation near the surface and reaction with detrital materials at depth increased the alkalinity and salinity of the groundwater. Where these aquifers pinch out and grade into less-permeable finer-grained material, the northeastward flow was forced upward. At the same time, sedimentation and the resulting compaction forced connate water up and outward from sediments in the deeper parts of the basins. Faults, especially those associated with salt anticlines in the Paradox basin, were especially favorable conduits. Due to dissolution of evaporites and reaction with detrital material, this groundwater was highly saline, possibly as much as 400,000 mg/l TDS, based on modern analyses. As these two types of groundwater approached the discharge areas, they displaced and forced upward pore water ahead of them. Consequently, connate saline water trapped in Middle to Upper Jurassic marine and evaporitic marginal-marine and/or lacustrine sediments (Curtis and Summerville Formations and Tidwell and Recapture Members of the Morrison Formation) tended to move upward and displace fresh water in the base of the Morrison sandstones. The resulting interface sloped upward toward the basin in the direction of flow.

Discharge areas were not only where aquifers pinch out, but also in topographically low areas where fine-grained lacustrine sediments accumulated. The decrease in slope and the finer-grained sediments combined to favor discharge at lake margins. Deeper, regional flow that passed under the lake ultimately was forced up to the surface upon encountering the buried Precambrian blocks of the Uncompahgre and San Luis uplifts.

A third source of groundwater was the connate alkaline-saline brine trapped in the lacustrine facies of the Brushy Basin muds. Compaction tended to drive this water upward, but its higher density relative to fresh water, especially in the center of the playa, might have tended to cause it to displace fresh water outward and downward (TURNER-PETERSON, 1985; TURNER-PETERSON and FISHMAN, 1986).

Downward flow through the base of the Brushy Basin Member encountered upward gravity- and compaction-driven brine. If the upward-flowing fluid were a denser brine, either hypersaline connate brine from marginal-marine evaporites, or a saline brine from dissolution of evaporites, the lighter lacustrine alkaline-saline brine would be displaced upward.

If the upward-flowing groundwater were less dense, the forces due to topographic elevation and compaction would still tend to force the deeper groundwater upward, because the small volume of pore water in the Brushy Basin muds would be overwhelmed by the much greater volume of water from below. An estimate of the relative volumes of pore water from a column one meter square and the thickness of the sedimentary section deep can be made using observed porosity-depth curves (*e.g.* HANOR, 1979; BOND and KOMINZ, 1984) and stratigraphic thicknesses. Given a thickness for the Brushy Basin of 100 m, a porosity of 50% at the top, and a porosity of 15% at the bottom, the amount of water expelled per meter of burial is about 100 m × (50%–15%) or 35 m. (Units are volume of fluid in m^3 expelled per unit area in m^2).

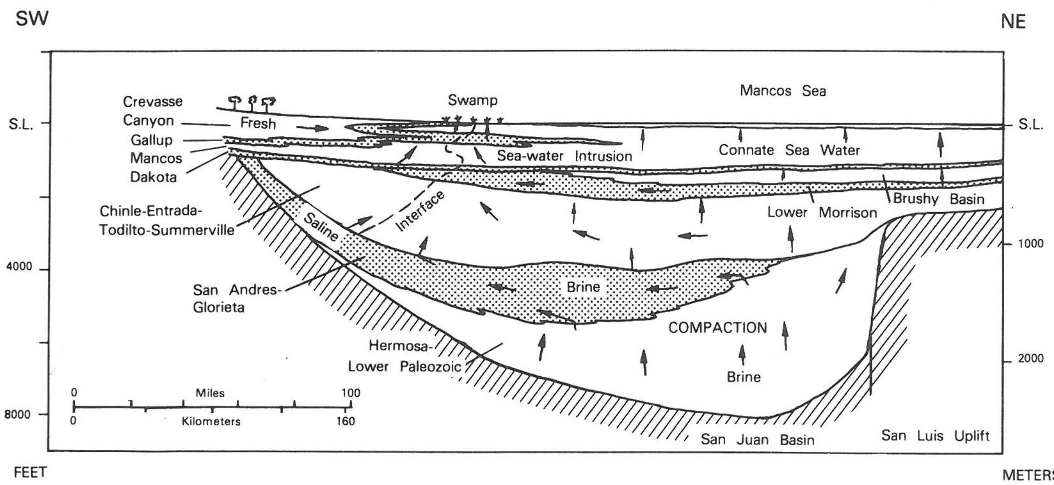

FIG. 9. Paleo ground water flow in Santonian time (late Cretaceous). Lines of sections are shown in Fig. 4e. S.L. stands for sea level. (Stratigraphy from MOLENAAR, 1983; and references cited for Fig. 8). Selected lithostratigraphic units labeled.

Given a thickness for the Paleozoic and Mesozoic rocks beneath the Brushy Basin of 3600 m, a porosity of 40% at the top, and a porosity of 20% at the base, the corresponding amount of pore water expelled per meter of burial is about 3600 m × (40%–20%) or 720 m, 20 times that from the Brushy Basin. The porosities selected are deliberately chosen to maximize the contribution from the Brushy Basin, and thus favor the hypothesis that pore water from the Brush Basin is significant. Even with this bias, the pore water from the Brushy Basin is small compared to that from the underlying sediments. Despite the Brushy Basin muds having greater porosity than the lithified sediments below, the much greater volume of these sediments can yield many times more pore water from compaction.

Alteration patterns indicate that playa lake water locally may have moved downward into the underlying fluvial sandstones. In the San Juan basin, alteration typical of the central playa lake generally extends only into the upper part of the underlying Westwater Canyon Member of the Morrison Formation, except in the central part of the paleo-playa lake (HANSLEY, 1989). In the Paradox basin, the playa lake facies are confined to the upper part of the Brushy Basin Member and do not extend down into the Salt Wash Member of the Morrison Formation (KELLER, 1962; TURNER-PETERSON, 1987).

The available evidence suggests that the interface between playa lake and deeper pore water was within the Brushy Basin Member in the Paradox basin, was in the upper part of the Westwater Canyon Member on the margins of the San Juan basin, and was near the base of the Westwater Canyon Member in the center of the San Juan basin. The difference in interface location between the Paradox and San Juan basins can be explained by the greater thickness of underlying Paleozoic and Mesozoic sediments and thus the greater volume of upward moving pore fluid in the Paradox basin.

Saline pore water expelled from depth near the margins of the playa lake and flanks of the basin encountered fresh or slightly alkaline shallow meteoric groundwater flowing down dip in the fluvial sandstones of the Salt Wash and Westwater Canyon Members. A fresh-water lens formed on top of the brine like that in coastal aquifers and continental basins today. Present-day interfaces are marked by deposition of dolomite, humic matter, and metals (SWANSON and PALACAS, 1965; SWANSON *et al.*, 1966; MAGARITZ and LUZIER, 1985; RANDAZZO and BLOOM, 1985). Similarly, in the Salt Wash and the Westwater Canyon Members, dolomite, humic matter, uranium, and metals may mark the former position of this fresh water-brine interface (GRANGER *et al.*, 1961; GRANGER *et al.*, 1980; ADAMS and SAUCIER, 1981; NORTHROP, 1982). The zone of iron-titanium oxide destruction, which has been attributed to mildly alkaline relatively fresh shallow groundwater (ADAMS *et al.*, 1974; REYNOLDS *et al.*, 1986; TURNER-PETERSON and FISHMAN, 1986), may define the shape and position of the fresh water lens. The shape of this zone is irregular but remarkably like that of present-day fresh-water lenses. The slope of the tabular uranium deposits, stratigraphically upward toward the basin, is also consistent with observed brine interface today.

As the Brushy Basin and overlying Cretaceous strata were deposited, the saline groundwater beneath the Morrison eventually rose and displaced all of the fresh water in the fluvial sandstones. The interface occupied progressively higher positions in the stratigraphic column. Uranium deposits in the Jackpile Sandstone Member at the top of the Morrison Formation (ADAMS *et al.*, 1978), and in the base of the Upper Cretaceous Dakota Sandstone (GREEN, 1980) may be relicts of progressively higher positions of the interface.

In the early Cretaceous, moderate uplift over most of the Colorado Plateau, especially in the southern part, led to beveling of exposed units and only minor deposition of fluvial sediments. The topographic slope was to the northeast as in the late Jurassic. Fresh water recharged at the outcrop and displaced shallow saline and alkaline-saline groundwater. Widespread kaolinite alteration beneath the Dakota Formation suggests that organic acid-bearing, oxidizing fresh water percolated downward prior to Dakota deposition (GREEN, 1980; ADAMS and SAUCIER, 1981).

Cycle 4: late Cretaceous to early Tertiary

Late Cretaceous transgressions and regressions of the sea from the northeast accompanied the most voluminous and rapid depositional event since the uplift of the ancestral Rocky Mountains in the late Pennsylvanian and Permian (Fig. 4e and 9). Locally, rapid deposition continued into the Paleocene and Eocene. Absence of evaporites and abundance of coal beds in the late Cretaceous indicate that the climate had fully changed from arid subtropical to humid temperate.

As marine sediments were deposited over fluvial deposits in the late Cretaceous, gravity-driven flow became less important, and compaction-driven flow increased. Expelled connate sea water from the marine sediments moved upward through the compacting muds and also downward into the Dakota

Sandstone aquifer and then landward. Fresh water in sandstones of the Morrison and Dakota may have been replaced either by connate sea water from above or saline pore water from depth. At the maximum extent of marine transgression, when most of the Colorado Plateau was beneath the sea, compaction-driven flow tended to drive pore fluid west and southwest toward the shoreline.

The deepest and highest temperature fluids in the Colorado Plateau were expelled at this time (excluding local systems associated with Tertiary igneous intrusions). Temperatures recorded by vitrinite reflectance in Upper Cretaceous rocks of the San Juan Basin (HANSLEY, 1989) are highest over the thickest accumulations of Paleozoic and Mesozoic sedimentary rocks, which were the major sources of deeper pore fluid. Conversion of smectite to illite and the formation of chlorite may also have been the result of late Cretaceous deposition and compaction. In the Westwater Canyon Member, illite and chlorite distribution and isotopic relations suggest a warm fluid from depth (WHITNEY, 1986; WHITNEY and NORTHROP, 1987) as does the etching of detrital garnets (HANSLEY, 1987). Post-ore calcite, barite, dolomite, and copper minerals in the Morrison Formation in the Paradox basin suggest a warm brine from the Pennsylvanian evaporites at depth (BREIT, 1986). The timing and temperature relations of these diagenetic features are consistent with maximum pore water expulsion during the late Cretaceous.

Rapid deposition and low-permeability sediments may have caused over-pressuring, pressure in excess of hydrostatic pressure, during the late Cretaceous. A calculation suggests that the Mancos and Lewis Shales were probably the only clastic units in the Colorado Plateau that might have had excess pore pressure due to compaction. (The Paradox evaporites may also have had excess pressure.) The theory of BREDEHOEFT and HANSHAW (1968) with the following parameters (MOLENAAR, 1983; BREDEHOEFT and HANSHAW, 1968):

	Mancos Shale	Lewis Shale
Thickness (m)	690	745
Elapsed time (my)	13	7
Specific storage (m^{-1})	3×10^{-3}	3×10^{-3}
Hydraulic conductivity (m/s)	10^{-11}	10^{-11}
Density of sediment (gm/cm^3)	1.9	1.9

yields:

Calculated heads at base of unit (m)		
Hydrostatic	690	745
Lithostatic	1311	1416
Excess over hydrostatic	62	148

The results show that pore pressure might be 10 and 22 percent, respectively, of the difference between hydrostatic and lithostatic pressure at the close of deposition. Lower values are more likely, however, because fracture permeability could raise the hydraulic conductivity by several orders of magnitude and because some pore water would escape through basal and interfingering aquifers. No other shale or mudstone, such as the Petrified Forest Member of the Chile Formation or the Brushy Basin Member of the Morrison Formation, is likely to have had significant excess pore pressure.

Uplift during the latest Cretaceous and early Tertiary caused progradation of fluvial, lacustrine, and palludal sediments over Upper Cretaceous marine deposits (OSMOND, 1965; PETERSON *et al.*, 1965; QUIGLEY, 1965; JOHNSON, 1985). A deep and widespread kaolinite alteration zone at the beveled top of Cretaceous rocks indicates a hiatus in deposition and a period of soil formation (JOHNSON and MAY, 1980; JOHNSON, 1985). Largely isolated continental basins generally received fluvial sediments early in their evolution and later received lacustrine sediments in the central parts of the basins and intertonguing fluvial sediments around the margins. In the Uinta and Piceance basins, where the most voluminous lower Tertiary sediments were deposited, early fluvial sedimentation was followed by fresh water lacustrine sedimentation. More fluvial sediments filled the basin, then a new fresh water lake formed. During the Eocene, salinity gradually increased while the lake expanded. Finally, vast amounts of volcanic detritus were deposited in a fluvial-deltaic complex that filled in the lake (JOHNSON, 1985).

In the basins, the complex transgressions and regressions of lakes and the episodic influxes of fluvial sediments created a complex hydrologic system (Fig. 4f and 10). The early fluvial and fresh water lacustrine stages were characterized by fresh water runoff and near-surface groundwater that probably left the basin. Increased alkalinity and salinity may indicate a change to locally more arid conditions, but could simply be a result of a rising outlet (JOHNSON, 1985). In either case, later lake sediments contained alkaline-saline pore water instead of fresh water. Fresh-water lenses probably overlay brine at the lake margins.

Topographic and compaction-driven flow would

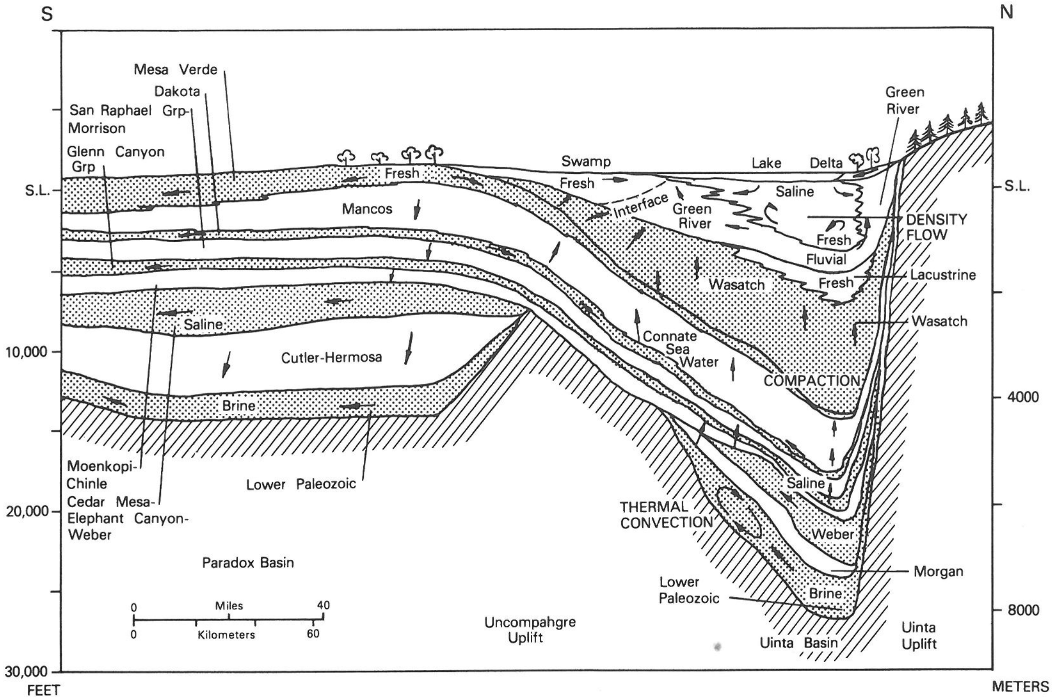

FIG. 10. Paleo ground water flow in Eocene time. Line of section is shown in Fig. 4f. S.L. stands for sea level. (Stratigraphy from OSMOND, 1965; QUIGLEY, 1965; JOHNSON, R. C., 1981; JOHNSON, 1985; and references cited for Fig. 8). Selected lithostratigraphic units labeled.

have first brought up relatively fresh water from the underlying fluvial sediments such as the Paleocene and Eocene Wasatch and Upper Cretaceous Mesaverde Formations. Within the lake sediments, an unstable interface formed between alkaline-saline brine on top and fresh water below. The combination of gravity head and compaction counteracted the density difference, as discussed for the Jurassic Brushy Basin lake, except that the denser brine above fresh water tended to favor downward migration. The relative volumes of pore water suggests that the interface gradually moved upward, but mineral alteration patterns may also indicate flow directions.

The depositional and hydrologic setting during Green River time was similar to that during Triassic Petrified Forest and Jurassic Brushy Basin time; lacustrine sediments containing volcanic material overlay fluvial channel sandstones. However, there are no significant tabular uranium deposits of Tertiary age. The volcanic rocks contained enough uranium to have been a source and were present during lacustrine deposition. The major difference between the Tertiary environment and the Mesozoic environments is the absence of a shallow interface between fresh water above and brine below in the Tertiary. Because of the climatic change in the Cretaceous, the late Cretaceous marginal marine environments were characterized by coal swamps with fresh to brackish, organic-rich, acidic water instead of evaporites with interstitial hypersaline brine. The Tertiary lake therefore overlay some 3000 m of fluvial sediments originally with fresh pore water grading down into marginal marine sediments originally with fresh to brackish water. The sediments immediately beneath the lake would have contained the freshest water. There were no evaporites or marine sediments just below the lacustrine sediments and none at depth in hydrologic continuity. Even though the shallow fresh water percolating down through volcanic-rich sediments probably would have carried ample uranium, there was no interface with brine below to cause precipitation of uranium. Instead, roll-type deposits formed locally, as discussed below.

Areas of substantial uplift, exposure, and erosion increased sporadically throughout the Cenozoic. Sedimentary units that had been buried for all or most of their history were for the first time uplifted above sea level. Dense brine that may have resided in the deepest parts of the basin for a long time could now be drained owing to the deep incision of rivers. Sediments that previously had experienced small fluctuations in groundwater flow due to gentle tilting, downwarping, uplift in marginal areas, and so on, now were raised far above sea level. Regional flow began to assume the directions now taken by surface drainage and groundwater in the Colorado River basin. The total volume of flow increased dramatically as topographic relief increased to thousands of meters. Large volumes of rock, particularly the upper units at higher elevations, became underpressured or unsaturated and subject to oxidation for the first time. While depositional basins dominated in pre-Tertiary time, downward-moving fluid was nearly matched by upward-moving fluid; after the Colorado Plateau region rose, in latest Cretaceous and Tertiary, much of the recharge simply passed downward through the sedimentary section and discharged at lower elevations.

For uranium resources, the interaction of the oxidizing environment with preexisting reducing conditions was important in altering existing deposits and forming new ones. In the San Juan basin, tabular uranium deposits were partly destroyed and new roll-type deposits formed by the downdip flow of shallow, oxidizing groundwater. In Wyoming, roll-type deposits formed from uranium leached from fresh volcanic rock or recently exposed granitic basement. As pyrite and organic matter in the fluvial sandstones was oxidized, the groundwater progressively became less oxidized until hexavalent uranium was reduced and precipitated as UO_2. In the Uravan mineral belt, in the northeastern Paradox basin, carnotite deposits formed at the outcrop by oxidation of tabular uranium deposits.

Igneous activity took place in the Colorado Plateau and vicinity from late Cretaceous through Cenozoic time (STEVEN *et al.,* 1972). Upper Cretaceous and Paleocene intrusive bodies were emplaced along a northeast-trending zone from northeastern Arizona to north-central Colorado. Most of the exposed igneous rocks are Eocene and Miocene. Intrusive and extrusive rocks of this period are widely distributed in and around the Colorado Plateau and are remnants of a much larger volcanic field now largely removed by erosion. Upper Cenozoic volcanics were emplaced around the margins of the Colorado Plateau.

Regional flow of groundwater during each of these volcanic periods was disturbed by the local topographic and thermal effects of the intrusions. Uplift associated with magma intrusion caused groundwater flow away from the intrusions toward topographic lows. The locally elevated temperature set up thermal convection. Flow was upward where groundwater was heated next to the intrusions and downward as groundwater cooled away from the intrusions. Deposition of carbonate, sulfate, and copper-silver-sulfide minerals associated with faults in the Paradox Basin may have been related to these late Cretaceous and Cenozoic intrusions (MORRISON and PARRY, 1986).

SUMMARY

Groundwater in the Colorado Plateau during most of the Phanerozoic must have been significantly different in some respects from that observed today. In pre-Tertiary, before widespread uplift, saline groundwater was dominant, and fresh water was limited to the shallow subsurface of areas elevated moderately above sea level. The past environment most like today's may have been the early Permian, when high relief and arid conditions prevailed in the Colorado Plateau. For most of the Phanerozoic, however, the Colorado Plateau consisted of basins that probably were saturated with saline water and had much less total flow than today owing to low relief, lack of dissection, and density stratification.

Mixing of dissimilar groundwater types is probably a common phenomenon, and in some cases can be related to known diagenetic and ore-forming processes. This reconstruction of paleo groundwater in the Colorado Plateau indicates where such mixing zones may have occurred and may be useful as an exploration tool for concentrations of uranium, vanadium, and copper. The occurrence of tabular-type uranium deposits is closely related to the presence of evaporitic rocks below the fluvial sandstones and to the development of a fresh water-brine interface.

Diagenetic patterns can also be better understood when the entire flow system is examined. Paleotemperatures and alteration patterns of illite, chlorite, and anhydrite deposition and garnet etching in the San Juan basin, for example, can be related to upward flow of warm saline fluid from below during compaction in the late Cretaceous. In the Uravan area, sulfur isotopes and late-stage chlorite are consistent with the predicted groundwater flow upward from underlying evaporites.

The conceptual models presented in this paper illustrate only the broadest outline for ancient groundwater flow in the Colorado Plateau. Each of the time periods that were important for the accumulation of economic resources should be studied in greater detail with quantitative models. Quantitative models of groundwater in the San Juan basin during late Jurassic to early Cretaceous are in progress (SANFORD, 1989). More work is needed to evaluate hydrologic properties in the past.

Acknowledgements—I am ultimately indebted to the late Hans Eugster of Johns Hopkins University for this study because he gave me a permanent appreciation of the importance of the fluid phase in geologic phenomena. In his typical multidisciplinary fashion, he integrated the mineralogy, fluid chemistry, sedimentology, and hydrology in pioneering studies of evaporites and saline lakes. The Colorado Plateau attracted him especially because of the Tertiary Green River Formation. Thanks to his influence, I am able to appreciate better the complex interactions of fluids, sediments, evaporites, and diagenetic minerals of the Colorado Plateau. Grant Garven, Charles Kreitler, C. M. Molenaar, and Warren Wood reviewed the manuscript and made many constructive suggestions.

REFERENCES

ADAMS S. S. and SAUCIER A. E. (1981) Geology and recognition criteria for uraniferous humate deposits, Grants uranium region, New Mexico. *Nat. Uranium Res. Eval.*, U.S. Dept. of Energy, GJBX-2(81), 226p.

ADAMS S. S., CURTIS H. S. and HAFEN P. L. (1974) Alteration of detrital magnetite-ilmenite in continental sandstones of the Morrison Formation, New Mexico. In *Formation of Uranium Deposits*, pp. 219–253. Intl. Atomic Energy Agency, Vienna.

ADAMS S. S., CURTIS H. S., HAFEN R. L. and NEJAD H. S. (1978) Interpretation of postdepositional processes related to the formation and destruction of the Jackpile-Paguate uranium deposit, northwest New Mexico. *Econ. Geol.* **73,** 1635–1654.

ANDREWS S. A. (1981) Physical modeling of controls on primary uranium ore deposition in alluvial fans. M.S. Thesis, Colorado State University, Fort Collins, 83p.

BAARS D. L. (1962) Permian system of Colorado Plateau. *Amer. Assoc. Petrol. Geol. Bull.* **46,** 149–218.

BAARS D. L., PARKER J. W. and CHRONIC J. (1967) Revised stratigraphic nomenclature of Pennsylvanian system, Paradox Basin. *Amer. Assoc. Petrol. Geol. Bull.* **51,** 393–403.

BACK W. and HANSHAW B. B. (1965) Chemical geohydrology. In *Advances in Hydrosci.*, (ed. V. T. CHOW), pp. 49–109. Academic Press, New York.

BACK W., HANSHAW B. B., HERMAN J. S. and VAN DRIEL J. N. (1986) Differential dissolution of a Pleistocene reef in the groundwater mixing zone of coastal Yucatan, New Mexico. *Geology* **14,** 137–140.

BALDWIN B. and BUTLER C. O. (1985) Compaction curves. *Amer. Assoc. Petrol. Geol. Bull.* **69,** 622–626.

BELL T. E. (1983) Deposition and diagenesis of the Brushy Basin and upper Westwater Canyon Members of the Morrison Formation in northwest New Mexico and its relationship to uranium mineralization. Ph.D. thesis, University of California, Berkeley, 101p.

BELL T. E. (1986) Deposition and diagenesis of the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico. In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON E. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 77–91. Amer. Assoc. Petrol. Geol.

BERRY F. A. F. (1959) Hydrodynamics and geochemistry of the Jurassic and Cretaceous systems in the San Juan basin, northwestern New Mexico and southwestern Colorado. Ph.D. thesis, Stanford University, 192p.

BETHKE C. M. (1985) A numerical model of compaction-driven groundwater flow and heat transfer and its application to the paleohydrology of intracratonic sedimentary basins. *J. Geophys. Res.* **90,** 6817–6828.

BLAKEY R. C. (1974) Stratigraphic and depositional analysis of the Moenkopi Formation, southeastern Utah. *Utah Geol. and Min. Surv. Bull.* **104,** 81p.

BLAKEY R. C. (1980) Pennsylvanian and Early Permian paleogeography, southern Colorado Plateau and vicinity. In *Paleozoic Paleogeography of the West-Central United States,* (eds. T. D. FOUCH and E. R. MAGATHAN), *Rocky Mountain Paleogeog. Symp. 1,* pp. 239–257. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

BLAKEY R. C. and GUBITOSA R. (1983) Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona. In *Mesozoic Paleogeography of the west-central United States,* (eds. M. W. REYNOLDS and E. D. DOLLY), *Rocky Mountain Paleogeog. Symp. 2,* pp. 57–77. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

BLAKEY R. C., PETERSON F., CAPUTO M. V., GEESAMAN R. C. and VOORHEES B. J. (1983) Paleogeography of Middle Jurassic continental, shoreline, and shallow marine sedimentation, southern Utah. In *Mesozoic Paleogeography of the west-central United States,* (eds. M. W. REYNOLDS and E. D. DOLLY), *Rocky Mountain Paleogeog. Symp. 2,* pp. 77–100. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

BLAKEY R. C., PETERSON F. and KOCUREK G. (1988) Synthesis of late Paleozoic and Mesozoic eolian deposits of the western interior of the United States. *Sed. Geol.* **56,** 3–125.

BOND G. C. and KOMINZ M. A. (1984) Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning. *Geol. Soc. Amer. Bull.* **95,** 155–173.

BREDEHOEFT J. D., BLYTH C. R., WHITE W. A. and MAXEY G. B. (1963) Possible mechanism for concentration of brines in subsurface formations. *Amer. Assoc. of Petrol. Geol.* **47,** 257–269.

BREDEHOEFT J. D. and HANSHAW B. B. (1968) On the maintenance of anomalous fluid pressures: I. Thick sedimentary sequences. *Geol. Soc. Amer. Bull.* **79,** 1097–1106.

BREIT G. N. (1986) Geochemical study of authigenic minerals in the Salt Wash Member of the Morrison Formation, Slick Rock district, San Miguel County, Colorado. Ph.D. thesis, Colorado School of Mines, Golden, 267p.

BRIOT P. (1983) L'Environnement hydrogéochimique du calcrete uranifère de Yeelirrie (Australie Occidentale). *Mineralium Deposita* **18,** 191–206.

CAMPBELL J. A. (1980) Lower Permian depositional systems and Wolfcampian paleogeography, Uncompahgre basin, eastern Utah and southwestern Colorado. In *Paleozoic Paleogeography of the West-Central United States,* (eds. T. D. FOUCH and E. R. MAGATHAN), *Rocky Mountain Paleogeog. Symp. 1,* pp. 321–340. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

CARLISLE D., MERIFELD P. M., ORME A. R., KOHL M. S., KOLKER O. and LUNT O. R. (1978) The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability based on a study of deposits in Western Australia and South West Africa (Namibia). U.S. Dept. Energy, Subcontract Number 76-022-E, 274p.

CASEY J. M. (1980) Depositional systems and paleogeographic evolution of the Late Paleozoic Taos Trough, northern New Mexico. In *Paleozoic Paleogeography of the West-Central United States,* (eds. T. D. FOUCH and E. R. MAGATHAN), *Rocky Mountain Paleogeog. Symp. 1,* pp. 181–196. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

CATER F. W. (1972) Salt anticlines within the Paradox basin. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 137–138. Rocky Mountain Assoc. Geol.

CONDON S. M., FRANCZYK K. J. and BUSH A. L. (1984) Geologic map of the Piedra River Wilderness Study Area, Archuleta and Hinsdale Counties, Colorado. U.S. Geol. Surv. Misc. Field Studies Map MF-1630-B, scale: 1:50,000.

CONDON S. M. and HUFFMAN A. C. JR. (1988) Revisions to stratigraphic nomenclature of Jurassic and Cretaceous rocks of the Colorado Plateau. U.S. Geol. Surv. Bull. 1633-A, 1–12.

CONDON S. M. and PETERSON F. (1986) Stratigraphy of Middle and Upper Jurassic rocks of the San Juan Basin: Historical perspective, current ideas, and remaining problems. In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON, E. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 7–26. Amer. Assoc. Petrol. Geol.

COOLEY M. E., HARSHBARGER J. W., AKERS J. P. and HARDT W. F. (1969) Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah. U.S. Geol. Surv. Prof. Paper 521-A, 61p.

COOPER H. H. JR., KOHOUT F. A., HENRY H. R. and GLOVER R. E. (1964) Sea water in coastal aquifers. U.S. Geol. Surv. Water-Supply Paper 1613-C, 84p.

CRAIG L. C., HOLMES C. N., CADIGAN R. A., FREEMAN V. L., MULLENS T. E. and WEIR G. W. (1955) Stratigraphy of the Morrison and related formations, Colorado Plateau Region, a preliminary report. U.S. Geol. Surv. Bull. 1009-E, 168p.

CUSTODIO E. (1981) Sea water encroachment in the Llobregat and Besós areas, near Barcelona (Catalonia, Spain). *International Hydrological Programme,* Seventh Salt Water Intrusion Meeting, Uppsala, Sweden, pp. 120–171.

DOMENICO P. A. and ROBBINS G. A. (1985) The displacement of connate waters from aquifers. *Geol. Soc. Amer. Bull.* **96,** 328–335.

DUBIEL R. F. (1983) Sedimentology of the lower part of the Upper Triassic Chinle Formation and its relationship to uranium deposits, White Canyon area, southeastern Utah. U.S. Geol. Surv. Open-File Report 83-459, 48p.

DUBIEL R. F. (1987a) Sedimentology and new fossil occurrences of the Upper Triassic Chinle Formation, southeastern Utah. *Four Corners Geol. Soc. Guidebook,* 10th Field Conference, Cataract Canyon, pp. 99–107.

DUBIEL R. F. (1987b) Sedimentology of the Upper Triassic Chinle Formation, southeastern Utah: Paleoclimatic implications. *J. Arizona-Nevada Acad. Sci.* **22,** 35–45.

DUBIEL R. F. (1989) Depositional and climatic setting of the Upper Triassic Chinle Formation, Colorado Plateau. In *Dawn of the Age of Dinosaurs in the American Southwest,* (eds. S. G. LUCAS and A. P. HUNT), New Mexico Museum of Natural History, Albuquerque, pp. 171–187.

ETHRIDGE F. G., ORTIZ N. V., GRANGER H. C., FERENCHAK J. A. and SUNADA D. K. (1980a) Effects of groundwater flow on the origin of Colorado Plateau-type uranium deposits. *New Mexico Bur. Mines and Min. Res., Mem.* **38,** 98–106.

ETHRIDGE F. G., ORTIZ N. V., SUNADA D. K. and TYLER N. (1980b). Laboratory, field, and computer flow study of the origin of Colorado Plateau type uranium deposits. U.S. Geol. Surv. Open-File Rept. 80-805, 81p.

EUGSTER H. P. (1980) Geochemistry of evaporitic lacustrine deposits. *Annual Reviews Earth Planetary Sci.* **8,** 35–63.

EUGSTER H. P. and HARDIE L. A. (1978) Saline lakes. In *Lakes—Chemistry, Geology, Physics,* (ed. A. LERMAN), pp. 237–293. Springer-Verlag.

FISCHER R. P. (1947) Deposits of vanadium-bearing sandstone. In *Mineral Resources of Colorado* (ed. J. W. VANDERWILT), pp. 451–456. State of Colorado Mineral Resources Board, Denver.

FOUCH T. D. and MAGATHAN E. R. (EDS.) (1980) *Paleozoic Paleogeography of the West-Central United States. Rocky Mountain Paleogeography Symposium 1.* Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

FREETHEY G. W. and CORDY G. E. (1989) Geohydrology of Mesozoic rocks in the upper Colorado River Basin—Excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah and Wyoming. U.S. Geol. Surv. Prof. Paper 1411-C. (in press).

FREETHEY G. W., KIMBALL B. A., WILBERG D. E. and HOOD J. W. (1984) General hydrogeology of the aquifers of Mesozoic age, upper Colorado River Basin—excluding the San Juan Basin—Colorado, Utah, Wyoming, and Arizona. U.S. Geol. Surv. Open-File Rept. 84-716, 11p.

FREEZE R. A. and CHERRY J. A. (1979) Groundwater. Prentice-Hall, Englewood Cliffs, 604p.

FREEZE R. A. and WITHERSPOON P. A. (1967) Theoretical analysis of groundwater flow. 2. Effect of water-table configuration and subsurface permeability variation. *Water Resources Res.* **3,** 623–634.

FRENZEL P. F. and LYFORD F. P. (1982) Estimates of vertical hydraulic conductivity and regional groundwater flow rates in rocks of Jurassic and Cretaceous age, San Juan Basin, New Mexico and Colorado. U.S. Geol. Surv. Water-Resources Investig. 82-4015, 36p.

GARVEN G. and FREEZE R. A. (1984) Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. I. Mathematical and numerical model. *Amer. J. Sci.* **284,** 1085–1124.

GELDON A. L. (1989) Hydrologic properties and flow systems of the Paleozoic rocks in the upper Colorado Basin, excluding the San Juan Basin, in Arizona, Colorado, Utah, and Wyoming. U.S. Geol. Surv. Prof. Paper 1411-B. (in press).

GEVANTMAN L. H. (ED.) (1981) Physical properties data for rock salt. *U.S. Dept. Commerce/Nat. Bur. Standards NBS Monograph* **167,** pp. 3–43.

GRANGER H. C., FINCH W. I., BROMFIELD C. S., DUVAL J. S., GRAUCH V. J. S., GREEN M. J., HILLS F. A., PETERSON F., PIERSON C. T., SANFORD R. F., SPIRAKIS C. S. and WAHL R. R. (1988) The Colorado Plateau uranium province, USA. In *Recognition of Uranium Provinces,* pp. 157–193. International Atomic Energy Agency, Vienna.

GRANGER H. C., FINCH W. I., KIRK A. R. and THADEN R. E. (1980) Research on uranium resource models, a progress report: Part III—Genetic-geologic model for tabular humate uranium deposits, Grants Mineral Belt, San Juan Basin, New Mexico. U.S. Geol. Surv. Open-File Rept. 80-2018-C, 58p.

GRANGER H. C. and SANTOS E. S. (1986) Geology and ore deposits of the Section 23 mine, Ambrosia Lake district, New Mexico. In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON, E. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 185–210. Amer. Assoc. Petrol. Geol.

GRANGER H. C., SANTOS E. S., DEAN B. G. and MOORE F. B. (1961) Sandstone-type uranium deposits at Ambrosia Lake, New Mexico—An interim report. *Econ. Geol.* **56,** 1179–1210.

GRANGER H. C. and WARREN C. G. (1981) Genetic implications of the geochemistry of vanadium-uranium deposits in the Colorado Plateau region. (abstr.) Amer. Assoc. Petrol. Geol., Rocky Mountain Section, 29th Annual Meeting p. 24.

GREEN M. W. (1975) Paleodepositional units in Upper Jurassic rocks in the Gallup-Laguna uranium area, New Mexico. U.S. Geol. Surv. Open-File Rept. 75-610, 13p.

GREEN M. W. (1980) Disconformities in Grants mineral belt and their relationship to uranium deposits. *New Mexico Bur. Mines and Min. Res., Mem.* **38,** 70–85.

GROSS L. T. (1972) Tectonics. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 35–44. Rocky Mountain Assoc. Geol.

HANOR J. S. (1979) The sedimentary genesis of hydrothermal fluids. In *Geochemistry of Hydrothermal Ore Deposits, Second Edition,* (ed. H. L. BARNES), pp. 137–172. Wiley-InterSci., New York.

HANSHAW B. B. and COPLEN T. B. (1973) Ultrafiltration by a compacted clay membrane—II. Sodium ion exclusion at various ionic strengths. *Geochim. Cosmochim. Acta* **37,** 2311–2327.

HANSHAW B. B. and HILL G. A. (1969) Geochemistry and hydrodynamics of the Paradox Basin region, Utah, Colorado and New Mexico. *Chem. Geol.* **4,** 263–294.

HANSLEY P. L. (1987) Petrologic and experimental evidence for the etching of garnets by organic acids in the Upper Jurassic Morrison Formation, northwestern New Mexico. *J. Sed. Petrol.* **57,** 666–681.

HANSLEY P. L. (1989) Regional diagenesis of sandstones in the Upper Jurassic Morrison Formation, San Juan Basin, New Mexico and Colorado: geologic, chemical and kinetic constraints. *U.S. Geol. Surv. Bull. 1808H.* (in press).

HECKEL P. H. (1980) Paleogeography of eustatic model for deposition of midcontinent Upper Pennsylvanian cyclothems. In *Paleozoic Paleogeography of the West-Central United States,* (eds. T. D. FOUCH and E. R. MAGATHAN), *Rocky Mountain Paleogeog. Symp. 1,* pp. 197–215. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

HITCHON B. (1969) Fluid flow in the western Canada sedimentary basin. *Water Resources Res.* **5,** 186–195.

HITE R. J. (1968) Salt deposits of the Paradox basin, southeastern Utah and southwestern Colorado. *Guidebook to the Geology of the Paradox basin, Intermountain Assoc. Petrol. Geol. 9th Ann. Field Conf.,* pp. 221–225.

HITE R. J. and CATER F. W. (1972) Pennsylvanian rocks and salt anticlines, Paradox basin, Utah and Colorado. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 133–138. Rocky Mountain Assoc. Geol.

HOLSER W. T. and KAPLAN I. R. (1966) Isotopic geochemistry of sedimentary sulfates. *Chem. Geol.* **1,** 93–135.

HOOD J. W. (1976) Characteristics of aquifers in the northern Uinta basin area, Utah and Colorado. State of Utah Dept. Nat. Res., Tech. Pub. No. 53, 71p.

HOOD J. W. and PATTERSON D. J. (1984) Bedrock aquifers in the northern San Rafael Swell area, Utah, with special emphasis on the Navajo sandstone. State of Utah Dept. Nat. Res. Tech. Pub. No. 78, 128p.

HUBBERT M. K. (1940) The theory of groundwater motion. *J. Geol.* **48,** 785–944.

HUBBERT M. K. (1953) Entrapment of petroleum under hydrodynamic conditions. *Bull. Amer. Assoc. Petrol. Geol.* **37,** 1954–2026.

HUNTOON P. W. (1983) Fault severing of aquifers and other geologically controlled permeability contrasts in the basin-mountain interface, and the implications for groundwater recharge to and development from the major artesian basins of Wyoming. Wyoming Water Research Center, University of Wyoming, Research Project Technical Completion Report (A-034-WYO), Agreement No. 14-34-0001-2154, pp. 1–16.

IORNS W. V., HEMBREE C. H. and OAKLAND G. L. (1965) Water resources of the upper Colorado River basin—Technical report. U.S. Geol. Surv. Prof. Paper 441, 370p.

ISSAR A. (1981) The rate of flushing as a major factor in determining the chemistry of water in fossil aquifers in southern Israel. *J. Hydrology* **54,** 285–296.

JOBIN D. A. (1962) Relation of the transmissive character of the sedimentary rocks of the Colorado Plateau to distribution of uranium deposits. *U.S. Geol. Surv. Bull. 1124,* 151p.

JOHNSON K. S. (1981) Dissolution of salt on the east flank of the Permian basin in the southwestern U.S.A. *J. Hydrology* **54,** 75–93.

JOHNSON R. C. (1981) Stratigraphic evidence for a deep Eocene Lake Uinta, Piceance Creek Basin, Colorado. *Geology* **9,** 55–62.

JOHNSON R. C. (1985) Early Cenozoic history of the Uinta and piceance creek basins, Utah and Colorado, with special reference to the development of eocene Lake Uinta. In *Cenozoic Paleogeography of the West-Central United States,* (ed. R. M. FLORES and S. S. KAPLAN), pp. 247–276. Soc. Econ. Paleont. and Mineral., Rocky Mountain Section.

JOHNSON R. C. and KEIGHIN C. W. (1981) Cretaceous and Tertiary history and resources of the Piceance Creek basin, western Colorado. *New Mexico Geol. Soc., Guidebook, 32nd Field Conference,* Western Slope Colorado, pp. 199–210.

JOHNSON R. C. and MAY F. (1980) A study of the Cretaceous-Tertiary unconformity in the Piceance Creek Basin, Colorado: The underlying Ohio Creek Formation (Upper Cretaceous) redefined as a member of the Hunter Canyon or Mesaverde Formation. *U.S. Geol. Surv. Bull. 1482-B.* 27p.

KELLER W. D. (1962) Clay minerals in the Morrison Formation of the Colorado Plateau. *U.S. Geol. Surv. Bull. 1150,* 90p.

KISHI Y., FUKUO Y., KAKINUMA T. and IFUKU M. (1982) The regional steady interface between fresh water and salt water in a coastal aquifer. *J. Hydrology* **58,** 63–82.

KORCUREK G. and DOTT R. H. JR. (1983) Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region. In *Mesozoic Paleogeography of the west-central United States,* (eds. M. W. REYNOLDS and E. D. DOLLY), *Rocky Mountain*

Paleogeog. Symp. 2, pp. 101–116. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

KREITLER C. W. (1979) Groundwater hydrology of depositional systems. In *Depositional and Groundwate Flow Systems in the Exploration for Uranium,* (eds. W. E. GALLOWAY, C. W. KREITLER and J. H. MCGOWEN), pp. 118–176. Bureau Econ. Geol., University of Texas, Austin.

KREITLER C. W., GUEVARA E., GRANATA G. and MCKALIPS D. (1977) Hydrogeology of Gulf Coast aquifers, Houston-Galveston area, Texas. *Gulf Coast Assoc. Geol. Socs. Trans.,* 27.

LESSENTINE R. H. (1965) Kaiparowits and Black Mesa Basins: stratigraphic synthesis. *Amer. Assoc. Petrol. Geol. Bull.* **49,** 1997–2019.

LUDWIG K. R., RASMUSSEN J. D. and SIMMONS K. R. (1986) Age of uranium ores in collapse-breccia pipes in the Grand Canyon area, northern Arizona. (abstr.) *Geol. Soc. Amer., Rocky Mountain Section Meeting, Abstracts with Programs* **18,** 392.

LUDWIG K. R. and SIMMONS K. R. (1988) Progress in U/Pb isotope studies of collapse-breccia pipes in the Grand Canyon region, northern Arizona. (abstr.) *Geol. Soc. Amer., Annual Abstracts with Programs Meeting* **20,** A139.

LUPE R. (1977) Depositional environments as a guide to uranium mineralization in the Chinle Formation, San Rafael Swell, Utah. *J. Res. U.S. Geol. Surv.* **5,** 365–372.

LYFORD F. P., FRENZEL P. F. and STONE W. J. (1980) Preliminary estimates of effects of uranium-mine dewatering on water levels, San Juan Basin. *New Mexico Bur. Mines and Min. Res., Memoir 38,* 320–333.

MACK G. H., SUTTNER L. J. and JENNINGS J. R. (1979) Permo-Pennsylvanian climatic trends in the ancestral Rocky Mountains. *Four Corners Geol. Soc. Guidebook, 9th Field Conference,* Permianland, pp. 7–12.

MAGARA, K. (1976) Water expulsion from clastic sediments during compaction—directions and volumes. *Amer. Assoc. Petrol. Geol.* **60,** 543–553.

MAGARITZ, MORDECKAI and LUZIER J. E. (1985) Water-rock interactions and seawater-freshwater mixing effects in the coastal dunes aquifer, Coos Bay, Oregon. *Geochim. Cosmochim. Acta* **49,** 2515–2525.

MALLORY W. W. (EDITOR) (1972) *Geologic atlas of the Rocky Mountain region.* Rocky Mountain Assoc. Geol., Denver, 331p.

MCLEAN J. S. (1970) Saline groundwater resources of the Tularosa basin, New Mexico. U.S. Geol. Surv. Res. and Devel. Prog. Rept. No. 561, 128p.

MCLEAN J. S. (1975) Saline groundwater in the Tularosa Basin, New Mexico. *New Mexico Geol. Soc. Guidebook, 26th Field Conference,* Las Cruces Country, p. 237–238.

MOLENAAR C. M. (1983) Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas. In *Mesozoic Paleogeography of the west-central United States,* (eds. M. W. REYNOLDS and E. D. DOLLY), *Rocky Mountain Paleogeog. Symp. 2,* pp. 201–224. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

MORRISON S. J. and PARRY W. T. (1986) Carbonate-sulfate veins associated with copper ore deposits from saline basin brines, Lisbon Valley, Utah: Fluid inclusion and isotopic evidence. *Econ. Geol.* **81,** 1853–1866.

NEUZIL C. E. and POLLOCK D. W. (1983) Erosional unloading and fluid pressures in hydraulically "tight" rocks. *J. Geol.* **91,** 179–193.

NORTHROP H. R. (1982) Origin of tabular-type vanadium-uranium deposits in the Henry structural basin, Utah. Ph.D. Thesis, Colorado School of Mines, Golden, 194p.

OHLEN H. R. and MCINTYRE L. B. (1965) Stratigraphy and tectonic features of Paradox basin, Four Corners area. *Amer. Assoc. Petrol. Geol. Bull.* **49,** 2020–2040.

ORR E. D. and KREITLER C. W. (1985) Interpretation of pressure-depth data from confined underpressured aquifers exemplified by the deep-basin brine aquifer, Palo Duro basin, Texas. *Water Resources Res.* **21,** 533–544.

OSMOND J. C. (1965) Geologic history of site of Uinta Basin, Utah. *Amer. Assoc. Petrol. Geol. Bull.* **49,** 1957–1973.

PARRISH J. T. and PETERSON F. (1988) Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States—a comparison. *Sediment. Geol.* **56,** 261–282.

PARRISH J. T., ZIEGLER A. M. and SCOTESE C. R. (1982) Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. *Palaeogeog., Palaeoclim., Palaeoecol.* **40,** 67–101.

PAYNE J. N. (1968) Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas. U.S. Geol. Surv. Prof. Paper 569-A, 17p.

PAYNE J. N. (1970) Geohydrologic significance of the lithofacies of the Cockfield Formation of Louisiana and Mississippi and of the Yegua Formation of Texas. U.S. Geol. Surv. Prof. Paper 569-B, 14p.

PAYNE J. N. (1972) Significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas. U.S. Geol. Surv. Prof. Paper 569-C, 17p.

PAYNE J. N. (1975) Hydrologic significance of the lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas, and the Meridian Sand of Mississippi. U.S. Geol. Surv. Prof. Paper 569-D, 11p.

PERLMUTTER N. M., GERAGHTY J. J. and UPSON J. E. (1959) The relation between fresh and salty groundwater in southern Nassau and southeastern Queens counties, Long Island, New York. *Econ. Geol.* **54,** 416–435.

PETERSON F. (1988a) Pennsylvanian to Jurassic eolian transportation systems in the western United States. *Sediment. Geol.* **56,** 207–260.

PETERSON F. (1988b) Stratigraphy and nomenclature of Middle and Upper Jurassic Rocks, Western Colorado Plateau, Utah and Arizona. *U.S. Geol. Surv. Bull. 1633-B,* 13–56.

PETERSON J. A. (1980) Permian paleogeography and sedimentary provinces, west central United States. In *Paleozoic Paleogeography of the West-Central United States,* (eds. T. D. FOUCH and E. R. MAGATHAN), *Rocky Mountain Paleogeog. Symp. 1,* pp. 271–292. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

PETERSON J. A. and HITE R. J. (1969) Pennsylvanian evaporite-Carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains. *Amer. Assoc. Petrol. Geol. Bull.* **53,** 884–908.

PETERSON J. A., LOLEIT A. J., SPENCER C. W. and ULLRICH R. A. (1965) Sedimentary history and economic geology of San Juan Basin. *Amer. Assoc. Petrol. Geol. Bull.* **49,** 2076–2119.

PLUMMER L. N. (1975) Mixing of sea water with calcium carbonate groundwater. *Geol. Soc. Amer., Mem. 142,* 219–236.

PRICE D. and ARNOW T. (1974) Summary appraisals of the nation's groundwater resources—Upper Colorado region. U.S. Geol. Surv. Prof. Paper 813-C, 40p.

PRYOR W. A. (1973) Permeability-porosity patterns and variations in some Holocene sand bodies. *Amer. Assoc. Petrol. Geol. Bull.* **57,** 162–189.

QUIGLEY M. D. (1965) Geologic history of Piceance Creek-Eagle Basins. *Amer. Assoc. Petrol. Geol. Bull.* **49,** 1974–1996.

RANDAZZO A. F. and BLOOM J. I. (1985) Mineralogical changes along the freshwater/saltwater interface of a modern aquifer. *Sediment. Geol.* **43,** 219–239.

RANGANATHAN V. and HANOR J. S. (1988) Density-driven groundwater flow near salt domes. *Chem. Geol.* **74,** 173–188.

RASCOE B. JR. and BAARS D. L. (1972) Permian systems. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 143–165. Rocky Mountain Assoc. Geol.

RAUP O. B. (1982) Gypsum precipitation by mixing seawater brines. *Amer. Assoc. Petrol. Geol. Bull.* **66,** 363–367.

RAWSON R. R. (1980a) Uranium in the Jurassic Todilto Limestone of New Mexico—An example of a sabkha-like deposit. In *Uranium in Sedimentary Rocks: Application of the Facies Concept to Exploration,* (ed. C. E. TURNER-PETERSON), Short Course Notes, pp. 127–147. Rocky Mountain Sec., Soc. Econ. Paleont. Mineral.

RAWSON R. R. (1980b) Uranium in Todilto Limestone (Jurassic) of New Mexico—Example of a sabkha-like deposit. *New Mexico Bur. Mines and Min. Res., Mem. 38,* 304–312.

RENFRO A. R. (1974) Genesis of evaporite-associated stratiform metalliferous deposits—A sabkha process. *Econ. Geol.* **69,** 33–45.

REYNOLDS R. L., FISHMAN N. S., SCOTT J. H. and HUDSON M. R. (1986) Iron-titanium oxide minerals and magnetic susceptibility anomalies in the Mariano Lake-Lake Valley cores—Constraints on conditions of uranium mineralization in the Morrison Formation, San Juan Basin, New Mexico, In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON, E. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 303–313. Amer. Assoc. Petrol. Geol.

RUNNELS D. D. (1969) Diagenesis, chemical sediments, and the mixing of natural waters. *J. Sediment. Petrol.* **39,** 1188–1201.

SANFORD R. F. (1982) Preliminary model of regional Mesozoic groundwater flow and uranium deposition in the Colorado Plateau. *Geology* **10,** 348–352.

SANFORD R. F. (1983) Reconstruction of paleo-flow systems: Applications to sedimentary uranium deposits. (abstr.) *Geol. Soc. Amer., Annual Meeting, Abstracts with Programs* **15,** 677.

SANFORD R. F. (1989) Late Jurassic paleohydrology of the San Juan basin: simulated effects of variable transmissivity and lake levels. (abstr.). *Amer. Assoc. Petrol. Geol., 1989 Rocky Mountain Section Meeting, Abstracts with Programs,* p. 90.

SPENCER C. W. (1975) Petroleum geology of east-central Utah and suggested approaches to exploration. *Four Corners Geol. Soc. Guidebook, 8th Field Conf.,* Canyonlands, p. 263–276.

STEVEN T. A., SMEDES H. W., PROSTKA H. J., LIPMAN P. W. and CHRISTIANSEN R. L. (1972) Upper Cretaceous and Cenozoic igneous rocks. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 229–232. Rocky Mountain Assoc. Geol.

SUTHERLAND P. K. (1972) Pennsylvanian stratigraphy, southern Sangre De Cristo Mountains, New Mexico. In *Geologic Atlas of the Rocky Mountain Region,* (ed. W. W. MALLORY), pp. 139–142. Rocky Mountain Assoc. Geol.

SWANSON V. E., FROST I. C., RADER L. F. JR. and HUFFMAN CLAUDE JR. (1966) Metal sorption by northwest Florida humate. U.S. Geol. Surv. Prof. Paper 550-C, C174–C177.

SWANSON V. E. and PALACAS (1965) Humate in coastal sands of northwest Florida. *U.S. Geol. Surv. Bull. 1214-B,* 29p.

THACKSTON J. W., MCCULLEY B. L. and PRESLO L. M. (1981) Groundwater circulation in the western Paradox Basin, Utah. *Rocky Mountain Assoc. Geol. 1981 Field Conference,* pp. 201–225.

TREMAIN C. M., BORECK D. L. and KELSO B. S. (1981) Methane in Cretaceous and Paleocene coals of western Colorado. *New Mexico Geol. Soc., Guidebook, 32nd Field Conference,* Western Slope Colorado, pp. 241–248.

TURK L. J., DAVIS S. N. and BINGHAM C. P. (1973) Hydrogeology of lacustrine sediments, Bonneville Salt Flats, Utah. *Econ. Geol.* **68,** 65–78.

TURNER-PETERSON C. E. (1985) Lacustrine-humate model for primary uranium ore deposits, Grants Uranium Region, New Mexico. *Amer. Assoc. Petrol. Geol. Bull.* **69,** 1999–2020.

TURNER-PETERSON C. E. (1987) Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization. Ph.D. Thesis, University of Colorado, Boulder, 169p.

TURNER-PETERSON C. E. and FISHMAN N. S. (1986) Geologic synthesis and genetic models for uranium mineralization in the Morrison Formation, Grants uranium region, New Mexico. In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON, F. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 357–388. Amer. Assoc. Petrol. Geol.

WARD W. C. and HALLEY R. B. (1985) Dolomitization in a mixing zone of near-seawater composition, Late Pleistocene, northeastern Yucatan Peninsula. *J. Sediment. Petrol.* **55,** 407–420.

WARNER J. W., HEIMES F. J. and MIDDELBURG R. F. (1985) Groundwater contribution to the salinity of the upper Colorado River Basin. U.S. Geol. Surv. Water-Resources Investig. Rept. 84-4198, 113p.

WENRICH K. J. (1985) Mineralization of breccia pipes in northern Arizona. *Econ. Geol.* **80,** 1722–1735.

WENRICH K. J. and SUTPHIN H. B. (1989) Lithotectonic setting necessary for formation of a uranium-rich, solution-collapse breccia-pipe province, Grand Canyon region, Arizona. U.S. Geol. Surv. Open-File Rept. 89-0173, 33p.

WHITNEY C. G. (1986) Petrology of clay minerals in the subsurface Morrison Formation near Crownpoint, southern San Juan Basin, New Mexico: An interim report. In *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico,* (eds. C. E. TURNER-PETERSON, E. S. SANTOS and N. S. FISHMAN), *Studies in Geol. 22,* pp. 315–329. Amer. Assoc. Petrol. Geol.

WHITNEY C. G. and NORTHROP H. R. (1987) Diagenesis and fluid flow in the San Juan Basin, New Mexico—Regional zonation in the mineralogy and stable isotope composition of clay minerals in sandstone. *Amer. J. Sci.* **287,** 353–382.

WINTER T. C. (1976) Numerical simulation analysis of the interaction of lakes and groundwater. U.S. Geol. Surv. Prof. Paper 1001, 45p.

WIT K. E. (1967) Apparatus for measuring hydraulic conductivity of undisturbed soil samples. In *Permeability and Capillarity of Soils.* Amer. Soc. Test. Mat., Spec. Tech. Pub. No. 417, 72–83.

WOOD J. R. and HEWITT T. A. (1982) Fluid convection and mass transfer in porous sandstones—a theoretical model. *Geochim. Cosmochim. Acta* **46,** 1707–1713.

WOODING R. A. (1962) Convection in a saturated porous medium at large Rayleigh number or Peclet number. *J. Fluid Mechanics* **15,** 527–546.

ZIELINSKI R. A. (1983) Tuffaceous sediments as source rocks for uranium: A case study of the White River Formation, Wyoming. *J. Geochem. Expl.* **18,** 285–306.