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THE ARTESIA GROUP AND SALADO FORMATION (GUADALUPIAN/OCHOAN) OF PALO DURO BASIN: DEPOSITIONAL SYSTEMS AND EFFECTS OF POST-PERMIAN SALT DISSOLUTION

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ABSTRACT

Interbedded red sandstone, siltstone, mudstone, anhydrite, and halite comprise the Artesia Group and Salado Formation (Guadalupian/Ochoan) of the Palo Duro Basin (fig. 1). These deposits accumulated in a 10,000-mile^2 low-relief epicontinental basin that was characterized by regional aridity and episodic, nearly basinwide influx of marine-derived hypersaline waters. A variety of depositional environments developed in this basin including eolian dunes, interdune areas, eolian flats, intermittent fluvial, mud flats, and broad, shallow brine pans. Clastic sources were in the west and northwest whereas evaporites were derived from the south.

Eolian dune deposits are represented by medium to high angle (15°-35°) cross-bedded fine sandstone. Interdune areas accumulated rippled, bimodal, medium to very fine sandstone with frosted, spherical, medium sand grains and pedogenic structures. Eolian flats are characterized by deposits of very fine sandstone with poorly defined ripples. Intermittent fluvial deposition resulted in very fine sandstones and siltstones with graded bedding, ripples with mud drapes, and intraclasts. Mud-flat deposition produced mudstones with very disturbed ripples. Bedded halite and anhydrite were precipitated in brine pan environments. Landward margins of brine pans are characterized by deposits of sandstone and siltstone with displacive halite to chaotic halite-mudstone rock.

Artesia and Salado facies occur in a characteristic vertical sequence that comprises, from base to top, bedded anhydrite, bedded halite, chaotic halite-mudstone, sandstone, and siltstone with displacive halite, very disturbed rippled mudstone, intermittent fluvial, and eolian clastics. The sharp contacts between these shallowing-upward sequences suggest that transgressions were rapid.

Subsequent to upper Permian deposition, undetermined amounts of halite strata have been removed by dissolution. This resulted in truncation of halite beds and collapse and diagenetic alteration in overlying strata.

INTRODUCTION

The Artesia Group and Salado Formation in the Palo Duro Basin of the Texas Panhandle (fig. 1) comprise Upper Permian red beds (sandstone, siltstone, and mudstone) and evaporites (anhydrite and halite) that were deposited under arid conditions in a low-relief, shallow epicontinental basin. The section includes evaporites of the upper Seven Rivers, Tansill, and Salado formations and dominantly regressive red sandstones, siltstones and mudstones of the Grayburg, Queen, lower Seven Rivers, and Yates formations (figs. 2 and 3). The section is underlain by the San Andres Formation and overlain by the Alibates Formation. Collectively, these units record deposition during late stage Permian infilling of the Palo Duro Basin. This report addresses the stratigraphy and distribution of depositional facies of the Artesia Group and Salado Formation within the Palo Duro Basin, presents a depositional/paleogeographic model, and addresses briefly aspects of halite dissolution within the evaporite bearing section. Special emphasis is placed on the Queen/Grayburg formation because salt-dissolution has not affected it greatly in the study area; therefore, original facies relations are preserved. It may be used as a model of comparison for the dissolution-affected formations within the basins.

Stratigraphic nomenclature has not been formally established for geologic units in the Palo Duro Basin. However, regional correlations of well logs and outcrops are possible (Tait and others, 1962) and lithologic units in Palo Duro Basin can be correlated with lateral equivalents in the Midland and Delaware Basins. Stratigraphic nomenclature in this report follows that used in previous studies of the Palo Duro Basin (Nicholson, 1960; McGillis and Presley, 1981) and that used in the Midland and Delaware Basins (Silver and Todd, 1969; Hills, 1972). Regional stratigraphic relationships are shown in figures 4 and 5. Figure 4 (Hills, 1972) shows the relationship of the post-San Andres Permian formations to the Guadalupian Reef complex. Figure 5 (McGillis and Presley, 1981) extends this nomenclature into the Palo Duro Basin. During deposition of most of the Artesia Group

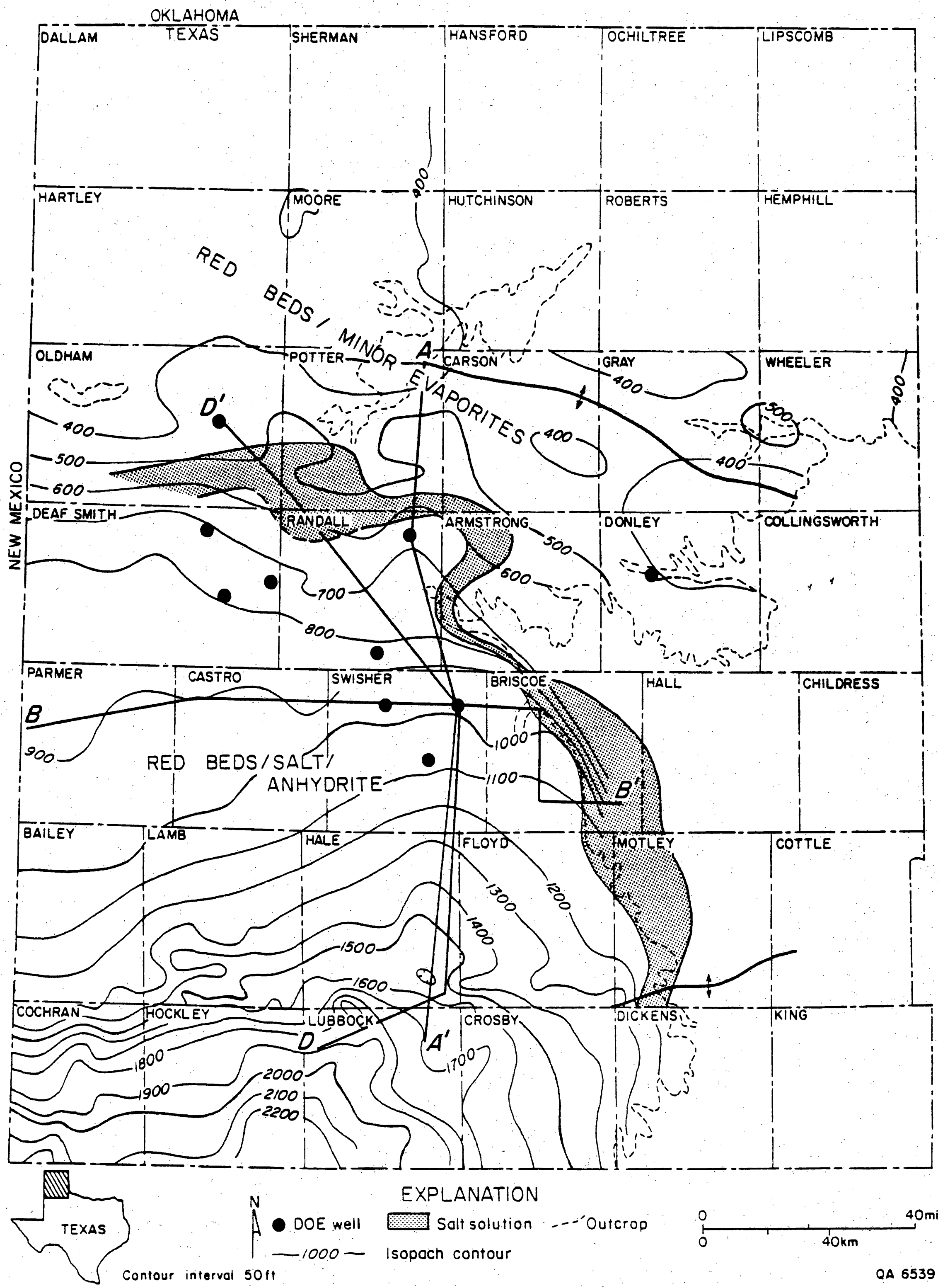

Figure 1. Post San Andres Permian formations, Texas Panhandle: isopach, general lithologic associations, and lines of cross section. Also includes relatively thin Alibates/ Dewey Lake interval. Crosshatched areas indicates Artesia Formation residual halite in the dissolution zone.

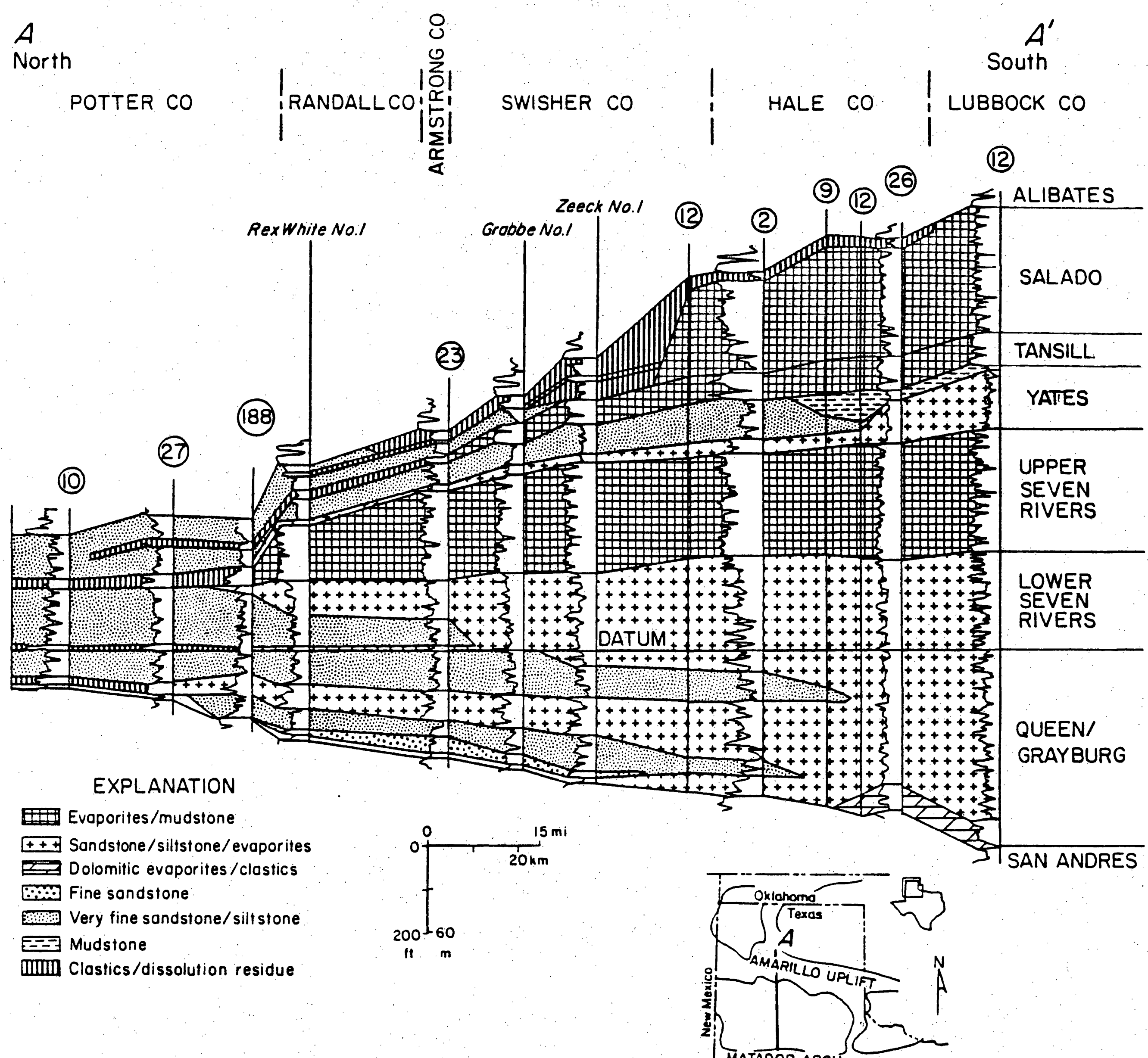

Figure 2. Artesia Group, Palo Duro Basin: north-south cross section A-A'. T: Tansill clastic member (see fig. 13); L, M, U: Queen lower, middle, and upper evaporite cycles.

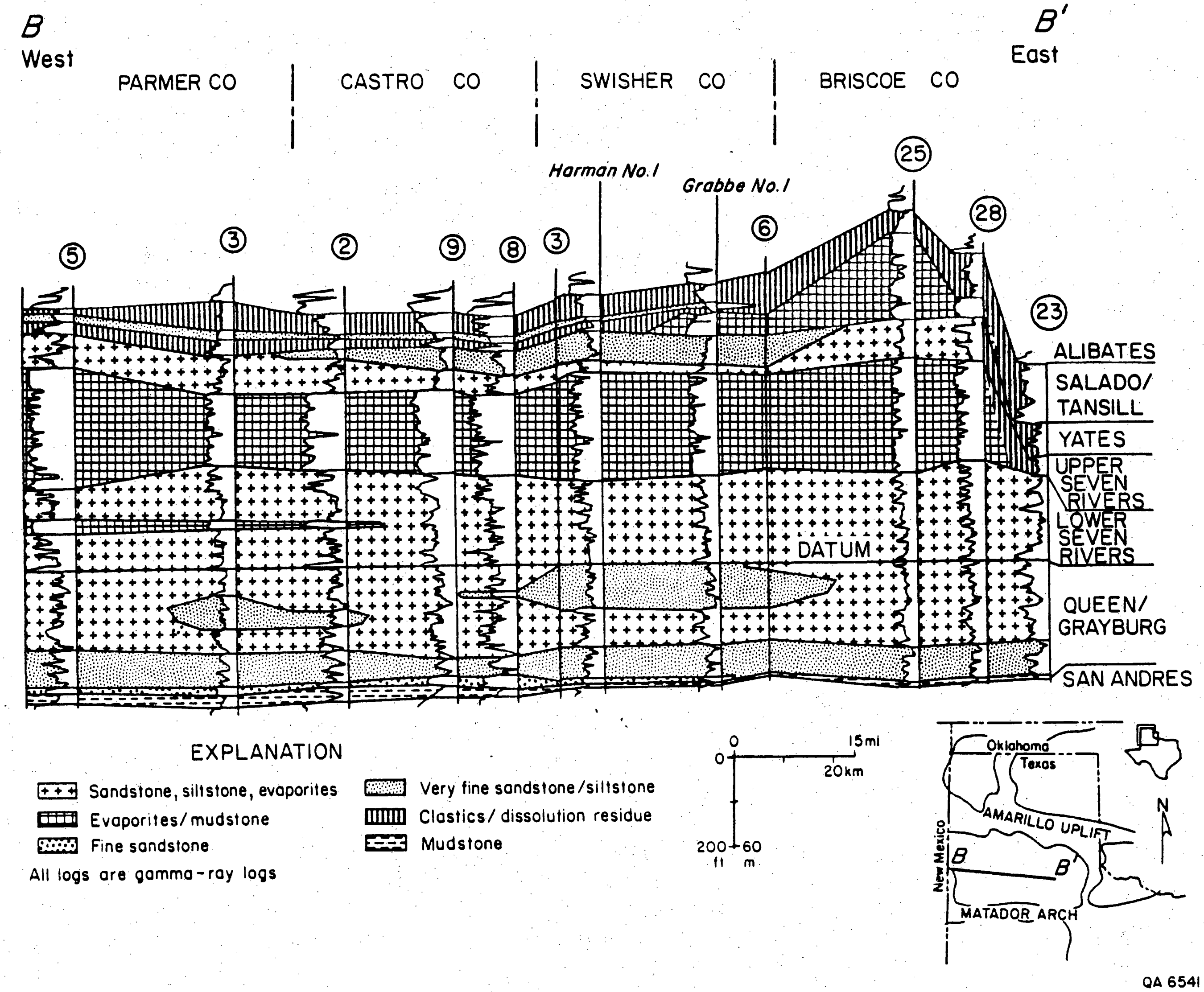

Figure 3. Artesia Group, Palo Duro Basin: west-east cross section B-B′.

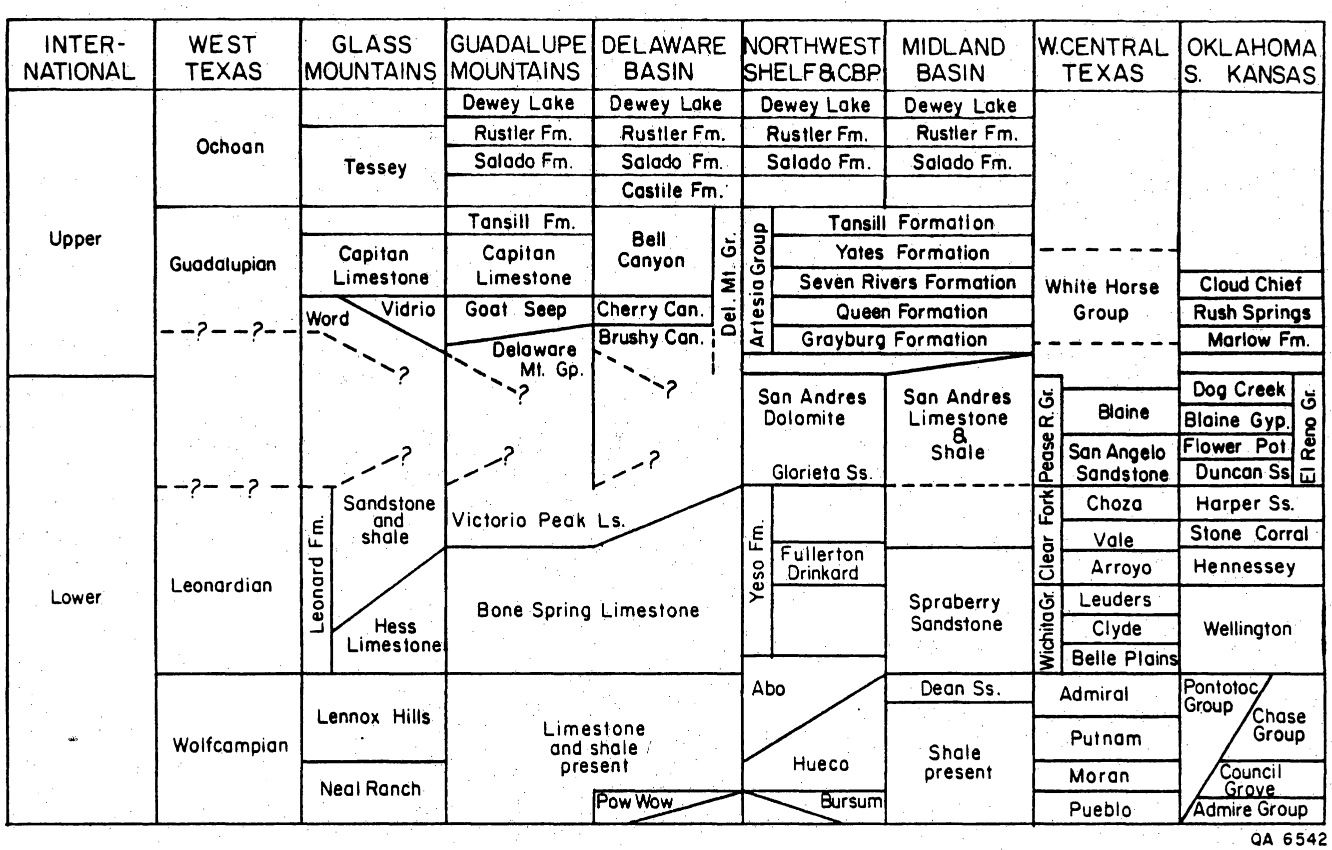

Figure 4. Stratigraphic chart for the Permian Basin (Hills, 1972).

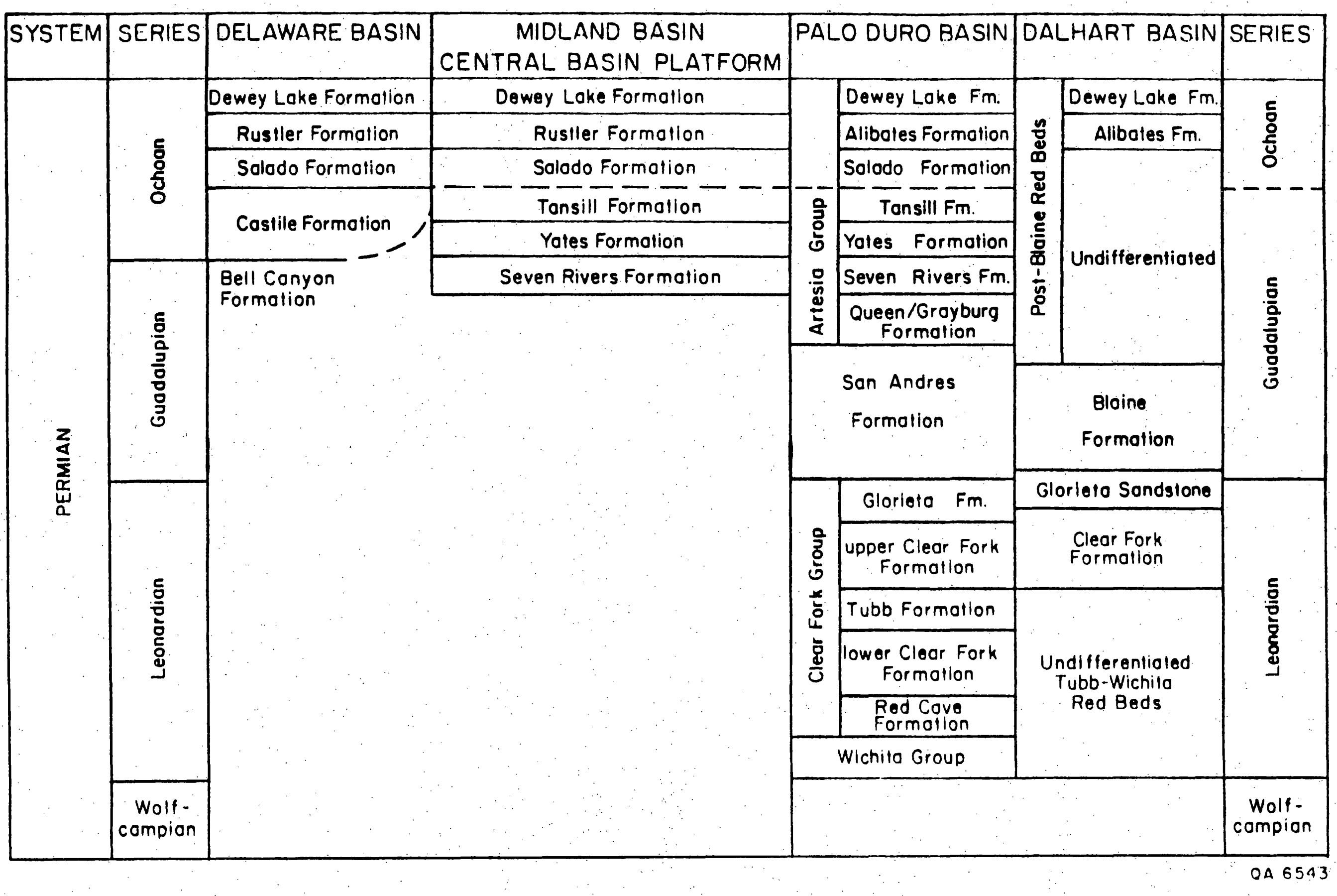

Figure 5. Stratigraphic chart for the Texas Permian Basin, including the Palo Duro Basin (McGillis and Presley, 1981).

and Salado Formation the Palo Duro Basin was a locus of alternating terrestrial, shallow shelf, and hypersaline environments (fig. 6). Facies characteristics and their spatial distributions are the result of the interplay of relative sea level change, differential tectonic subsidence, and clastic sediment supply in a broad, shallow basin whose surface topography consistently stood close to sea level.

The Palo Duro Basin is one of several adjacent Pennsylvanian/Permain depocenters which included the Delaware Basin, Midland Basin, and Northwest Shelf of Southern New Mexico. The Palo Duro Basin developed north of the Midland Basin during the Pennsylvanian. In the southern Texas Panhandle, it is bounded on the south and separated from the Midland Basin by the Matador Arch. To the north, it is bounded by the Amarillo Uplift and the Bravo Dome, or Oldham Nose (fig. 7). During the Pennsylvanian clastic sediment was supplied to the Palo Duro Basin from uplifted elements mostly to the north and west while marine shelf limestones were deposited in the south. Commencing with the upper Wolfcamp in early Permian time, carbonate and anhydrite, and siliciclastic deposition dominated the basin. After early Wolfcamp deposition, the Palo Duro Basin became less distinct and functioned essentially as a northern extension of the Midland Basin, although its structural boundaries (the Amarillo Uplift and Matador Arch) continued to subtly affect deposition. Overall shallowing characterized the remaining Permian (Dutton and others, 1979), resulting in the deposition of dolomite, gypsum, halite, and red beds. Maximum evaporite accumulation is recorded in the San Andres while maximum clastic accumulation is recorded in the immediately overlying Grayburg Formation, the basal formation of the Artesia Group. The end of Salado sedimentation was signaled by a marine transgression that resulted in the deposition of the Alibates carbonates, gypsum (calcium sulfate), and clastics. The final regressive phase of Permian deposition in the Palo Duro Basin is recorded by the Dewey Lake red beds which overlie the Alibates Formation and, probably unconformably, underlie the Upper Triassic Dockum Group fluvial and lacustrine deposits. Subsequent to deposition various amounts of halite were dissolved

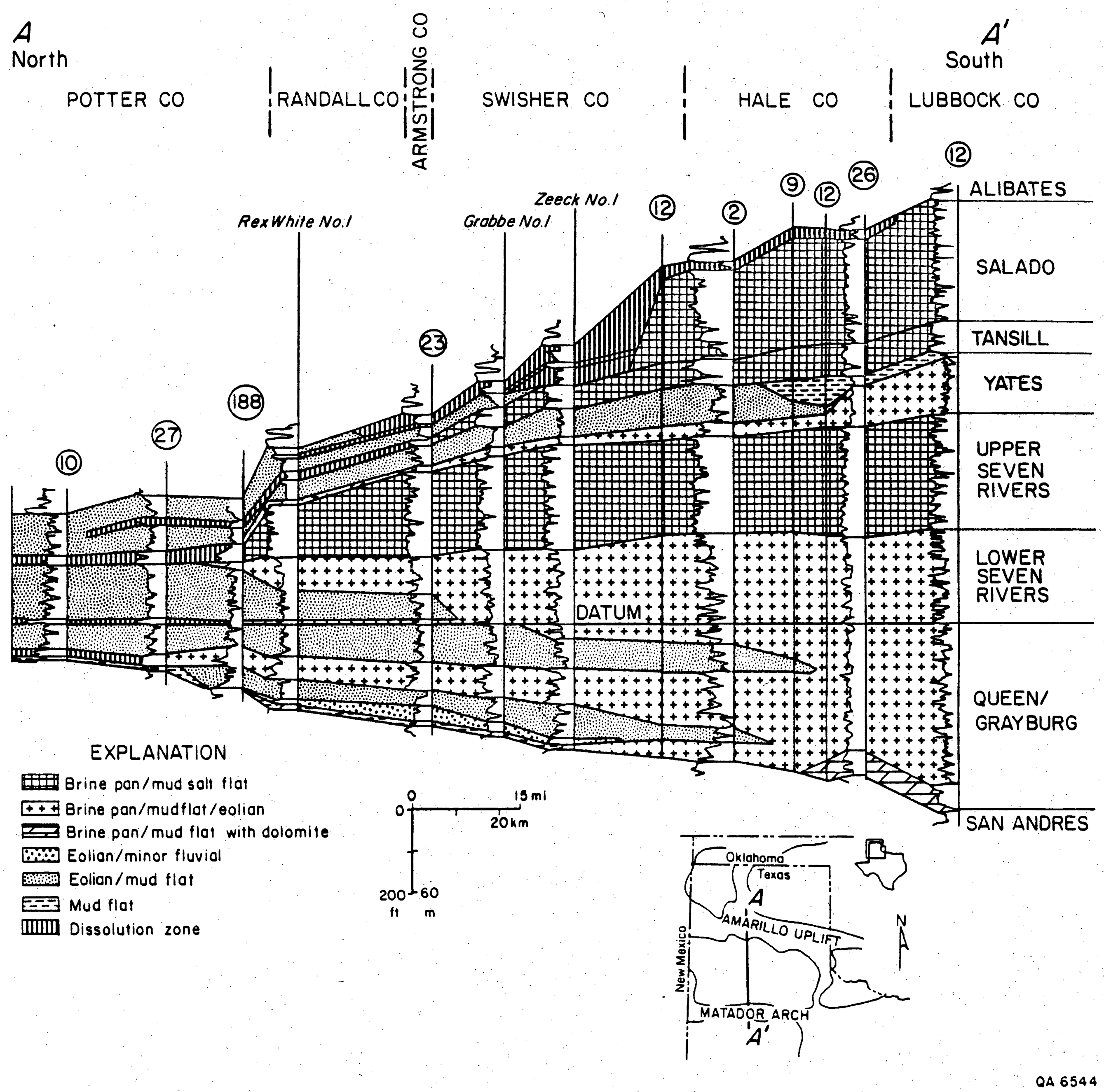

Figure 6. Artesia Group, Palo Duro Basin: Facies associations and depositional systems. T: Tansill clastic member; L, M, U: Queen lower, middle, and upper evaporite cycles.

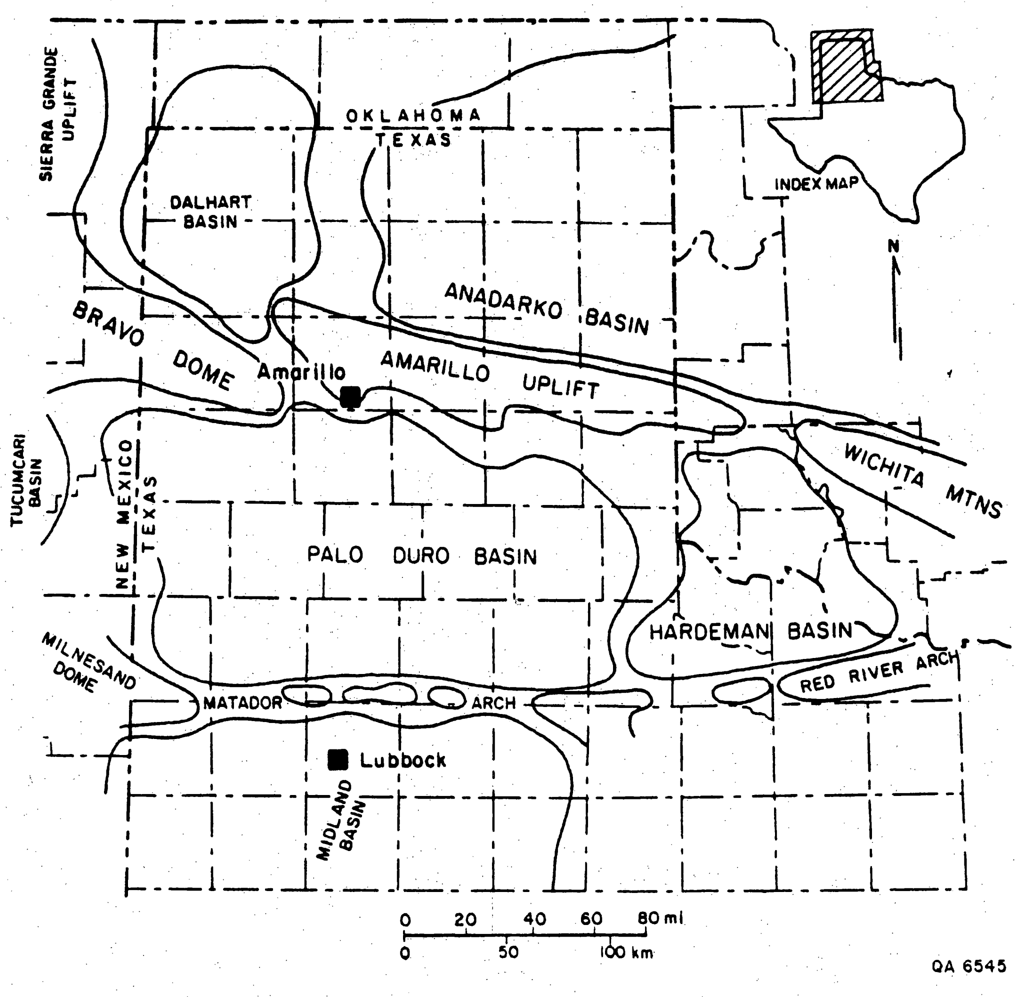

Figure 7. Tectonic elements of the Texas Permian Basin (Nicholson, 1960).

from Guadalupian/Ochoan strata (Gustavson and others, 1980; McGillis and Presley, 1981) resulting in abrupt thinning of salt units in some areas (especially along the Eastern Caprock Escarpment and Canadian River Breaks), compaction of insoluble residues, and fracturing and collapse of overlying strata.

The deposition of late Guadalupian/Ochoan strata in the Texas-New Mexico Permian Basin was characterized by a general increase in salinity through time with a corresponding decrease in clastic influx from the land. In the Palo Duro Basin, the decrease in clastic sediment supply was accompanied by an areal expansion of evaporite environments.

To the southwest, prior to deposition of the Castile and Salado formations, a normal marine environment lay to the south of the Guadalupian Goat Seep and Capitan "reef" Complex, which developed on the north and eastern flanks of the Delaware Basin. The character of the Capitan Complex as a wave-resistant reef versus an algae-bound carbonate detrital bank is controversial (Silver and Todd, 1969; Achauer, 1969). However, its trend along the margin of the Northwest Shelf and onto the Central Basin Platform (which separates the Delaware and Midland Basins) apparently provided a barrier to circulation. Behind the Capitan Complex, Artesia Group evaporites were precipitated on a very broad shallow platform which was present throughout most of the Palo Duro and Midland Basins and the Northwest Shelf. The Capitan Complex may simply have been the seaward edge of this platform. Terrigenous clastics were introduced from the north, west, and east, but the western sources were dominant. Coarser grained Artesia clastics are limited to the west in the Delaware Basin (Silver and Todd, 1969). Artesia clastic strata in the Palo Duro Basin generally thin toward the Delaware Basin and have been suggested to be indicative of paleoslope during time of deposition (Presley, 1979).

By using the correlation of shelf detrital horizons (Silver and Todd, 1969) and geophysical well log correlations (Tait and others, 1962) depositional phases in the Palo Duro Basin have been tied to those of their downdip, more seaward, carbonate and evaporite equivalents in the Midland and Delaware Basins. Because halite is more abundant than sulfate in stratigraphically higher intervals in the Guadalupian/Ochoan series it appears that the Palo Duro Basin became progressively isolated from marine influence during post-San Andres deposition. In the Palo Duro Basin, in areas outside those affected by post-Permian dissolution the number of evaporite beds increases upward through the Seven Rivers Formation (fig. 8). This trend is interrupted by the dominantly clastic Yates Formation. The overlying Tansill and Salado formations show a return to evaporite deposition.

Increased isolation from the marine environment or decreased circulation of marine-derived waters also can be inferred from the increase of halite/anhydrite ratios in evaporite strata stratigraphically above the base of the lower Seven Rivers. Inspection of core recovered from Palo Duro Basin indicates that deposition of the Guadalupian San Andres Formation evolved along similar lines becoming more hypersaline with increasing abundance of sulfate precipitation; compared to the thick carbonate units of the lower San Andres cycles, upper San Andres carbonate units are thin.

METHODS

This study is based upon the correlations and interpretations of geophysical logs from more than 150 wells, and the analysis of sample logs and core descriptions. Ten United States Department of Energy (DOE) cores from Oldham, Deaf Smith, Randall, Swisher, and Donley Counties, each accompanied by a comprehensive suite of geophysical logs, were studied. Wells drilled and cored with DOE funding include, in Randall County, Gruy Federal (GF) Rex White No. 1 and Stone and Webster Engineering Company (SWEC) Holtzclaw No. 1; in Swisher County, GF Grabbe No. 1, SWEC Harman No. 1, and Zeeck No. 1; in Donley County, SWEC Sawyer No. 1; in Deaf Smith County, SWEC J. Friemel No. 1, G. Friemel No. 1, and Detten No. 1; and in Oldham County, SWEC Mansfield No. 1. Lithologic data used for mapping of clastic trends and facies distributions were derived,

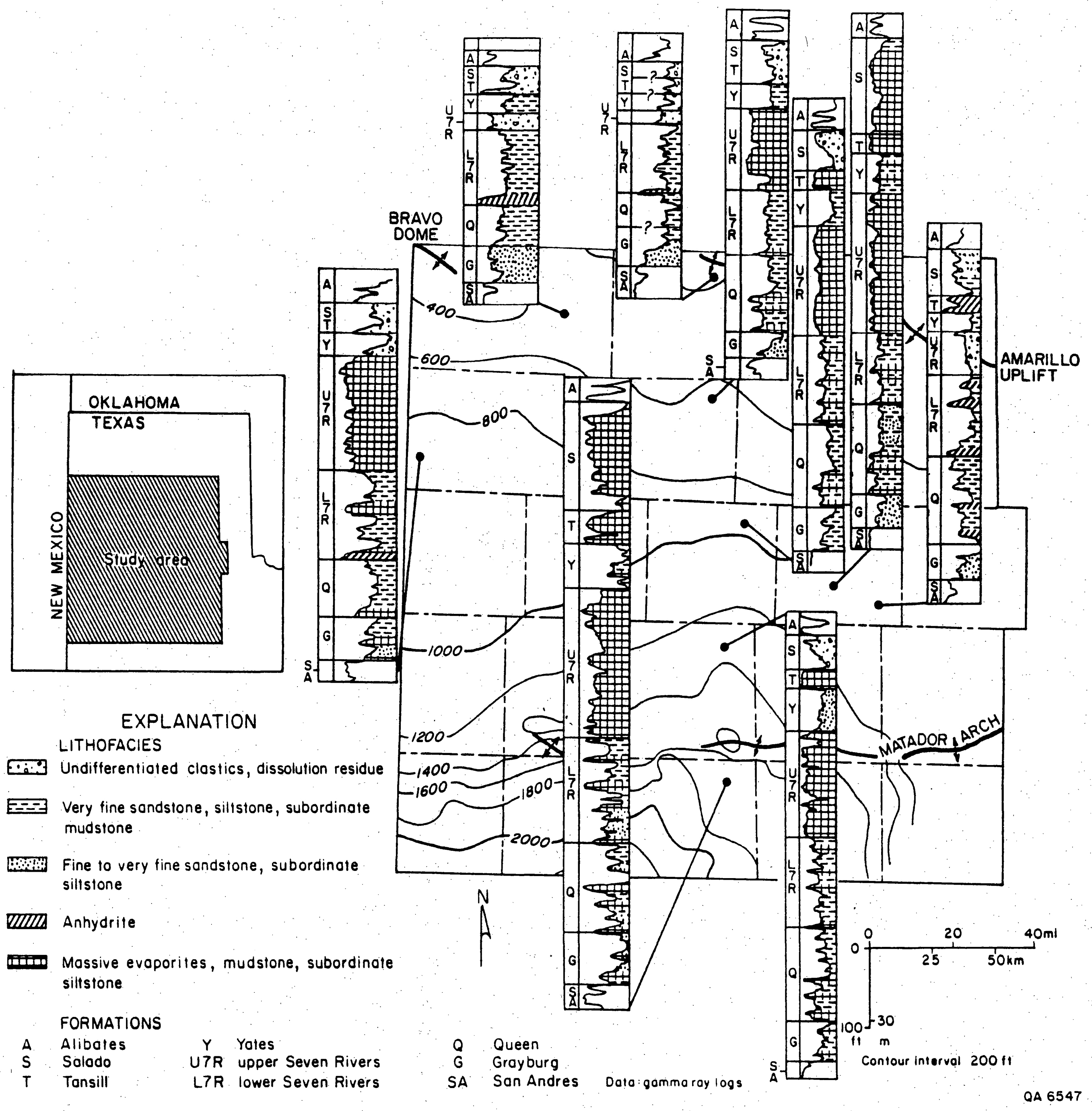

Figure 8. Post San Andres Permian formations, Texas Panhandle: isopach and regional log patterns (isopach mod. after Presley, 1980; isopach includes thin Dewey Lake Formation; logs do not include Dewey Lake).

mainly, from gamma ray logs. Textural descriptions of clastic rocks in core were spot-checked with grain-size analyses using sieve, pipette (Folk, 1974), and Coulter Counter techniques (Shideler, 1976). An isopach map and the approximate locations of cross sections are shown in figure 1.

ARTESIA GROUP AND SALADO FORMATION FACIES

The Artesia Group and Salado Formation includes evaporites and red beds deposited in and around a broad shallow brine pan situated in an arid intracratonic setting. Artesia Group and Salado Formation evaporite deposits are regionally extensive on a scale unmatched by modern analogs such as Bristol Dry Lake in California (Handford, 1982), or the salt lakes of South Australia (Warren, 1982). However, textural features within the evaporites indicate a shallow subaqueous origin (Hovorka, written communication). Further evidence of shallow water for evaporite precipitation includes interfingering of evaporites with sandstone beds deposited in a terrestrial eolian setting (discussed below). Additionally, carbonate sediments that would result as an initial evaporative precipitate in deep water are lacking at the base of Artesia Group/Salado Formation evaporite sequences. Brine-pan deposits include anhydrite or gypsum and halite. Red beds collectively include siliciclastics (quartz and feldspar) deposited in terrestrial environments, dominantly eolian, but including a subordinate component of water-laid deposits. Rocks produced in transitional areas between the brine pan and siliciclastic depositional environments include various mixtures of halite and red siliciclastic sediment.

Evaporite Facies

Guadalupian/Ochoan evaporites occur in cyclic sequences. A complete cycle includes, in ascending order, slightly dolomitic anhydrite, anhydrite, anhydritic halite, halite, and muddy halite. Incomplete sequences, capped by anhydrite or lacking anhydrite, are also present. These cycles are characteristically 2 to 8 ft thick and are bounded by siliciclastic breaks. Geophysical log correlations demonstrate that evaporites occur as regionally extensive sheets.

The lowermost evaporite of the Queen/Grayburg formation in No. 1 Grabbe (figs. 9 and 10) is an example of a complete evaporite/clastic cycle. Preserved in basal anhydrite (but originally precipitated as gypsum) are numerous halite pseudomorphs (crystalline minerals that mimic the crystal habit of the mineral they replace) after gypsum (indicating original gypsum precipitation in a brine pool) and minor dolomite inclusions. Notably, primary halite chevron structures, evidence of precipitation in a halite brine pool, are present in only the base of the overlying halite. One possibility is that recrystallization of the uppermost halite in this bed occurred subsequent to original evaporite precipitation; another possibility is that equant, non-chevron halite crystals were deposited in the brine pool (Hovorka and others, 1985).

The middle evaporite of the Queen (fig. 10) includes repetitiously interbedded halite and anhydritic halite. This sequence record may return to gypsum precipitation following initial halite precipitation or concentration of anhydrite following dissolution of anhydritic halite. Variable circulation and influx of somewhat fresher marine-derived waters may account for this pattern. Freshening of brines by rainfall could produce a similar rock but would have to be widespread because this anhydrite layer can be correlated to Rex White No. 1 thirty miles away.

At other times, however, halite evidently was precipitated in isolated brine ponds (fig. 11c). This probably occurred during late desiccation (drying) stages in the life of the brine pan. An illustration of this stage is seen in the Tansill clastic member (figs. 6 and 12). Figure 12 (based on gamma ray logs) is an isopach map of a mudstone break in the halite-dominated Tansill Formation. The map also includes laterally equivalent halite and halite-bearing clastic rocks. Laterally equivalent halite rocks were cored (GF Grabbe No. 1) in Swisher County. In no well was core taken of the mapped clastic bed depicted in

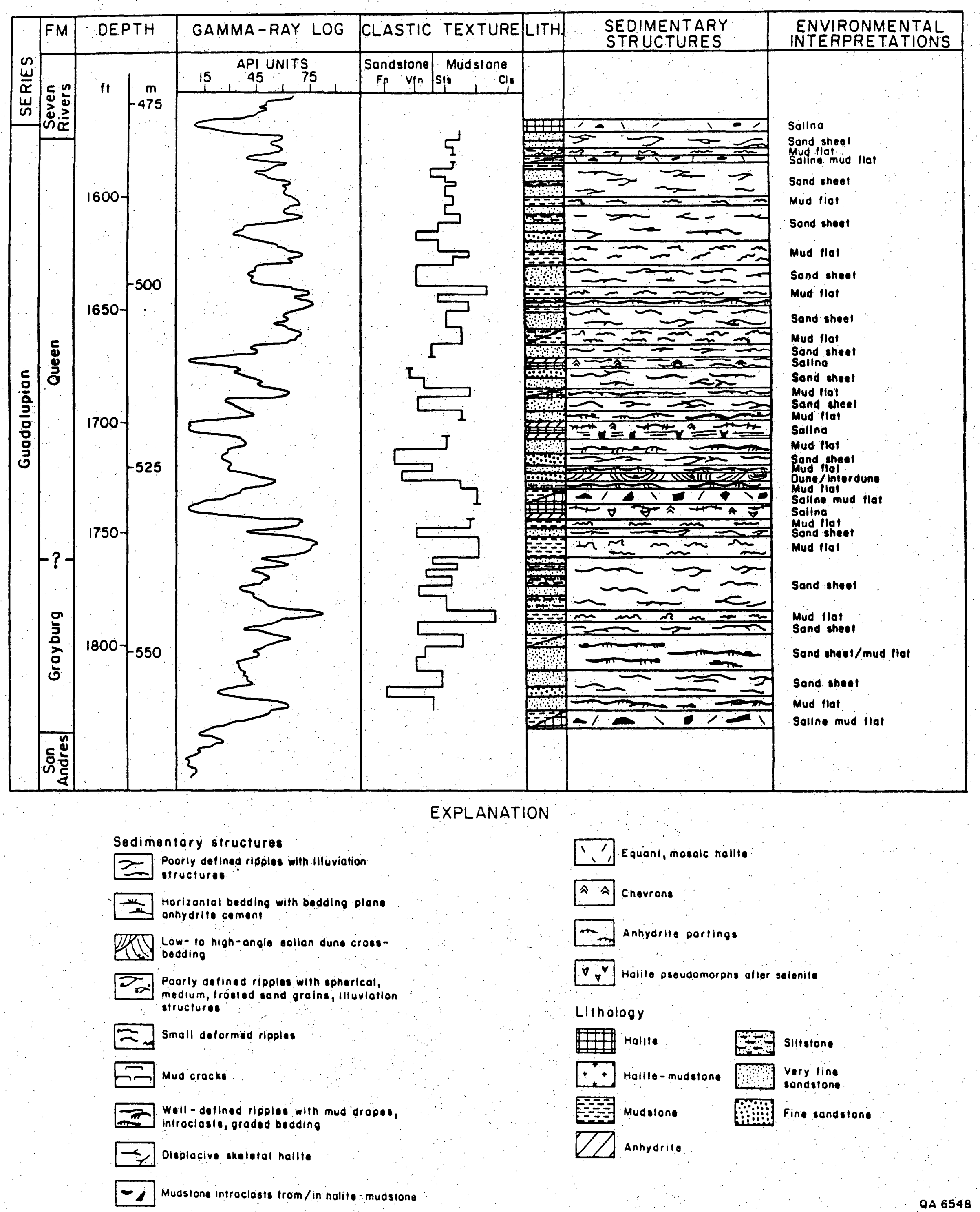

Figure 9. Queen/Grayburg formation-Swisher County Grabbe No. 1: gamma ray log, core description, and environmental interpretations. L, M, U: Queen lower, middle, and upper evaporite cycles. Key to symbols used in figures 9, 10, 13, and 14.

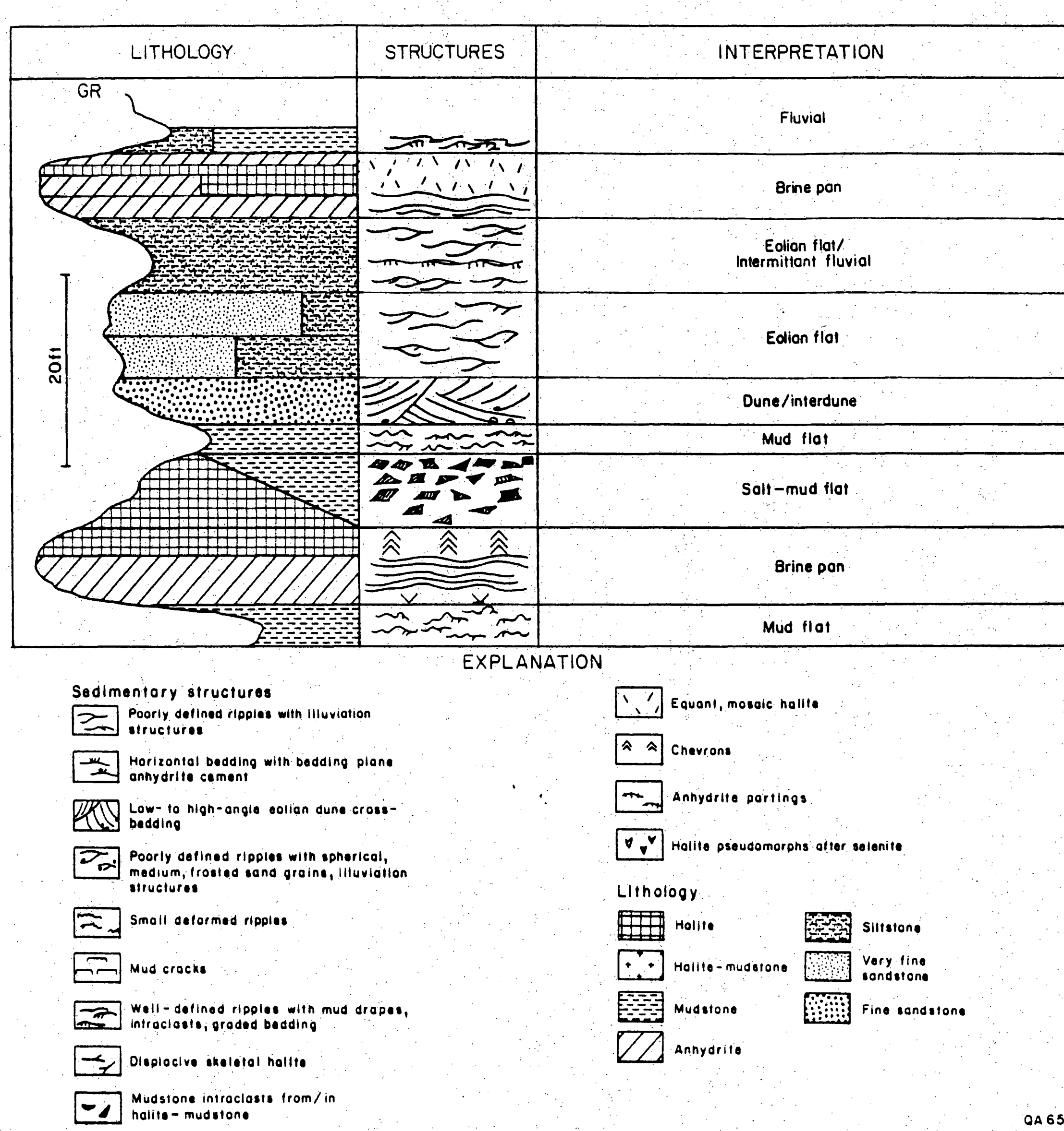

Figure 10. Queen/Grayburg formation, lower through middle evaporite interval–Swisher County Grabbe No. 1, 1,700–1,745 feet (datum: K.B.). See figure 10 for key to symbols.

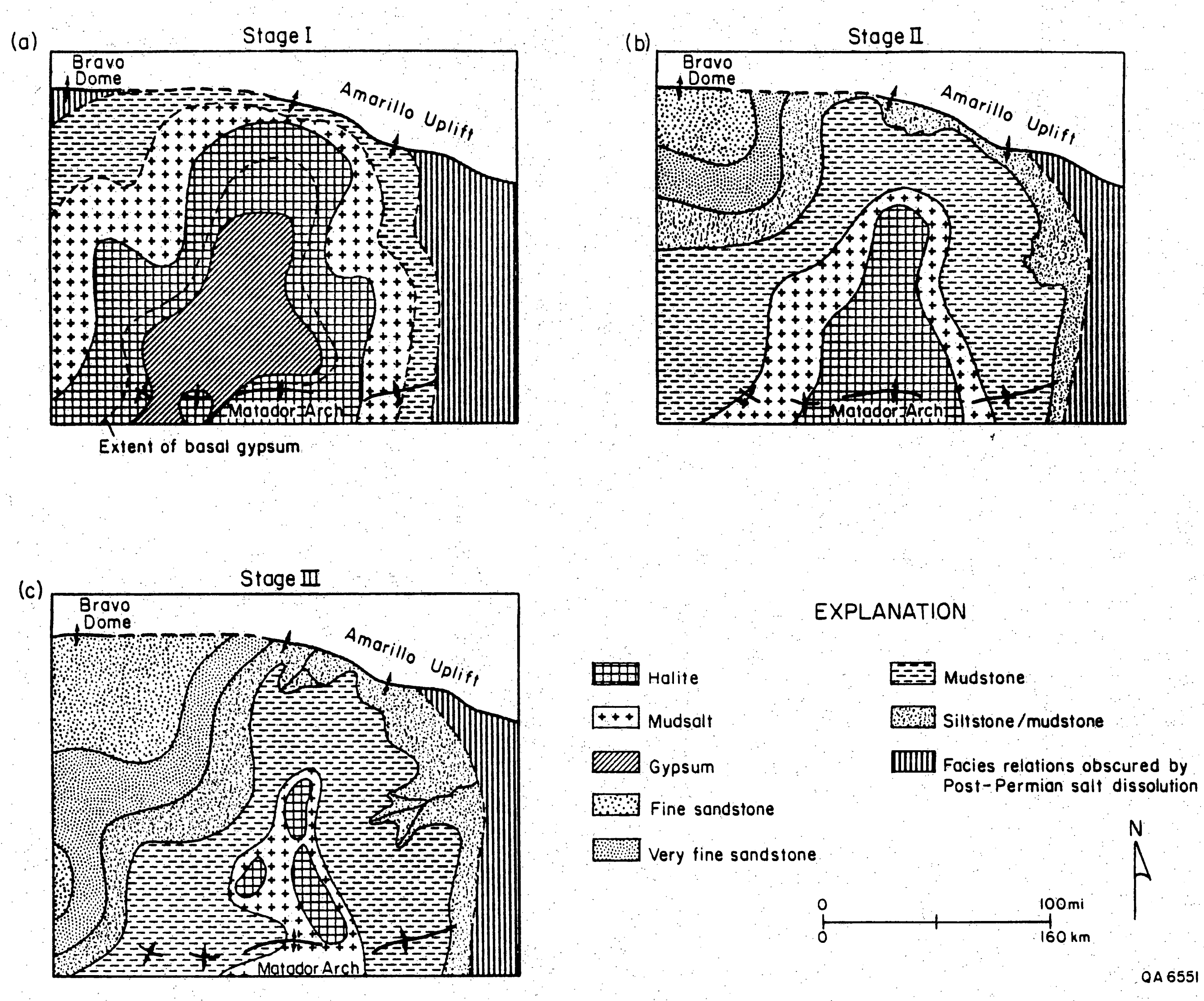

Figure 11. Paleogeography and distribution of sediment during transgression/progradation cycle: example based on Queen lowermost evaporite and Tansill clastic member. In 12a, basal sulfate pinches out whereas halite dominates upslope evaporite deposits.

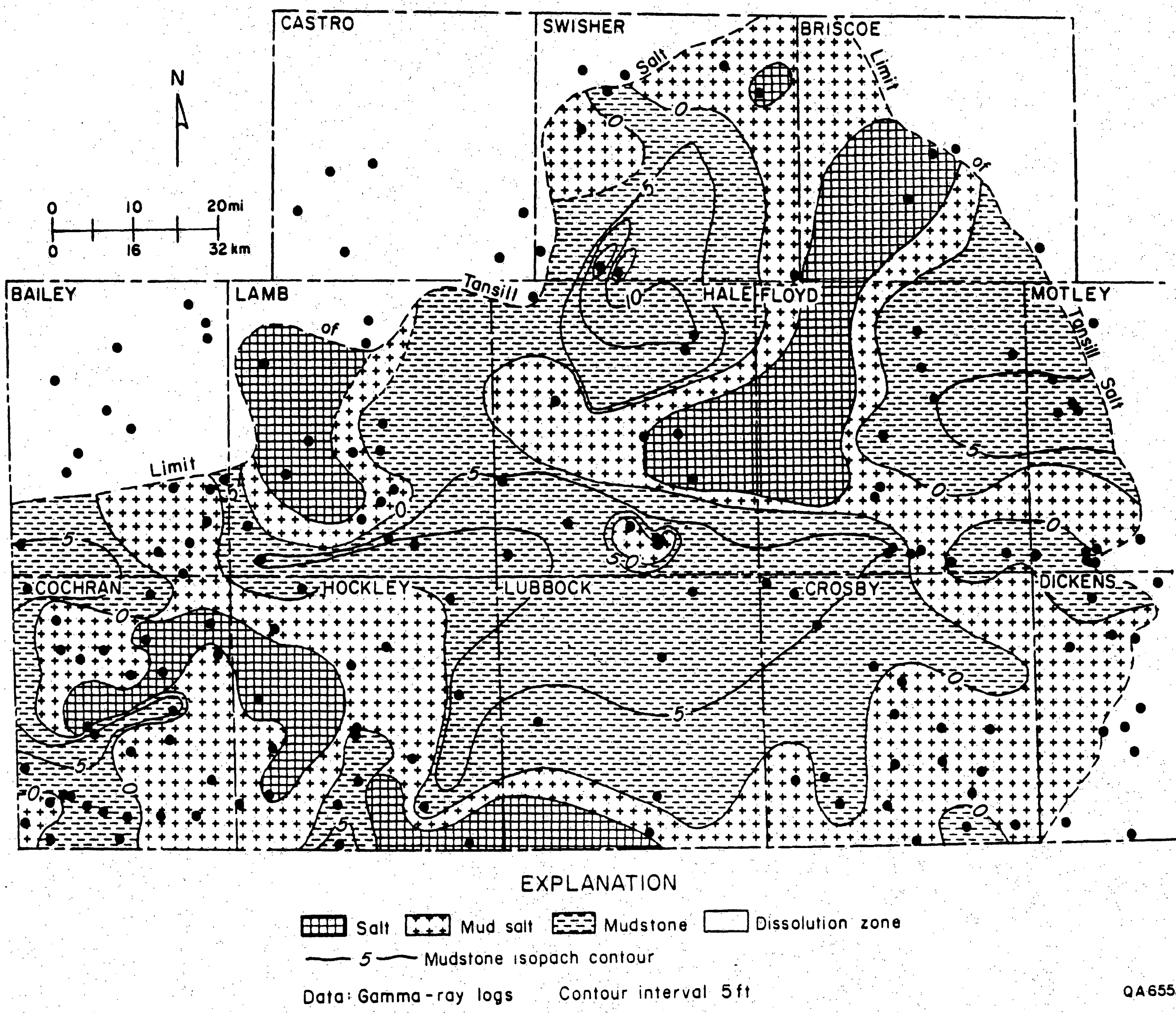

Figure 12. Tansill Formation, clastic member: isopach and distribution of time-equivalent facies. See figure 4 for stratigraphic position.

figure 12. Isolated brine pools are logically to be expected in the late stages of brine pan desiccation.

Notably absent from post-San Andres evaporite sequences is the prominent carbonate phase which precedes anhydrite precipitation in many San Andres evaporite cycles (Hovorka, 1984). Also of importance is the presence of relatively halite-pure phases in many of the evaporite sequences which compose the Seven Rivers Formation. In the upper Seven Rivers predominantly clastic-free massive halite beds of similar thickness (8 ft on average) are interbedded with chaotic halite-mudstone. Some halite-mudstones probably record episodic clastic influx into former halite-precipitating environment or they may be the result of interstitial growth of displacive halite within mud-flat sediments. Other halite-mudstones may record diagenetic mixing of mud and halite (Hovorka, Luneau, and Thomas, 1985). Decrease in the proportion of anhydrite to halite in lower and upper Seven Rivers evaporite sequences indicates an increase in salinity of evaporite-producing brines subsequent to deposition of Queen and San Andres evaporites which characteristically have anhydrite at the base of cycles.

In the middle and uppermost evaporites of the Queen Formation, sequences are capped by anhydrite, not halite, as in complete sequences seen in the Queen lower evaporite or in many San Andres evaporite cycles. Anhydrite beds are overlain by siliciclastics rather than by halite-mudstone. Halite, which originally capped evaporite cycles, was probably dissolved by freshened waters associated with the prograding terrestrial clastics. Dissolution stopped when a relatively insoluble sulfate layer was reached or constructed with insoluble sulfate residue originally mixed with the halite. The loss of salt caused some collapse and deformation of the overlying sediment, but this disturbed zone is only a few inches thick. Beds overlying the thin layer of disturbed sediments are undeformed. This suggests that halite was removed prior to deposition of the undeformed interval. Halite-dissolution commenced soon after initiation of progradation.

Sandstone Facies

Clastic sediments deposited in arid, eolian environments are preserved as 1) massive to cross-bedded, well-sorted, fine sandstones; 2) massive to ripple cross-bedded, moderately sorted, very fine sandstones to coarse siltstones, with pedogenic textures; 3) massive to ripple cross-bedded, moderately sorted, very fine sandstones to coarse siltstones, with a subordinate fraction of very well-rounded, frosted, medium sand grains; 4) and evenly laminated, well sorted, very fine sandstone to coarse siltstone, with prominent anhydrite cement on bedding planes.

Core which record deposition in an upper Permian eolian desert environment display diagnostic characteristics of modern and ancient arid eolian desert environments, including good sorting, rounding, frosting, and reddening of detrital grains. Suspected pedogenic features are also present which suggests deposition in an arid eolian environment. Component sand and coarse silt-sized particles in Artesia eolian sediments are, on the average, subrounded. The small but significant population of very well rounded, essentially spherical, medium sand grains are frosted. Krinsley and Doornkamp (1973) suggested that such frosted surfaces resulted from prolonged abrasion combined with solution and reprecipitation of silica. Such frosting is diagnostic of desert sediments. Sorting values for crossbedded fine to very fine sandstone in core range from .35 phi to .50 phi (well to very well sorted). Good sorting typifies many modern desert sands (Ahlbrandt, 1979). Included detrital, probably illuviated, clay composes a small fraction, generally less than five percent, and is discussed below.

Graded sequences, well defined ripples, and clay drapes expected in water transported materials (Reineck and Singh, 1975) are uncommon in Artesia and Salado core, as are channel-cut surfaces. Very little clay is present. Mudstones are present in parts of the Artesia geologic section so their conspicuous absence in other places is attributed to processes which do not allow deposition of fine particles or, alternately, winnow them out after initial deposition. Wind is the obvious agent for these processes.

Ripples which are in general poorly defined in eolian sand (Hunter, 1977) are difficult to discern in Artesia sandstones. Where observed in cored materials many ripples are partially delineated by thin ($\leq$ .5 mm) laminae of clay and fine silt-sized material. These laminae are discontinuous and in some places may partly delineate upper surfaces of ripple forms or highlight otherwise indiscernible ripple cross-laminae. These structures resemble "dissipation structures" which are described from eolian-related interdune deposits (Ahlbrandt and Fryberger, 1981) and apparently form from the downward washing of fine particles through the soil. These fines come to rest on horizontal or inclined surfaces such as on the upper side of a ripple form or cross-laminae. As particles begin to accumulate along a boundary, downward permeability is reduced and the process discontinues at that particular location. The source of very fine illuviated grains could be washdown of fines trapped in the wind-baffled microenvironments between sand grains at the surface. Because feldspars and rock fragments in Artesia sandstones are relatively pristine it is unlikely that illuviated fines originated as weathered disintegration products of the soil.

Medium to high angle (15-32°) cross-bedding occurs in 6 inch to one and one-half foot thick sets in some fine-grained Artesia sandstones. These sets are bounded by surfaces which truncate underlying structures and record changing wind directions (McKee, 1979) and sediment transport. Cross-laminae are subtle and avalanche faces are rare in Artesia eolian deposits. Based upon similiarity to sedimentary structures seen in Navajo sandstone in Utah (Hunter, 1981), the cross-bedded fine sandstones of the Artesia Group may be the result of grainfall lamination. Both processes operate in the eolian dune environment. Because avalanche stratification is seldom seen in Artesia cross-bedded sandstone, such intervals are interpreted as deposited on small dunes with angles of repose less than 28°. Apparent dip angles of up to 35° of some cross-laminae seen in core may be the result of deposition on damp surfaces. Where continuous core intervals could be fitted end-to-end, cross-strata dip azimuth repeatedly showed about 90° counterclockwise migration before abruptly returning to the original orientation. Barcanoid dunes characteristically show dip azimuth shifts of about 90° (Glennie, 1970).

Weakly bimodal, moderately to poorly sorted sandstone with dissipation structures present in Artesia core are similar to interdune deposits of the Navajo sandstone of Colorado described by Ahlbrandt and Fryberger (1981). In Palo Duro Basin core these deposits generally occur below cross-bedded dune sandstone or vertically adjacent to other interdune deposits. By application of Walther's Rule of Facies it is concluded that the bimodal sandstone was deposited laterally to dune sandstone in an interdune area.

No evidence for vegetation or unequivocal evidence of bioturbation is present in core, although some apparently massive sandstones may have lost primary sedimentary structures through bioturbation. Absence of evidence for organic activity and scarcity of fluvial deposits in core suggest an arid environment for deposition of most Artesia Group sandstones.

In the Queen/Grayburg wet interdune deposits are evenly laminated very fine sandstone to coarse siltstone with anhydrite cement on bedding planes. Bedding averages 2 to 3 cm-thick and grading is absent. Mud is absent and only a few ripples with wavelengths of approximately 1-1.5 cm are present. This suggests that interdune ponds trapped saltating sand during windstorms but collected relatively less of the suspended load.

Cementation by anhydrite preferentially on bedding planes suggests that desiccation followed clastic deposition in interdune pools. Bimodal sands, interpreted as intermittently wet (because of the presence of dissipation structures which require washing down of fine clastics) occur at the top of these "ponded" sediments. This further supports an interdune interpretation for the evenly laminated, anhydrite-cemented interval.

Some sand and coarse silt was transported by wind but was deposited in interdune pools. These pools were intermittently wet, perhaps due to rise of the water table into blowout areas adjacent to dunes. Similar features are present along the Texas Gulf Coast (Weise and White, 1980) in barrier-island dune fields.

Mixed Salt/Siliciclastic Facies

Varying mixtures of salt and red clastic sediment were deposited in transitional areas between purely evaporite basins and purely terrestrial (eolian and intermittent fluvial) environments. The halite-dominated end member is massive halite with approximately 10 percent red mudstone to claystone included as straight-edged equant masses distributed uniformly among halite crystals. The linear boundaries of mudstone masses define the edges of displacive halite crystals. This suggests that halite formed by crystallization from brine within unlithified sediment. The clastic-rich end member comprises rippled sandstone to structureless clayey siltstone. The claystone contains 10 percent displaced halite which, during crystallization, incorporated clastic sediment into the halite structure to produce a zoned appearance. All intermediate variations in relative proportions of clastic material to salt are represented in core of Artesia and Salado rocks. The relative amount of halite in mud/salt flat-deposited rocks is related to position in the tract between the evaporite and purely clastic environments, with halite decreasing in abundance landward. Even if more landward rocks were exposed to fresh-water vadose conditions and halite abundance was thus reduced by dissolution, landward rocks would contain less halite. Similar mud/salt-flat-deposited rocks have been described from the San Andres (Hovorka, Luneau, and Thomas, 1985). Three origins seem possible: clastic sedimentation in a hypersaline environment; displacive halite growth in clastic sediment after flooding by brine; or postdepositional mixing of salt and mudstone.

Chaotic halite-mudstone rocks of the Artesia Group and Salado Formation are similar to those seen in the upper Clear Fork interpreted to have been deposited on mud/salt flats (Presley and McGillis, 1982). Modern examples of chaotic halite-mudstone have been described from saline-mudflat sediment associated with Bristol Dry Lake, California (Handford, 1982).

Siltstone/Mudstone Facies

Clastic sediments deposited on intermittently flooded mud flats comprise red rippled siltstones to plane-bedded claystones. Characteristically, the ripples have wavelengths of .5 to 1.5 cm and are composed of coarse to medium silt. These silty ripples are suspended in a finer siltstone or mudstone matrix. Similar sedimentary structures are described for sandstone from the Green River Formation of Wyoming interpreted to have been deposited by sheet floods on a distal alluvial fan (Smoot, 1983). Clay is not abundant, but the structural appearance is that of flaser to lenticularly bedded clastic sediment such as that described by Reineck and Singh (1975). In silt-rich Artesia and Salado sediments, the role traditionally played by clay in flaser bedding is assumed by the finer silt fraction plus available clay. Usually flaser and lenticular bedding occurs in mudstone, which is defined by Folk as containing greater than 30 percent clay (1974). For convenience, siliciclastics containing greater than 20 percent clay-sized particles are called mudstones in this report.

Reineck and Singh (1975) suggest flaser and lenticular bedding is most common in intertidal or subtidal environments. But rocks described here characteristically occur in core at the base of a prograding eolian sequence and overlie a desiccating brine pan sequence. The lack of abundant halite in these mudstones is an indication of a relatively fresh-water environment and not the landward margin of a brine pan. If the brine pan had been invaded by sediment and flood water from the land, subsequent desiccation should have produced abundant displacing halite in the mud. However, the former presence of only small amounts of displacing halite are suspected in some mudstones and no halite seems to have been present in others. Therefore deposition of fine grain siliciclastics subsequent to halite precipitation and prior to progradation of eolian clastics appears to have occurred in a purely terrestrial environment, but the exact depositional processes are unknown. Sand and coarse silt grains show some rounding of particles and suggest a previous history in an eolian environment. A reasonable conclusion is that the clastics were transported by eolian and intermittent fluvial processes, then reworked by sheetflow from the land after rainstorms.

In many places ripples in siltstones and mudstones are contorted, suggesting soft sediment deformation, perhaps in response to the postdepositional dissolution of small interstitial halite crystals (such as suggested by Smith, 1971, for certain upper Permian rocks in England) or in response to loading of water saturated sediment by overburden.

A gradation exists both between the relative proportions of coarse and finer silt in these rocks (reflected in a ripple to matrix ratio) and the degree of deformation of ripples. Generally, finer grained rocks have fewer and smaller (about 0.5 cm) ripples and show more disturbance than do coarser textured rocks. Coarse-grained rocks typically have more ripples of longer wavelength (up to 1.5 cm), and show less disturbance. The greater disturbance seen in the muddier rocks may reflect a greater proportion of primary halite (subsequently removed) compared to coarser textured examples.

Some mudstones were deposited on episodically wetted mud flats, probably near the brine pan where haloturbation (Smith, 1971) has disturbed fabrics by dissolution of included halite crystals. Relatively undisturbed mudstones were deposited further inland and away from halite sources.

Intermittent-fluvial deposits, of which there are few unequivocal examples, comprise sandstones to siltstones with mud clasts and mud drapes. Cross lamination is well defined in ripples because of grain size differences between separate cross laminae. Wavelengths average approximately 1.5 cm. Graded beds are present and sorting is poor to locally moderate. Most intermittent fluvial deposits overlie fine clastics which are interpreted to be nearshore or mud-flat deposits. Fluvial deposits are themselves locally overlain by eolianites which record progradation of eolian environments over formerly wetted areas. These relations are similar to those described by Fryberger and others (1983) for an offshore prograding sand sea in the Dhahran area of Saudi Arabia.

FACIES ASSOCIATIONS AND DISTRIBUTION

Artesia and Salado rocks display characteristic vertical sequences. The ordered cyclic nature of these, and similar cyclic sequences in clastics in the upper and lower Clear Fork, Tubb, Glorieta, and San Andres Formations in the Palo Duro Basin, was previously recognized by Handford (1980).

Evaporite cycles composed of halite beds with or without basal anhydrite, overlain by progradational siliciclastic deposits characterize the Artesia Group and Salado Formation. Sequences are most completely developed in Swisher County (Grabbe No. 1) and Randall County (Rex White No. 1) core from the Queen/Grayburg formation (figs. 9, 10 and 13). Three cyclic intervals are present which demonstrate characteristic vertical ordering. The Queen lowermost evaporite sequence includes, from bottom to top, basal anhydrite, originally deposited as gypsum, anhydritic halite, halite, chaotic halite-mudstone, red mudstone with contorted ripples, and cross-laminated coarse siltstone to fine sandstone.

Two Queen evaporite sequences overlying the lowermost sequence do not have halite as their uppermost evaporite deposit. Rather, a thin bed of anhydrite caps the uppermost halite (see figs. 9, 10, 11, and 13). The upper halite was dissolved probably soon after intiation of progradation of the overlying clastics (see evaporite facies section).

Most evaporite sequences seen in core above the Queen lack basal anhydrite, suggesting that circulation of marine-derived waters became poorer or discontinued during precipitation of much of the Seven Rivers, Yates, and Salado/Tansill.

In the Seven Rivers, Yates, and Salado/Tansill formations siliciclastics are generally finer grained than those of the Queen. Fine sandstone is less common above the Queen, and eolian dune crossbedding is uncommon except for one thin interval in the upper Seven Rivers. Following evaporite precipitation, progradation (migration of terrestrial environments basin-ward) was dominated by deposition of rippled very fine sandstone and coarse siltstone on eolian flats and of rippled siltstones and mudstones on mud flats and in shallow subaqueous environments (fig. 11).

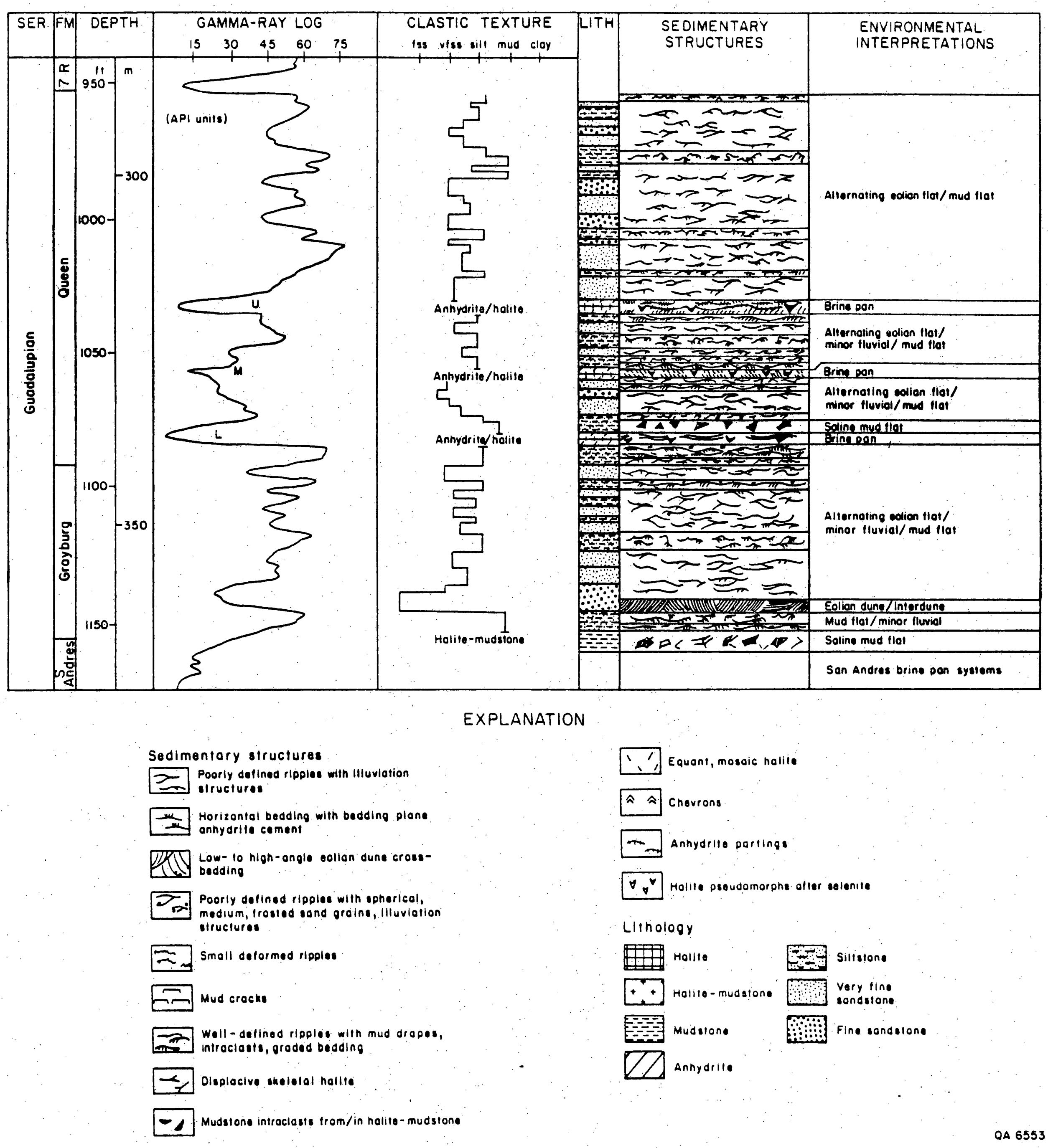

Figure 13. Queen/Grayburg interval--Randall County Rex White No. 1. L, M, U: Queen lower, middle, and upper evaporite cycles. See figure 10 for key to symbols.

Up paleoslope in the northwest Palo Duro Basin in Oldham County (#1 Mansfield well; fig. 14) Artesia and Salado evaporites are less abundant. Some amount of upper Seven Rivers and Salado/Tansill salt has been dissolved in this area, but thick evaporites probably never were deposited with other Queen/Grayburg or lower Seven Rivers sediments in the northwest Palo Duro Basin. (An exception is the occurrence of a thin, regionally extensive, anhydrite/halite-bearing sequence informally used as the regional boundary to define the base of the Seven Rivers Formation.) The interpretation that no major evaporite deposition occurred in northwest Palo Duro Basin prior to deposition of the upper Seven Rivers is supported by the absence of evidence for salt dissolution and overburden collapse in the Grayburg, Queen, or lower Seven Rivers in core from Oldham and Deaf Smith Counties. Upper Seven Rivers halite is preserved at Deaf Smith County #1 Detten and J. Friemel No. 1 wells, which suggests the underlying rock has not suffered post-Permian dissolution. Regional transgressions produced bedded evaporites down depositional slope in Randall and Swisher Counties but produced mud-flat or shallow subaqueous environments in Oldham and Deaf Smith Counties where rippled siltstones and mudstones were deposited. Infrequency of brine influx probably preempted original deposition of abundant salt in these areas. A disturbed fabric characterizes many rippled siltstones and mudstones which are interbedded with eolian clastics at #1 Mansfield. Dissolution and precipitation of soluble minerals in unconsolidated sediments can produce disturbed fabrics (Smith, 1971) and this mechanism has been proposed to explain similar rocks associated with evaporite sequences in the San Andres Formation of Palo Duro Basin (Hovorka, Luneau, and Thomas, 1985).

Post-transgression progradation began as regional expansion of mudstone-producing environments from their initial locations near the periphery of evaporite environments. A similar scenario was suggested for post-evaporite phases of Glorieta deposition (Presley and McGillis, 1982). The expansion of muddy environments was followed by migration of progressively more landward environments (mainly eolian) over mud-flat/subaqueous deposits. Dominant progradation proceeded from the northwest and west as demonstrated

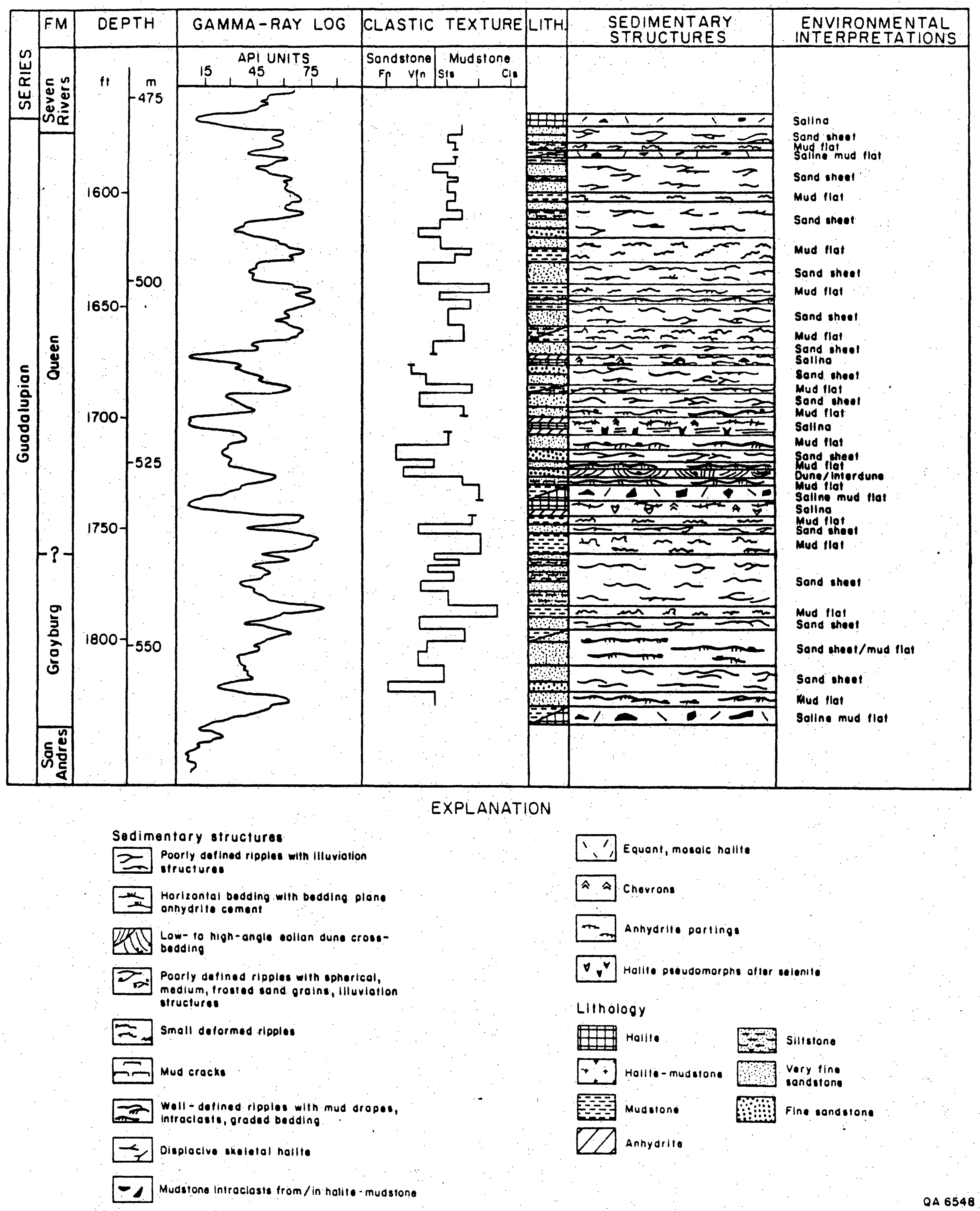

Figure 14. Queen/Grayburg interval--Oldham County Mansfield No. 1. See figure 9 for key to symbols.

by sand distribution patterns of the Yates and Queen/Grayburg formations (figs. 15 and 16) while the marine-derived brine body receded to the south and southeast. Subordinate easterly sources also contributed clastic sediment but it was of a finer texture than was sediment contributed from the northwest and west. These conclusions are based on the locations of sand depocenters in Oldham and Deaf Smith Counties defined by sand maps of the Queen/Grayburg and Yates formations (fig. 16). The patterns of siliciclastic distribution seen on isopach and facies maps of the Tansill Clastic Member (fig. 12) not only suggest a dominant westerly source for clastics but also indicate an easterly source.

Notably, Tansill salt was still being precipitated during regressive phase (fig. 12) in areas which generally correspond to the highest frequency of the preserved evaporite beds in the Queen, Seven Rivers, Yates, Tansill, and Salado formations of the Palo Duro Basin. Evidently a consistent pattern of sediment dispersal characterized post-San Andres depositional cycles with evaporite environments preferentially located south and east of the Deaf Smith-Oldham County area and clastic progradation proceeding dominantly from the west and northwest, and subordinately from the east.

Evidence from core shows that, during some cycles of the upper Seven Rivers, evaporites were deposited in Deaf Smith County. In these few examples significant anhydrite is associated with evaporite cycles in Deaf Smith County which are correlative to sulfate-deficient evaporite sequences seen in Randall and Swisher Counties.

POST-EVAPORITE SILICICLASTIC DEPOSITION

Progradation better describes the relationship of clastics to the underlying evaporites in the Permian Basin than does the term "regression," which refers to a lowering of sea-level (Silver and Todd, 1969). Progradation can proceed under any conditions of sea level. Queen/Grayburg evaporite cycles (figs. 9, 10, and 13) illustrate that progradation of clastics may have proceeded while brine pan environments were still present following lowermost evaporite precipitation.

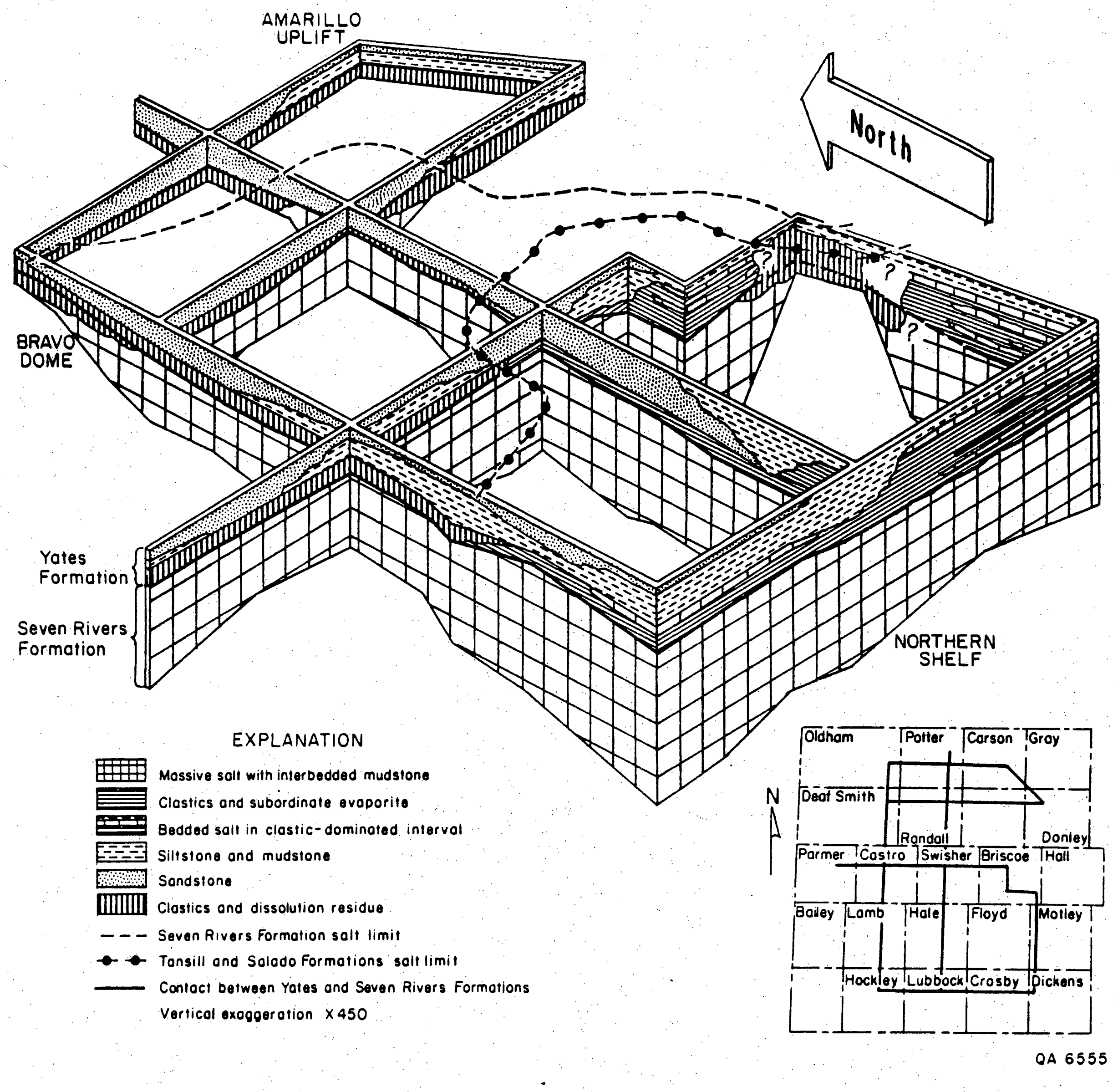

Figure 15. Upper Seven Rivers and Yates Formations: Generalized fence diagram (Datum: base/Tansill Formation).

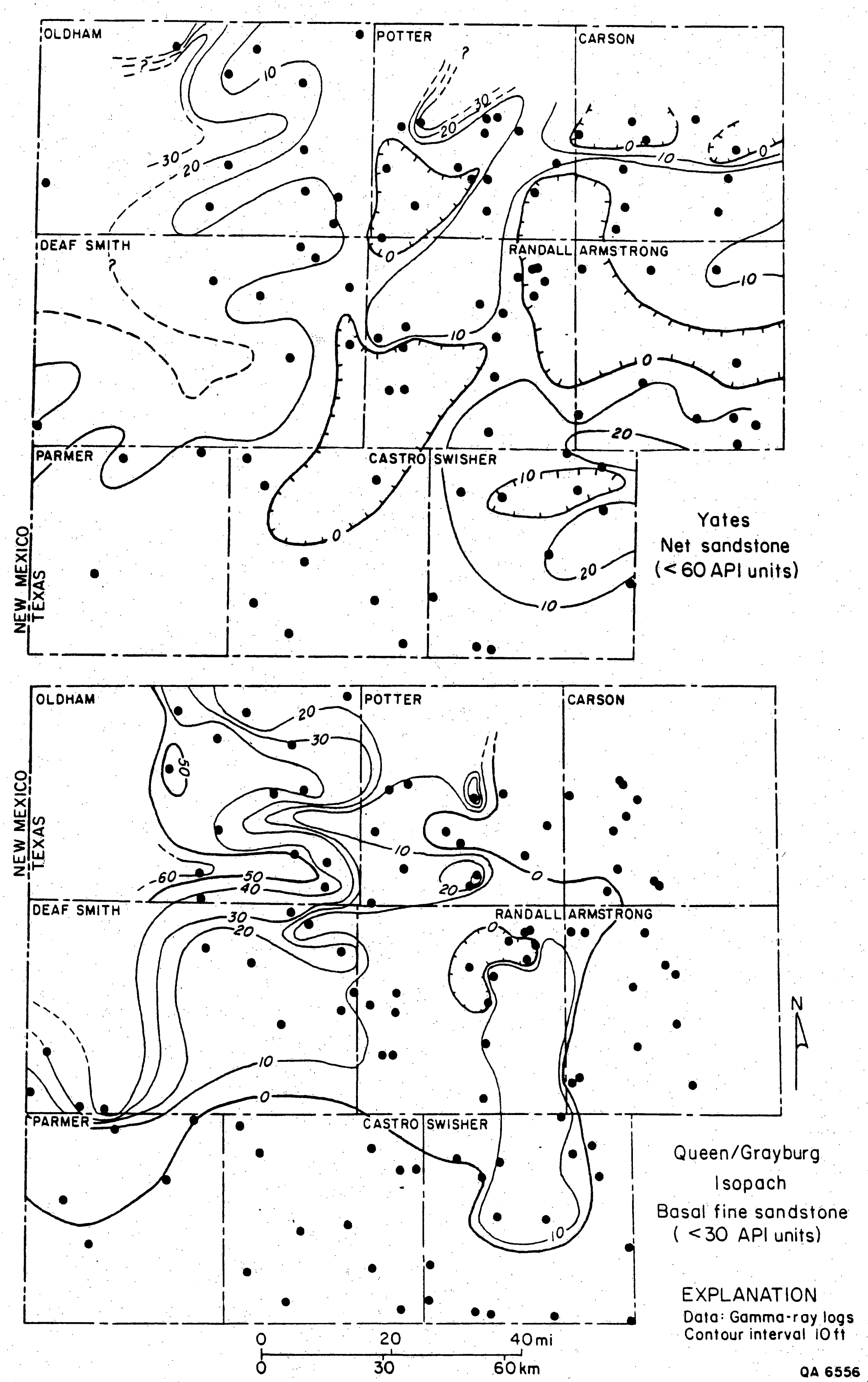

Figure 16. Grayburg Formation, basal fine sandstone: isopach; Yates Formation: net sandstone.

Progradational deposition evolved from mud dominated to sand dominated, but sandstones in many places become siltier upward with an increased abundance of coarse silt. Some sandstone units, therefore, fine somewhat upward to the base of the next transgressive cycle. This is the case seen in one Queen/Grayburg cycle (fig. 10). Fining may be due to reduction of clastic sediment supply to the basin. Eolian sandstones are not transitional to the overlying evaporites. Contacts between evaporites and underlying clastics are sharp. There are, generally, no mixtures of clastics and salt, or insoluble residues implying dissolution of a previously existing mud-salt bed. Mud salt or its insoluble residues would be an expected transitional facies. Therefore, transgressions were relatively rapid. This conclusion is also supported by the regionally uniform sheet geometry of evaporite cycles. Changes in wind direction may have been responsible for upward-fining sandstones. Further analysis will be required to resolve more clearly the causes of textural changes in eolian sediment from the Queen/Grayburg.

STRATA GEOMETRIES AND RELATIVE DURATION OF DEPOSITIONAL ENVIRONMENTS

Artesia sandstones commonly have a sheet-like geometry. Distinctive geophysical log responses, which correlate with sandstone beds in core, can be traced throughout 6,000 mi^2 with only subtle, local variations in thickness. From core analysis it is apparent that these sands were originally deposited and reworked in a regionally extensive desert eolian setting. The flat upper surface of sand sheets could be an original planed surface related to the existing regional water table, or a zero-depositional surface (Rubin and Hunter, 1984) resulting from the clastic filling of a subsidence basin. During sea-level lowstands, the area defined geographically as the Palo Duro Basin, and perhaps including portions of the Midland Basin, Central Basin Platform, and Northwestern Shelf areas, were probably covered with eolian sand. Desert alluvial processes intermittently reworked eolian sand. Periodic flooding by marine-derived waters trapped and worked fines into sheet-like mudstones, perhaps containing various amounts of interstitial halite, and probably some thin salt beds which were dissolved by fresh waters associated with subsequent clastic progradation. Mudstones, often with disturbed sedimentary structures resulting from soft sediment deformation or "haloturbation," are the only evidence of these transgressional episodes.

Assuming uniform subsidence rates, the intervals of time represented by individual clastic units are evidently much more than that represented by equally thick individual strata of evaporite rock. This is apparent from comparison of changes in stratigraphic thicknesses of evaporite and clastic strata in the Queen/Grayburg formation (fig. 17). For example, the largely clastic Queen/Grayburg doubles in thickness from Randall County to east- central Hale County. Each of the three Queen evaporites increase in thickness by only 13 percent across the same section. Similar discrepancies in clastic and evaporite thickening are present through most of the Artesia Group. There is little overall correspondence between an isopach map of the dominantly clastic Queen/Grayburg and a net clean evaporite map of the same interval (fig. 18). Assuming for now sediment compaction was uniform, the clastic isopach pattern reflects subsidence patterns during deposition of the Queen/Grayburg, and because evaporite distribution patterns show no similar response and are essentially uniform in thickness, it is concluded that the period of time required for the deposition of individual evaporite units was brief relative to local subsidence rates. Brevity of evaporite deposition is supported by evidence seen in core when abrupt basal contacts are generally present between transgressive anhydrite units and the underlying clastic rocks. No transitional facies or residual materials preserved from dissolution of formerly existing chaotic mud salt are observed.

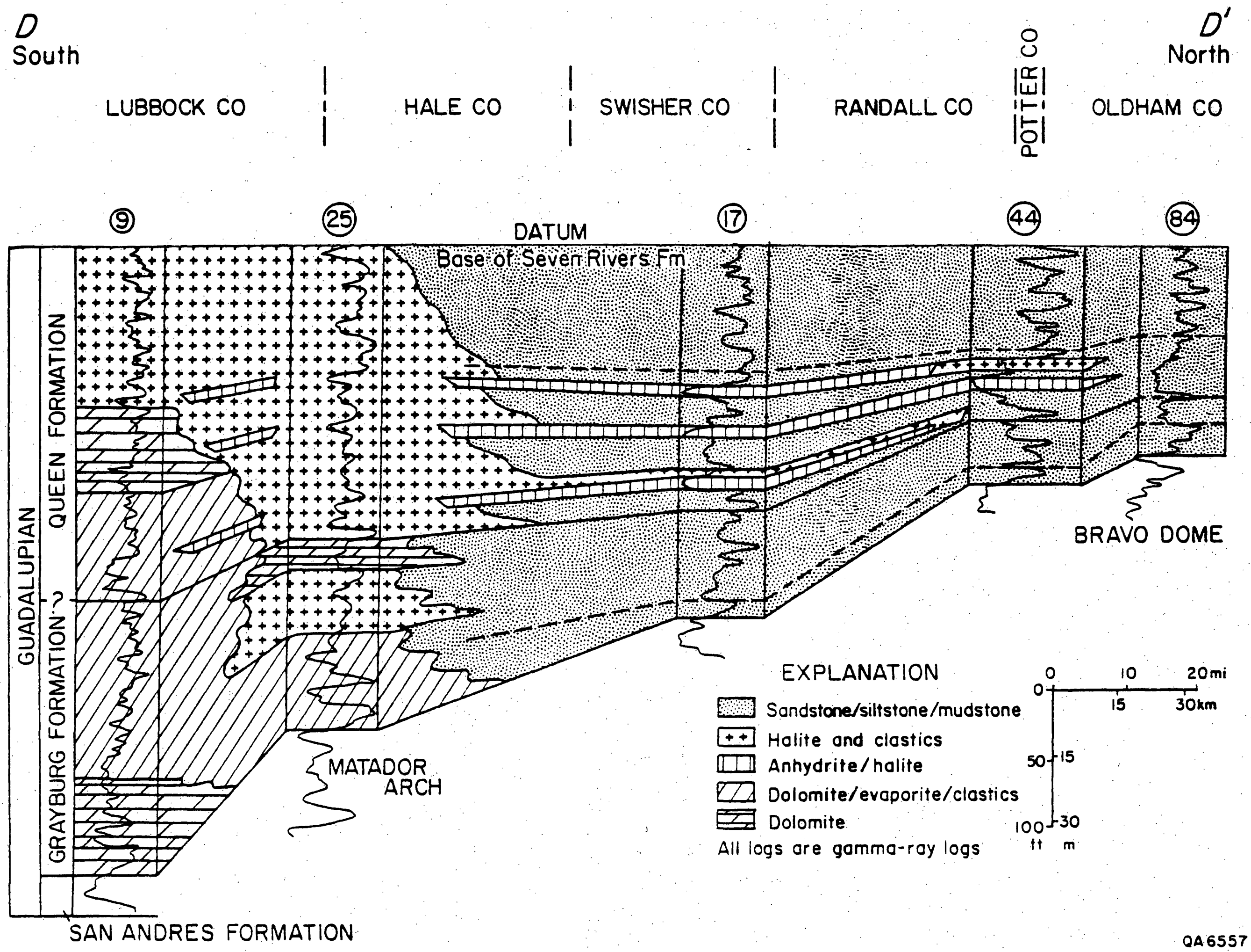

Figure 17. Queen and Grayburg formations: generalized N-S cross section D-D', Palo Duro and northern Midland Basins; vertical exaggeration 1050:1.

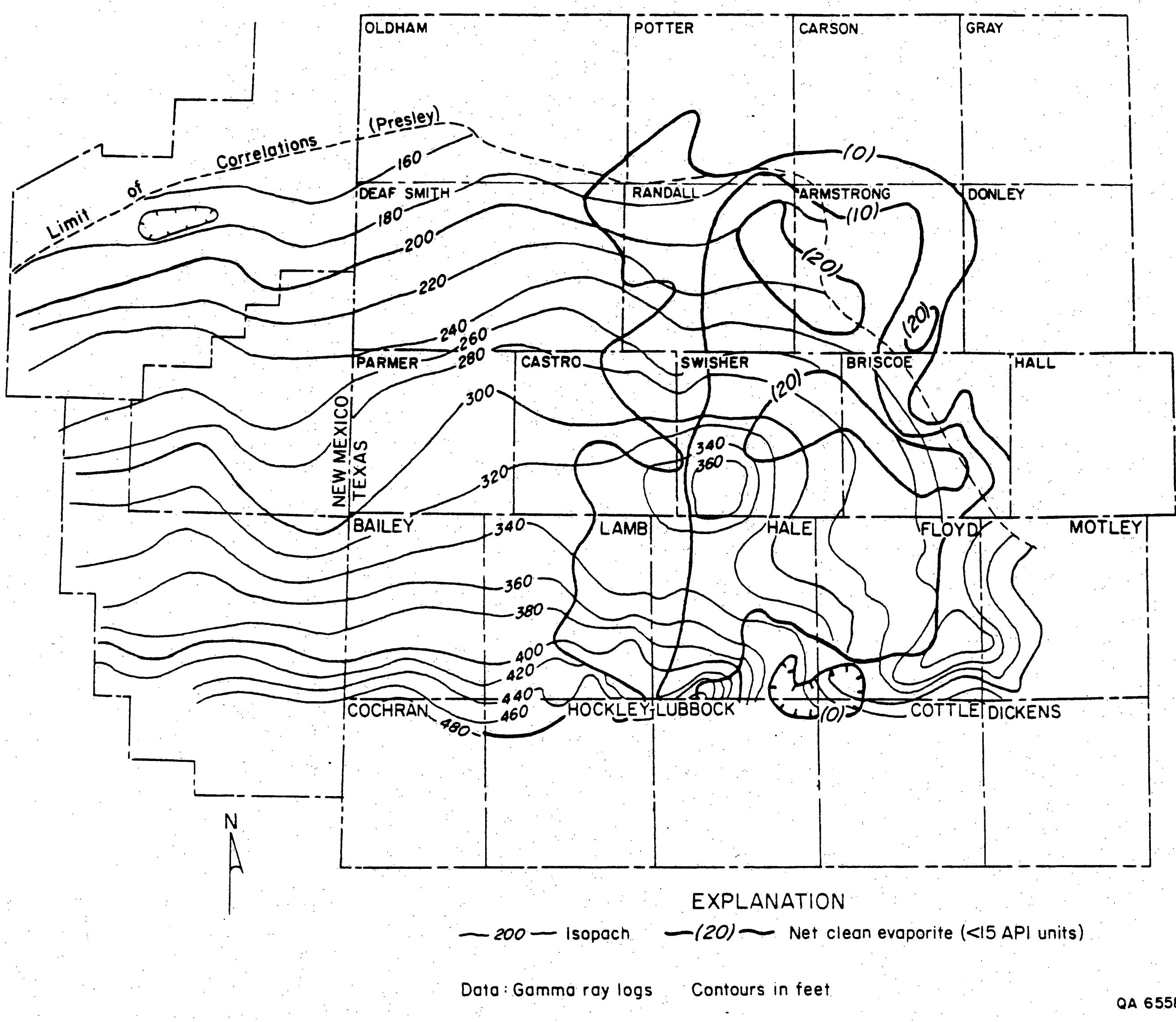

Figure 18. Queen/Grayburg interval: isopach (after Presley, unpublished map); net clean evaporite (anhydrite and/or halite).

SUBSIDENCE AND FACIES PATTERNS

Clastic-free Queen evaporites were preferentially deposited in an area of subtly greater subsidence away from clastic sources (fig. 18). Clean evaporites are concentrated where Queen/Grayburg isopach patterns show a thickened section in eastern Palo Duro Basin. Subsidence along with siliciclastic influx probably controlled basin topography and thus controlled the configuration of the flooded areas. In western Deaf Smith County and to the south of Deaf Smith County halite was deposited but included a clastic component because of its proximity to clastic sources. These halite mudstones were not cored but gamma ray log responses can be correlated between well logs recorded in clean evaporite strata in Swisher County and well logs in Deaf Smith County. Well logs indicate higher gamma ray values than those in Randall and Swisher Counties, such as would be expected if a significant component of mudstone (> 15 percent) were included with the salt. Also, sample logs of the area, based upon well cuttings, report interbedded Queen anhydrite, salt, and red beds in western Deaf Smith County. Northwestern and western sources provided most of the coarsest clastics of the Artesia Group in Palo Duro Basin. Detrital influx from the west and regional subsidence (all Artesia formations thicken to the southeast) probably controlled the preferential deposition of clastic-free evaporites in the eastern and southern parts of the Palo Duro Basin.

In the halite dissolution zones to the west (Pecos River area), north (Canadian River Valley), and east (Eastern Caprock Escarpment), Artesia and Salado salt strata are not present, and some yet undetermined amount of salt was removed by post-Permian dissolution (Gustavson and others, 1980). However, clastic rocks cored in Deaf Smith, Oldham, Randall, and Swisher Counties are stratigraphically equivalent to the Tansill/Salado salt section in southern Palo Duro Basin (figs. 2, 3 and 6), and contain sand. Core descriptions for DOE wells show some sand in the Salado. The relationship, if any, between the distribution of clastic rocks in the Tansill/Salado dissolution zone and the restriction of preserved Salado salt to the east and southern basin needs further investigation. However, a western and northwestern source for Tansill/Salado clastic units is evident. Where core is available in the upper Seven Rivers and Tansill salt sections, sand is not generally interbedded with bedded salt. However, sand is found interbedded with finer clastics and salt in one cycle of the upper Seven Rivers in Deaf Smith County so the presence of sand does not preclude the possibility that thick salt beds have been dissolved from the Salado since the Permian.

Subsidence behavior coupled with consistent patterns and varying intensities of clastic influx are mainly responsible for the distribution of Artesia/Salado evaporite and clastic depositional facies in the Palo Duro Basin. Along the Matador Arch in southern Hale, Floyd, and northern Lubbock Counties subsurface deposits of Grayburg dolomitic sediments are preferentially located in structural lows as defined by the top of the San Andres Formation (figs. 2 and 3). This suggests that movement of tectonic elements (distinct blocks of basement rock) affected topography which, in turn, affected circulation of marine-derived brines.

Structural elements also affected facies distributions in the northwest. In Oldham County, near the Bravo Dome (as sampled at #1 Mansfield), Artesia deposits are characteristically sandy and show evidence for the least amount of original evaporite deposition. Evaporite deposition in the Grayburg, Queen, and lower Seven Rivers apparently was essentially nonexistent over the Bravo Dome. No evidence for the former presence is seen and in many places overlying halite deposits are still present. Post-Permian dissolution probably was not responsible for the absence of Queen/Grayburg/lower Seven Rivers halite. Additionally, the ratio of sandstone to mudstone abundance in Oldham County (as seen at #1 Mansfield) is significantly higher than in Swisher County (as seen at #1 Grabbe). Dominance of coarser clastics to the northwest is manifestly evident for the Queen/Grayburg and lower Seven Rivers. This probably corresponds to a low incidence of transgressive flooding in these areas.

To the east, in central and south-central Potter County, thick accumulations of Queen/Grayburg eolian sandstone (extrapolated from DOE core-well log correlations) occur somewhat isolated from the main sand body in Oldham and Deaf Smith Counties (fig. 17). These two sand depocenters overlie elevated tectonic elements of the Bush Dome to the south of the Amarillo Uplift.

The correspondence of preferential accumulation of sand and buried basement highs suggests that persistent movement of tectonic blocks kept some areas topographically elevated. These topographic features were probably subtle, but were high enough to either escape prolonged flooding (no evaporites are present at these locations) or to make preservation unlikely because of increased erosion or dissolution potential following deposition.

A comparison of formational isopach maps with net evaporite maps of Artesia rocks outside of the dissolution zone (e. g., the Queen/Grayburg Formation, fig. 18) suggests that transgressive flooding of Palo Duro Basin followed subsidence. Due to the extremely low relief, flooding was frequently almost basinwide. Initial precipitation in the evaporitic environment included gypsum over most of the flooded area, but halite dominated the margins of the evaporite environment producing bedded halite and clastic-salt mixtures. As desiccation proceeded, halite was precipitated on top of the sulfate. This stage probably occurred simultaneously with the initiation of siliciclastic progradation. The progradation was dominantly from the northwest, west, and subordinately from the east.

In some places, uppermost halite-bearing sediments, including transitional mud-salt mixtures, were preserved although perhaps altered (dissolved and recrystallized) by postdepositional processes. In other places, uppermost halite was dissolved by waters associated with the following progradational cycle. The arid eolian environment that generally prevailed following evaporite precipitation and subsequent mud-flat deposition eventually extended basinwide, depositing sheets of eolian sand and silt.

During upper Seven Rivers and Tansill evaporite (mainly halite) deposition, sand was apparently unavailable to much of the basin, and mudstone deposition records the progradational phase. Siliciclastic deposition was intermittently punctuated by transgressive evaporite precipitation during the Grayburg, Queen, lower Seven Rivers, and Yates deposition. Evaporite (mainly halite) precipitation, intermittently punctuated by progradational mudstone deposition, characterized upper Seven Rivers and Tansill deposition. The nature of the Salado in the Palo Duro Basin is unclear. It shows evidence of the former presence of salt, but also contains some sand. It originally may have been similar to the upper Seven Rivers which still contains thick halite beds and some cross-bedded eolian sandstone, as well.

In summary, deposition of the Artesia Group and Salado Formation of the Palo Duro Basin resulted from the interplay of subsidence patterns, relative sea-level rise, and clastic sediment input. Subsidence, as shown by isopach patterns, was greatest in the southern and southeastern basin. From this resulted slightly lower elevations in the south and east, more frequent flooding and, because of its remote location from dominant western clastic sources, cleanest salt deposition. Transgressions were generally rapid, evidenced by sharp contacts between terrestrial clastic rocks and transgressive evaporites, and by the uniform thickness (sheet geometry) of evaporite units. Initial evaporite precipitation produced gypsum over most of the flooded areas but halite dominated transitional zones where salt-clastic mixtures were produced between evaporitic and terrestrial environments. As evaporation proceeded, halite precipitation replaced sulfate precipitation basinwide. Episodic rejuvenation of marine-derived water influx resulted in renewed sulfate production. Prior to and during burial by prograding shallow subaqueous and terrestrial (dominantly eolian) facies, some uppermost salt in subjacent evaporite sequences was dissolved. Prograding clastics include mud, silt, and sand when available; otherwise, mud composed the progradational stage. Differential local subsidence and relative longevity of eolian environments produced more pronounced thickening of clastic sequences than of evaporite sequences.

EVOLUTION OF THE ARTESIA GROUP AND SALADO FORMATION

Individual Guadalupian/Ochoan formations of the Palo Duro Basin can be distinguished by their relative proportions of clastic and evaporite strata, the textural character of clastic strata, and the relative proportions of halite to bedded sulfate. By these criteria, the following statements summarize the stratigraphic development of Artesia and Salado facies in the Palo Duro Basin. Post-San Andres environments overall became more hypersaline with time. Sulfate/halite cycles in the Queen and lowermost Seven Rivers were characterized, with several exceptions, by dominantly halite cycles. Abundance of evaporites and their depositional extent were controlled by subsidence patterns, subsidence rates, and availability of clastic sediments. Clastic influx was greatest during the Grayburg but decreased in relative importance (compared to evaporite occurrence) through the Queen and Seven Rivers. General fining of clastic sediments accompanied their declining influence. Yates deposition recorded a return to progradation of more abundant and coarser-grained clastics following accumulations of bedded evaporite deposits in the upper Seven Rivers Formation. Tansill and Salado deposition marked a return to halite-dominated evaporite deposition.

POST-PERMIAN DISSOLUTION IN THE ARTESIA GROUP AND SALADO FORMATION

Salt dissolution and associated dissolving fluids have been postulated as causing many geomorphic, structural, and geochemical features seen in the Palo Duro Basin. Also, certain environmental conditions and topographic features may affect the continuation of salt dissolution (see table included with this report). This section presents a brief summary of these features, and additional results compiled during an ongoing investigation of post-San Andres Permian strata. Results of this and other studies support the contention that salt dissolution has operated on post-San Andres Permian strata and that overlying rock has been affected by collapse and diagenesis. Analysis of well-preserved

TABLE. Previous investigations of salt-dissolution and related features in the Palo Duro Basin.

Feature, Location	Evidence	Reference
Geomorphic		
1. Escarpment retreat rates: Eastern Caprock Escarpment, 5,500-9,000 yr/km; Canadian River Escarpment, 2,400-32,000 yr/km.	archeology, topographic profile projection, terrace mapping	Gustavson, Finley, and Baumgardner, 1980.
2. Topographic rise of Eastern Caprock Escarpment correlates with concentration of rainfall, may enhance escarpment erosion, retreat.	Rainfall records.	Finley and Gustavson, 1980.
3. Alignment of linear depressions, stream courses, and regional fracture trends along margins of High Plains.	Map patterns.	Gustavson, Hoadley, and Simpkins, 1981; Gustavson and Budnik, 1985.
4. Caprock Escarpment retreat 24 mi and surface lowered 270 ft in 380,000 yr, Little Red River Basin.	Hypsometric analysis (distribution of mass and elevation).	Finley and Baumgardner, 1981.
5. Collapse due to dissolution of Salado salt below uppermost salt, Wink Sink, Winkler County.	Presence of sinkhole, well log correlations.	Baumgardner, Hoadley, and Gustavson, 1981.
6. Escarpment retreat 114 km/600,000 yr, avg. rate 19 cm/yr.	Volcanic age date on Pleistocene escarpment-derived Seymour Fm and preserved formational extent.	Simpkins and Baumgardner, 1982.
7. Canadian River formed along depressions (dissolution-related?) during Ogallala deposition, remained in depressions after Ogallala deposition.	Map patterns of thickened Ogallala corresponds with lows on pre-Ogallala surface.	Gustavson, 1982.
8. In future, importance of spring sapping on escarpment retreat will diminish.	Human depletion of Ogallala aquifer.	Gustavson, 1983.
9. Development of karst, Hall and Briscoe Cos.	Sinkholes, closed depressions.	Gustavson, Simpkins, Alhades, and Hoadley, 1982.
Structural/Stratigraphic		
1. Collapsed Permian strata and collapse-breccias, Caprock Canyons, Borger, Texas.	Outcrop exposures.	Gustavson, 1980.
2. Abrupt thinning and non-presence of salt short distances from salt-bearing strata in transitional areas between High Plains and Rolling Plains.	Correlations of core and well logs.	Gustavson, Hoadley, and Simpkins, 1981; Gustavson and Budnik, 1985.
3. Structural dip reversals in transitional areas between High Plains and Rolling Plains.	Geophysical well log correlations.	Gustavson, Hoadley, and Simpkins, 1981.
4. Collapse and fracturing of strata above dissolving salt.	Gypsum-filled extension fractures above uppermost salt in core.	Goldstein, 1982.

TABLE (continued)

Feature, Location	Evidence	Reference
Physiochemical		
1. Salt dissolution is ongoing.	High measured solute loads in streams.	Gustavson, Hoadley, and Simpkins, 1981.
2. Chaotic, poorly consolidated, gypsum-bearing "residue" and replacement dolomite above uppermost bedded salt in Oldham, Deaf Smith, Randall, Swisher, and Donley Counties.	Petrographic and macroscopic core analysis.	Gustavson, Hoadley, and Simpkins, 1981; McGillis and Presley, 1981; Ruppel and Hovorka, 1983a, b.
3. Hydration of anhydrite to gypsum and subsequent dehydration of gypsum to anhydrite, Donley Co.	Petrographic and macroscopic core analysis.	Hovorka, 1983.
4. Halite recrystallization may precede dissolution, DOE well locations.	Recrystallized halite core beneath dissolution zone.	Hovorka, 1983.
5. Dissolution waters are shallow, meteoric.	Br, Cl, $\delta^{18}O$, $\delta^{2}H$ analyses.	Kreitler and Bassett, 1983.

evaporite/clastic sequences in post-San Andres strata (unaffected by post-Permian regional dissolution) allows estimation of the original abundance of salt in the dissolution zones of the Seven Rivers, Tansill, and Salado formations.

Previous Investigations

Because San Andres halite strata in the Palo Duro Basin has been targeted as possible repository host rocks, studies were initiated to identify and assess geologic processes which might affect the security of a salt-hosted repository. The table summarizes major published findings that relate stratigraphic and geomorphic effects to dissolution processes in the Palo Duro Basin. These are broadly grouped under three categories of dissolution-related features: 1) physiochemical, or effects on composition and texture of the rocks; 2) geomorphic, or effects on the land surface; and 3) structural/stratigraphic, or effects on character or attitude of strata in the dissolution zones.

Pre-Dissolution Salt Abundance

Geologic effects suggested to be dissolution-related have been well documented in recent literature (table). However, complex structural relations in northern Palo Duro Basin, in the vicinity of the Amarillo Uplift, make determinations of pre-dissolution salt abundance and extent difficult. An upper limit, however, can be set confidently at a thickness of salt equal to that of the remaining coeval salts preserved in the southern part of the basin, for instance, in south-central Lubbock County (fig. 2) outside the dissolution zone (including the Tansill/Salado paleodissolution zone of McGillis and Presley, 1981). The suggestion of an upper limit is predicated on the premise that salt deposits were not originally thicker in the dissolution zone than are equivalent salt deposits preserved outside the dissolution zone.

Given this qualification, a maximum of 260 ft of upper Seven Rivers salt and 140 ft of Tansill/Salado salt could have been dissolved as far to the northwest as SWEC-Mansfield

No. 1 in Oldham County where intervals of rock correlative with preserved salt sections to the south contain residues and brecciated mudstones, indicative of the former presence of salt. As much as 400 ft of total salt could have been dissolved from the upper Seven Rivers, Tansill, and Salado formations at #1 Mansfield if salt at its present thickness in Swisher County originally extended into east-central Oldham County.

Another approach to reconstruction of the original salt section involves calculating the proportion of relatively insoluble components, sulfates and siliciclastics, in the preserved salt section and recalculating original salt abundance in the dissolution zone wells.

Values for ratios of soluble versus insoluble components in the salt sections were calculated from core logs by the author at #1 Grabbe where both Tansill salt (defined by correlation to published cross sections of Tait and others, 1962) and upper Seven Rivers salt are apparently entirely preserved. At No. 1 Grabbe, the upper Seven Rivers is about 25 percent insoluble and the Tansill about 15 percent insoluble. No Salado salt core has been recovered; therefore, determination of its insoluble fraction is not yet practical. The Salado is not included in the following discussion.

Applying salt/insoluble component relationships to #1 Mansfield results in the following. At #1 Mansfield, in the Upper Seven Rivers interval, 35 ft of non-salt material remains. No salt is present. Because this material is assumed to be 25 percent of the original section, 105 ft of upper Seven Rivers salt may have been removed since deposition. By this calculation the upper Seven Rivers Formation would have been 140 ft thick at No. 1 Mansfield. Reconstruction of the Tansill section at No. 1 Mansfield, based on an insoluble component of 15 percent (determined at No. 1 Grabbe), suggests that 57 ft of salt was removed from that formation for a reconstructed formation thickness of 67 ft. Based on the abundance of insoluble components, salt totaling 162 ft thick may have been removed from the upper Seven Rivers and Tansill formations at this location. Combined reconstructed thickness for the upper Seven Rivers and Tansill formations is 207 ft at No. 1

Mansfield, whereas that for the combined formation thickness in south-central Lamb County is about 400 ft. It is concluded that the Seven Rivers and Tansill formations thinned to the north prior to post-Permian halite dissolution. This is consistent with the thinning of clastic-dominated formations (e. g., the Queen/Grayburg and Yates formations) and the thinning of entirely preserved Queen evaporite cycles in the same direction.

Reconstitution of the original upper Seven Rivers and Tansill salt sections in the way just discussed results in section thicknesses similar to the section thicknesses seen where the total salt section is preserved, outside the dissolution zone and north of Lamb County, essentially north of the Matador Arch. South of this area, the upper Seven Rivers evaporite section thickens considerably into the Midland Basin. The Tansill Formation does not thicken similarly.

The amount of insoluble material expected to remain after dissolution of an even thicker section of salt would be higher than is actually present. This would be true if the original salt thickness in the dissolution zone were similar to that preserved in south-central Lamb County. Also, if original salt purity was lower in the northwest due to proximity of siliciclastic sources, the proportion of insolubles to halite would have been greater than measured in Swisher County. If true, even less halite was originally deposited in Oldham County than calculated in the reconstruction above. K. S. Johnson (written communication) suggests that a reasonable approach to reconstitution of the missing halite section is to project evaporite section thinning rates from basin center near Grabbe No. 1 to Mansfield No. 1. By this calculation about 50 ft of Seven Rivers halite may have originally been present at Mansfield No. 1. Projection of Salado/Tansill halite thinning from southern Hale County (original Salado/Tansill salt at Grabbe No. 1 has been largely dissolved) toward Mansfield No. 1 suggests that no Salado/Tansill halite was ever present there. Future efforts will be directed toward refining and applying this "reconstruction" procedure to the remainder of the dissolution zone in the Palo Duro Basin.

Effects of Dissolution on Preservation of Individual Evaporite Units

Detailed mapping of individual evaporite strata located within the Artesia Group, especially in the Queen and Yates Formations, provides evidence for salt dissolution. In the Queen/Grayburg formation, to the south of the dissolution zone, evaporite sequences occur as interbedded anhydrite and halite (figs. 9, 10 and 13). North of the limit of preserved Seven Rivers salt, where the Queen dissolution zone should be located, only anhydrite or gypsum remains in correlative beds. Post-Permian dissolution probably removed all halite from this horizon.

In the Queen depositional environment salt was probably everywhere precipitated landward of gypsum (now altered to anhydrite outside of the dissolution zone). This is demonstrated by facies relations observed along the western margins of Queen/Grayburg evaporite horizons (fig. 11), where salt dissolution has not been documented in either underlying or immediately overlying halite-bearing units (fig. 3).

The conspicuous absence of Queen salt where salt dissolution has been well documented for the overlying Seven Rivers and the underlying upper San Andres (Gustavson and others, 1980) is a compelling reason to suspect salt dissolution in the Queen, as well. Syndepositional dissolution also removed original halite in extreme west and east Swisher County and west Briscoe County.

Some areas showing anhydrite (figure 19) are not in the dissolution zone as defined by Gustavson and others, but exist where overlying salt strata (Seven Rivers) are still present. Notably these occur near where mapped evaporite beds begin to include a significant clastic component (>15 percent) in the landward direction. These isolated patches of anhydrite probably record dissolution of uppermost salt from the evaporite sequence by meteoric waters associated with the post-evaporite progradation of siliciclastics. This process exposed basal sulfate which extensively underlaid the salt sheet, as discussed above.

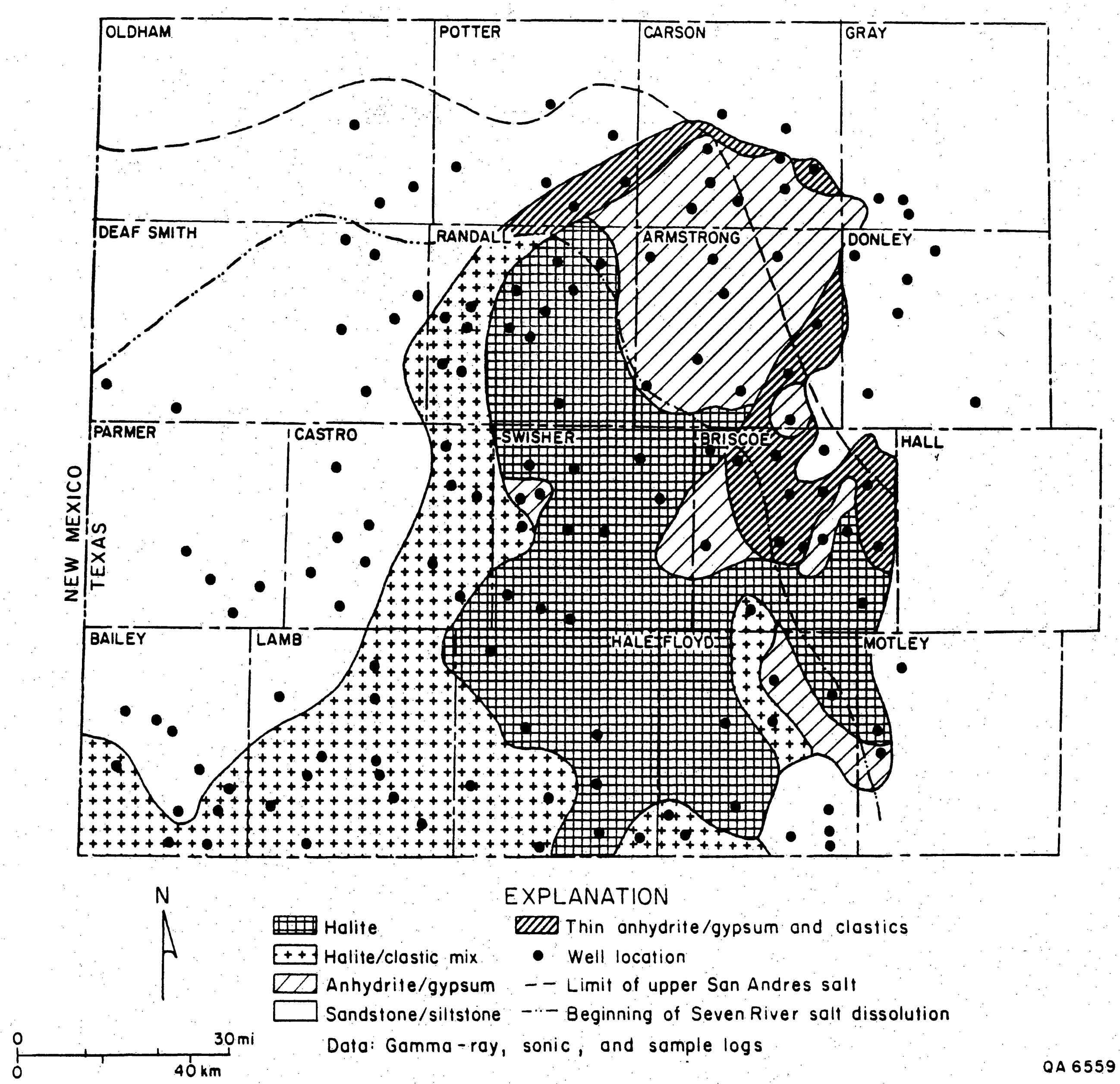

Figure 19. Queen/Grayburg formation, lower evaporite: facies distribution at top of clastic-free evaporite interval and within laterally time-equivalent sediments. Seven Rivers/Queen/upper San Andres dissolution zone indicated between dashed boundaries. Anydrite is stratigraphically below halite (see fig. 11).

Thinning of entire salt sections has been used to suggest salt dissolution (Gustavson and others, 1980; Gustavson and Budnik, 1985). However, more detailed analysis of individual salt strata and their facies relations are required to discriminate between a dissolution margin and a zone of changing depositional facies. Maps of individual salt strata can be used to illustrate the dissolution process along the Eastern Caprock Escarpment. An isopach map of one clean evaporite bed from the Yates Formation (fig. 20) shows abrupt truncation along its eastern margin. The remaining evaporite section actually thickens toward the eastern margin and probably extended originally some distance to the east into Dickens, Motley, and southeastern Briscoe Counties (see fig. 12 for examples of truncated salt facies in the Tansill).

Irregularities along the eastern margin of Yates salt units correspond closely to topography in places along the Eastern Caprock Escarpment. This correspondence supports the conclusions of previous studies which relate many geomorphic features along the Caprock Escarpment to salt dissolution and the collapse of strata overlying the dissolution site (table).

Tansill and Salado Facies Relations and Salt Dissolution

The uppermost salt cored in the Palo Duro Basin occurs at No. 1 Zeeck. This salt, informally referred to as Salado/Tansill salt in previous studies, is probably coeval with Tansill strata in the Midland Basin and on the Northwest Shelf. This conclusion is based upon correlation of #1 Grabbe well logs with published regional cross sections (Tait and others, 1962). Comparisons of gamma ray logs at Swisher County #1 Grabbe and #1 Harman show that the 35 ft of Tansill salt seen at Grabbe does not extend to Harman. The distance between the two well sites is only 11 miles. The zone above the top of halite at No. 1 Harman is characterized by abundant extension fractures filled with fibrous gypsum. Such features are reported to result from dissolution of underlying halite and subsidence of overburden in the Palo Duro Basin (Goldstein, 1982). It is apparent that

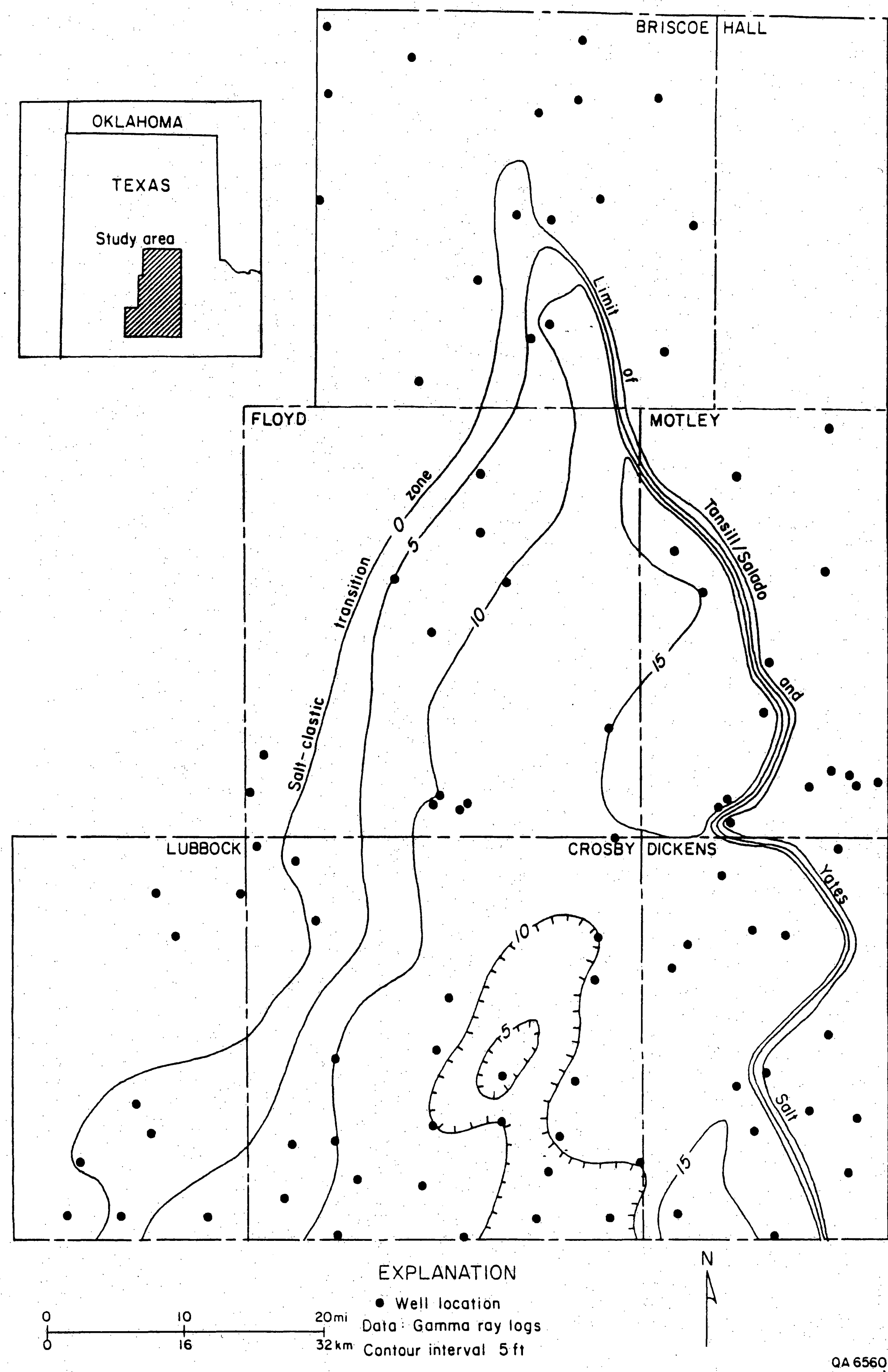

Figure 20. Yates Formation, upper salt bed: isopach map.

halite has been removed from the Tansill Formation at No. 1 Harman, but detailed facies relationships between rocks in the dissolution zone and those in the preserved halite section have not yet been defined.

Salado-equivalent clastic rocks seen in core from the southern Palo Duro Basin are like those interbedded with evaporites in the upper Seven Rivers and Tansill Formations. Mudstones comprise most of the interbeds in preserved evaporite sections, including the San Andres evaporite section, but some sand is present in the upper Seven Rivers. The Salado contains some sandstone in the dissolution zone. Further investigation of the Salado, especially of the distribution of clastic textures and insoluble residues, will better define the original facies relationships and establish estimates of pre-dissolution salt extent and abundance.

Effects of Dissolution on Overlying Strata

Dissolution of salt has been suggested to explain the occurrence of horizontal and inclined fibrous gypsum-filled extension fractures seen in clastic rocks above the uppermost occurrences of bedded salt in the dissolution zone (Goldstein, 1982). In core these mineralized fractures occur preferentially in sandstones, siltstones, and (in places) anhydrite beds. Mudstone beds in these zones of fracturing are highly brecciated with sulfate-coated slickensides on some surfaces. Competency of the affected rocks is an important factor in deformation style. Relatively competent sandstones, siltstones, and anhydrite collapsed as decimeter-scale and larger blocks, while less competent, fine siltstone to mudstone, intervals fragmented into centimeter-to-millimeter-scale pieces.

The mudstone breccias can be identified in sonic logs of rocks above the uppermost bedded salt in the dissolution zone (fig. 21), where sonic travel times are well in excess of 100 μs/ft, which is typical value for mudstones (Schlumberger, 1972). This response is probably due to "cycle skipping," which is characteristic of sonic logs in underconsolidated or fractured rock (Schlumberger, 1972).

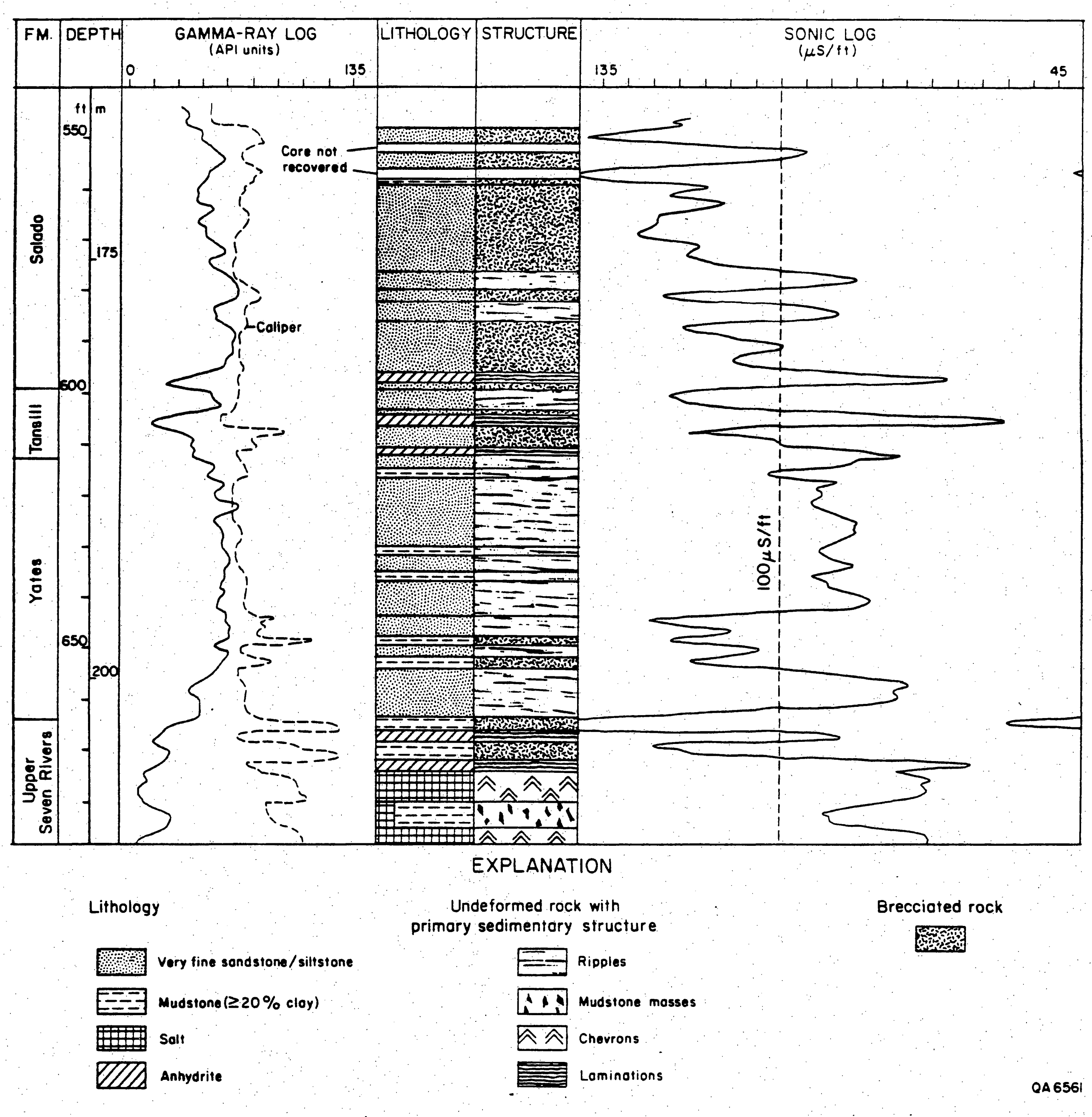

Figure 21. Randall County--DOE Rex White No. 1, dissolution zone: comparison of geophysical logs and state of deformation seen in core.

Close examination of figure 21 reveals good correspondence between brecciated rocks and the previously mentioned sonic response in No. 1 Rex White well. It also shows correspondence with caliper log responses where brecciated zones were preferentially washed out during drilling. In places, such as at 643 ft where no breccia was logged from core, but which demonstrates a slow sonic travel time, the caliper log indicates some amount of washout. This suggests that some core may not have been recovered from this interval. This is clearly the case at approximately 560 ft. An interesting variation of the pattern occurs at about 600-607 ft. This interval is dominated by unbrecciated rock; however, it also corresponds to a slow travel time shown on the sonic log. This competent interval is immediately underlain and overlain by thin brecciated beds, however. These incompetent beds apparently affect the sonic response within the unbrecciated interval as well.

It is important to note that the sonic responses discussed above are not indicative of intervals characterized by the fibrous gypsum-filled horizontal and inclined fractures discussed by Goldstein (1982). These fractures occur within all rock types (except halite, which they inevitably overlie) but occur preferentially in sandstone and siltstone. Identification of these fractured zones by interpretation of well log responses has not been yet attempted.

Excessive sonic travel times can be used to identify rocks which originally overlay bedded salt deposits that have subsequently been dissolved. In the future this tool may be used to help discriminate salt dissolution zones from areas where little salt was originally deposited.

Appendix. Wells used in cross sections and fence diagram in this report

County	BEG Location Code	Operator, Well Name
Armstrong	A 23	Burdell, Mc Gehee Strat Test No. 1
Briscoe	B 23	Amerada, J. C. Hamilton No. 1
	B 25	Exploration, Graham No. 1
	B 28	B. L. N., Sual-Schott No. 1
Carson	CAR 27	L. B. Newman, Meaker No. 4
Castro	C 1	Amarillo, C. R. Veigel No. 1
	C 2	Skelly, M. S. Wilson No. 1
	C 8	Stephans, I. C. Little No. 1
	C 9	Ashmun & Hilliard, Willis No. 1
	C 13	Amarillo, L. C. Boothe No. 1
Deaf Smith	DS 2	Frankfort, Allison-Hayes No. 1
	DS 22	Stone and Webster, J. Friemel No. 1
Dickens	DICK 12	Gulf, L. Hickman No. 1
Donley	D 1	H. E. Bryan, Hermesmeyer No. 1
Hale	H 2	De Kalb, W. B. Pool No. 1
	H 9	Honolulu, Clements No. 1
	H 12	Ray Albaugh, Hormell No. 1
	H 25	Stanolind, J. J. Hegi No. 1
	H 26	Plymouth, Daly & Hurlburt No. 1
Hartley	HART 33	Cities Service, Jackson No. D-1
Hockley	HOCK 8	Collins & Allen, Halliburton No. 1
	HOCK 10	Hamon & Champlin, Kelly A No. 1
Lamb	L 1	Gulf, L. E. Bartlett No. 1-A
	L 92	Depco, Young No. 10
Lubbock	LUBB 9	Tenneco, Crump No. 1
	LUBB 12	Humble Oil, Bernice Couch No. 1
Oldham	O 5	Shell and Atlantic, Fulton No. 98-1
	O 45	Shell, Alamosa No. 315-4
	O 84	Stone and Webster, Mansfield No. 1
Parmer	P 3	Ashmun & Hilliard, London No. 1
	P 5	Shell, Shell Strat 30-69
Potter	POTT 10	Sinclair, Bivins Estate No. 17
	POTT 27	Whittenburg, Masterson No. 1

Appendix (cont.)

County	BEG Location Code	Operator Well Name
	POTT 44	Humble, O. H. Gouldy No. 1
	POTT 188	Texaco, Amarillo Plant Fee No. 1
Randall	R 25	Gruy Federal, Rex H. White No. 1
Sherman	SHER 31	Petroleum Explor., Bullington No. 1
	SHER 39	Petroleum Assoc., Ponger No. 1-332
Swisher	S 3	Frankfort, Culton No. 1
	S 6	Standard, Alan B. Johnson No. 1
	S 12	Frankfort, Sweatt No. 1
	S 16	Stone and Webster, Zeeck No. 1
	S 17	Gruy Federal, Grabbe No. 1
	S 18	Stone and Webster, Harman No. 1

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