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Revision 01

CROSS-FORMATIONAL FLOW IN THE PALO DURO BASIN, TEXAS PANHANDLE

Final Contract Report

by
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ABSTRACT

Permian evaporite strata have been proposed as media for nuclear waste storage. Repository integrity is dependent on the extent of cross-formational flow, or leakage, through the Evaporite aquitard into the underlying Deep-Basin Brine aquifer. Pertinent data were reviewed and integrated to evaluate potential leakage. The Deep-Basin Brine aquifer is underpressured and has hydraulic heads hundreds of meters below those of the fresh-water Upper aquifer, indicating potential for downward flow between the Upper and Deep-Basin Brine aquifers. In the northwestern part of the basin, water in the Deep-Basin Brine aquifer has a meteoric isotopic signature, and its presence is cited as evidence for leakage from the Upper aquifer downward through the Evaporite aquitard. A plausible alternative source is lateral recharge from eastern New Mexico. Darcian leakage rates calculated from numerical models are very small (hundredths to thousandths of a μm/d) and depend primarily on the permeability of salt, which is stress dependent and overestimated in testing. If salt permeability is 10^{-5} md, as measured recently in situ in competent New Mexico bedded salt, leakage through the Evaporite aquitard would be 6×10^{-9} m/d and flow through an area of 25 km^2 (9 mi^2) approximately 0.15 m^3/d (40 gal/d). Though fractured, the Evaporite aquitard probably behaves regionally as an extremely low-permeability, low-flux porous medium. Basinal brines are compositionally stratified, ruling out substantial vertical mixing or mass transfer. Hydrologic isolation of the salt is further indicated by the inferred presence of Permian connate water in the aquitard, high bromide content of halite, and dominance of syndepositional and early diagenetic halite textures. Only the salt dissolution zone, atop the aquitard, has experienced post-Permian dissolution. Available geochemical and petrographic evidence shows that cross-formational flow, or leakage, through the Evaporite aquitard is very slight.

INTRODUCTION

Bedded salt in Permian evaporite strata is the proposed geologic media for a potential high-level nuclear waste repository in Deaf Smith County (fig. 1); its integrity among other things is dependent on the amount of cross-formational flow, or leakage, between the overlying Ogallala and Dockum fresh-water aquifers and the Deep-Basin Brine aquifer below the salt. Ground-water hydraulics and numerical modeling show potential for downward flow through the evaporites and contribution of ground water to the Deep-Basin Brine aquifer. Estimates of potential leakage are primarily dependent on the permeability of bedded halite and were made assuming a value of 10^{-4} md. Lower values substantially reduce leakage. In the northwestern basin, water in the Deep-Basin Brine aquifer has a meteoric isotopic signature. Both recharge vertically downward and laterally from the west have been proposed as sources for this water. Recharge downward requires that fractures are the primary pathway for fluid flow and significant movement of dissolved ions (mass) into the Deep-Basin Brine aquifer. Depending on lithology, evaporite strata have been variously fractured (see section on Fracture Abundance); thus, potential pathways (fractures) are available for flow. Whether or not fractures are open to significant flow is problematical and dependent on their vertical continuity and extent of mineral fill and on the regional stress field. Clear differences in chemical composition among basinal brines do not unequivocally rule out interstratal flow, but neither do they support substantial vertical mass transfer. Halite bromide content and petrographic textures do not indicate pervasive post-Permian dissolution.

Pertinent data from the existing literature are reviewed, evaluated, and synthesized to assess the importance of leakage through the evaporite strata. Hydrostratigraphic units are defined, followed by a discussion of their potential energy, or heads, and the key factors affecting vertical ground-water flow in the evaporite strata--permeability of salt and fracturing. Lastly, evidence that bears on actual ground-water flow is presented. The

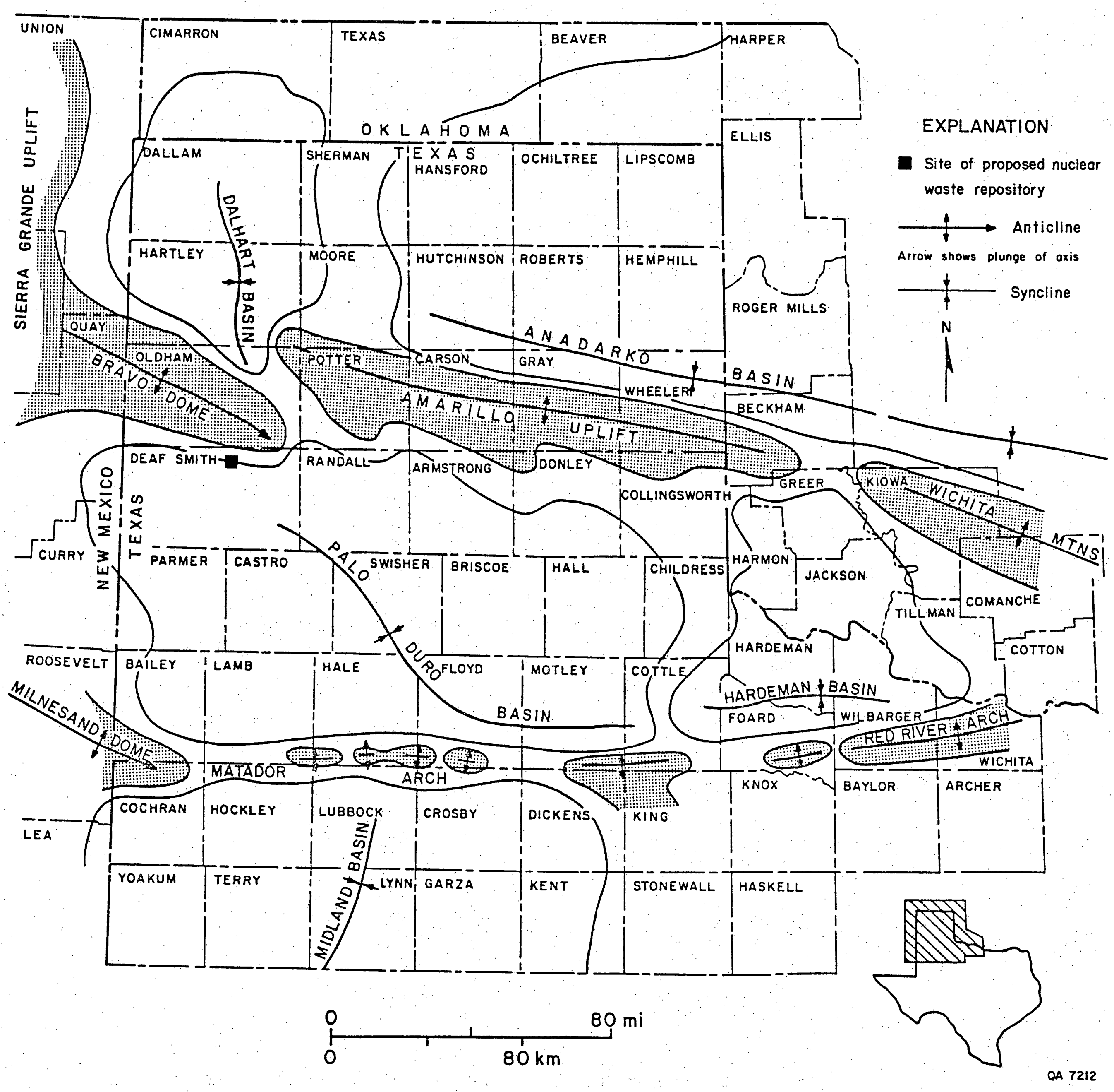

Figure 1. Structural elements of the Texas Panhandle (from Nicholson, 1960).

discussion of chemical and isotopic composition of brines focuses on the San Andres Formation in the evaporite section and the Wolfcamp aquifer, the first permeable strata below the evaporites. The bromide content and textural types of halite are reviewed with an emphasis on dissolution.

HYDROSTRATIGRAPHY

The Palo Duro Basin has been divided into three hydrogeologic units by Bassett and Bentley (1983): an Upper aquifer, a middle Evaporite aquitard, and a lower Deep-Basin Brine aquifer (table 1). The Upper aquifer contains mainly fresh water in fluvial-deltaic and lacustrine sediments of the Tertiary Ogallala Formation and Triassic Dockum Group. The Evaporite aquitard includes all middle and upper Permian strata above the lower Permian Wolfcampian Series and is dominantly bedded halite and anhydrite (60 to 65 percent), fine-grained red beds (about 30 percent), and carbonate (5 to 10 percent) (McGowen, 1981) totaling 650 to 1,550 m (2,130 to 5,080 ft) thick. The San Andres unit 4 salt is the proposed repository horizon (table 2). The Deep-Basin Brine aquifer is composed of Wolfcampian and pre-Wolfcampian strata--upper Paleozoic shelf-margin carbonates and arkosic fan-delta deposits (granite wash), lower Paleozoic carbonates, and basal Cambrian sandstones.

Atop the Evaporite aquitard is the salt dissolution zone, or zone of salt removal; it is 30 to 160 m (100 to 520 ft) thick, thickens at the basin margin, and stratigraphically ranges downward from the Dewey Lake clastics into the lower San Andres unit 4 (table 2) (Dutton, 1985; Hovorka and others, 1985b). Salt dissolution is active today along the western, northern, and eastern margins of the Palo Duro Basin (Gustavson and others, 1981) and may or may not be active today in the interior basin.

Table 1. Generalized stratigraphy and equivalent hydrogeologic units (modified from Bassett and Bentley, 1983).

System	Series	Group	General lithology and depositional setting	Hydrogeologic element	Hydrogeologic unit
Quaternary			Fluvial and lacustrine clastics	Ogallala aquifer	Upper aquifer
Tertiary					
Cretaceous			Nearshore marine clastics		
Triassic		Dockum	Fluvial-deltaic and lacustrine clastics and limestones	Dockum aquifer	
Permian	Ochoan		Salt, anhydrite, red beds, and peritidal dolomite	Evaporite aquitard	Evaporite aquitard
	Guadalupian	Artesia			
		Pease River			
	Leonardian	Clear Fork			
		Wichita			
	Wolfcampian		Shelf and platform carbonates, basin shale, and deltaic sandstones	Wolfcamp carbonate aquifer	Deep-Basin Brine aquifer
Pennsylvanian				Pennsylvanian carbonate aquifer Basin shale aquitard Upper Paleozoic granite-wash aquifer	
Mississippian			Shelf limestone and chert	Lower Paleozoic carbonate aquifer	
Ordovician		Ellenburger	Shelf dolomite		
Cambrian			Shallow marine (?) sandstone	Lower Paleozoic sandstone aquifer	
Precambrian			Igneous and metamorphic	Basement aquiclude	Basement aquiclude

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Table 2. Stratigraphic column, Texas Panhandle (modified from Regan and Murphy, 1984).

RECENT TO EARLY MISSISSIPPIAN

ERA	SYSTEM	SERIES	GROUP	FORMATION
CENOZOIC	QUATERNARY			Recent fluvial, lacustrine, and eolian deposits
	TERTIARY			Ogallala
MESOZOIC	TRIASSIC		Dockum	
PALEOZOIC	PERMIAN	Ochoan		Dewey Lake
				Alibates
		Guadalupian	Artesia/ Whitehorse	Salado/Tansill
				Yates
				Seven Rivers
				Queen/Grayburg
			Pease River	San Andres upper
				lower - unit 5
				unit 4
				unit 3
				unit 2
				unit 1
		Leonardian		Glorieta
			Clear Fork	upper Clear Fork
				Tubb
				lower Clear Fork
				Red Cave
			Wichita	
		Wolfcampian		
	PENNSYLVANIAN	Virgilian	Cisco	
		Missourian	Canyon	
		Desmoinesian	Strawn	
		Atokan Morrowan	Bend	
	MISSISSIPPIAN	Chesterian Meramecian Osagean		

EARLY MISSISSIPPIAN TO PRECAMBRIAN

ERA	SYSTEM	SERIES	PALO DURO/DALHART BASINS	ANADARKO BASIN
PALEOZOIC	MISSISSIPPIAN	Kinderhookian		Kinderhook Shale
				Woodford Shale
	DEVONIAN			Hunton Group
	SILURIAN			
	ORDOVICIAN			Sylvan Formation
				Viola Group
				Simpson Group
			Ellenburger Group	Arbuckle Group
	CAMBRIAN		Unnamed	Reagan Sandstone
PRECAMBRIAN			Igneous and metamorphic rocks	

EXPLANATION

〰〰 Unconformity

- - - - - Boundary in dispute

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GROUND-WATER HYDRAULICS

Ground-water flow in the Upper and Deep-Basin Brine aquifers is horizontal and in the Evaporite aquitard is vertical (fig. 2). Flow in the Upper aquifer is east and southeast (Gutentag and Weeks, 1980). The Upper aquifer is essentially two separate aquifers in which the potentiometric surface of the Ogallala is 90 to 210 m (300 to 690 ft) above the Dockum (Dutton and Simpkins, 1986).

Lateral flow in the confined Deep-Basin Brine aquifer is from southwest to northeast across the basin toward granite wash deposits that flank the Amarillo Uplift and west to east parallel to the Matador Arch (fig. 1), after exiting the Midland Basin (Smith and others, 1985; Wirojanagud and others, 1986). The Deep-Basin Brine aquifer is interconnected regionally and underpressured. Regional flow patterns can be characterized by an average potentiometric surface. Fresh-water equivalent heads in the Deep-Basin Brine aquifer are 550 to 250 m (1,800 to 820 ft) below those in the Upper aquifer. San Andres brine heads are above the Wolfcamp and below the Dockum. Underpressuring in the Deep-Basin Brine aquifer is reflected in a pressure gradient (0.39 psi/ft) less than that of brine hydrostatic (0.47 psi/ft) (Orr and others, 1985). Clearly, potential for regional ground-water flow from the Upper aquifer to the Deep-Basin Brine aquifer exists (Senger and Fogg, 1984; Senger and others, 1985; Wirojanagud and others, 1986) and is greatest in the northwestern part of the basin.

The Deep-Basin Brine aquifer is thought to receive recharge laterally from eastern New Mexico and the Midland Basin and cross-formationally by leakage through the Evaporite aquitard (Bassett and Bentley, 1983; Fisher and Kreitler, 1987; Kreitler and others, 1985; Senger and others, 1985). Recharge of meteoric water occurs in the Sacramento Mountains of eastern New Mexico. Much of this water moves in a local flow system and discharges into the Pecos River; the remainder passes beneath the Pecos River and into the Deep-Basin Brine aquifer (fig. 2) (Senger and Fogg, 1984; Senger and others,

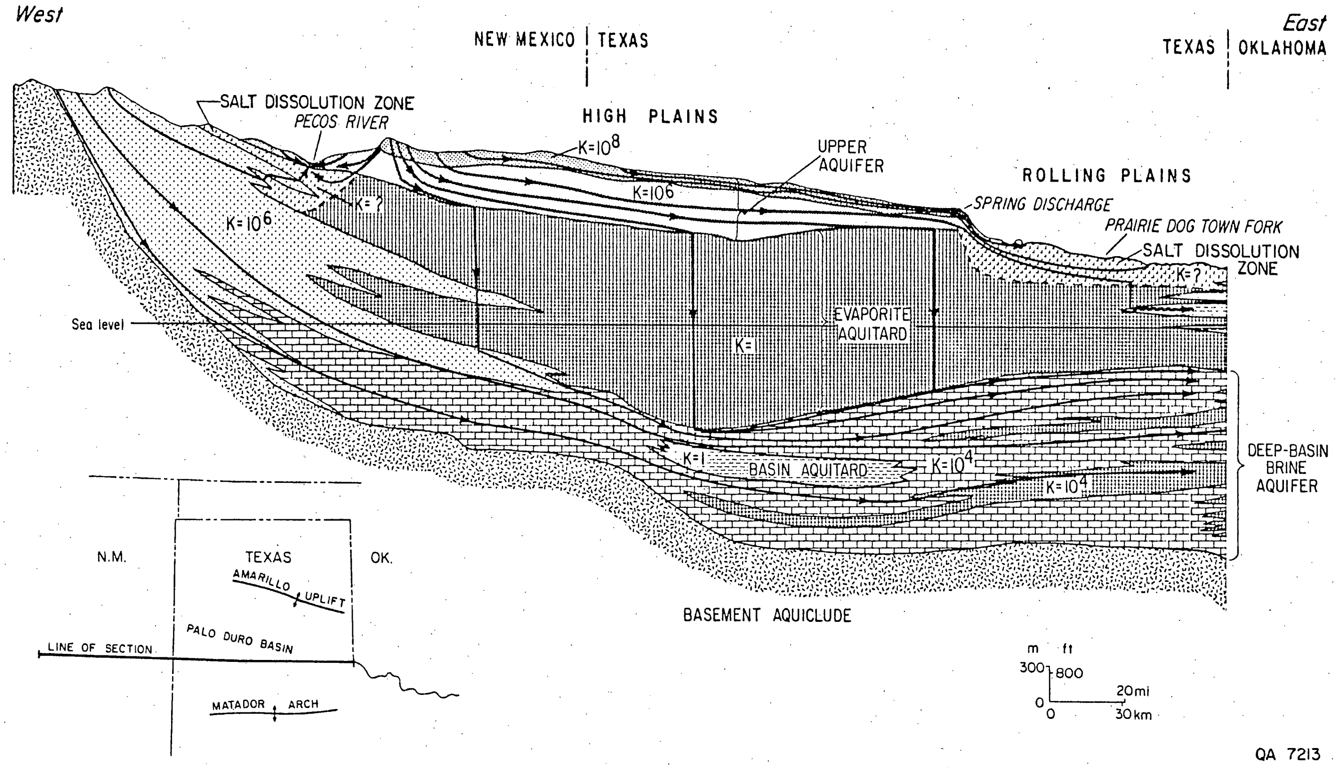

Figure 2. Schematic ground-water flow and distribution of major hydrogeologic units and their relative hydraulic conductivities (K) (modified from Bassett and Bentley, 1983).

1985; Smith and others, 1985). Total leakage through the Evaporite aquitard is potentially large because of the large area of contact (about 22,000 km^2; 8,500 mi^2) between the Evaporite aquitard and the Deep-Basin Brine aquifer. The amount of potential leakage has been estimated from numerical modeling by Senger and Fogg (1984) and Wirojanagud and others (1986).

NUMERICAL MODELING

Areal and cross-sectional numerical models have been used to simulate ground-water flow in the Palo Duro Basin where, in cross-sectional modeling, variable density and viscosity of the basinal brines were neglected. Numerical modeling indicates that the potential for leakage is downward through the Evaporite aquitard. The areal model best simulated heads in the Wolfcamp aquifer by using a permeability value of 8×10^{-5} md for the Evaporite aquitard (Wirojanagud and others, 1986). Cross-sectional modeling (Senger and Fogg, 1984) indicates that 2.8×10^{-4} md is an upper limit for aquitard permeability; below this value, Senger and Fogg (1984) saw little effect on computed heads in the Deep-Basin Brine aquifer.

Leakage was computed to contribute about 30 percent of the flow through the Deep-Basin Brine aquifer and about 50 percent through the Wolfcamp aquifer (Wirojanagud and others, 1986). Senger and Fogg (1984) estimated the Darcian leakage rate to be 9.4×10^{-3} m^3/d (6×10^{-8} m/d), assuming an aquitard permeability of 2.8×10^{-4} md and no head difference between the Ogallala and Dockum aquifers. When they reduced permeability by 5 orders of magnitude, leakage rate was correspondingly reduced. Thus, the computed leakage rate is very sensitive to permeability, but it is also affected by the 90- to 210-m (300- to 690-ft) head difference between the Ogallala and Dockum aquifers (Dutton and Simpkins, 1986). For example, if the head difference is 150 m (490 ft), leakage through the Evaporite aquitard would be reduced from 9.4×10^{-3} m^3/d to 4.5×10^{-3} m^3/d

(Senger and Fogg, 1984). Leakage will also be affected by interbedded carbonates and sandstones having permeabilities greater than the evaporites. Vertical flow lines in the aquitard would be deflected 2 to 50 km (1.2 to 30 mi) southeast by horizontal flow in the San Andres carbonates (Dutton and Orr, 1986). Horizontal flow in the San Andres unit 4 carbonate was simulated to extend more than 100 km (60 mi) to the outcrop when aquitard and carbonate permeability were assumed to be less than 2.8×10^{-5} md and 0.1 md, respectively (Senger, 1985). Nevertheless, Senger concluded that vertical flow is expected to dominate and that horizontal flow lines in the carbonate will eventually be deflected downward into the Evaporite aquitard.

Numerical models assume porous-media flow and neglect fracture flow. Modeling of fluid flow in an idealized fracture (parallel-plate) indicate that fractures could act as conduits for leakage across the Evaporite aquitard (Senger, 1985). However, because the effects of fracture roughness, tortuosity, connectivity, and aperture-size distribution are neglected, the permeability of fractured media cannot be adequately modeled using parallel-plate idealization of each fracture, the standard assumption in state-of-the-art modeling. Consequently, the permeability of the fractured medium is greatly overestimated, perhaps by several orders of magnitude (Tsang and Witherspoon, 1985). Permeability of fracture zones in the evaporite strata has not been measured. However, by analogy with more competent crystalline rocks, it is predicted to be less than an order of magnitude greater than that of unfractured rock. Fracture zones in crystalline rocks have permeabilities about an order of magnitude higher than those of unfractured rock (Neretnieks, 1985).

PERMEABILITY OF SALT

Laboratory and in situ measurements of the permeability of domal and bedded salt show a range from several hundred to 10^{-6} md. Measurements are extremely sensitive to testing method. Laboratory values have a lower limit ranging from 10^{-2} to 10^{-4} md and an upper limit of several hundred md (fig. 3). Permeabilities determined in situ are lower and range from 10 to 10^{-6} md. The wide range in measured values is attributed to a combination of physical and experimental factors, including differences in salt porosity, dependence of permeability on stress and time, stress history during sampling, resolution of test method, and test technique.

Differences between laboratory and in situ permeability values are attributed to sample disturbance and the effects of confinement. Extracting, transporting, and testing of a sample tends to increase permeability. Laboratory permeabilities can vary by several orders of magnitude, depending on confining stress (fig. 4), whereas variations under confinement can be attributed to variation in porosity (fig. 5) (Kelsall and Nelson, 1985).

Permeabilities of bedded salt from the Permian Salado Formation at the Waste Isolation Pilot Project (WIPP) site 40 km (25 mi) east of Carlsbad, New Mexico, have been determined in the laboratory and in situ. Sutherland and Cave (1980) investigated in the laboratory the effects of confining pressure and time on this salt and reported permeabilities between 10^{-2} and 10^{-4} md, finding that permeability decreased with time, even after 21 days of loading. Whether or not the decrease is due to fracture healing or porosity reduction is uncertain. They concluded that representative values for in situ permeability could be obtained by testing under long-term confinement. In situ measurements by Peterson and others (1981, 1985) at the WIPP site yielded ranges of 10^{-2} to 10^{-3} md and 10^{-4} to 10^{-6} md, respectively. The more recent tests were conducted at a depth of 610 m (2,000 ft) in boreholes drilled into the roof, floor, and walls of a 10-m-wide by 4-m-high (30-ft by 13-ft) rectangular entry. Permeability and porosity values were determined using pressure decay tests assuming the formation could be modeled as an unsaturated, isotropic, porous medium. Results suggest that salt is isotropic and has no preferred flow direction. Competent salt as well as argillaceous and anhydritic salt were found to have a permeability of less than 10^{-5} md and an approximate porosity of 0.001 (0.1 percent). Salt

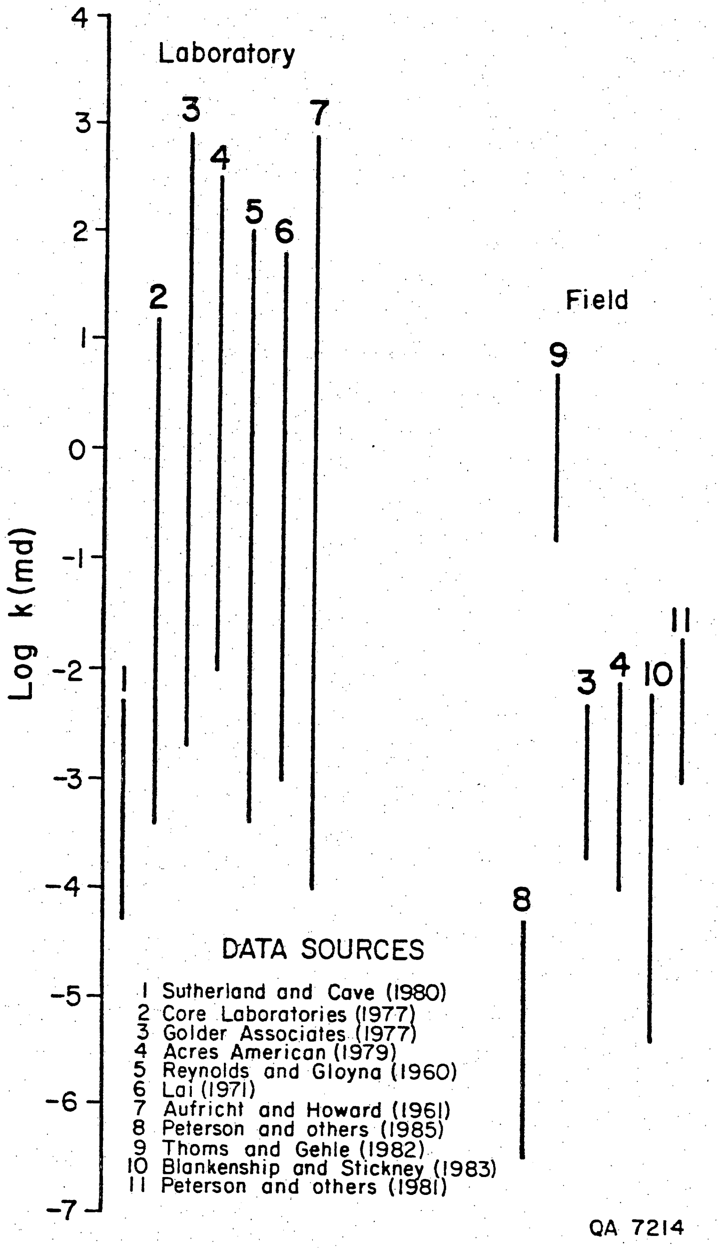

Figure 3. Comparison of laboratory and field measurements of the permeability of salt. Test conditions vary, especially confining stress and time. Lower boundaries may represent limit of resolution of test method.

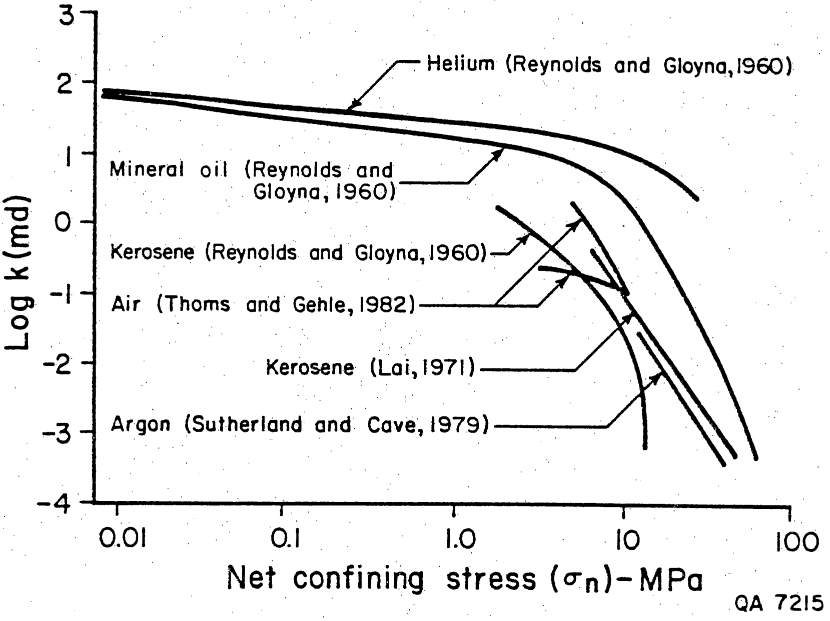

Figure 4. Permeability of salt versus net confining stress (from Isherwood, 1979).

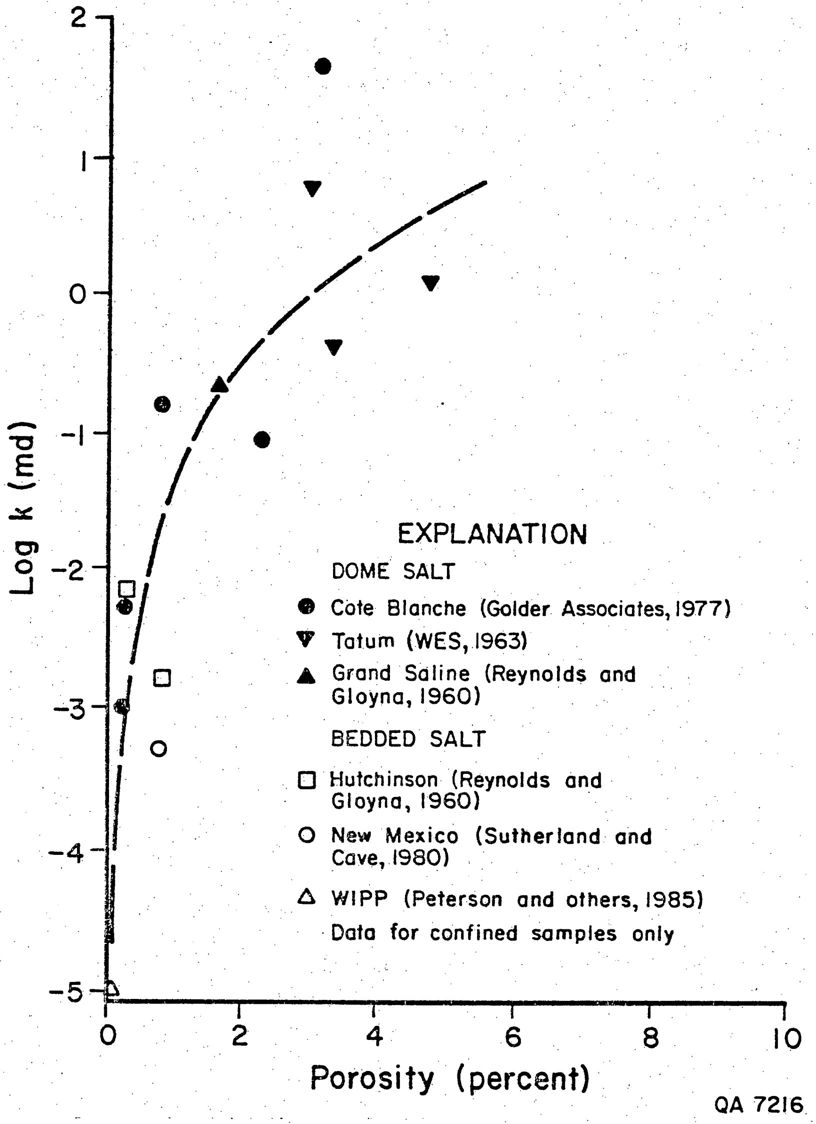

Figure 5. Permeability of dome and bedded salt versus porosity (modified from Kelsall and Nelson, 1985).

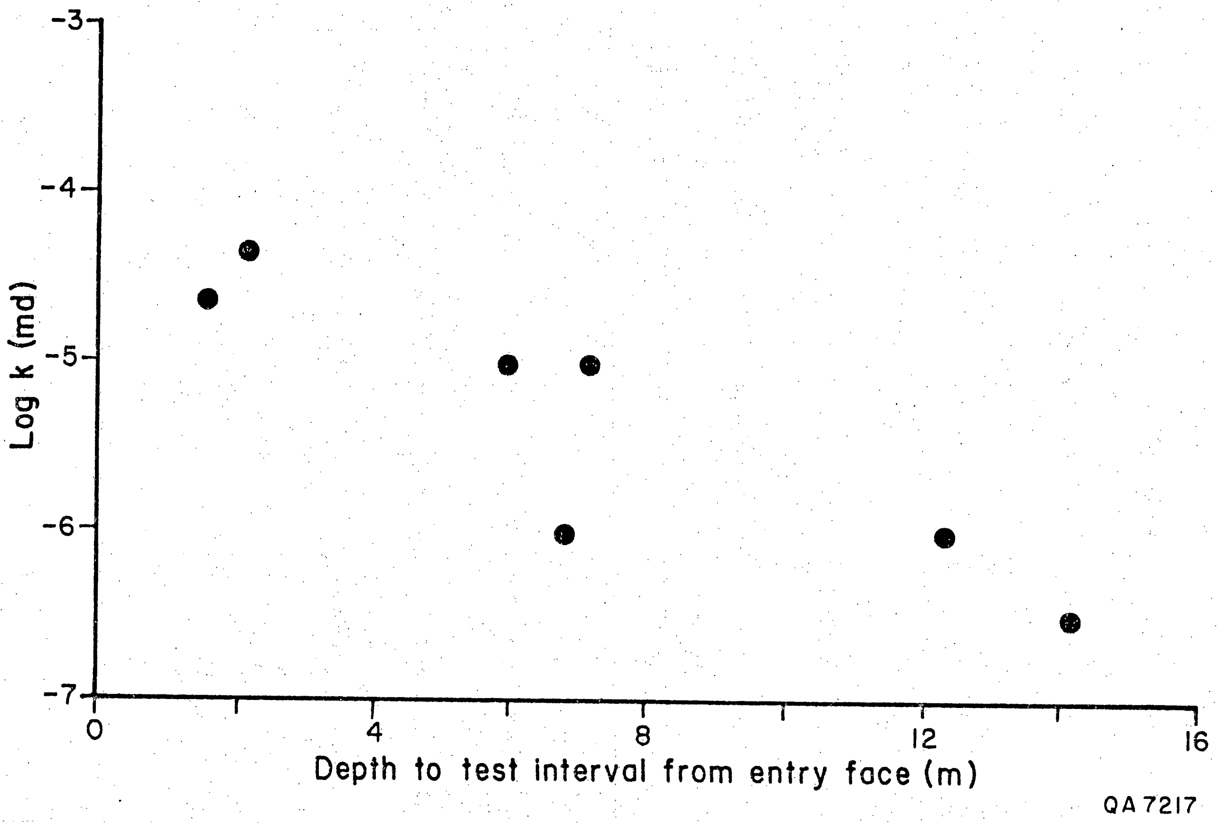

Figure 6. Permeability of bedded salt at the WIPP site versus depth of test interval (from Peterson and others, 1985).

permeability decreases from 10^{-4} to 10^{-6} md as test interval increases over depths of 1 to 14 m (3 to 46 ft) (fig. 6); this is expected because permeability measurements were made progressively away from the entry face in the direction of increasing stress (Case and Kelsall, 1985). Permeability apparently decreases away from an excavation as stress increases to the farfield value, or that beyond the immediate opening at a distance of approximately 5 to 10 radii of the excavation's size (P. C. Kelsall, personal communication, 1985).

Laboratory measurement of salt permeability is unlikely to yield representative in situ values unless the tests are done under high confining stress over periods of at least several months (Case and Kelsall, 1985). In situ testing is also stress dependent but is preferred because sample disturbance is less and fracture anomalies are detectable.

FRACTURING

Fracture Distribution

Permian, Triassic, and Tertiary strata of the Palo Duro Basin are fractured in response to farfield stresses (Hancock, 1985). Fractures in Permian and Triassic rocks commonly strike east-west and northwest-southeast and secondarily northeast-southwest in the northwestern part of the basin; regionally, fractures are uncommon in the Tertiary Ogallala Formation (Collins and Luneau, 1986). In situ stress measurements, following hydraulic fracturing of Permian strata in a Randall County well, indicate that the principal compressive stress is oriented northeast-southwest (Gustavson and Budnik, 1985) and that northwest-southeast trending fractures are closed.

Fracture orientations in the Permian rocks differ slightly from those in the Triassic and Tertiary rocks having the same orientations. Zones of closely spaced vertical fractures (joints) exist in outcropping Permian and Triassic strata along the Eastern Caprock Escarpment and show no evidence of cutting the Ogallala Formation. These zones are inferred from lineament analysis (Finley and Gustavson, 1981) to be widely spaced areally. Zones are 10 to 40 m (30 to 130 ft) wide, extend laterally for at least 1 km (0.6 mi), and have a density of approximately 5 joints per meter. They cut Triassic and upper Permian clastics (Collins and Luneau, 1986), but their full stratigraphic range is unknown. Regan and Murphy (1984) report faults cutting the lower San Andres Formation in eastern Oldham County and one cutting the Alibates Formation. They postulated that most faults in the area do not propagate upward through Permian strata.

Fractures are also reported in Permian evaporites in and about the WIPP site. Vertical, west-northwest oriented, open fractures, associated with gas blowouts, have been encountered in potash mining (McNutt potash zone of the Salado Formation). These dry fractures are continuous for no more than a few tens of feet and indicate en echelon formation or localized explosive activity associated with sudden release of pressure (Chaturvedi, 1984). Brine-filled vertical fractures in the Castile Formation below the Salado have been intercepted in five boreholes at the base of anhydrite units and are believed to be caused by basin tilting to the east (Spiegler, 1982).

Fracture Abundance

The abundance of fractures and filled fractures (veins) in Palo Duro Basin Permian strata have been analyzed in core from six boreholes in Oldham, Deaf Smith, and Swisher Counties (fig. 7). The salt dissolution zone is most fractured, and the Evaporite aquitard is least fractured. Fractures and veins occur in aquitard mudstone, siltstone, carbonate, and impure salt beds and are not visibly evident in pure salt and anhydrite beds. Almost all fractures in the aquitard are probably filled (fig. 8). Fracture frequency in the Wolfcamp aquifer decreases away from the Bravo Dome - Amarillo Uplift (fig. 1), whereas frequency in the Evaporite aquitard is similar in all boreholes (fig. 9).

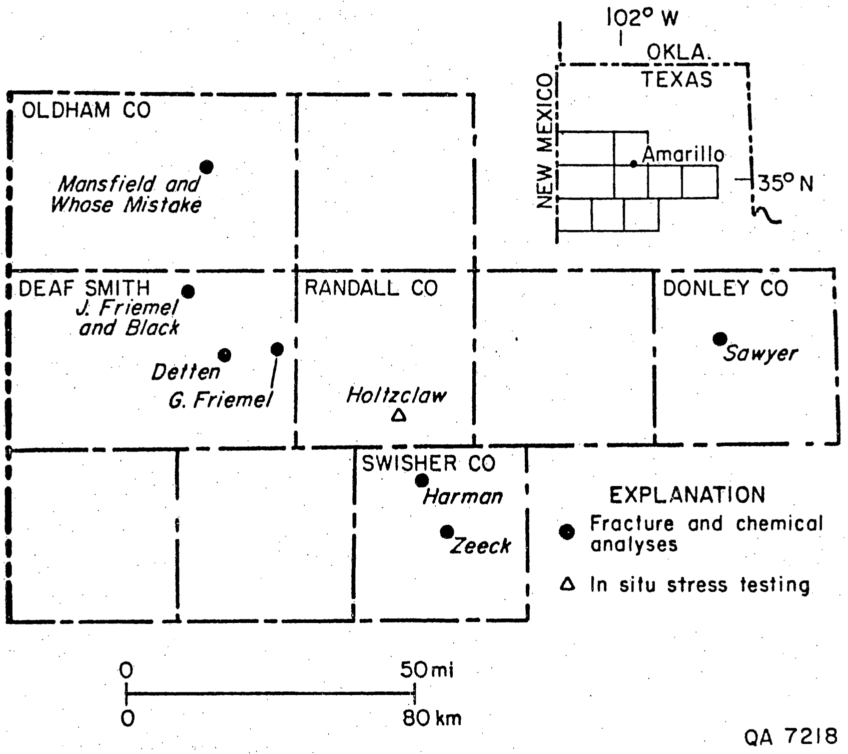

Figure 7. Wells sampled for fracture and chemical analyses.

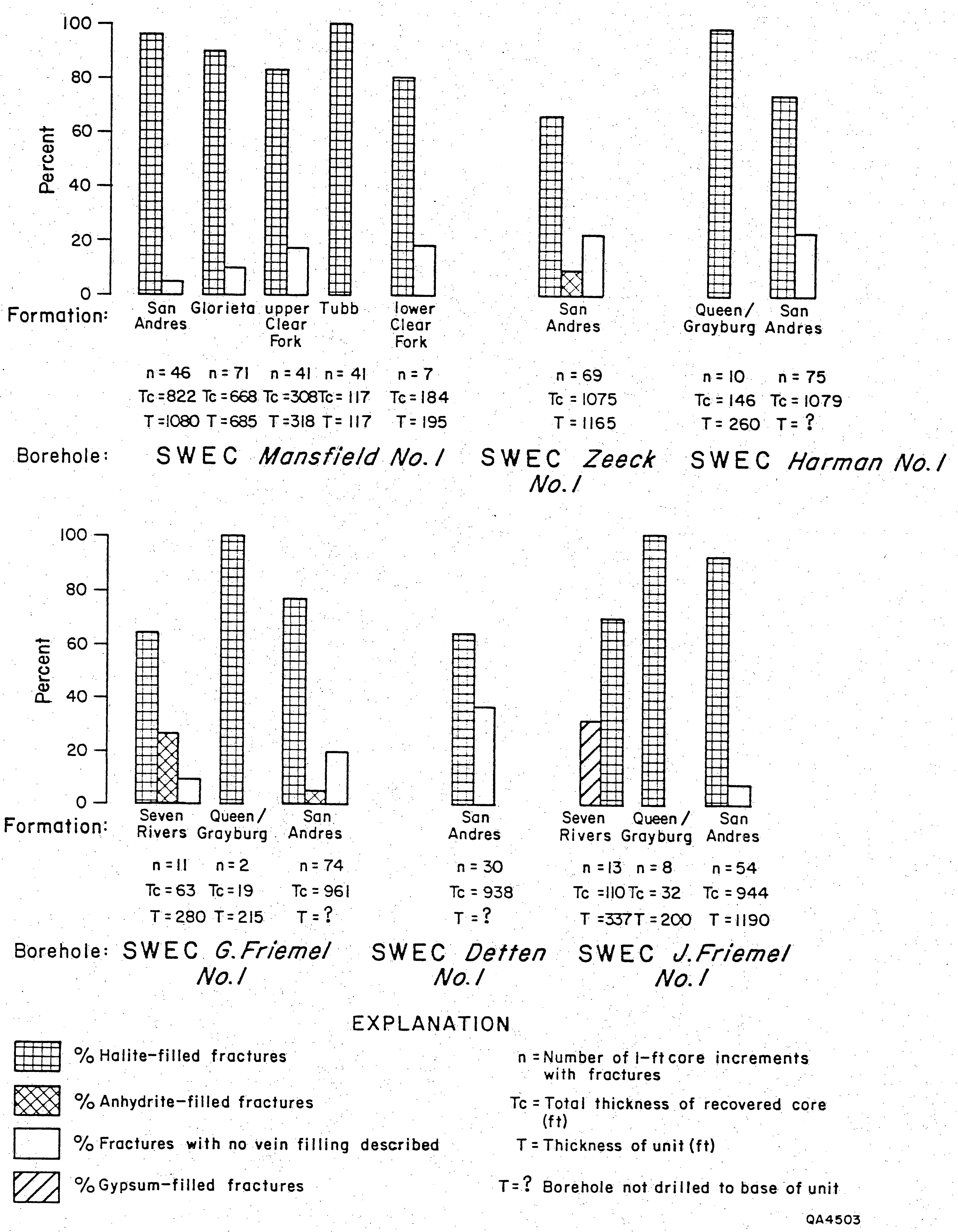

Figure 8. Percentage of filled and unfilled fractures in the Evaporite aquitard (from Collins and Luneau, 1986).

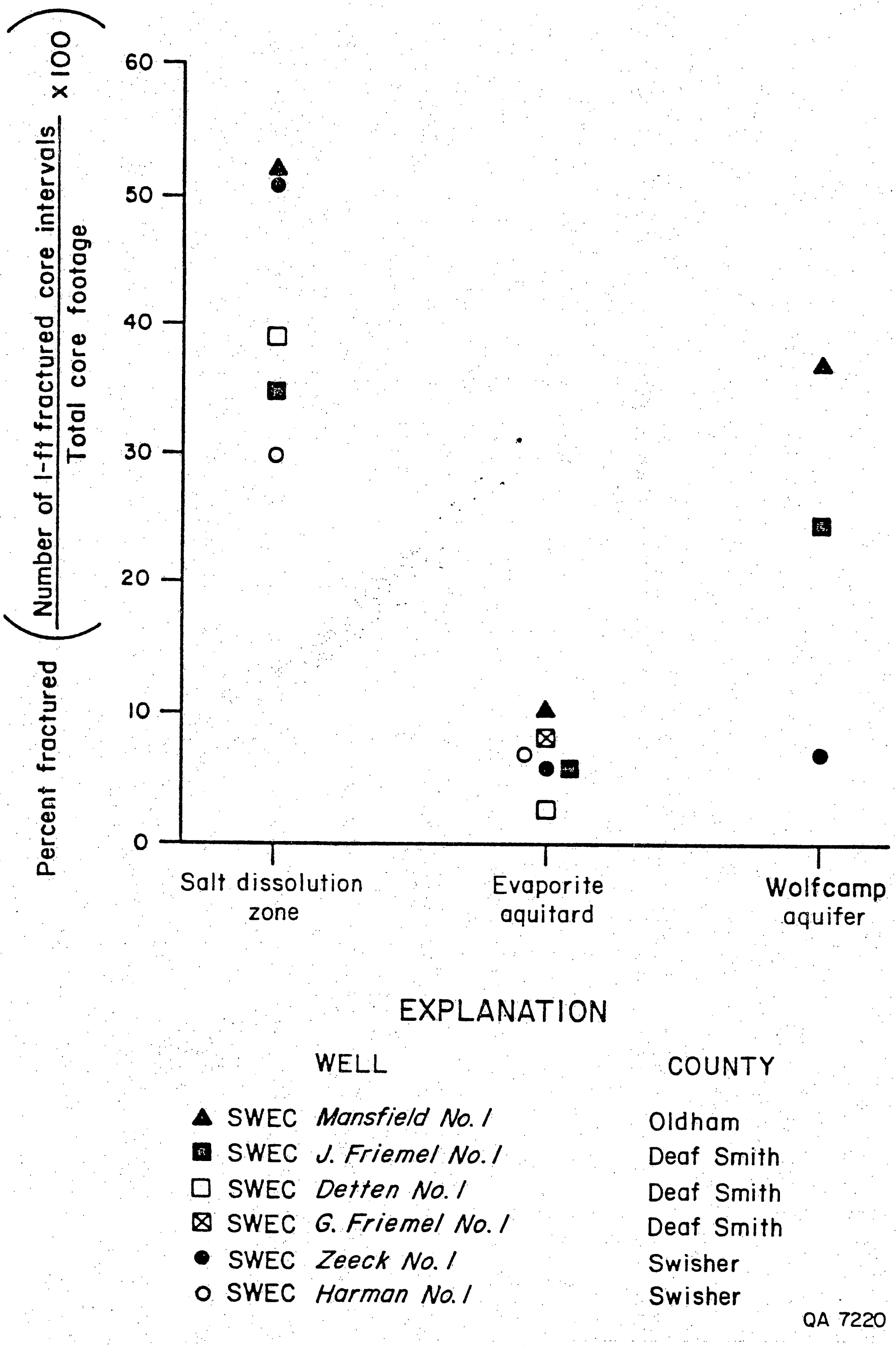

Figure 9. Percentage of fractured core by hydrogeologic unit (from Collins and Luneau, 1986). See figure 7 for well locations.

Vein Mineralogy

Permian strata are commonly cut by gypsum, halite, and calcite veins. Fibrous gypsum veins, 1 to 1.5 cm wide, typify the salt dissolution zone and developed in response to salt dissolution and collapse of overlying strata (Goldstein and Collins, 1984). Orange-red, fibrous halite veins about 1 cm wide are common in clastic and carbonate units and absent in anhydrite units of the Evaporite aquitard. The reddish color is probably due to ferric iron. Their parallelism with regional structural trends suggests development in response to the regional stress field. Rare, thin veins (<3 mm wide) of mosaic calcite and anhydrite and unfilled fractures occur in the Wolfcamp aquifer.

BRINE COMPOSITION

Major Ions and Ratios

Brines in the Palo Duro Basin are Na^+- and Cl^--dominated, having total dissolved solids (TDS) contents of 68 to 384 g/L. In the salt dissolution zone and San Andres unit 4 carbonate, Na^+ content ranges from 24 to 68 g/L with chlorinities of 36 to 250 g/L (Dutton, 1985; Dutton and Orr, 1986). Total dissolved solids and chlorinities in the Deep-Basin Brine aquifer are intermediate to these and range from 140 to 290 g/L and 86 to 180 g/L, whereas Na^+ content ranges from 43 to 88 g/L (Fisher and Kreitler, 1987).

Among samples from the Deep-Basin Brine aquifer, two groups are chemically evident, Wolfcamp and granite wash/carbonate. Wolfcamp brines are Na^+-dominated, generally contain less Cl^-, and have lower Ca/Mg ratios (3.9 versus 7.3). Wolfcamp Na/Cl weight ratios are high (about 0.58) relative to those in granite wash/carbonate brines and very high relative to San Andres brines (0.085 and 0.33) (fig. 10). Those of the salt dissolution zone are closest to 0.65, the weight ratio for a brine derived solely from halite dissolution. Wolfcamp chlorinities are relatively low (<138 g/L), whereas those of the San

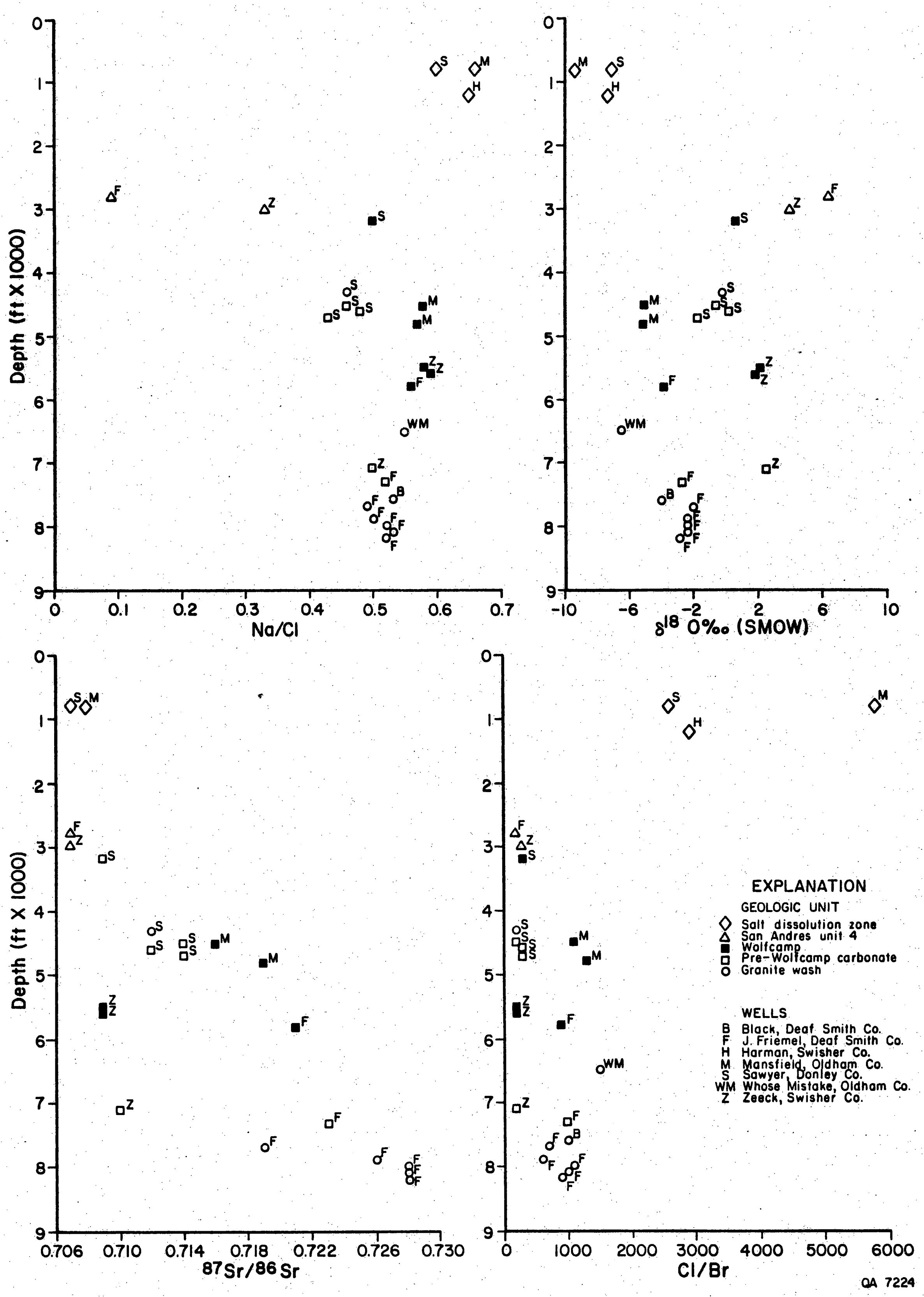

Figure 10. Na/Cl and Cl/Br weight ratios, $\delta^{18}O$ values, and $^{87}Sr/^{86}Sr$ ratios by depth and geologic unit. Chemical analyses from Dutton, 1985; Fisher and Kreitler, 1985; and Dutton and Orr, 1986. See figure 7 for well locations.

Andres are high (207 and 250 g/L). The Wolfcamp mean Ca/Mg ratio is similar to that of the salt dissolution zone (3.8) and dissimilar to the San Andres value (5.4).

Chloride/bromide ratios are large in the salt dissolution zone, characteristic of halite dissolution by meteoric water (Whittemore and Pollock, 1979). Basinal waters group about two Cl/Br ratios: 250 and 1,000 (fig. 10), the former from samples in the central and eastern basin and the latter from samples in the northwestern part of the basin. Brines having small Cl/Br ratios (200 to 300) result from equilibration of brine and halite (Land and Prezbindowski, 1981) or as residuals of marine origin from which halite has precipitated (Holser, 1979) and are typical of oil field brines (Collins, 1975). Ratios of approximately 1,000 indicate dissolution of marine salt (Holser, 1979).

Oxygen and Strontium Isotopes

Brines of the salt dissolution zone are isotopically light and lie on the meteoric water line, having oxygen isotope compositions ($\delta^{18}O$ of −7 to −9 ‰) consistent with values of rainfall on the Southern High Plains and of shallow ground water in eastern New Mexico and the Texas Panhandle (Dutton, 1985). San Andres brines are isotopically heavy ($\delta^{18}O$ of +4.0 to + 6.4 ‰) with respect to San Andres carbonates which in turn are heavy with respect to meteoric water. San Andres brines and fluid inclusions of inferred Permian origin in chevron halite crystals are isotopically similar (Dutton and Orr, 1986; Knauth and Beeunas, 1986). Brines from the Deep-Basin Brine aquifer have variable isotopic compositions depending on geographic location. Those from the central and eastern basin have $\delta^{18}O$ values that range from −1.7 to +2.5 ‰ and approach isotopic equilibrium with calcite and dolomite (Fisher and Kreitler, 1985; Kreitler and others, 1985), whereas brines from the northern basin margin are isotopically light (−4.0 to −6.5 ‰), similar to the isotopic composition of waters in the Upper aquifer, falling close to the meteoric water line. Isotopically heavy brines have small Cl/Br ratios (about 250), and light ones large ratios (600 to 1,500) (fig. 10). In the northwestern basin, deep brines are at isotopic disequilibrium with calcite and have intermediate $\delta^{18}O$ values (-2.0 to -3.8 ‰) that appear to indicate a mixture of basinal and meteoric waters (Kreitler and others, 1985). Clearly, deep-basin brines in the northwest contain a significant amount of isotopically light, nonequilibrated fluid whose volume has been estimated from oxygen isotopic mass balance to be approximately 50 percent (Fisher, 1984) and, from simple mixing calculations, as high as 75 percent (Kreitler and others, 1985).

Kreitler and others (1985) called upon leakage and fracture flow through the Evaporite aquitard to explain the presence and geographic distribution of meteoric water in the Deep-Basin Brine aquifer. Greater fracture abundance in the northwest basin is correlated with isotopically light water. Fisher and Kreitler (1987) interpreted the same facts in terms of lateral flow, length of flow path, and dominant lithology along the flow path. Brines in the northwestern basin originated as meteoric recharge, entered the subsurface in eastern New Mexico, and flowed northeastward largely through siliciclastics, whereas brines in the central and eastern basin entered the flow system to the southwest and flowed across the Midland Basin through dominantly carbonate aquifers to achieve isotopic equilibrium.

Differences in brine $^{87}Sr/^{86}Sr$ ratios also appear to reflect differences in lateral travel paths. Basinal ratios range from 0.707 to 0.728 where the least radiogenic ratios (0.707 and 0.708) are from San Andres brines and those of the salt dissolution zone. All deeper brines are more radiogenic (fig. 10). Those from the northwestern part of the basin are more radiogenic (0.716 to 0.728) than those of the central and eastern basin (0.709 to 0.714). Fisher and Kreitler (1987) suggest that brines flowing westward have relatively short flow paths, largely through arkosic rocks, whereas those entering from the Midland Basin have long flow paths through dominantly carbonate rocks. Consequently, brines in the northwest are thought to have acquired their radiogenic Sr from detrital potassium-bearing silicates, whereas those passing through carbonates would acquire little radiogenic Sr.

BROMIDE IN HALITE

Bromide content in halite initially precipitated from evaporating sea water is 65 to 75 ppm Br^-. Upon further evaporation and precipitation, Br^- increases, reaching 2,300 ppm in the brine and 270 ppm in the halite at the beginning of sylvite precipitation (Valiashko, 1956). Halite recrystallized or recycled by seawater or fresh water will have reduced bromide content and can be as low as 10 ppm and 3 ppm, respectively (Holser, 1979).

Modal concentrations of bromide in bedded and recrystallized halite are 35, 75, and 45 ppm, respectively, in the Clear Fork and Tubb, lower San Andres, and upper San Andres Formations (Collins and Luneau, 1986) (fig. 11). Bromide-depleted salt in the Clear Fork and upper San Andres is the result of recrystallization from low-bromide water nearly contemporaneous with initial halite precipitation or post-Permian meteoric ground water. Bromide content in vein halite for each formation falls within the range for bedded halite, having modes of 55, 105, and 85 ppm, respectively. Overall similarity of bromide values in vein and bedded halite indicates precipitation from brines of similar salinity formed in the course of evaporite sedimentation. In fact, higher modes in vein halite suggest its precipitation from slightly more saline brines somewhat enriched in bromide.

EVAPORITE PETROGRAPHY

Halite textural types have been assigned primary, synsedimentary, early diagenetic, or post-Permian dissolution origins by petrographically comparing bedded halite (Hovorka, 1983a; Hovorka and others, 1985a) with that of the salt dissolution zone (Hovorka, 1983b). Permian dissolution is evidenced by truncation of zoned halite crystals, formation of shallow, disconnected vertical pits in bedded halite, thin, insoluble residues having a chaotic intraclastic texture, and dark, thick, pyritic insoluble residues. Post-Permian dissolution fabrics probably resulted from the movement of large volumes of meteoric ground water into and through evaporite rock sequences. Complete removal of halite,

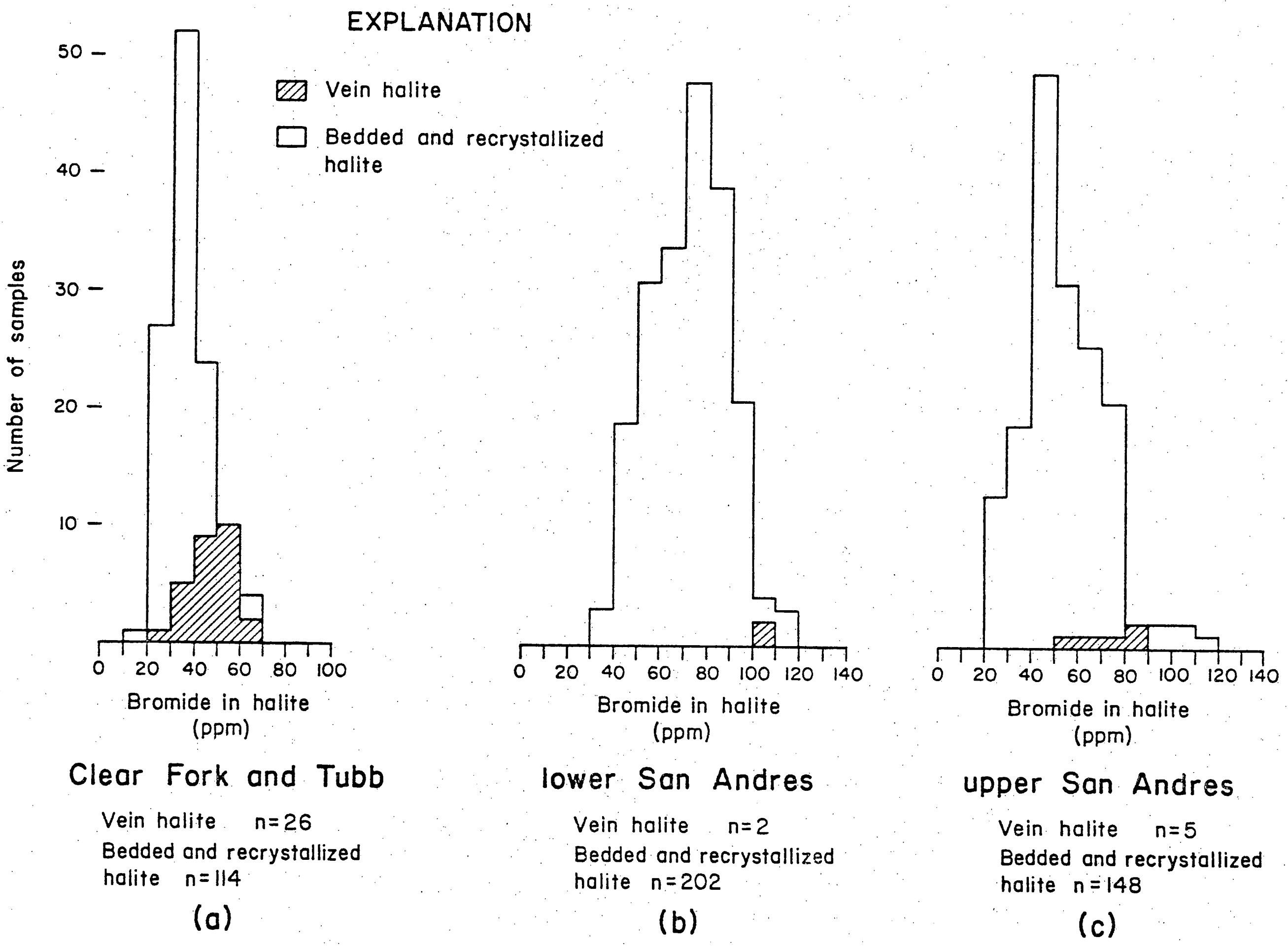

Figure 11. Bromide content in bedded and recrystallized halite and vein halite (from Collins and Luneau, 1986).

high-amplitude, wavily bedded insoluble residues, large-scale collapse breccias, and hydration of anhydrite to gypsum are common features. Dissolution of halite results in formation of insoluble residues and loss of volume, which results in formation of breccias (mainly gypsum) and horizontal fractures filled with vertically oriented, fibrous gypsum. In unaltered evaporites, all $CaSO_4$ is in the form of anhydrite. Upon contact with cool, low-ionic-strength ground water, anhydrite hydrates to gypsum at the top and bottom of beds, along bedding planes and vertical cracks, and in isolated patches. Recrystallization of halite can occur at any time and is evidenced by mudstone stringers within large halite crystals, presence of large, equant crystals, and absence of fluid inclusions near crystal boundaries.

DISCUSSION

Pressure-depth data, head distribution, and numerical modeling clearly indicate the potential for downward, vertical flow of ground water (leakage) regionally through the Evaporite aquitard with some possible lateral diversion by permeable carbonates. Major evidence cited for leakage is the presence in the northwestern Palo Duro Basin of brines in the Deep-Basin Brine aquifer having a meteoric isotopic signature. Meteoric water may have been derived from the overlying Upper aquifer, and salinity presumably by passage through the Evaporite aquitard. The presence of meteoric water can also be explained by lateral flow. Such brines would acquire their salinity early in their flow history through dissolution of salt by meteoric water in the shallow subsurface of eastern New Mexico and would be recharged eastward, as suggested by Bassett and Bentley (1983) (fig. 2). They would have the meteoric signatures--isotopically light, high Na/Cl ratios, and large Cl/Br ratios--seen in some of the Wolfcamp brines. Thus, a plausible alternative can account for meteoric water in the basinal brines provided that New Mexican recharge water is not isotopically too light (Senger and Richter, 1983) to accommodate values measured in the deep brines .

Hydraulic heads show only the potential direction of ground-water flow, whereas chemical composition records actual ground-water or mass movement. If ground-water flow through the Evaporite aquitard is large, there must be significant movement of dissolved ions (mass) into the Deep-Basin Brine aquifer. Numerical models indicate that leakage contributes about 50 percent of the flow through the Wolfcamp aquifer, implying significant mass transfer from the Evaporite aquitard to the Wolfcamp aquifer. Such transfer is not reflected in the chemical composition of San Andres and Wolfcamp brines. Comparison made between them using chloride, the major ion least affected by water-rock interaction, shows that chlorinities in the San Andres are approximately twice those in the underlying Wolfcamp and that they increase in the Deep-Basin Brine aquifer with depth below the salt.

Compositional stratification of basinal brines is further reflected in $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ and Cl/Br ratios. San Andres $\delta^{18}O$ values are much heavier than those in the underlying Wolfcamp (fig. 10) and are enriched relative to values predicted for isotopic equilibration between brine and carbonate host rock (Dutton and Orr, 1986), suggesting the presence of evaporatively concentrated Permian connate water (Knauth and Beeunas, 1986). San Andres $^{87}Sr/^{86}Sr$ ratios (0.707) are similar to Guadalupian (Permian) seawater values (Burke and others, 1982) and less radiogenic than Wolfcamp ratios (0.709 to 0.721), which vary widely regionally and locally. Large ratios in the northwest basin (0.716 to 0.721) are more readily explained by lateral flow along a long flow path through potassium-rich arkoses than by cross-formational flow along a short flow path through evaporites and carbonates of the Evaporite aquitard. Moreover, in the northwest the vertical difference in ratios is very substantial, 0.716 to 0.719 over a 300-ft (90-m) carbonate interval (Posey, 1985). San Andres Cl/Br ratios are small (259 and 212) and indicative of evaporatively concentrated seawater or of brines in equilibrium with halite rather than of active dissolution of marine salt (fig. 10). Thus, San Andres $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ and Cl/Br ratios reflect a sluggish hydrodynamic system and hydrologic isolation of the salt.

San Andres brines bear Permian chemical (Na^+ depletion, K^+ enrichment) and isotopic signatures (similar $\delta^{18}O$ values in brines and fluid inclusions) and are believed to represent modified marine connate brines (Dutton and Orr, 1986). Bein and Land (1982) postulated basinwide production of Na-depleted brines by evaporative concentration of seawater and halite precipitation. The presence of connate water is consistent with low San Andres Na/Cl ratios, which resemble those in highly evaporated seawater and halite fluid inclusions produced during evaporite sedimentation or by subsequent participation in dolomitization (Hubbard and others, 1984; Roedder, 1984).

The amount of potential leakage through the Evaporite aquitard depends primarily on vertical permeability in the aquitard. Computed Darcian leakage rates through the aquitard vary directly with permeability and are very small, hundredths to thousandths of a µm/d. The Ogallala-Dockum head difference serves to further reduce computed leakage by up to 50 percent or more. If pores and microfractures are very small and flow is non-Newtonian, then leakage rates will be even lower (Remson, 1984).

The permeability range estimated from numerical ground-water models is 8×10^{-5} to 2.8×10^{-4} md, or approximately 10^{-4} md, and is in general agreement with laboratory measurements. However, this value may be an upper limit. Laboratory and in situ testing confirm that the permeability of salt is stress dependent, and therefore measured values probably overestimate true in situ permeability. At the WIPP site, competent bedded salt was found to have a permeability of less than 10^{-5} md and an approximate porosity of 0.001 (0.1 percent). Values of 10^{-6} md and less were measured (fig. 6) at presumed higher stress levels.

If the permeability of salt is 10^{-4} md, the computed leakage rate is 6×10^{-8} m/d and the contribution of leakage to Wolfcamp flow 50 percent; however, if permeability is

10^{-5} md, leakage is 6×10^{-9} m/d and the contribution 5 percent. The latter contribution is minor and probably would not be reflected in the brine chemistry.

Permo-Triassic rocks in the Palo Duro Basin are fractured, and therefore fracture flow is possible. In view of salt's extremely low matrix permeability, significant matrix flow is unlikely, leaving fracture flow the only possible alternative mode for cross-formational flow. Evaluation of that possibility awaits future research. Veining proves that ancient fracture flow occurred and open fractures, though rare and of limited continuity, do occur in bedded salt. Densely fractured zones at the outcrop are narrow and widely spaced, representing a small percent of the total area available and subject to flow, and probably do not fully penetrate the Evaporite aquitard. Potential for fracture flow is greatest in these zones and cannot be adequately modeled using the cubic law. Because almost all fractures in the aquitard are closed by mineral fill or in response to the regional stress field, fracture permeability is postulated to be low. Analogy with more competent crystalline rocks suggests that fracture permeability may be no more than an order of magnitude greater than matrix permeability.

Bromide values in vein (fracture-fill) and bedded halite are similar and do not support distinct post-Permian dissolution events. In fact, bromide values are apparently higher in vein halite than in bedded and recrystallized halite and may indicate precipitation from late-stage, evaporatively concentrated brines enriched in bromide. Retention of high bromide levels in bedded salt (particularly in lower San Andres salts), dominance of halite textural types assigned syndepositional or early diagenetic origins, and absence of gypsum show that only the salt dissolution zone has experienced post-Permian dissolution.

CONCLUSION

The potential exists for downward flow of ground water (leakage) from the Upper aquifer, through the Evaporite aquitard, and into the Deep-Basin Brine aquifer, but compositional stratification of brines and the inferred presence of Permian connate water in the aquitard rules out substantial cross-formational mass exchange, or vertical mixing. The permeability of bedded salt is very low (about 10^{-5} md), and computed leakage through the Evaporite aquitard is very small (about 6×10^{-9} m/d). Thus, the volume of water moving through an area of 25 km^2 (9 mi^2) is minimal, on the order of 0.15 m^3/d (40 gal/d) or less. Fracture flow should be minor and discrete. Hydrologic isolation of the salt is further indicated by similarity of bromide values in vein and bedded halite, by high bromide content of bedded salt, and by dominance of syndepositional and early diagenetic halite textures. Available geochemical and petrographic evidence shows that leakage through the Evaporite aquitard, or cross-formational flow, is very slight.

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