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Review Paper

HYDROGEOLOGY OF SEDIMENTARY BASINS

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ABSTRACT

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Hydrogeologic environments in sedimentary basins are as variable as are the different types of basins. Important hydrologic characteristics can be used to distinguish the different types of basin: (1) the topographic setting as determined by the geologic and structural history of the basin; (2) permeability distribution within the basin; and (3) potential energy distributions and flow mechanisms. These parameters control residence times of waters, rates and directions of saline groundwater flow and the origin and chemical composition of the saline waters.

The Gulf Coast and Palo Duro Basins, Texas, exemplify two end member types of sedimentary basins. The Gulf Coast Basin is a relatively young, Tertiary-age basin which is presently compacting; fluid movement is from the overpressured, undercompacted sediments up the structural dip or up fault zones into the hydrostatic section, natural fluid pressures are either hydrostatic or overpressured. The Palo Duro is an older, Paleozoic-age basin that has been tectonically uplifted. Fluid flow is gravity driven from topographically high recharge areas to discharge in topographically low areas. Fluid pressures are subhydrostatic. Fluids discharge more easily than they are recharged. Not all flow is derived by a simple recharge discharge model. Brines may flow from other basins into the Palo Duro Basin and waters may discharge from the Palo Duro Basin into other basins. Areal differences in the chemical composition of the basin brines may be the result of different origins.

INTRODUCTION

Within the State of Texas are several sedimentary basins which include the Gulf Coast, the East Texas, the Fort Worth, the Kerr, the Val Verde, and the Permian Basins (Fig. 1). The Permian Basin is composed of the Hardeman, the Midland, the Delaware, the Palo Duro, the Anadarko, and the Dalhart Basins (Fig. 1). Most of these basins have been prolific bearers of hydrocarbons and therefore extensive data bases are available for geologic and hydrologic interpretations. Over the last ten years an intense effort has been made to understand the hydrology of these basins because of their importance as oil and gas producers, as analogues for mineral deposits, and as possible repositories for chemical and nuclear wastes. The emphasis of this paper is on observations

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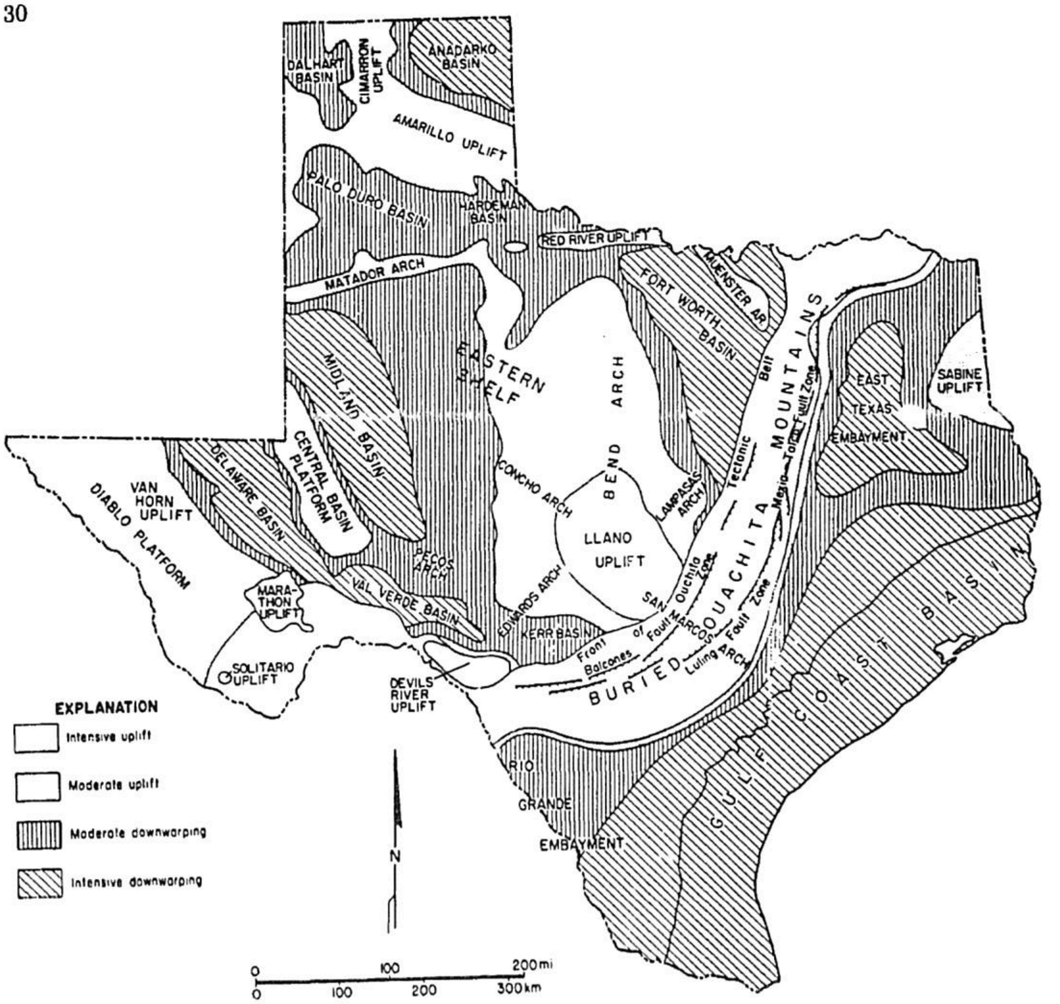

Fig. 1. Generalized tectonic map of Texas showing location of sedimentary basins.

of saline groundwater flow in sedimentary basins in Texas. Two of these basins with distinctly different hydrologic regimes are the Gulf Coast Basin and the Palo Duro Basin (part of the Permian basin). They represent end members of basin hydrologic conditions that can be observed worldwide.

The Gulf Coast Basin is a large, predominantly Tertiary-age sedimentary basin fringing and extending into the Gulf of Mexico (the terms Gulf of Mexico Basin and Gulf Coast Basin are used interchangably in the literature) that is still being infilled with fine-grained terrigenous clastic sediments. At least three different hydrologic systems are present (Fig. 2): (1) a shallow freshwater regime; (2) a hydrostatic saline regime; and (3) a deep overpressured regime (referred to as geopressured) that consists of a thick, predominantly shale section. These overpressured shales are slowly compacting as a result of continuous sedimentation; thereby expelling pore fluids into the shallower hydrostatic section. Extensive growth faulting and deltaic sedimentation have compartmentalized sandbody distribution; lateral fluid movement in the basin is restricted. Growth faults are likely pathways for the upward migration of saline waters into shallower sections. A fourth zone, a thermobaric zone, may

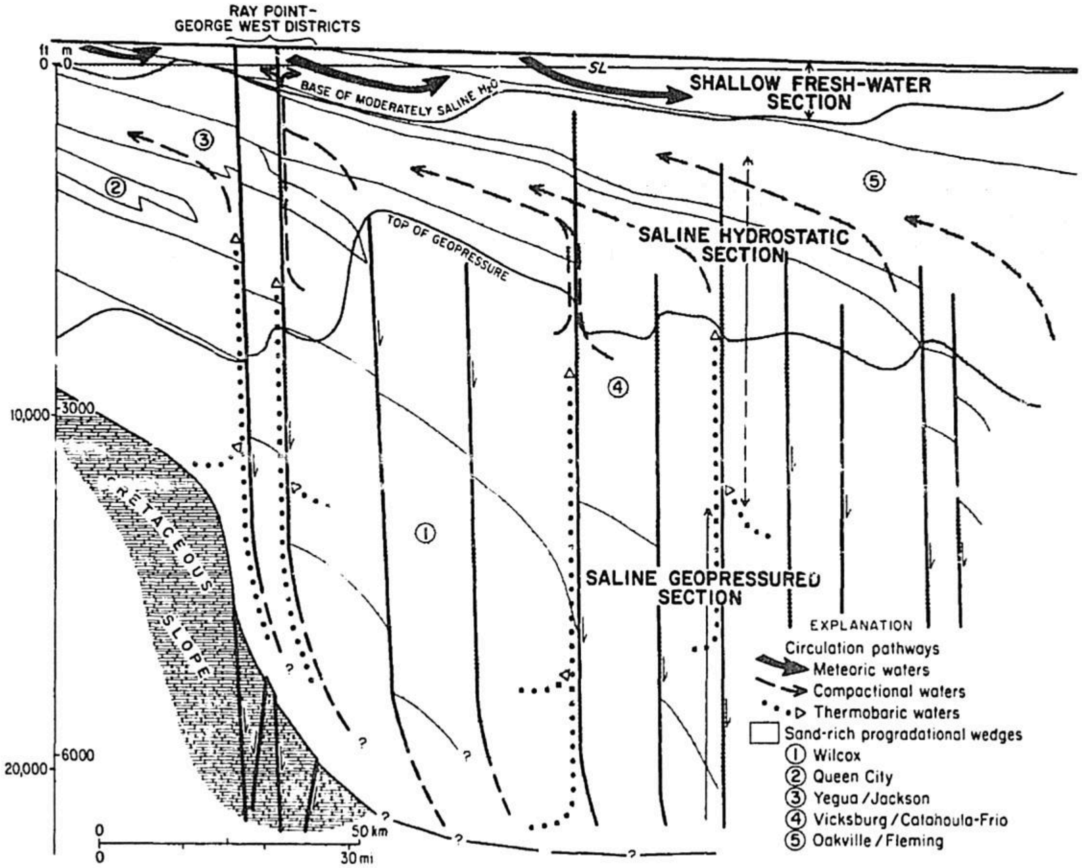

Fig. 2. Schematic hydrogeologic section of the Texas Gulf Coast Basin (modified from Galloway, 1982).

exist beneath the zone of overpressuring; in this thermobaric zone, metamorphic conditions may cause overpressuring through water released by mineral dehydration (Galloway and Hobday, 1983). Other geologically young basins with thick undercompacted sediments, such as the Niger delta, are expected to have similar hydrologic characteristics.

The Palo Duro Basin is predominantly Paleozoic in age and has been filled with carbonates, terrigenous clastics, and evaporites. Saline groundwater flow is predominantly within carbonate and arkosic rocks beneath the evaporite strata. An integrated, gravity-driven hydrologic system (Fig. 3) was developed in the basin, which was uplifted and tilted in Tertiary time. The deep-basin aquifers are underpressured relative to the potentiometric surfaces of the shallow freshwater aquifers in the basin. Other examples of uplifted basins are the Alberta and Denver Basins (Hitchon, 1969; Belitz and Bredehoeft, 1984).

The hydrodynamics of these basins are controlled by the following hydrogeologic characteristics: (1) geologic history; (2) flow mechanisms; (3) permeability distributions; and (4) hydraulic potential distributions. One set of processes does not control the hydrologic conditions for all basins. In some basins, fluid flow is governed by sediment compaction, whereas in others flow

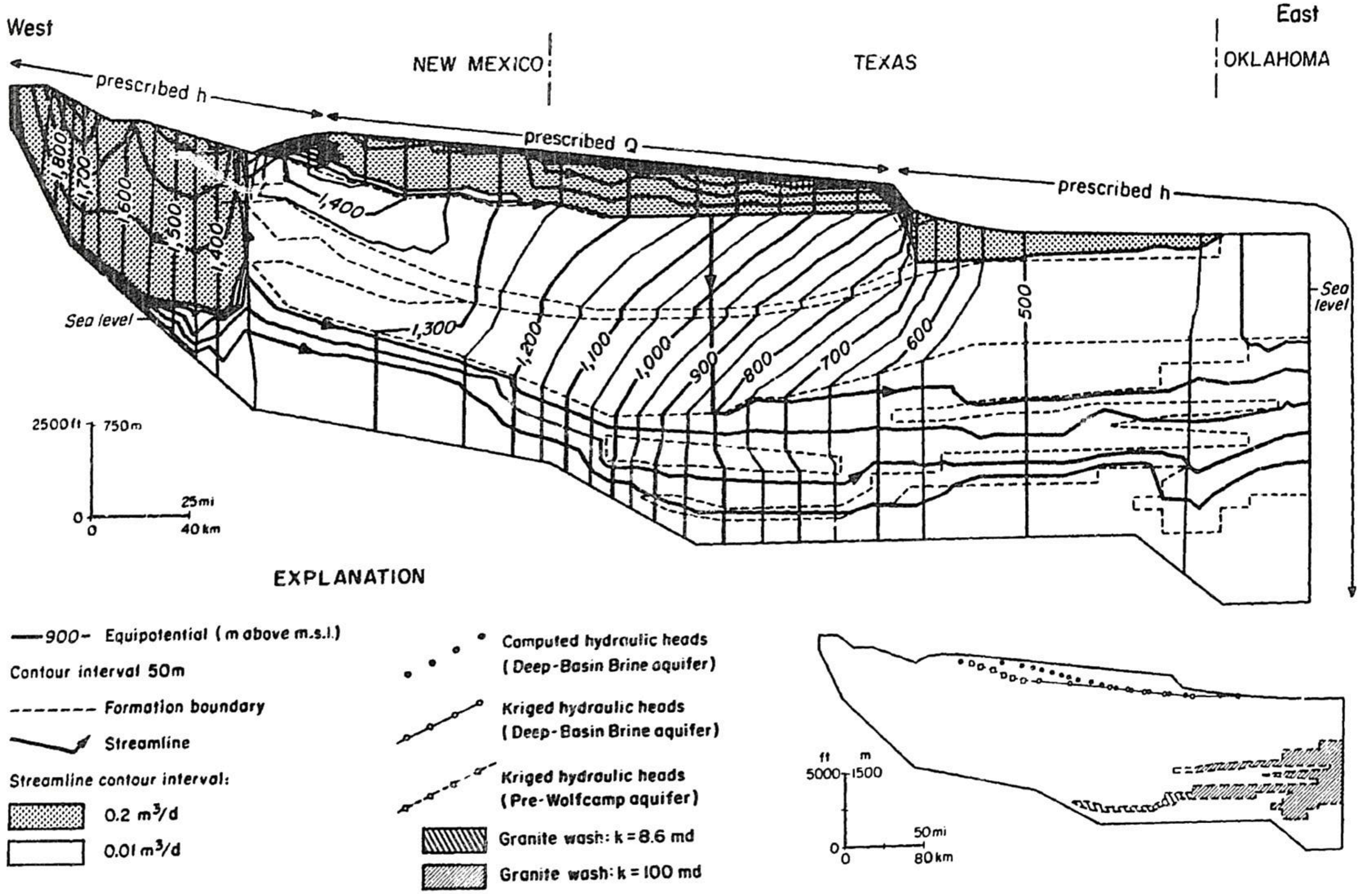

Fig. 3. Schematic west–east hydrogeologic section of the Palo Duro Basin with simulated potentiometric contours and streamlines (from Senger et al., 1987).

is gravity driven. Some basins have clearly defined recharge and discharge zones along outcrops, others do not. Recognition of this variability is important in understanding sedimentary basin hydrology. Each of these elements is discussed below with the Gulf Coast Basin and Palo Duro Basin used as examples.

GEOLOGIC HISTORY — BASIN EVOLUTION

The geologic history of a sedimentary basin plays a critical role in its hydrologic development. As a basin evolves from periods of sedimentation and compaction to uplift and erosion, hydrologic boundary conditions can be altered and hydrologic properties of the sediments may be affected. As the sediments become more lithified and basins become more tectonically deformed, fluid flow pathways may shift from the porous media to fractures. Flow mechanisms change as the dominant geologic processes change. During sedimentation and basinal subsidence, clay compaction and free thermal convection may be important forces for fluid migration. If the basin has been uplifted, then gravity-driven flow governed by topography may predominate. If basin uplift does not occur after compaction, basinal flushing may be restricted. Convection and diffusion may become important processes if flow from gravity or compaction is minimal.

The two previously described Texas basins illustrate different aspects of hydrogeologic evolution in a basin. The Gulf Coast Basin (Fig. 2) is predominantly a Tertiary-age sedimentary basin which is still subsiding and receiving sediments. Maximum thickness is approximately 10 km. Outcrop elevation is less than 200 m above sea level. Most formations are poorly consolidated and nonlithified. Compaction and thermal convection may be the most important hydrologic processes. The lack of basinal uplift may prevent regional flushing of the basin by continental waters. Lowering of sea level during the Pleistocene may have permitted a deeper penetration of meteoric water into the basin (Kreitler et al., 1977; Bethke et al., 1988). Porous media flow predominates over fracture flow.

The Palo Duro Basin (Fig. 3) was infilled during the Paleozoic and therefore is significantly older than the Gulf Coast Basin. The Palo Duro Basin was uplifted in Tertiary (Basin and Range) times by as much as 1200 m in Eastern New Mexico (McGookey, 1984). Because of differential uplift, recharge and discharge zones are present. Active, albeit slow, gravity-driven groundwater flow has developed in the saline formations. Older brines have been flushed (or are still being flushed) by meteoric water recharged at higher elevations. Discharge occurs at topographically lower elevations where shallow saline groundwaters with chemical and isotopic compositions similar to the basinal brines have been found (Richter and Kreitler, 1986). Because basin uplift is relatively recent (Tertiary), the number of pore volume flushings of the basin may be limited to 50–60 (Bassett and Bentley, 1983). Recharge to the Palo Duro Basin may not be limited to topographically high outcrops. The individual subbasins of the Permian Basin, the Palo Duro, Anadarko, Tucumcari, Delaware, Midland and Hardeman Basins, may be interconnected allowing interbasinal groundwater flow. Geochemical data of Palo Duro brines suggest flow from the Midland into the Palo Duro Basin (Fisher and Kreitler, 1987), and head data and numerical modeling results suggest flow from the Palo Duro Basin into the Anadarko Basin (Wirojanagud et al., 1986). Most formations are now well lithified; matrix permeability is relatively low because of cementation. Fractures may be important pathways for groundwater flow.

FLOW MECHANISMS

Movement of groundwater and transport of chemical constituents occur because of hydraulic or chemical gradients. At least six different mechanisms for fluid and chemical migration may be important in basin hydrodynamics.

(1) Compaction of mudstones may be the most important mechanism for driving fluids in relatively young basins with thick shale sequences. As porous shales are buried by continual sedimentation during basin subsidence, the increased overburden pressure decreases porosity and increases pore fluid pressures (Bredehoeft and Hanshaw, 1968; Sharp and Domenico, 1976). Fluids flow from compacting sediments into shallower units. Blanchard's (1987) numerical model of sediment compaction in the Gulf Coast Basin observed two phenomena: (a) The amount of overpressuring in a formation was controlled by later periods of sedimentation and loading, and, therefore the amount of overpressuring has varied through time; and (b) cumulative (Eocene to Quaternary) fluxes through the Eocene Wilcox sandstone were only on the order of 100 m^3 m^{-2}, or approximately 500 pore volumes, which is not a large volume considering the time period of 50 Ma since deposition.

(2) Gravity is considered the most important energy potential for groundwater flow in mature, topographically uplifted sedimentary basins (Hubbert, 1940; Toth, 1978; Garven and Freeze, 1984a; Bethke, 1985). Recharge points at higher elevations and discharge points at lower elevations are major controls on the rate and direction of flow. Uplifted sedimentary basins such as the Western Canada (Alberta) Sedimentary Basin (Hitchon, 1969) and the Palo Duro Basin (Bassett and Bentley, 1983; Senger et al., 1987) are currently being flushed by gravity-driven groundwater flow. A continuous regional potentiometric surface (Fig. 4) can be mapped for the deep brine aquifers in the Palo Duro Basin indicating recharge at high elevations and discharge at lower elevations (Wirojanagud et al., 1986). Regional hydraulic gradients indicate hydrologic continuity within the brine aquifer of the Palo Duro Basin.

The converse of compaction of low permeability rocks is decompaction, which may occur during erosion as a result of basin uplift. Erosion and reduction of overburden pressures permit underlying rocks to dilate (increase in pore space), resulting in decreased pore pressures and possible flow toward the locus of decompaction (Neuzil and Pollock, 1983; Neuzil, 1986).

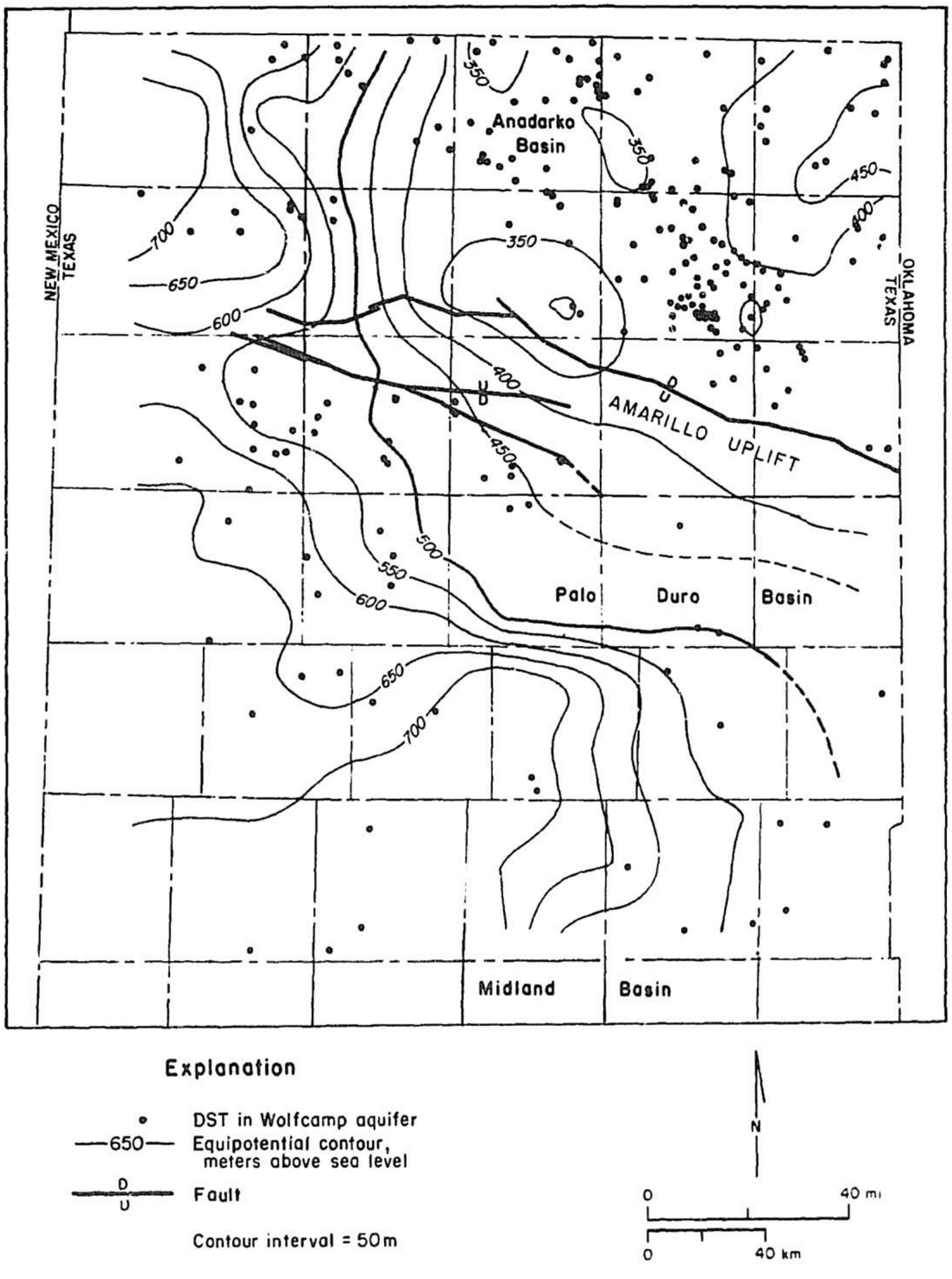

Fig. 4. Potentiometric surface from the saline Wolfcamp aquifer in the Palo Duro Basin, constructed from kriged estimates of head. Note the regional flow from west to northeast (from Smith et al., 1986: and Wirojanagud et al., 1986). See Fig. 1 for general location of basins.

(3) Free convection may result in formations where waters exhibit a density inversion, either as a result of variable temperatures or salinities. Wood and Hewett (1982) used thermal convection to explain diagenetic features observed in sandstones. Blanchard and Sharp (1985) suggested that free thermal convection may occur in the Gulf Coast Basin. Dense brines from salt-dome dissolution may develop convective cells on the flanks of domes and permit penetration of isotopically light meteroic waters deep into the sedimentary section (Workman and Hanor, 1985; Rangathan and Hanor, 1988).

(4) Osmosis is fluid flow resulting from a chemical gradient across a semipermeable membrane. Low-ionic-concentration waters flow across a membrane to dilute the higher ionic concentration fluid and to create an osmotic fluid pressure gradient. In reverse osmosis, fluid pressure gradients across a semipermeable membrane result in filtration of dissolved species with increased salinities on the high pressure side. Laboratory studies have demonstrated that both osmosis and reverse osmosis work with geologic materials (e.g., McKelvey and Milne, 1962; Coplen and Hanshaw, 1973). Both osmosis and reverse osmosis have been used to explain concentration gradients observed in sedimentary basins. Berry (1958) used osmosis to explain the very high TDS and closed-contoured potentiometric surfaces observed in the San Juan Basin (Colorado, New Mexico and Arizona). Marine (1974) explained the salinities and slight overpressuring observed in Triassic sediments of the Savannah River, South Carolina, region by chemical osmosis. Graf et al. (1965) used reverse osmosis to explain very high salinities in the Illinois Basin, where halite formations are absent. Graf (1982) suggested that paleo-geopressures in the Illinois Basin provided the necessary pressure gradients to drive reverse osmosis. Bethke (1985) felt that past paleopressure gradients were never sufficient in intracratonic basins for the process to occur.

(5) Fluids derived from mineral diagenesis may contribute to the regional hydrologic flow. For example, gypsum typically is altered to anhydrite and releases water during burial. Gypsum probably does not contribute significant quantities of water because the volume of anhydrite in most basins is relatively small and dehydration may occur predominantly syndepositionally. Smectite, an important clay mineral in many sedimentary basins, converts to illite at increased temperature and pressure during deep burial and releases bound water to the regional groundwater flow (Burst, 1969). The importance of the smectite–illite conversion to the regional fluid pressure distribution is not known, because it occurs simultaneously with the pore pressure buildup associated with clay compaction.

(6) Chemical species may migrate via diffusion as well as by advection of fluid flow. Ionic species migrate toward lower ionic concentrations following Fick's first law of diffusion. The relative importance of diffusion depends on the velocity of advective flow in the basin. The slower the advective flow, the more important diffusion will be. Some researchers have used diffusion to explain observed geochemical gradients. For example, Manheim and Bischoff (1969) used diffusion to explain a chloride halo observed around a shallow salt dome

in the Gulf Coast Basin. Hanor (1984) attributed the commonly observed relationship of increased salinity with depth in the Gulf Coast Basin to diffusion. Kaufman et al. (1984) used diffusion to explain the isotopic fractionation of ^{35}Cl and ^{37}Cl that they observed in Frio Formation waters (Gulf Coast Basin).

The relative importance of each of these mechanisms depends on the timing and duration of the process and the volume of the water and rock affected by the process. For example, the velocity of density-driven fluid flow from salt-dome dissolution brines may be greater than the velocities associated with compaction, but the fluid volumes associated with dissolution brines may be insignificant compared to the volumes associated with basinwide sediment compaction. Similarly, the total geologic history of a basin may determine the relative importance of hydrologic processes.

POTENTIAL ENERGY DISTRIBUTIONS

On the basis of fluid-pressure distributions, sedimentary basins and hydrostratigraphic units can be classified into three groups: hydrostatic, overpressured, and underpressured. Pressure–depth gradients are a measure of relative pressure distributions in the vertical direction and indicate the direction of potential vertical flow (Orr and Kreitler, 1985). The pressure–depth gradient for fresh water in a hydrostatic system is 0.433 psi ft^{-1} (0.095 bars m^{-1}). With increasing density of fluids, the gradient increases; a hydrostatic brine of 80,000 ppm has a gradient of 0.465 psi ft^{-1} (0.103 bars m^{-1}). A hydrostatic gradient implies no vertical flow within or between hydrostratigraphic units for a given fluid density. In an underpressured system, a pressure–depth gradient for fresh water is less than 0.433 psi ft^{-1} (0.465 psi ft^{-1} for brines). Potential vertical flow is downward in underpressured systems. In an overpressured system, a pressure–depth gradient is greater than 0.433 psi ft^{-1} (0.465 psi ft^{-1} for brines) and indicates a potential upward flow. Important hydrologic characteristics of a basin can be assessed from the presence of one of these three conditions.

Most freshwater aquifers are hydrostatic; flow is predominantly or almost horizontal. Shallow ($>$ 3000 m deep) saline sections of the Gulf Coast Basin are hydrostatic, which implies either horizontal flow or stagnant conditions (Fig. 5). Interconnection of permeability within an aquifer (or basin) is implied.

In an overpressured system where the pressure–depth gradients are greater than hydrostatic values, the potentiometric surface may be significantly above land surface. Overpressuring is typical in the deep, shaly sections of the Gulf Coast Basin. The low permeability of the shales restricts expulsion of water from the compacting shales. This relatively slow response time for dewatering has prevented the pore pressures from equilibrating with depth of burial (Bredehoeft and Hanshaw, 1968; Sharp and Domenico, 1976; Capuano, 1988). Based on observed pressure distributions (Hanor and Bailey, 1983; McCulloh, 1985) and thermal anomalies (Bodner et al., 1985; Woodruff and Foley, 1985),

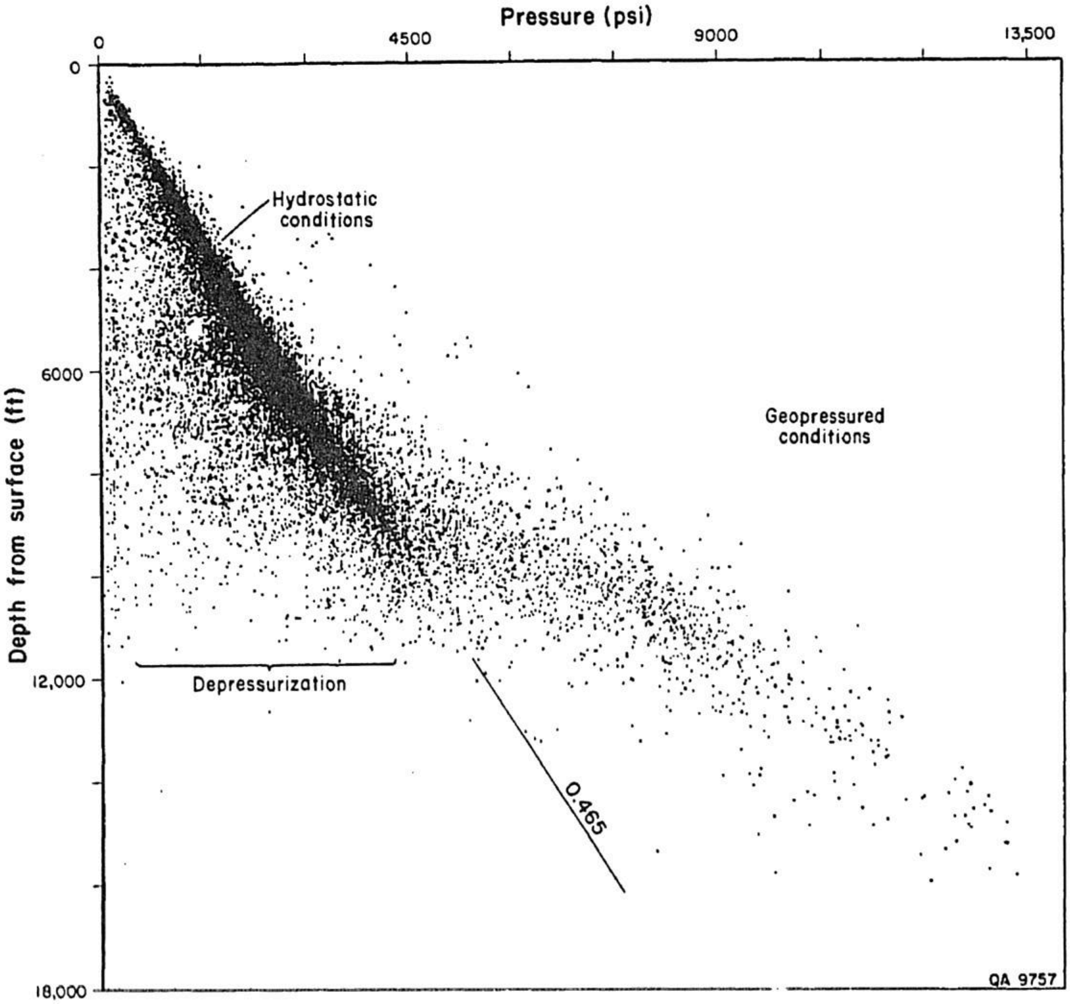

Fig. 5. Pressure depth plot of the Frio Formation, Texas Gulf Coast Basin, based on 17,411 pressure measurements. Note the presence of three different pressure conditions: hydrostatic, overpressured, and depressurized (Kreitler et al., 1987a).

some flow of water between the geopressured and the hydropressured sections should be occurring. The presence of regional overpressuring, however, indicates a lack of hydrologic continuity between the overpressured section and the shallower hydropressured sections. If there were moderate interconnection, then the high pressures observed in overpressured sections would have decreased to hydrostatic levels.

Underpressuring may be natural or artificial. In a natural underpressured hydrologic system the formations are more effectively drained than recharged. Two sedimentary basins that exhibit underpressuring are the Palo Duro Basin (Fig. 6) (Orr and Kreitler, 1985; Senger et al., 1987) and the Denver Basin (Belitz and Bredehoeft, 1984). Both are uplifted Paleozoic basins in which the deep, saline underpressured formations are overlain by low-permeability confining

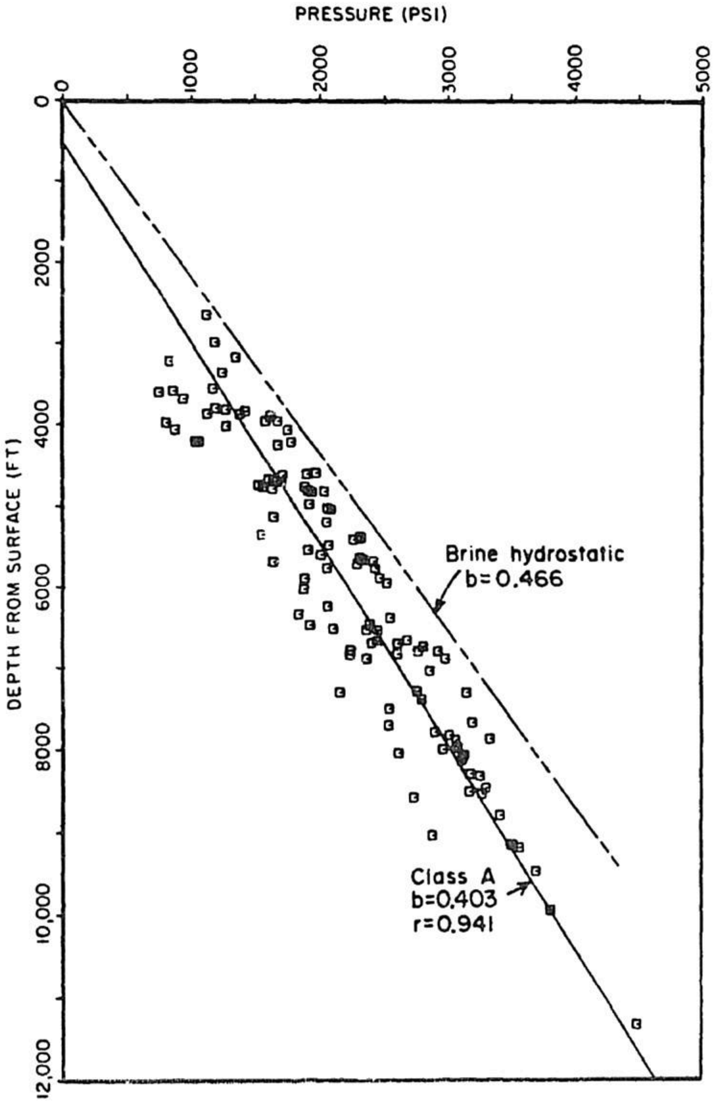

Fig. 6. Pressure–depth plot of high-quality (initial and final shut in pressures within 20%) DST data from Palo Duro Basin. Note that most pressure values fall beneath the brine hydrostatic line, indicating underpressuring (from Orr and Kreitler, 1985).

beds that inhibit recharge. The underpressuring indicates hydrologic continuity within the underpressured unit and discharge from the basin, but poor vertical hydraulic connection between shallow freshwater aquifers and the deeper saline formations.

Depressurization, artificially induced underpressuring, results from hydrocarbon production. The Frio Formation in the Gulf Coast Basin exhibits significant underpressuring (Fig. 5) (Kreitler et al., 1987a) as does the Woodbine Formation in the East Texas Basin (Bell and Shepherd, 1951). Historical fluid production (extraction of both oil and brine associated with oil production) from the Frio Formation is estimated to be approximately 4000 million barrels (mmbbl) ($\simeq 180 \times 10^6 m^3$) (Kreitler et al., 1988). Fluid pressures for individual fields should rise toward preproduction values after production has stopped. Senger et al., (1987) estimated that fluid pressures in a hypothetical field in the Palo Duro Basin should recover 75% of the original value in 1000 years and 90% in 10,000 years. This rate of recovery is dependent upon the permeability and storativity of the affected reservoir. The degree of pressure recovery for formations, such as the Frio, where extremely large volumes of fluid have been produced, is not known. Depressurization may make interpretation of initial, natural pressure distributions of a formation impossible.

HYDRAULIC PROPERTIES OF SEDIMENTARY BASINS

Permeability distributions

The dominant type of sediment in a basin is an important control on the overall hydrologic conditions within a basin. Basins filled with uncemented sands will be more permeable and will be more easily flushed of their original formation waters than basins filled with shales. Fluid movement in the Gulf Coast Basin via clay compaction or clay diagenesis is an important process because of the high percentage of mud in the basin. In contrast, shale percentages are small in the Palo Duro Basin where fluid movement from compaction cannot be a major process. Shale compaction may not have been of major importance during infilling of intracratonic basins at any time in their hydrologic histories (Bethke, 1985).

Permeability distribution is also a critical consideration in understanding basin hydrodynamics. Permeability in Gulf Coast sediments are probably very heterogeneous. Growth-faulted fluvial, deltaic, and marine sediments create extreme heterogeneity; horizontal continuity is limited. However, growth faults and salt dome flanks may create vertical permeability conduits. The presence of numerous small oil fields [< 200 million barrels (mmbbl) in place] but no giant fields (> 1000 mmbbl) in the Gulf Coast Basin (Galloway et al., 1983) suggests a heterogeneous distribution of permeability. In contrast, the Woodbine sandstone in the East Texas Basin may have good continuous lateral permeability. The Woodbine contains an extremely large oil field. Estimated oil in place for the East Texas Field along the eastern subcrop of the Woodbine is 7568 mmbbl (Galloway et al., 1983). Oil production from the East Texas Field has caused pressure declines over 150 km away (Bell and Shepherd, 1951). Both the accumulation of vast quantities of oil that may have occurred from hydrocarbon migration over a very large area and pressure declines at such great distances suggest excellent regional lateral continuity.

Determining the appropriate permeability data and spatial distribution for saline formations is difficult. Hydrologic data for deep saline formations are typically sparse. Because of this paucity of data, individual formations are often grouped into larger hydrostratigraphic units on the basis of similarity in hydraulic potentials rather than permeability. The more heterogeneous the rocks are within a hydrologic unit, the wider the range of possible permeability values will be. Estimated flow velocities and volumes are dependent on the permeability and porosity values used. By changing average permeability an order of magnitude, estimated discharge rates change by a similar amount. Three different permeability means describe permeability distribution in different scenarios based on a log-normal distribution (Warren and Price, 1961): an arithmetic mean permeability for flow parallel to bedding (maximum permeability direction), a harmonic mean permeability for flow perpendicular to bedding (minimum permeability distribution), or a geometric mean, if we assume permeability is randomly distributed. This variability of a mean permeability associated with flow directions relative to sedimentary structures creates a wide range for average flow velocity calculations, especially when dealing with basinwide flow systems with sparse data, and particularly long residence times. For example, in a low-permeability system with a long residence time, a hypothetical transit time would increase from 100,000 yr to 1,000,000 yr by changing mean permeability from 1 to 10 millidarcy (md).

To calculate the transit time for the fastest flow path in a basin rather than the average flow path requires knowing permeability values for the more permeable rocks and, more importantly, the degree of regional interconnection of the rocks with higher permeabilities. If the zones of higher permeability are not connected, then the fastest transit times will be limited by the lower permeability rocks. In a modeling study of groundwater flow through heterogeneous fluvial sandstones in East Texas, Fogg et al., (1983) observed that the average permeability of fluvial channel sand was approximately 100 times higher than for the interfluvial overbank sands. If the high-permeability channel sands are connected, then groundwater flow occurs predominantly through them and flow velocity is controlled by their higher permeability. If the sand bodies are not connected then calculated flow velocities are significantly reduced and controlled by the lower hydraulic conductivities of the interchannel sands and muds. De Marsily (1985) reached similar conclusions in studying fluid flow in fractures, where he postulated that fluid-flow velocities are more dependent on the interconnection of fractures than on the permeability of any specific fracture.

Our ability to determine whether flow is occurring via fractures or porous media in a sedimentary basin is limited. Velocities of groundwater flow in a basin may be significantly higher when flow is through fractures rather than through the porous rock matrix. If the effective porosity of a fracture is 0.1% but the effective porosity of a porous medium is 5% (and the permeability for both the fracture and the porous medium is the same), then flow, expressed as an average linear velocity, in the fracture would be approximately 50 times faster than in the porous media. This represents a significant difference in calculated transit times across a sedimentary basin. In addition, the orientation of the fractures (or fracture zones) are important in predicting flow direction.

Flow velocities and flow directions, however, may be difficult to quantify because of the lack of data on the presence or absence of fractures in a sedimentary basin. Fracture flow is probably more prevalent in tectonically deformed sedimentary basins with more indurated rocks. For example, oil production from the sandstone, shale, and limestone of the Spraberry Formation in the Midland Basin is predominantly from fractures (Wilkinson, 1953), as is production from many of the oil fields in the tectonically deformed Monterey Formation, California (Regan and Hughes, 1949). By contrast, oil production from poorly lithified units such as the Tertiary terrigenous clastic formations in the Gulf Coast Basin are typically from the porous matrix.

Flow through aquitards

Cross-formational flow or flow through low-permeability rocks has been considered an essential element for fluid flow in sedimentary basins. Freeze and Witherspoon (1967) demonstrated the effect of permeability variations on groundwater flow paths; groundwater flow through high-permeability units is essentially parallel to bedding, whereas groundwater flow through aquitards is perpendicular to bedding. The lateral area for vertical flow, or leakage, through aquitards is significantly greater than the cross-sectional area for lateral flow through an aquifer; significant volumes of water, therefore, can contribute to the overall budget even though permeabilities of the aquitard are very low. This concept has been used in several basin studies to explain both the hydraulics and the hydrochemistry of a basin. Osmosis and reverse osmosis in basin hydrology are dependent on cross-formational flow. Graf et al. (1965) used reverse osmosis to explain the presence of very concentrated brines in the Illinois Basin. Berry's (1958) interpretation of the hydrology of the San Juan Basin depended on osmosis and therefore on cross-formational flow. Toth's (1978) interpretation of regional flow through the Red Earth region (Western Canadian Basin) depended on large volumes of water flowing through aquitards. Recharge and discharge to the Dakota Sandstone aquifer may be controlled primarily by leakage through the overlying Pierre Shale (Bredehoeft et al., 1982, 1985). Wirojanagud et al. (1986) in an areal model estimated that up to 50% of the water flowing through the Wolfcamp aquifer in the Palo Duro Basin may result from leakage through the overlying evaporite strata. Senger et al. (1987) in a cross-sectional model for the Palo Duro Basin reached similar conclusions. These studies have generally approached the process of cross-formational flow from the perspective of physical hydrology; that is, the interpretation is based on pressure values and numerical modeling. Determining whether such processes actually exist and are important on a basinwide scale requires geologic investigations of the aquitard to determine actual fluid pathways (e.g., evidence of diagenetic alteration in the porous media or fractures), geochemical studies of the aquitard and the aquifer receiving the cross-formational leakage, as well as numerical modeling studies. In a study of the leakage through Permian evaporites of the Palo Duro Basin, Kreitler et al. (1985) found some geochemical and geologic evidence to support the concept of vertical leakage through the evaporite aquitard. In a further test of this concept, Fisher and Kreitler (1987), however concluded that the geochemical data from the subsalt formation brines supported a hypothesis of lateral inflow rather than vertical leakage through the evaporite aquitard.

IMPLICATIONS OF BASIN HYDROLOGY

Origin of the chemical composition of saline waters

The hydrologic environment has important implications to the origin of the chemical composition of saline formation waters within a basin. Basin waters often are referred to as either connate, or meteoric, or a mixture of both. The term "connate" is defined for this paper as water that was trapped at the time of sedimentation. The term "meteoric" indicates groundwater that originated as continental precipitation. By definition, the age of connate waters coincides with the age of deposition of the host sediments. Basinal waters of meteoric origin are younger than the host sediments. Though most basins are composed predominantly of marine sediments, formation waters generally do not resemble seawater in either chemical composition or concentration. Many basins contain waters with total dissolved solid concentrations significantly greater than seawater concentrations and as high as 400,000 ppm. Maximum salinities in the Tertiary section of the Gulf Coast Basin are approximately 130,000 ppm; in the East Texas Basin, 260,000 ppm; in the Palo Duro Basin, 250,000 ppm; in the Illinois Basin, 200,000 ppm; in the Alberta Basin, 300,000 ppm; and in the Michigan Basin, 400,000 ppm (Bassett and Bentley, 1983; Hanor, 1983). Two different types of brines are generally found, a Na-Cl brine and a Na-Ca-Cl brine, neither having chemical composition ratios similar to seawater.

In recent years, three mechanisms have been used to explain the high ionic concentrations and the chemical composition of the brines (Hanor, 1983): (1) the brines originated as residual bittern brine solutions left after the precipitation of evaporites: (2) basinal waters have dissolved halite that was present as either bedded or domal salt: and (3) basinal waters have been forced through low-permeability shales (reverse osmosis), leaving a brine on the high pressure side of the membrane. At present, there is no consensus about the relative importance of each of these three mechanisms to the origin of brines.

Basins that contain evaporite deposits typically have salinities greater than 100,000 ppm. Carpenter (1978) suggested that the Na-Ca-Cl brines in these basins were originally the residual bittern brines left after the precipitation of halite and other evaporite minerals. The chemical compositions of these brines follow the seawater evaporation curves and therefore originated from that process. The residual bittern brine was high in bromide (which is typical for brines evaporated beyond halite precipitation), but also high in Mg and SO_4

(which is atypical for Na-Ca-Cl brines). These Na-Ca-Cl brines become depleted in Mg and SO_4 because of dolomitization, which consumed the Mg and released Ca. The SO_4 was reduced by organic material.

Halite solution can produce Na-Cl concentrations higher than seawater. Morton and Land (1987) and Kreitler et al. (1988) in a study of the geopressured and hydropressured sections of the Frio Formation, Gulf Coast Basin, respectively, attributed the high Na-Cl concentrations in the brines to salt-dome dissolution in the Houston Embayment Salt Dome Region. The high Na-Cl concentrations in the Travis Peak and Cotton Valley Formations in the East Texas basin also appear to be related to salt-dome dissolution. Mass balance calculations indicate that the dissolved NaCl can be attributed to halite dissolution (Kreitler et al., 1987b). The brine may alter calcic plagioclase to albite (albitization), resulting in the exchange of calcium for sodium and the formation of a Na-Ca-Cl brine. Land and Prezbindowski (1981) used this process to explain the chemical origin of the concentrated Na-Ca-Cl brines in the deep Cretaceous formations in the Gulf Coast Basin.

Reverse osmosis has been used to explain brines (> 200,000 ppm) in basins that contain no evaporites such as the Illinois Basin (Bredehoeft et al., 1963; Graf et al., 1965). Reverse osmosis has also been used to explain the presence of high Ca concentrations in the brines. The increase in Ca resulted from the preferential filtration of divalent cations such as calcium (White, 1965). Substantial hydraulic gradients across shales are needed for this filtration process to occur, and such gradients have not been observed. Bethke (1985) argues that gradients within the Illinois Basin were not sufficient to provide the necessary hydraulic drive for reverse osmosis.

A different basin hydrology model is needed for each of the previous hypotheses. If a basinal brine is a modified residual bittern brine, then the brines are the approximate age of the evaporites; fluid movement and mixing may be extremely slow, almost stagnant. Using Carpenter's (1978) arguments, brines in southern Arkansas would have originated as residual waters left after precipitation of the Jurassic Louann evaporites and therefore would be Jurassic in age. If a basinal brine results from halite dissolution, fluid migration (or chemical migration, i.e., diffusion), has occurred, and the basin is hydrodynamically active. If reverse osmosis is a viable mechanism, then large volumes of water must have passed through the aquitards to concentrate the brines from either a freshwater or a seawater source.

Hydrogen and oxygen isotopes of basinal waters have been used to explain the origin and ages of the waters. Clayton et al. (1966) observed that the isotopic composition of basinal waters departs systematically from the isotopic composition of meteoric waters for basins in different geographic regions. For example, in the Alberta Basin, hydrogen and oxygen isotopic values ranged from very light isotopic values, which were similar to the isotopic composition of the shallow groundwater, to isotopically heavy values at depth (and higher temperatures). Meteoric groundwaters were recharging a basin, reacting with the rock matrix, and becoming isotopically enriched. Original formation waters were flushed out and replaced by meteoric waters. There is an implication in Clayton et al. (1966) that the waters must not be very old because they are evolving isotopically from a water with an isotopic composition similar to recent meteoric waters. Hitchon and Friedman (1969) offered an alternative interpretation that the observed isotopic trend resulted from mixing of isotopically light meteoric water with isotopically heavy original seawater or evaporite brine that has been diagenetically altered. This interpretation implies that much of the water in the basin may be very old (i.e., as old as the sediments in the basin). In a third alternative, Phillips and Bentley (1987) argued for ion filtration (reverse osmosis) as the mechanism for enriched oxygen and hydrogen values observed in basinal brines.

The origin of a brine with enriched $\delta^{18}O$ values, whether it be from a recharged meteoric or an old, connate water, cannot be determined from its measured ^{18}O composition if the water has isotopically equilibrated with its host rock. Equilibration obscures the water's isotopic history. Nonequilibrated isotopes, however, can provide hydrologic information. Isotopically light, nonequilibrated waters within a basin indicate that shallow groundwater has infiltrated into a sedimentary basin. Fisher and Kreitler (1987) found brines within the Palo Duro Basin with isotopic compositions approaching metoric water values for the region (Fig. 7), suggesting that at least the western half of the basin is being flushed by meteoric water. Both Fisher (1982) and Lundergard (1985) found saline waters with isotopically depleted oxygen in the Wilcox Formation in the Gulf Coast Basin, suggesting a deep flushing by meteoric waters.

Age of saline water

The presence of meteoric waters deep within a sedimentary basin does not necessarily indicate that these waters are relatively young waters because stable isotope compositions do not directly provide us with the absolute age of water. Estimates of water ages can be made by three approaches: (1) radioactive decay techniques; (2) flow velocity calculations from Darcy's law; or (3) reconstruction of the hydrogeologic history of the basin to constrain timing of hydrologic events. Each approach is discussed below.

Absolute ages of groundwaters can be estimated from radioactive isotopes such as ^{3}H (tritium), ^{14}C, ^{36}Cl, and ^{129}I, which have half-lives of 12.3 years, 5730 years, 300,000 years, and 16 million years (Fritz and Fontes, 1980; Fabryka-Martin et al., 1985; Bentley et al., 1986). ^{36}Cl or ^{129}I appear the most appropriate for evaluating basin hydrodynamics. All dating techniques relying on radioactive decay, however, have limitations, whether they be restricted by the short half-life of the radioisotope (e.g., ^{3}H) or the complexities created by multiple sources or competing chemical reactions. For example, ^{36}Cl cannot be used for dating deep basin brines. The radioactive isotope, ^{36}Cl, which results from cosmogenic fallout (Bentley et al., 1986), is overwhelmed by other chloride sources (e.g., salt dome dissolution, connate brines, etc.), which, because of

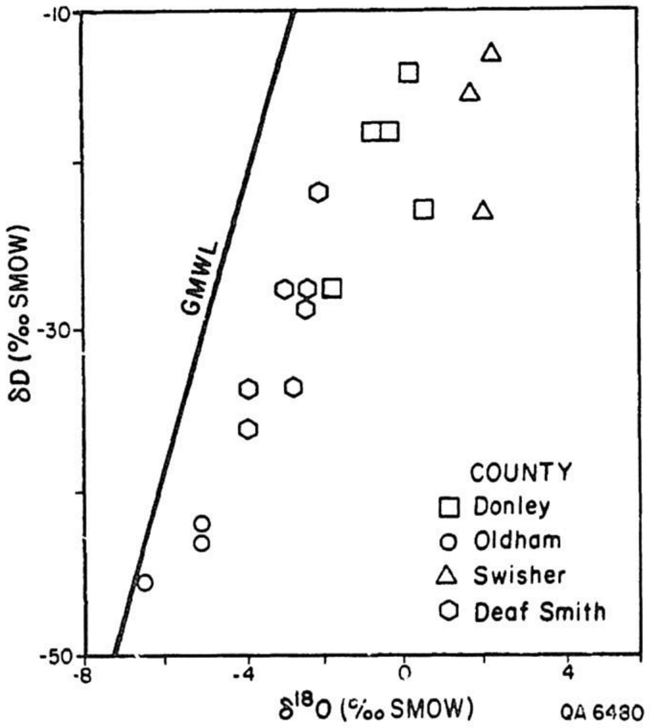

Fig. 7. Hydrogen and oxygen isotopic composition of waters from the deep-brine aquifers in the Palo Duro Basin. Waters from Oldham and Deaf Smith Counties in the western part of the basin trend toward the isotopic composition for meteoric water in the region. These waters are not isotopically equilibrated for their depth (temperature) of sampling. In contrast, waters from Donley and Swisher Counties (the eastern part of the basin) are in isotopic equilibrium for their depth of sampling (from Fisher and Kreitler, 1987). GMWL is Global Meteoric Water Line (Craig, 1961).

their old age, no longer contain original cosmogenic ^{36}Cl. In addition, there is subsurface generation of ^{36}Cl by neutron flux from the decay of radioactive minerals (Feige et al., 1968; Kuhn, 1984). ^{129}I, another long-lived radioisotope with a half-life of 16 million years may be appropriate for dating old waters but has problems similar to ^{36}Cl; iodide is leached from the basinal formations and ^{129}I produced in the subsurface by neutron flux (Fabryka-Martin et al., 1985). Even though these radiometric dating techniques have serious problems, they may provide general ages or, more importantly, approximate minimum ages. The presence of high ^{36}Cl or ^{14}C activities indicates a relatively young water, whereas the absence of these species may indicate an older water, all complications considered.

The age of waters within a basin can be estimated by calculating the flow velocity from the physical hydrologic parameters of the basin, such as potentiometric surfaces, permeabilities, viscosities, densities and boundary conditions. As described previously, this approach also has limitations. Sparse measurements of permeability, the unknown role of fracture versus porous media permeability, and degree of interconnection affect the accuracy of estimated permeability distributions. Permeability distributions and therefore flow velocities may vary by an order of magnitude. For example, Wirojanagud et al. (1986) and Senger et al. (1987) estimated travel times across the Palo Duro Basin ranging from 1 to 4 Ma, INTERA (1986), who also modeled flow in the Palo Duro Basin but used lower average permeability values, calculated transit times greater than 10 Ma. Stochastic approaches are needed to define ranges of velocities and residence times, not only because of the problem of accurately predicting permeabilities, but because the calulated flow velocities are generally average velocities. Maximum velocities for flow that may occur in a fracture zone or other high-permeability pathway are not recognized.

Understanding the hydrogeologic history of the basin can help constrain age determinations. In the Palo Duro Basin the occurrence of deep basinal waters with light isotopic compositions similar to shallow groundwaters in the area suggests that recharge occurred within the time period of the present tectonic setting. The basin was uplifted during Miocene Basin and Range extension (Gable and Hatton, 1984). The maximum age of these brines with a meteoric isotopic signature is probably less than 15 Ma. The early hydrologic history of old mature Paleozoic basins may be difficult if not impossible to determine from the basin's geologic history. The pre-uplift hydrologic history may be difficult to unravel in the Palo Duro Basin as well as in other Paleozoic basins. The presence of continental facies and unconformities may identify earlier times when meteoric water could have been recharged deep into the basin, but quantification of the extent and duration of meteoric penetration is impossible.

Mineral resources, oil and gas exploration, diagenesis, and waste isolation

Regional groundwater flow in sedimentary basins has been used to explain the occurrence of metalic minerals, and oil and gas as well as important diagenetic reactions. In a numerical model that incorporated the transport of water and energy, Garven and Freeze (1984a,b) concluded that gravity-driven groundwater flow in a sedimentary basin could produce temperature conditions and flow rates necessary to form lead–zinc deposits over relatively short geologic time. Sharp (1978) and Cathles and Smith (1983) explained Mississippi Valley type lead–zinc mineralization by updip migration of metal-bearing fluids derived from sediment compaction. The importance of groundwater flow in sedimentary basins for the accumulation of oil and gas has been argued since the early 1900's (Munn, 1909; Toth, 1987). Some diagenetic reactions in sedimentary rocks, such as quartz precipitation (Land and Dutton, 1978) and late-stage dolomitization (Machel and Mountjoy, 1986), are considered to require significant volumes of basinal water flow to account for the large volumes of mass needed for cementation (10^5 pore volumes for quartz precipitation). The volume of groundwater from either sediment compaction or gravity-driven systems (which may have only been uplifted in recent geologic past) may not be sufficient for the observed regional volumes of mineral diagenesis. Recognizing the variability of sedimentary basin hydrology, the limited volume of water that may flush through a basin, and the timing of hydrologic events may provide some hydrologic constraints needed for the explanation of these processes.

Sedimentary basins are also being either considered or currently used for disposal of nuclear and liquid chemical wastes. The Waste Isolation Pilot Project site in Carlsbad, New Mexico, the future repository for nuclear waste from the U.S. Department of Defense, is being mined into Permian salts of the Delaware Basin. Permian salts within the Palo Duro Basin have been considered as a possible repository for commercial nuclear waste. Deep-well injection of chemical wastes into saline formations of sedimentary basins is a common method of disposal in parts of the United States. In Texas deep-well injection is a major method of disposal; over 9 billion kilograms of liquid wastes per year are being injected into the Gulf Coast, East Texas, Permian Basins (Carpenter, 1987). The most likely method of contaminant release and transport to the biosphere is through the saline groundwater. Disposal of nuclear and chemical wastes requires an understanding of the hydrology of these sedimentary basins to safeguard fresh drinking water supplies and to prevent contamination of large areas of deep saline formations.

CONCLUSIONS

This paper has summarized some elements of basin hydrology; a few words of caution are warranted.

(1) The geologic history of a sedimentary basin plays a critical role in determining the hydrologic conditions of a basin. As the basin evolves from periods of sedimentation and compaction to uplift and erosion, fluid flow may change from being predominantly compactional to gravity-driven. Compactional flow is important in young basins containing large volumes of undercompacted shales. Fluid pressures are probably overpressured within the deeper parts of the basin and hydrostatic in shallower sections. Fluid flow may be up structural dip or up faults. Hydrologic base level is sea level, and this controls the depth of meteoric-water penetration. Sea-level changes may alter that depth of penetration. Compaction may not result in large volumes of water for diagenetic reactions; thermal convection may be more important. Groundwater in older topographically uplifted basins is gravity driven and may be underpressured. Underpressuring requires a poor interconnection between shallow and deep systems, moderate interconnection within the brine formations themselves, and basinal discharge. Many Paleozoic basins may have been uplifted geologically recently, and because of the low permeability of these formations, extensive flushing (multiple pore volumes) may not have occurred. This has important implications for a sedimentary petrologist who wants to use basin hydrodynamics to explain extensive diagenetic alteration. Much of the early hydrologic history of a basin may be impossible to determine. Numerical modeling and diagenetic studies may provide the best insight into early hydrologic conditions.

(2) Groundwater flow and solute transport are controlled by six mechanisms:

compaction of argillaceous sediments, gravity, free convection, osmosis, mineral diagenesis, and diffusion. The relative importance of each mechanism in controlling flow depends on the lithologic composition of the basin (e.g., percent clay) and hydrologic boundary conditions (e.g. degree of uplift).

(3) Hydraulic potential distributions can be classified as hydrostatic, overpressured, or underpressured and are controlled by the type and distribution of sediments in the basin and the hydrologic boundary conditions. Young compacting basins typically contain overpressured sections. Conversely, older uplifted basins contain some underpressured sections. Regional groundwater flow occurs in sedimentary basins and is documented by the ability to map regional potentiometric surfaces. Depressurization from oil and gas production may prevent reconstruction of original potentiometric surfaces.

(4) Permeability distributions and types of permeability probably are the most important controls on rates of groundwater flow. Permeability distributions vary logarithmically, whereas most other hydrologic parameters vary arithmetically. Fluid flow in basins with fractured formations will be faster than in basins where flow through porous media dominates. Fluid flow in fractures, however, may bypass much of the rock within a basin and permits meteoric waters to move deep within a basin without isotopic equilibration as is evident in the Palo Duro Basin (Fig. 7). If groundwater flow in fractures is important, older waters in the rock matrix (from earlier hydrologic events) may not be fully flushed from the basin.

(5) There is no general agreement as to the origin of the chemical composition of deep-basin brines. If brines are residual bittern brines from the precipitation of evaporites, then the brines are as old as the formation in which they occur, and stagnant conditions are implied. If these brines result from halite dissolution and diagenetic rock-water reactions, active hydrodynamic conditions are implied, though neither the mechanism nor the rate of fluid movement is indicated. If membrane filtration is an important mechanism, then large volumes of water had to have passed through low-permeability aquitards for a basin to reach the observed brine concentrations. Reverse osmosis requires an active rather than a stagnant hydrologic system.

(6) The precise age of deep-basin brines cannot be determined. Radioisotope techniques do not provide unequivocal dates. Numerical models often rely on sparse data. Models help our understanding of hydrologic processes more than our ability to calculate fluid-flow velocities in a basin. Reconstruction of the hydrogeologic history of a basin provides generalized maximum ages. This lack of precision is acceptable in developing models for geologic processes such as the timing of mineralization or the emplacement of oil. These techniques, however, should be applied with caution when trying to determine specific rates or dates for anthropogenic processes such as nuclear waste isolation.

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REFERENCES

Bassett, R.L. and Bentley, M.E., 1983. Deep brine aquifers in the Palo Duro Basin: Regional flow and geochemical constraints. The University of Texas at Austin, Bur. Econ. Geol., Rep. Invest., 130, 59 pp.

Belitz, K. and Bredehoeft, J.D., 1984. Hydrostratigraphy and hydrodynamics of the Denver Basin and adjacent midcontinent. Geol. Soc. Am., Abstr. Programs: 16(6) p. 441.

Bell, J.S. and Shepherd, J.M., 1951. Pressure behavior in the Woodbine sand. Pet. Trans., Am. Inst. Min. Eng., 192: 19–28.

Bentley, H.W., Phillips, F.M. and Davis, S.N., 1986. ^{36}Cl in the terrestrial environment. In: P. Fritz and J.C. Fontes (Editors), Handbook of Environmental Isotope Geochemistry Vol. 2. pp. 427–480.

Berry, A.F., 1958. Hydrodynamics and geochemistry of the Jurassic and Cretaceous Systems in the San Juan Basin, northwestern New Mexico and southwestern Colorado. Stanford University, Ph.D. Diss., 192 pp.

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

Bethke, C.M., Harrison, W.J., Upson, C. and Altaner, S.P., 1988. Supercomputer analysis of sedimentary basins. Science, 239: 261–267.

Blanchard, P.E., 1987. Fluid flow in compacting sedimentary basins. The University of Texas at Austin, Ph.D. Diss., 196 pp.

Blanchard, P.E. and Sharp, J.M., Jr., 1985. Possible free convection in thick Gulf Coast sandstone sequences. Trans. Southwest Sec. Am. Assoc. Pet. Geol., Fort Worth Geol. Soc., pp. 6–12.

Bodner, D.P., Blanchard, P.E. and Sharp, J.M., 1985. Variations in Gulf Coast heat flow created by groundwater flow. Gulf Coast Assoc. Geol. Soc., Trans., 35: 19–27.

Bredehoeft, J.D. and Hanshaw, B.B., 1968. On the maintenance of anomalous fluid pressures. I. Thick sedimentary sequences. Geol. Soc. Am., Bull., 79: 1097–1106.

Bredehoeft, J.D., Blyth, C.R., White, W.A. and Maxey, G.B., 1963. Possible mechanisms for concentration of brines in subsurface formations. Am. Assoc. Pet. Geol., Bull., 47: 257–269.

Bredehoeft, J.D., Back, W. and Hanshaw, B.B., 1982. Regional groundwater flow concepts in the United States: historical perspective. In: T.N. Narasimhan (Editor), Recent Trends in Hydrogeology. Geol. Soc. Am., Spec. Pap., 189: 297–316.

Bredehoeft, J.D., Neuzil, C.E. and Milley, C.D., 1985. Regional flow in the Dakota aquifer: a study of the role of confining layers. Int. Assoc. Hydrogeol., Mem., 17: p. 794.

Burst, J.F., 1969. Diagenesis of Gulf Coast clayey sediments and its possible relationship to petroleum migration. Am. Assoc. Pet. Geol., Bull., 53(1): 73–93.

Capuano, R.M., 1988. Chemical equilibria and fluid flow during compaction diagenesis of organic-rich geopressured sediments. University of Arizona, Ph.D, Diss., 134 pp.

Carpenter, A.B., 1978. Origin and chemical evolution of brines in sedimentary basins. In: K.S. Johnson and J.R. Russell (Editors), 13th Industrial Minerals Forum. Okla. Geol. Surv., Circ., 79: 78–88.

Carpenter, R., 1987. The road to recovery. Tex. Eng. Exp. Stn. Windows, 6(3): 3–5.

Cathles, L.M. and Smith, A.T., 1983. Thermal constraints on the formation of Mississippi Valley type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis. Econ. Geol., 78: 983–1002.

Clayton, R.N., Friedman, I., Graf, D.L., Mayeda, T.K., Meents, W.F. and Shimp, N.F., 1966. The origin of saline formation waters, I. Isotopic composition. J. Geophys. Res., 71: 3869–3882.

Coplen, T.B. and Hanshaw, B.B., 1973. Ultrafiltration by a compacted clay membrane. I Oxygen and hydrogen isotopic fractionation. Geochim. Cosmochim. Acta, 37: 2295–2310.

Craig, H., 1961. Isotopic variations in meteoric water. Science, 133: 1702–1703.

De Marsily, G., 1985. Flow and transport in fractured rocks: connectivity and scale effect. Int. Assoc. Hydrogeol., Mem., 17: 267–277.

Fabryka-Martin, J., Bentley, H., Elmore, D. and Airey, P.L., 1985. Natural iodine-129 as an environmental tracer. Geochim. Cosmochim. Acta, 49: 337–347.

Feige, Y., Oltman, B.G. and Kastner, J., 1968. Production rates of neutrons in soils due to natural radioactivity. J. Geophys. Res., 37: 3135–3142.

Fisher, R.S., 1982. Diagenetic history of Eocene Wilcox sandstones and associated formation waters, south-central Texas. The University of Texas at Austin, Ph.D. Diss., 185 pp.

Fisher, R.S. and Kreitler, C.W., 1987. Origin and evolution of deep-basin brines, Palo Duro Basin, Texas. The University of Texas at Austin, Bur. Econ. Geol., Rep. Invest. No. 166, 33 pp.

Fogg, G.E., Seni, S.J. and Kreitler, C.W., 1983. Three-dimensional groundwater modeling in depositional systems. Wilcox Group, Oakwood salt dome area, East Texas. The University of Texas at Austin, Bur. Econ. Geol. Rep. Invest., No. 133, 55 pp.

Freeze, R.A. and Witherspoon, P.A., 1967. Theoretical analysis of regional ground water flow: 2. Effect of water table configuration and subsurface permeability variation. Water Resour. Res., 3: 623–634.

Fritz, P. and Fontes, J.C., 1980. Handbook of Environmental Isotope Geochemistry. Elsevier, Amsterdam, 545 pp.

Gable, D.J. and Hatton, T., 1984. Amount of vertical crustal movements in the contemporaneous United States over the last 10 million years. U.S. Geol. Surv., Misc. Invest. Ser., Map I-1315.

Galloway, W.E., 1982. Epigenetic zonation and fluid flow history of uranium-bearing fluvial aquifer systems, South Texas uranium province. The University of Texas at Austin, Bur. Econ. Geol. Rep. Invest. No. 119, 31 pp.

Galloway, W.E. and Hobday, D.K., 1983. Terrigenous clastic depositional systems: applications to petroleum, coal and uranium exploration. Springer, Berlin, 423 pp.

Galloway, W.E., Hobday, D.K. and Magara, K., 1982. Frio Formation of the Texas Coastal Plain — depositional systems, structural framework and hydrocarbon distribution. Am. Assoc. Pet. Geol., 66: 649–688.

Galloway, W.E., Ewing, T.E., Garrett, C.M., Tyler, N. and Bebout, D.G., 1983. Atlas of major Texas oil reservoirs. The University of Texas at Austin, Bur. Econ. Geol., Spec. Publ., 139 pp.

Garven, G. and Freeze, R.A., 1984a. Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. 1. Mathematical and numerical model. Am. J. Sci., 284: 1085–1124.

Garven, G. and Freeze, R.A., 1984b. Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. 2. Quantitative results. Am. J. Sci., 284: 1125–1174.

Graf, D.L., 1982. Chemical osmosis, reverse chemical osmosis, and the origin of subsurface brines. Geochim. Cosmochim. Acta, 46: 1431–1448.

Graf, D.L., Meents, W.F., Friedman, I. and Shimp, N.F., 1965. The origin of saline formation waters. III. Calcium chloride waters. Ill. Geol. Surv., Circ. No. 397, 32 pp.

Hanor, J.S., 1983. Fifty years of development of thought on the origin and evolution of subsurface sedimentary brines. In: S.J. Boardman (Editor), Revolution in the Earth Sciences: Advances in the Past Half-Century. Kendall/Hunt, Dubuque., pp. 99–111.

Hanor, J.S., 1984. Large-scale, non-advective mass transport of dissolved salts in the northern Gulf Coast. Geol. Soc. Am., Abstr. Programs, 16, p. 529.

Hanor, J.S. and Bailey, J.E., 1983. Use of hydraulic head and hydraulic gradient to characterize geopressured sediments and the direction of fluid migration in the Louisiana Gulf Coast. Gulf Coast Assoc. Geol. Soc., Trans., 33: 115–122.

Hanshaw, B., 1965. Natural-membrane phenomena and subsurface waste emplacement. In: T.D. Cook (Editor). Underground Waste Management and Environmental Implications. Am. Assoc. Pet. Geol., Mem., 18: 308–315.

Hitchon, B., 1969. Fluid flow in the Western Canada sedimentary basin: 1 Effect of topography. Water Resour. Res., 5: 186–195.

Hitchon, B. and Friedman, I., 1969. Geochemistry and origin of formation waters in western Canada sedimentary basin: I. Stable isotopes of hydrogen and oxygen. Geochim. Cosmochim. Acta, 33: 1321-1349.

Hubbert, M.K., 1940. The theory of groundwater motion. J. Geol., 48: 785–944.

INTERA Technologies, Inc., 1986. Second status report on regional ground-water flow modeling for Palo Duro Basin, Texas. BMI/ONWI-604, prepared for Off. Nucl. Waste Isol., Battle Mem. Inst., Columbus, Ohio, 200 pp.

Jones, P.H., 1975. Geothermal and hydrocarbon regimes, northern Gulf of Mexico Basin. In: M.H. Dorfman and R.W. Deller (Editors), Proceedings. First Geopressured Geothermal Energy Conference. The University of Texas at Austin, pp 15–89.

Kaufman, R., Long, A., Bentley, H. and Davis, S.N., 1984. Natural chlorine isotopes variations. Nature, 309: 338–340.

Kreitler, C.W., Guevera, E.H., Granata, G.E. and McKalips, D.G., 1977. Hydrogeology of Gulf Coast aquifers, Houston-Galveston, Texas. Gulf Coast Assoc. Geol. Soc., Trans., 25: 72–89.

Kreitler, C.W., Fisher, R.S., Senger, R.K., Hovorka, S.D. and Dutton, A.R., 1985. Hydrology of an evaporite aquitard: Permian evaporite strata, Palo Duro Basin, Texas. Int. Assoc. Hydrogeol., Mem., 17: 150–178.

Kreitler, C.W., Akhter, M.S. and Wood, W.T., 1987a. Preliminary characterization of hydrologic regimes in the Frio Formation, Texas Gulf Coast, Drill-stem and bottom-hole-pressure measurements. Geol. Soc. Am., Abstr. Programs. 19(7), p. 733.

Kreitler, C.W., Collins, E.W., Fogg, G.E., Jackson, M.P.A. and Seni, S.J., 1987b. Hydrologic characterization of the saline aquifers, East Texas basin — implications to nuclear waste storage in East Texas salt domes. The University of Texas at Austin, Bur. Econ. Geol., Open-File Rep., OF-ETWI-1987-1, 157 pp.

Kreitler, C.W., Akhter, M.S., Wood, W.T. and Donnelly, A.C.A., 1988. Regional hydrologic hydrochemical characterization of saline formations in the Texas Gulf Coast that are used for deep-well injection of chemical wastes. Rep. U.S. Environ. Prot. Agency, Coop. Agreement, No. CR812786-01-0, 219 pp.

Kuhn, M.W., 1984. Subsurface neutron production and its impact on ^{36}Cl groundwater dating. The University of Arizona, Ms. Thesis, 45 pp.

Land, L.S. and Dutton, S.P., 1978. Cementation of a Pennsylvannia deltaic sandstone, isotopic data. J. Sediment. Pet., 48(4): 1167–1176.

Land, L.S. and Prezbindowski, D.R., 1981. The origin and evolution of saline formation water, Lower Cretaceous carbonates, south-central Texas, U.S.A. J. Hydrol., 54: 51–74.

Lundergard, P.D., 1985. Carbon dioxide and organic acids: origin and role in burial diagenesis (Texas Gulf Coast Tertiary). The University of Texas at Austin, Ph.D. Diss., 145 pp.

Machel, H. and Mountjoy, E.W., 1986. Chemistry and environments of dolomitization — a reappraisal. Earth-Sci. Rev., 23: 175–222.

Manheim, F.T. and Bischoff, J.L., 1969. Geochemistry of pore waters from Shell Oil Company drill holes on the continental slope of the northern Gulf of Mexico. Chem. Geol., 4: 63–82.

Marine, I.W., 1974. Geohydrology of buried Triassic at Savannah River Plant, South Carolina. Am. Assoc. Pet. Geol., Bull., 58: 1825–1837.

McCulloh, R.P., 1985. Patterns of fluid flow in the central Tuscaloosa trend, Louisiana. Gulf Coast Assoc. Geol. Soc., Trans., 35: 209–214.

McKelvey, J.G. and Milne, I.H., 1962. The flow of salt solutions through compacted clay. Proc. Ninth Natl. Conf. Clays Clay Miner., pp. 248–259.

McGookey, D.A., 1984. Uplift, tilting and subsidence of the Palo Duro Basin. The University of Texas at Austin, Bur. Econ. Geol., Open-File Rep. OF-WTWI-1984-2, 30pp.

Morton, R.A. and Land, L.S., 1987. Regional variations in formation water chemistry, Frio Formation (Oligocene), Texas Gulf Coast. Am. Assoc. Pet. Geol., Bull., 71: 191–206.

Munn, M.J., 1909. The anticlinal and hydraulic theories of oil and gas accumulation. Econ. Geol., 4(6): 509–529.

Neuzil, C.E., 1986. Groundwater flow in low-permeability environments. Water Resour. Res., 22(8): 1163–1195.

Neuzil, C.E. and Pollock, D.W., 1983. Erosional unloading and fluid pressures in hydraulically "tight" rocks. J. Geol., 91: 179–193.

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 Resour. Res., 21: 533–544.

Phillips, F.M. and Bentley, H.W., 1987. Isotopic fractionation during ion filtration: I. Theory. Geochim. Cosmochim. Acta, 50: 683–695.

Rangathan, V. and Hanor, J., 1988. Density driven ground-water flow near salt domes. Chem. Geol., 74: 173–188.

Regan, L.J., Jr. and Hughes, A.W., 1949. Fractured reservoirs of Santa Maria district, California. Am. Assoc. Pet. Geol., Bull., 33: 32–51.

Richter, B.C. and Kreitler, C.W., 1986. Geochemistry of salt-spring and shallow subsurface brines in the Rolling Plains of Texas and southwestern Oklahoma. The University of Texas at Austin, Bur. Econ. Geol., Rep. Invest., No. 155, 47 pp.

Senger, R.S., Fogg, G.E. and Kreitler, C.W., 1987. Effects of hydrostratigraphy and basin development on hydrodynamics of the Palo Duro Basin, Texas. The University of Texas at Austin, Bur. Econ. Geol., Rep. Invest., No. 165, 48pp.

Sharp, J.M., Jr., 1983. Energy and transport model of Ouachita Basin and its possible impact on formation of economic mineral deposits. Econ. Geol., 73: 1057–1068.

Sharp, J.M., Jr. and Domenico, P.A., 1976. Energy transport in thick sequences of compacting sediment. Geol. Soc. Am., Bull., 87: 390–400.

Smith, D.A., Akhter, M.S. and Kreitler, C.W., 1986. Groundwater hydraulics of the Deep-Basin Brine aquifer system, Palo Duro Basin, Texas Panhandle. The University of Texas at Austin, Bur. Econ. Geol., Open-File Rep., OF-WTWI-1985-16, 98 pp.

Toth, J., 1978. Gravity-induced cross formational flow of formation fluids, Red Earth region, Alberta, Canada: analysis, patterns and evolution. Water Resour. Res., 14: 805–843.

Toth, J., 1987. Petroleum hydrogeology; an new basic in exploration. World Oil, Sept., 3pp.

Warren, J.E. and Price, H.S., 1961. Flow in heterogeneous porous media. J. Soc. Pet. Eng., 1: 153–169.

White, D.E., 1965. Saline waters of sedimentary rocks. In: A. Young and J.E. Galley (Editors), Fluids in the Subsurface Environments. Am. Assoc. Pet. Geol., pp. 343–366.

Wilkinson, W.M., 1953. Fracturing in Spraberry reservoir, West Texas. Am. Assoc. Pet. Geol., Bull., 37: 250–265.

Wirojanagud, P., Kreitler, C.W. and Smith, D.A., 1986. Numerical modeling of regional groundwater flow in the Deep-Basin Brine aquifer of the Palo Duro Basin, Texas Panhandle. The University of Texas at Austin, Bur. Econ. Geol., Rep. Invest., No. 159, 68 pp.

Wood, J.R. and Hewett, T.A., 1982. Fluid convection and mass transfer in porous sandstones — a theoretical model. Geochim. Cosmochim. Acta, 46: 1707–1713.

Woodruff, C.M. and Foley, D., 1985. Thermal regimes of the Balcones/Ouachita trend, central Texas. Trans. Gulf Coast Assoc. Geol. Soc., 35: 287–292.

Workman, A.L. and Hanor, J.C., 1985. Evidence for large-scale vertical migration of dissolved fatty acids in Louisiana oil field brines: Iberia Field, South-Central Louisiana. Trans. Gulf Coast Assoc. Geol. Soc., 35: 293–300.