REPORT OF INVESTIGATIONS NO. 106

Regional Dissolution of Permian Salt in the Anadarko, Dalhart, and Palo Duro Basins of the Texas Panhandle

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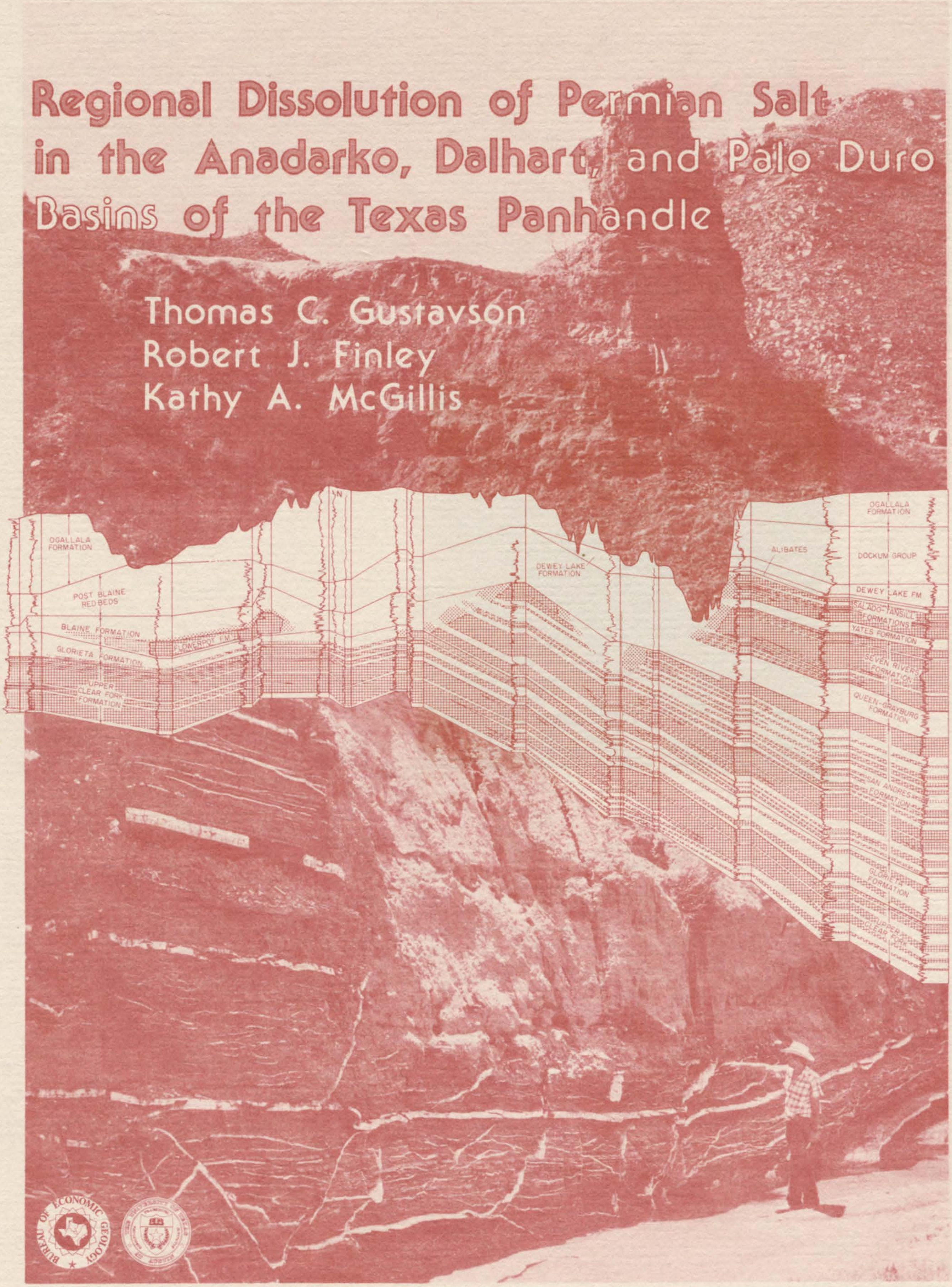

Bureau of Economic Geology • W. L. Fisher, Director • The University of Texas at Austin • Austin, Texas 78712

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ABSTRACT

A broad zone of salt dissolution that affects parts of the Permian Salado, Seven Rivers, San Andres, Glorieta, and upper Clear Fork Formations occurs beneath the Canadian River Valley from New Mexico eastward toward Amarillo, Texas, and southeastward parallel to the eastern Caprock Escarpment. Structure contours on the base of the Tertiary Ogallala Formation show broad areas with as much as 120 m (400 ft) of relief that are attributed to salt dissolution and subsidence in the Anadarko Basin and along the northern and eastern margins of the Palo Duro and Dalhart Basins. Cumulative thickness of salt dissolution ranges up to 335 m (1,100 ft) and has resulted in the collapse of overlying beds to form breccias, chimneys filled with collapse breccias, faults, sinkholes, and complexly folded terrane.

In the Anadarko and Dalhart Basins, dissolution followed deposition of Lower Cretaceous sandstones of the Kiowa Formation and Dakota Group. Late Cretaceous and early Tertiary erosion removed most Cretaceous and Triassic sediments, leaving only plugs of brecciated Cretaceous sandstone preserved as collapse chimney fillings in Permian sediments. Dissolution probably continued throughout the Tertiary. During and following deposition of the Miocene-Pliocene Ogallala Formation, dissolution resulted in numerous large solution basins up to 310 km^2 (120 mi^2) in area and solution troughs up to 80 km (50 mi) long. Continued dissolution led to over 75 m (250 ft) of regional lowering of the Great Plains surface over parts of the Dalhart and Anadarko Basins by the late Pleistocene.

Active dissolution along the northern margin and central part of the Palo Duro Basin creates collapse sinks, salt seeps, salt pans, and saline springs. The annual average solute load of streams draining these areas is 2.8 x 10^6 tons of total dissolved solids. Analysis of salt distribution in the Salado, Seven Rivers, San Andres, Glorieta, and Clear Fork Formations, when compared with solute loads of streams draining the Texas Panhandle, suggests that salt dissolution is much more rapid in the center of the Palo Duro Basin along the High Plains Escarpment than along the northern margin of the basin below the Canadian River Valley. Rates of horizontal salt dissolution for areas in the vicinity of the Prairie Dog Town Fork of the Red River, the Little Red River, and for tributaries of the Brazos and Wichita Rivers range from 0.03 to 81.7 cm (9.84 x 10^{-5} to 2.68 ft) per year.

INTRODUCTION

Permian bedded salts of the Palo Duro and Dalhart Basins occur in sufficient thicknesses and at sufficient depths to be evaluated as potential sites for long-term storage or isolation of nuclear waste. Properties of salt that make it desirable as a host rock are low permeability, low moisture content, high plasticity, and high gamma-ray shielding. A major limitation of isolation of nuclear waste in salt is the extremely high solubility of salt. To ensure that subsurface dissolution of salt will not affect waste isolation sites at some future time, a thorough understanding of the characteristics, geographic and stratigraphic extent, and mechanisms of salt dissolution must be available.

Subsurface dissolution of Permian bedded salt is an active and widespread phenomenon in the Permian Basin of the southwestern United States. As early as 1901, W. D. Johnson (1901) recognized that dissolution of buried Permian salt accounted for the structure of the Meade Basin in southwestern Kansas — an area comprising approximately 142 km^2 (55 mi^2). Later workers suggested that solution of salt or gypsum at depth has resulted in a variety of surface and subsurface structures and geomorphic features. Adams (1963), Jordan and Vosberg (1963), Brown (1967), Hills (1968), Bachman and Johnson (1973), and Johnson (1976) all attributed certain subsurface structures and anomalous thinning of shallow buried evaporite and gypsum sequences to dissolution. Lee (1923) and Morgan (1941) suggested that dissolution phenomena associated with the Permian San Andres and Salado Formations in eastern New Mexico are largely responsible for the rapid spreading of the Pecos River during the late Tertiary and Pleistocene. Eck and Redfield (1963) and Bock and Crane (1963) identified numerous chimneys at the excavation of Sanford Dam northeast of Amarillo, Texas, that were attributed to solution and collapse of gypsum beds within the Blaine Formation. In southeastern New Mexico, Anderson (1978) described geomorphic features such as sinkholes, linear depressions, domes, castles, and collapsed outliers and attributed them all to dissolution of salt and other soluble material within the Upper Permian Ochoan Series. Dissolution of Permian salts within the Palo Duro, Dalhart, and Anadarko Basins of the Texas Panhandle has been recognized by Johnson (1976), Gustavson and others (1978, 1979a, 1979b, and 1980), and Dutton and others (1979).

The Palo Duro and Dalhart Basins lie primarily within the Texas Panhandle (fig. 1) and the southern part of the Great Plains Physiographic Province (Fenneman, 1931 and 1938). The flat surface of the Great Plains is broken by the valley of the Canadian

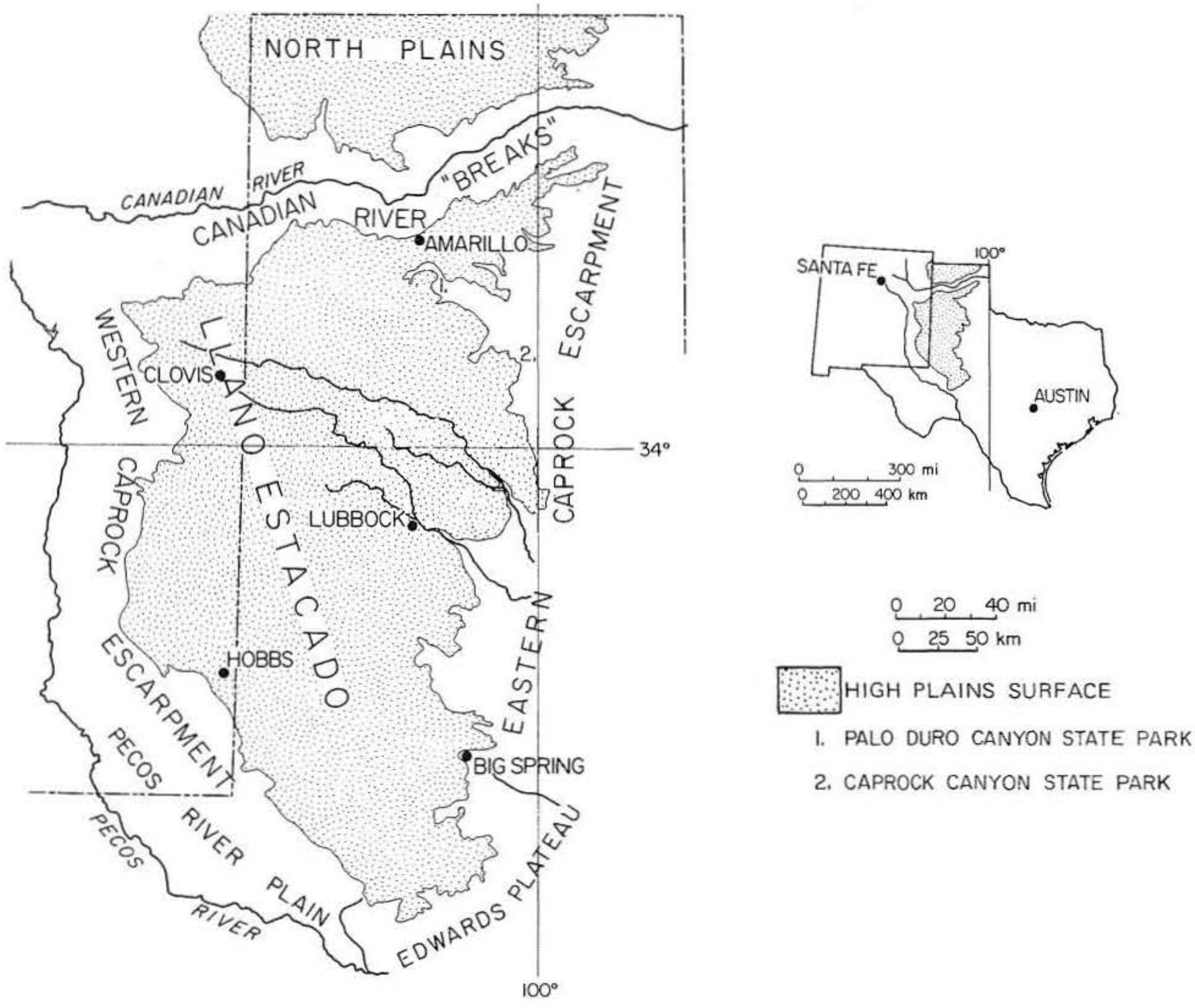

Figure 1. Physiographic units of the Texas Panhandle and eastern New Mexico.

River that is called the Canadian River Breaks. The Great Plains south of the Canadian River are also called the Southern High Plains or the Llano Estacado. To the east and west, the High Plains are truncated at the Caprock Escarpment, an erosional scarp where relief locally exceeds 500 m (1,500 ft). East of the escarpment lie the Rolling Plains. The High Plains of the Texas Panhandle are developed on the Tertiary Ogallala Formation, the remnants of a large alluvial apron that spread eastward as a result of uplift and erosion of the southern Rocky Mountains of New Mexico. Several tens of feet of Pleistocene eolian sediment cap the Ogallala in many areas. Drainage is poorly developed on the Southern High Plains and is mostly internal into the thousands of playas that cover its surface (Woodruff and others, 1979). Integrated drainage exists mainly as a series of extremely elongated rectilinear draws. The Caprock Escarpment is supported by a massive caliche horizon that marks the top of the Ogallala Formation and to a lesser extent by well-indurated sandstones that occur in the upper part of the Triassic Dockum Group. Eastward from the Caprock Escarpment, the Rolling Plains are developed on structurally disturbed Permian red beds. The Pecos River Valley and the Pecos River Plain lie westward of the Southern High Plains.

The major positive tectonic elements that surround the Anadarko, Dalhart, and Palo Duro Basins in the Texas Panhandle (fig. 2) have been described by Nicholson (1960) and Johnson (1976). Tectonic activity that created the series of arches, domes, and uplifts defining the basins occurred primarily during the Pennsylvanian Period and was largely completed by the end of that period. Minor movements have occurred since the Permian, but they may have resulted from differential compaction of basin sediments or from post-tectonic adjustments in the earth's crust.

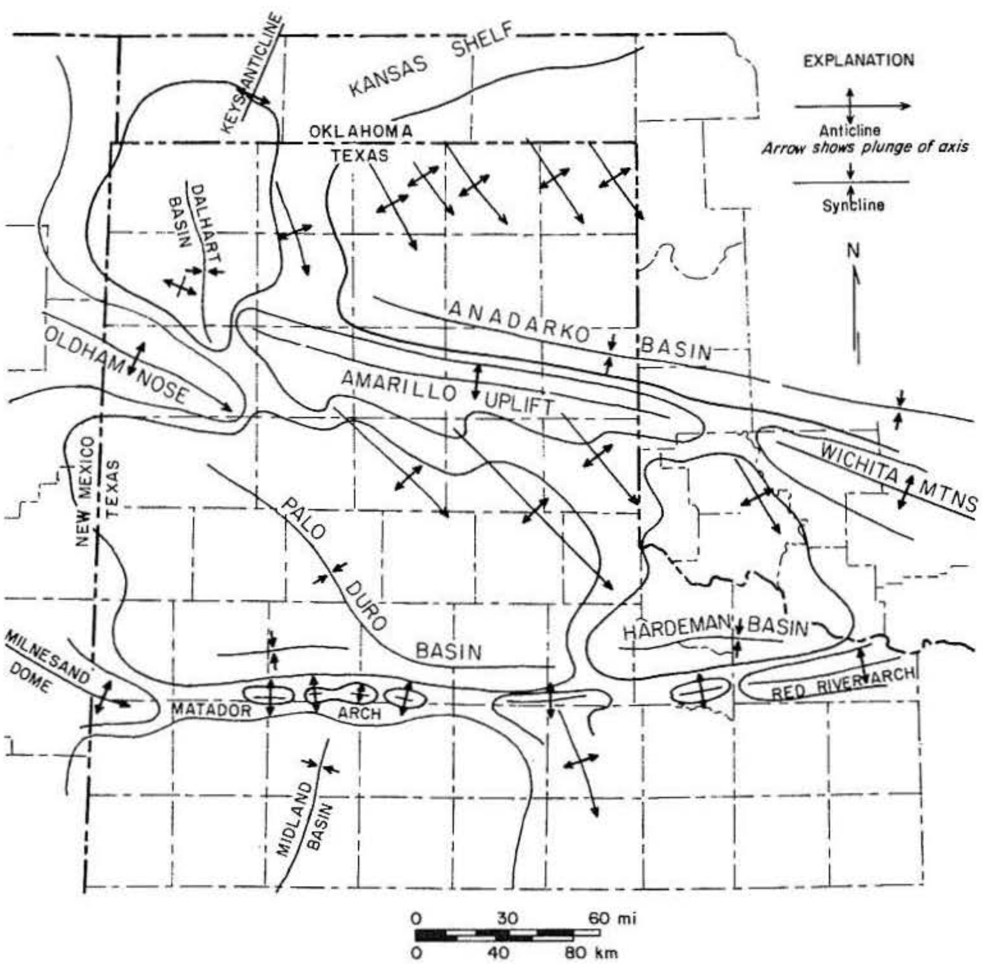

Figure 2. Major structural elements of the Texas Panhandle. After Nicholson, 1960.

REGIONAL SALT DISSOLUTION AND SUBSIDENCE

Salt, anhydrite, dolomite, limestone, and red beds compose Permian strata in the Anadarko, Dalhart, and Palo Duro Basins (Dutton and others, 1979). These units were probably deposited in a range of subtidal to supratidal environments. Lithofacies north to south are upper sabkha salt, lower sabkha anhydrite, supratidal to subtidal dolomite, and subtidal carbonates. Red beds consist of mudstones and fine-grained sandstones that intertongue with evaporites and dolomite.

There are seven salt-bearing units within the Anadarko, Dalhart, and Palo Duro Basins (fig. 3). With the probable exception of the lower Clear Fork Formation (lower Cimarron Salt in the Anadarko Basin), all of the younger salt-bearing units are undergoing salt dissolution on a regional scale (fig. 4).

Recognition of Salt Dissolution

Recognition of zones of active salt dissolution is based on several lines of evidence: (1) All the streams draining the Southern High Plains carry high solute loads. For example, the Prairie Dog Town Fork of the Red River carries a mean annual solute load of 1.0035×10^6 tons of dissolved solids per year, including 0.4253×10^6 tons of chloride per year. Brine seeps, salt springs, and salt pans occur along the stream valley. (2) The abrupt loss of salt sequences between relatively closely spaced wells and the abrupt thinning of stratigraphic sequences away from salt-bearing strata suggest dissolution rather than facies change (figs. 5 and 6). (3) Maps of regional facies distribution show that zones of abrupt salt thinning truncate facies tracts, indicating that the thinning is due to dissolution rather than to facies changes (Dutton and others, 1979). (4) Examinations of cored intervals through the Seven Rivers and Salado Formations from the D.O.E./Gruy Federal, No. 1 Rex H. White well in Randall County and the D.O.E./Gruy Federal, No. 1 D. N. Grabbe well in Swisher County reveal that dissolution of the upper parts of these salt beds has occurred. Several feet of poorly consolidated to unconsolidated red-brown mud overlie the uppermost salt beds penetrated in these wells. The muds are probably an insoluble residue. (5) Permian outcrops along the Canadian River Valley and east of the High Plains Escarpment are replete with folds, collapse chimneys, breccia blankets, and sinkholes that are the

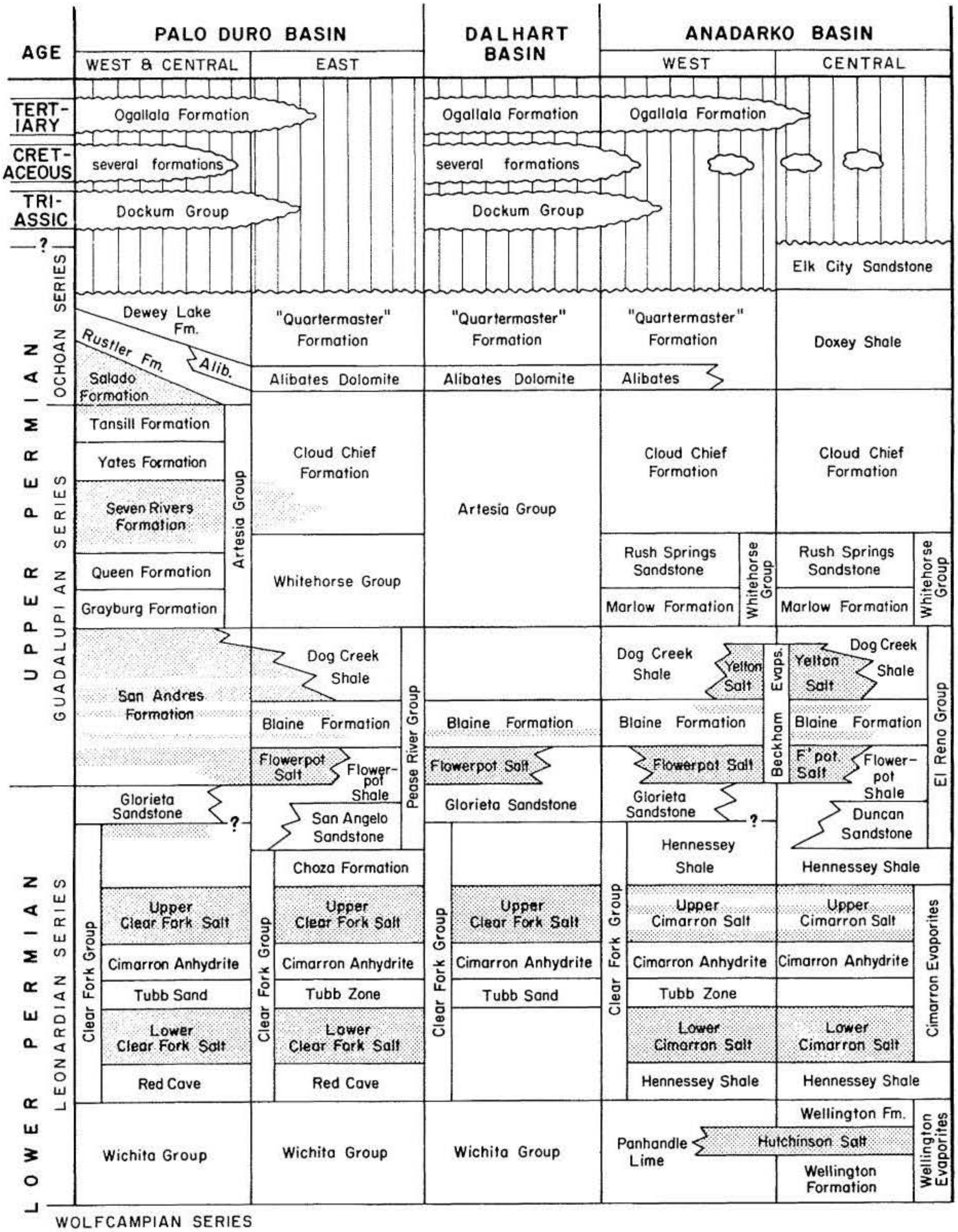

Figure 3. Stratigraphic nomenclature of Permian and younger strata in the Texas Panhandle and western Oklahoma. Principal salt units are shown in gray. From data in Fay (1965), Jordan and Vosberg (1963), McKee (1967), McKee and others (1967), and Tait and others (1962), compiled by Johnson (1976).

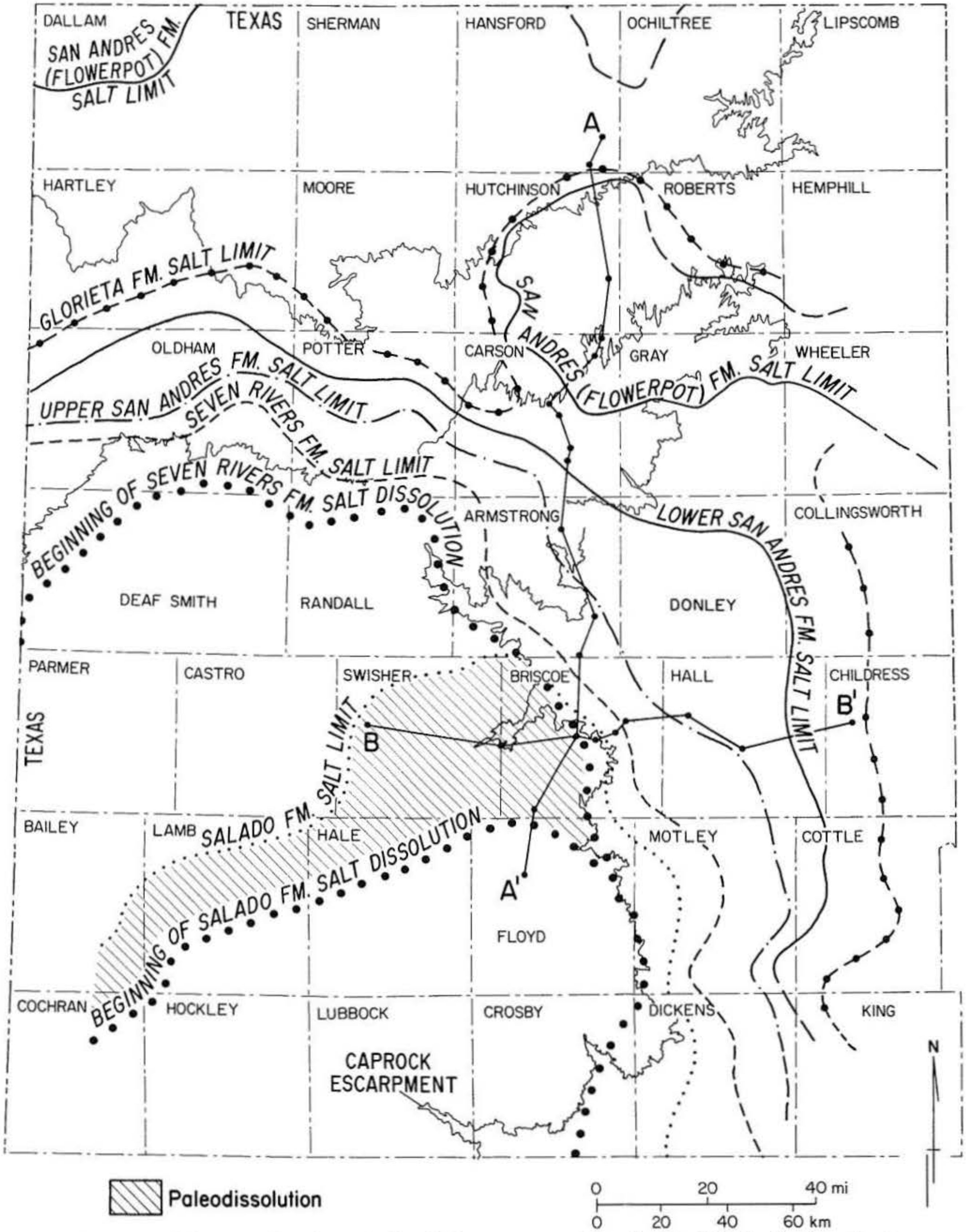

Figure 4. The zone of active salt dissolution occurs north and east of the beginning of salt dissolution lines and parallels the Caprock Escarpment. Small additional areas of salt are undergoing dissolution in northwest Dallam, northeast Hansford, and northwest Ochiltree Counties.

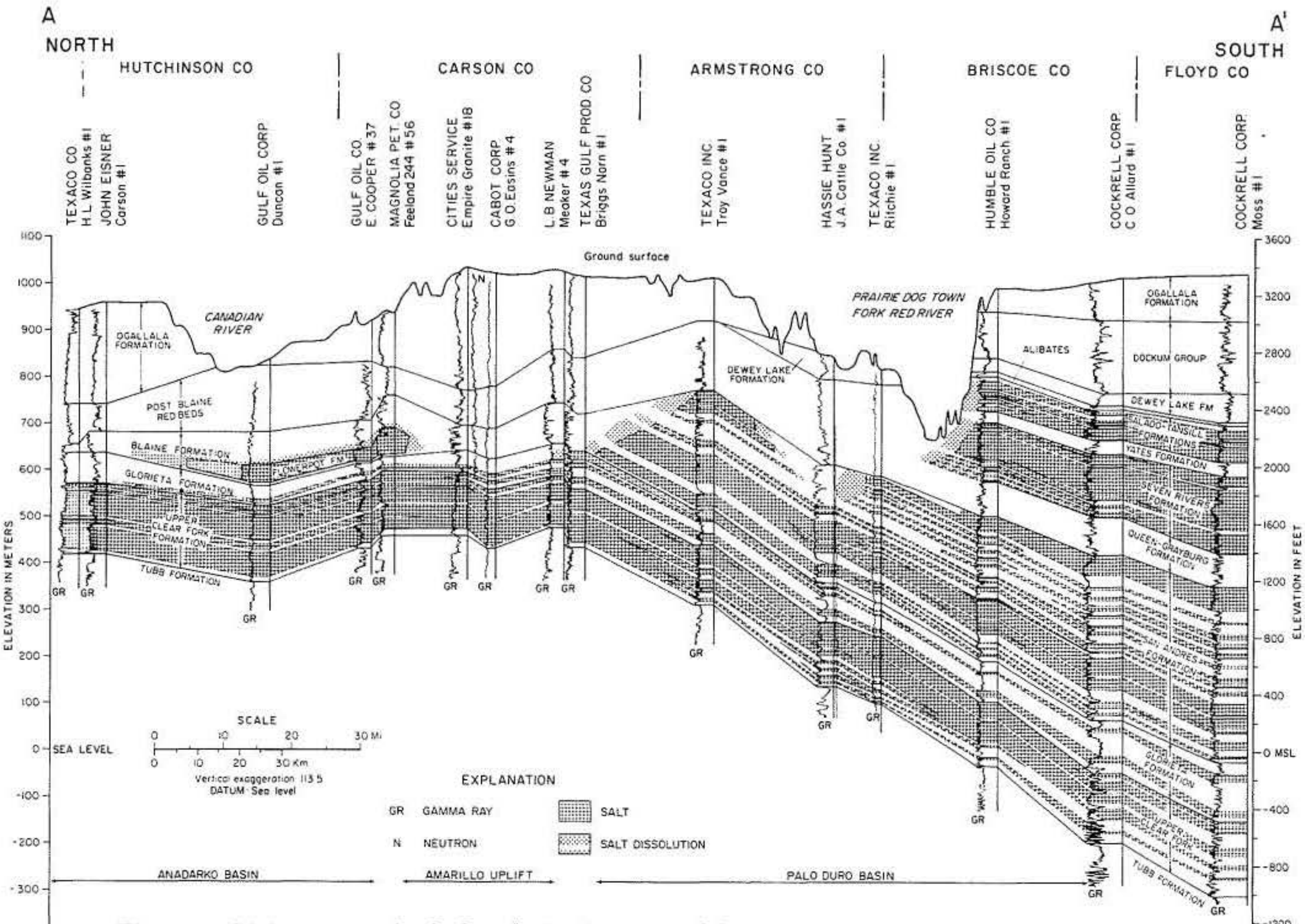

Figure 5. Major zones of salt dissolution interpreted from gamma-ray logs underlie the eastern margin of the Southern High Plains. This cross section (A-A′) is located in figure 4.

structural products of salt dissolution and collapse of overlying sediments.

Streams draining the Texas Panhandle also carry a substantial volume of calcium and sulfate in their solute load (U.S. Geological Survey, 1969-1977), indicating that solution of gypsum is an important process. Gypsum crops out in numerous localities along the Canadian River and in the Rolling Plains. Solution of gypsum in outcrop has produced karren, enlarged fractures, and small caverns. Examination of anhydrite/gypsum sequences in numerous cross sections, however, reveals that anhydrite/gypsum beds do not thin substantially in the shallow subsurface. This suggests that compared with salt dissolution, anhydrite/gypsum dissolution is not an important process in the subsurface and that, furthermore, gypsum dissolution is a surface or very near surface process that has not played an important role in causing the major structural adjustments and dissolution collapse features occurring in the Texas and Oklahoma Panhandles.

Zones of active salt dissolution occur beneath and eastward of the High Plains Escarpment on the eastern margin of the Southern High Plains and underlie the Canadian River Breaks and the northern edge of the Southern High Plains (fig. 4). The youngest and stratigraphically highest salt units have undergone relatively more extensive salt dissolution, and salt dissolution zones in these formations lie nearer to the center of the Palo Duro Basin. The steplike character of salt dissolution zones and their relationship to major physiographic features — Canadian River Valley, Palo Duro Canyon, and Caprock Escarpments — are clearly illustrated in structural cross sections (figs. 5 and 6). In both cross sections, Glorieta Formation and younger salts are interpreted as undergoing dissolution.

The regional extent of salt dissolution is best shown by the structure-contour map (fig. 7) on the base of the Ogallala Formation (Miocene-Pliocene). The structure-contour map was constructed from numerous drillers' and geophysical logs from water, oil, and gas wells. In effect it is a topographic map of the surface of all older formations in contact with the overlying Ogallala, including Permian, Triassic, Jurassic, and Cretaceous formations.

South and west of the active salt dissolution zone, the structure-contour map shows a regular topographic surface with a regional slope of approximately 1.9 m per km (10 ft per mi) to the southeast. In this same area there is only a single shallow closed basin in the southeastern corner of Deaf Smith County. The paleodrainage system that occupied this surface can also be recognized

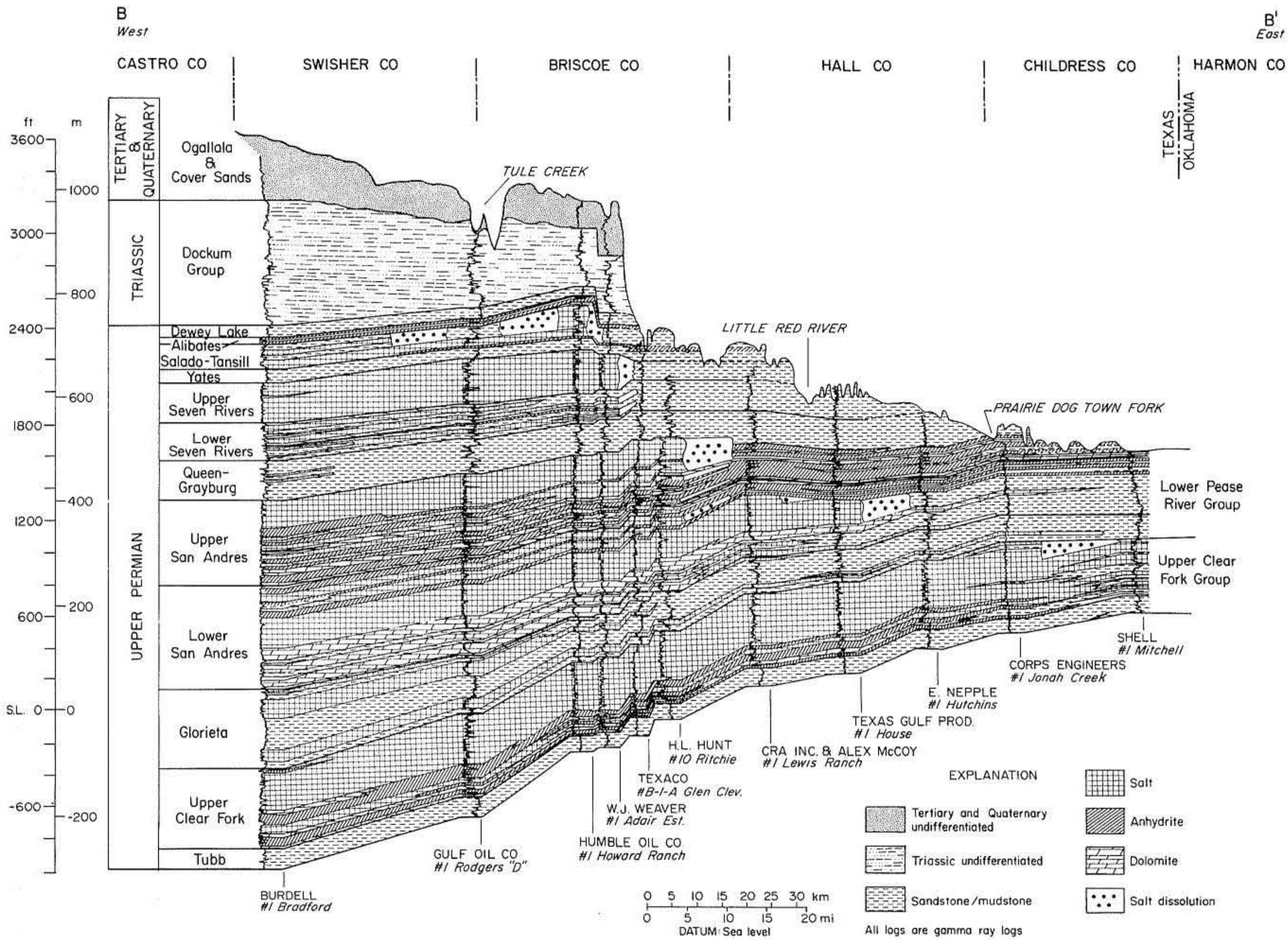

Figure 6. Zones of salt dissolution interpreted from gamma-ray logs. Cross section extends from Briscoe County, Texas, eastward across the Rolling Plains Physiographic Province to the Oklahoma border. This cross section (B-B′) is located in figure 4.

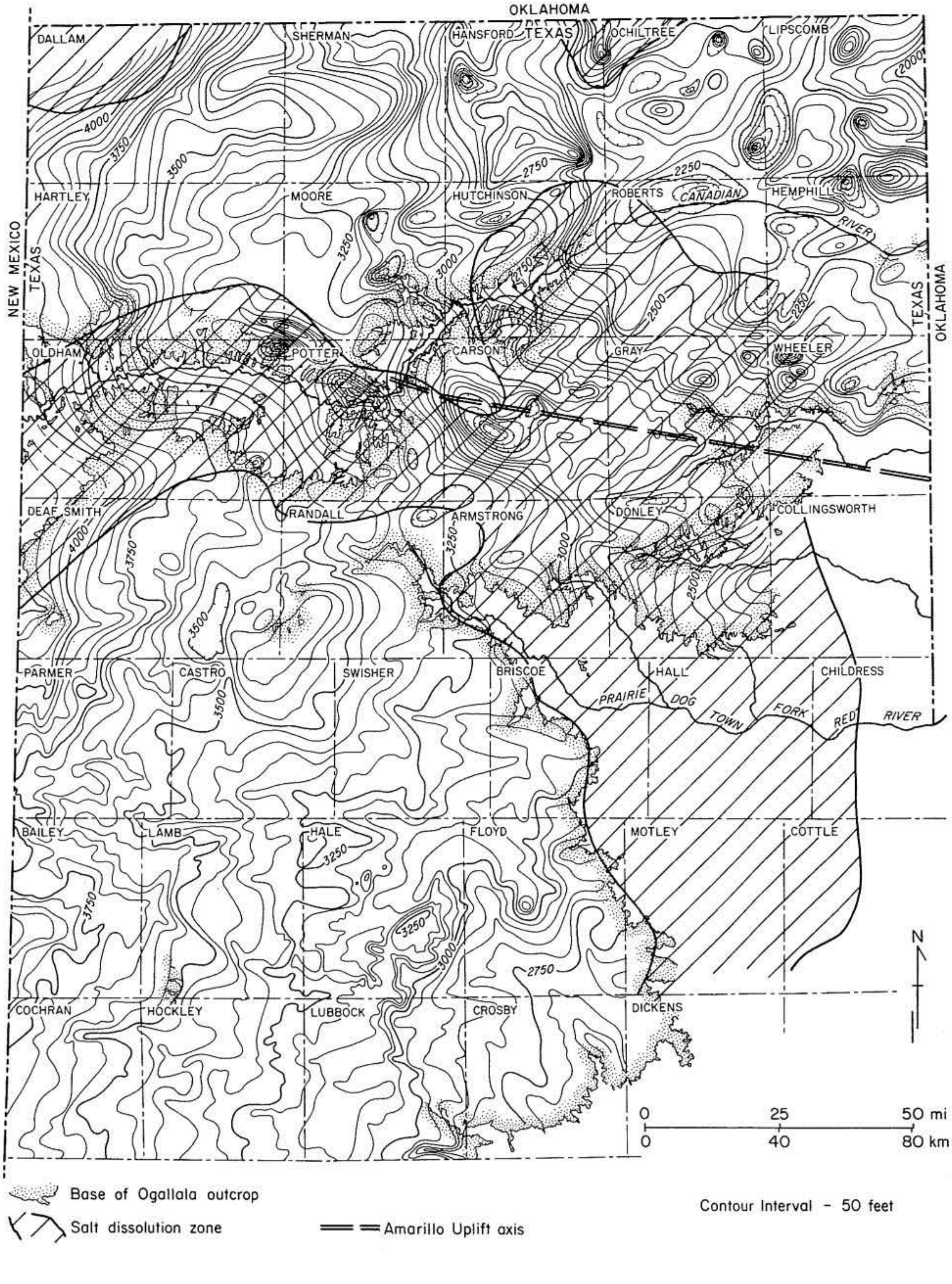

Figure 7. Structure-contour map on the base of the Ogallala Formation (in part from Cronin, 1961). Map also indicates the active salt dissolution zone for the Salado, Seven Rivers, San Andres, and Glorieta Formations.

easily as a series of major valleys and tributaries. If figure 7 and figure 8 are compared, it is evident that a system of integrated dendritic drainage extended from northwest to southeast across what is now the Southern High Plains. Several additional stream segments flowed northeastward out of Deaf Smith County into Randall County.

Structure on the base of the Ogallala is chaotic within the active dissolution zone and northward (fig. 7). The area is characterized by a number of large closed basins that range in area up to 310 km^2 (120 mi^2) and in depth to over 107 m (350 ft). There is no evidence of Tertiary pre-Ogallala sediments in any of these basins; thus the basins probably formed while Ogallala sedimentation was underway. Although there is a regional slope to the east, all other structural elements that lie east of Dallam and Hartley Counties appear to be distributed randomly with one exception. Several basins and troughs are aligned beneath the valley of the Canadian River, between Hemphill County on the east and Oldham County on the west. The Canadian River has apparently accelerated salt dissolution beneath its valley, and this is reflected in the series of basins and troughs.

The area north of the dissolution zone contains Permian through Cretaceous sediments beneath the Ogallala Formation. This area was exposed to erosion throughout the Late Cretaceous and early Tertiary, which was sufficient time to establish an integrated drainage system. It is evident that the erosion surface beneath the Ogallala Formation has been severely disturbed and no longer reflects any vestiges of a drainage pattern. Differences in the overall character of the structure-contour surface southwest of the dissolution zone and the surface within and north of the dissolution zone are attributed to the probable dissolution of more than 182 m (600 ft) of salt. Salt thicknesses for nearby areas are shown by gamma-log cross sections in figures 5 and 6.

Regional Subsidence Estimates

If it is accepted that regional salt dissolution has taken place over large parts of the northern Panhandle, then it is possible to estimate the amount of structural collapse that has occurred as the result of dissolution. The structure-contour surface is offset within the salt dissolution zone along a line from southeastern Armstrong County to central Oldham County as a result of regional salt dissolution and subsidence (fig. 7). Elevation differences across the offset suggest that the base of the Ogallala has subsided from 150 m (500 ft) in Hartley and Dallam Counties on the west to as much as 300 m (1,000 ft) in a deep closed basin in Roberts, Ochiltree, and Lipscomb Counties in the east.

Topography of the High Plains and Canadian River Valley also reflects the influence of regional subsidence south of the dissolution zone. Slope on the Southern High Plains is about 1.9 m per km (10 ft per mi) to the east-southeast (azimuth 120°). North of the Canadian River, the slope of the High Plains is erratic, but generally eastward. Slope is approximately 2.7 m per km (14.4 ft per mi), or about 44 percent steeper than in the area to the south of the Canadian River Valley. Furthermore, if the strike of the topographic contours south of the Canadian River is projected northeastward, it is apparent that the northern side of the Canadian River Valley is approximately 75 m (250 ft) lower than the south side of the valley (fig. 9). This difference in elevation is also illustrated in gamma-log cross sections (figs. 5 and 6); the cross section shows that both the top of the Permian System as marked by the Alibates Formation and the base of the Ogallala Formation lie 120 to 180 m (400 to 600 ft) lower on the north side of the Canadian River than on the south side. It is also apparent that salt dissolution of the same magnitude has taken place. Thus, post-Ogallala Formation salt dissolution north of the presently active zone of salt dissolution is probably responsible for the differences in elevation and slope of the High Plains from the south to the north side of the Canadian River Valley.

Additional evidence supports the contention that as much as 75 m (250 ft) of salt has been removed since Ogallala time. Ancient alluvial channels of the Ogallala Formation trended south-southeastward from central Dallam and eastern Hartley Counties on the north side of the Canadian River Valley (Seni, 1980, p. 17, fig. 11). Furthermore, Seni reports that three major depositional trends occur south of the Canadian River Valley: two southeasterly trends, one in Gray and one in Carson County, and one southerly trend in Deaf Smith County. It appears from analyses of these thick sand trends and from paleocurrent indicators observed in outcrop that Ogallala alluvial channels flowed from central Dallam and eastern Hartley Counties south and southeastward across the present Canadian River Valley.

The present surface slope of the Southern High Plains and the slope of the pre-Ogallala surface beneath it are approximately 1.9 m per km (10 ft per mi). This is inferred to be representative of the magnitude of slopes of streams that deposited the Ogallala Formation. Furthermore, slopes of this magnitude are necessary to transport sediment in the coarse-sand to fine-gravel size range. Therefore, using the figure of 1.9 m per km (10 ft per mi), it is possible to estimate the elevation of the Ogallala Formation surface at the time that deposition was underway in Dallam County and eastern Hartley County by projecting upslope from major channel fills in Gray, Carson, and Deaf Smith Counties. Slope projections from Gray and Carson Counties to eastern Hartley County suggest that the Ogallala should be approximately 75 m (250 ft) higher in Hartley County than it is today in order to have sustained transportation of sediments to the southeast. A similar projection northward from sand thicks in Deaf Smith County indicates that the Ogallala in eastern Hartley County should be at least 120 m (400 ft) higher to have sustained sediment transport to the south. Although this analysis is speculative, the 75 m to 120 m (250 ft to 400 ft) of indicated lowering of the post-Ogallala surface is similar to the amount of surface collapse calculated by analysis of the topographic data.

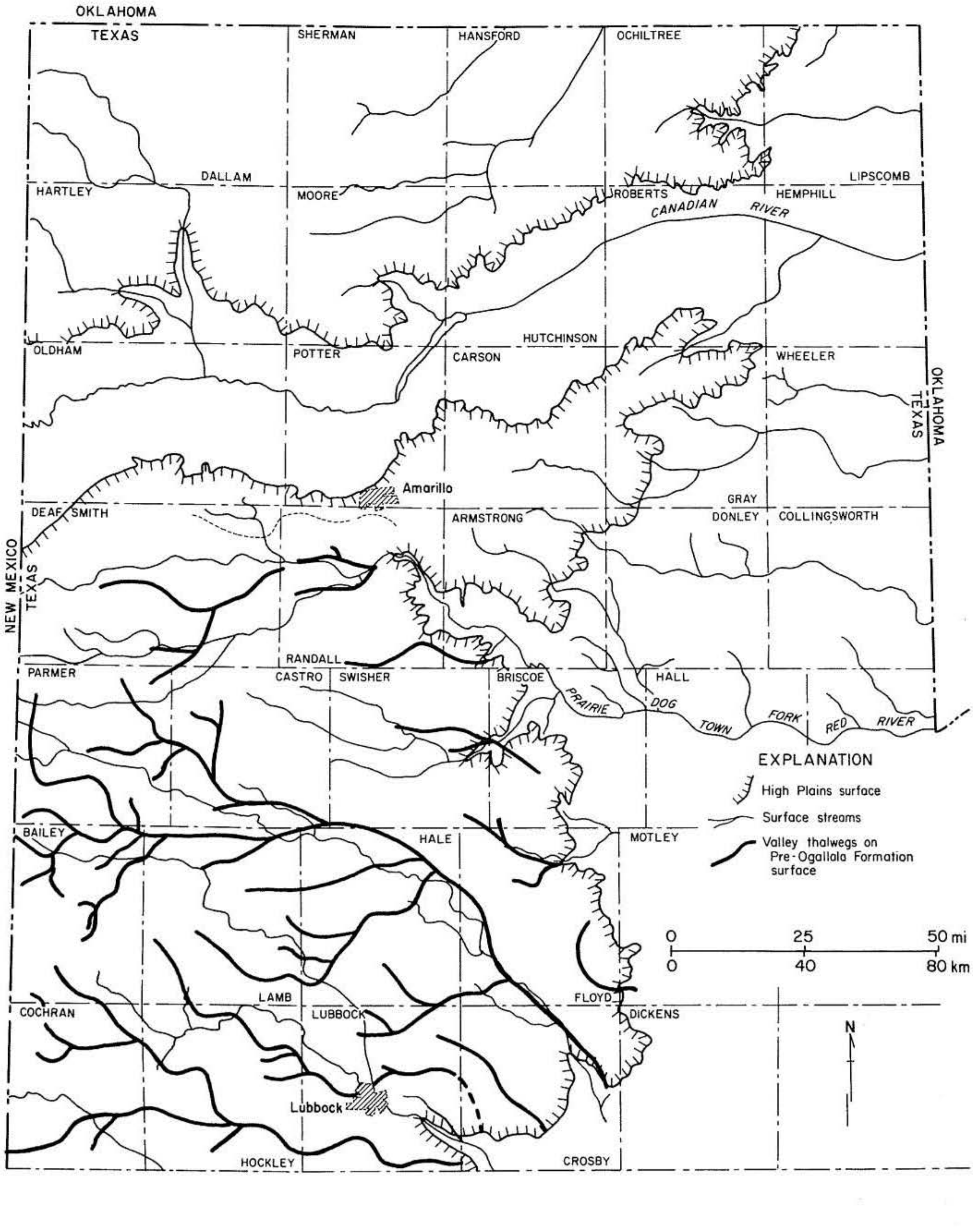

Figure 8. Comparison of modern drainage with pre-Ogallala Formation drainage interpreted from figure 7.

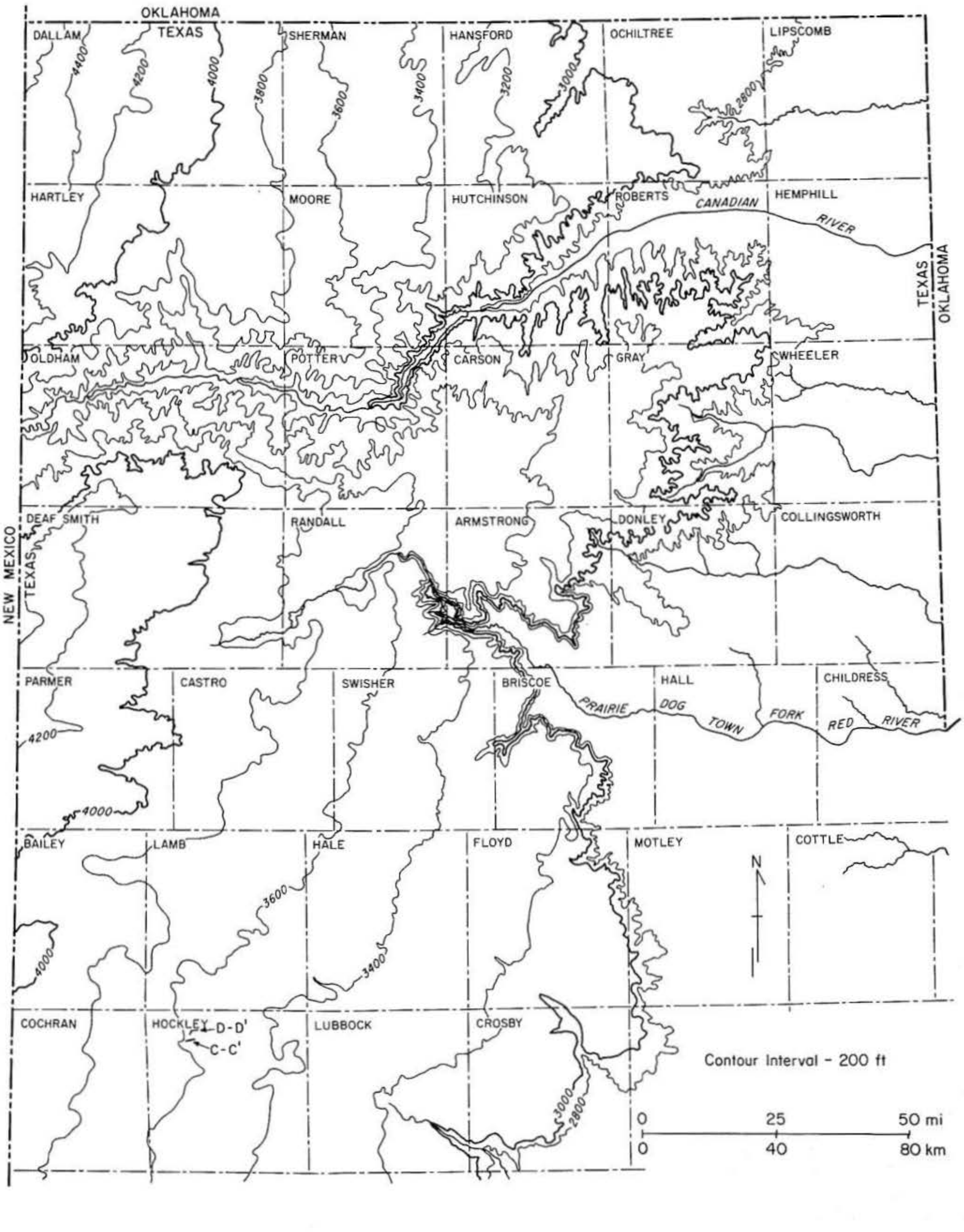

Figure 9. Topography of the High Plains, Texas Panhandle.

PLAYAS, COLLAPSE CHIMNEYS, AND DRAWS

The surface of the Texas High Plains is covered with thousands of playa lakes ranging from less than 10 m (30 ft) to more than 5,000 m (3 mi) wide and from less than 1 m (3 ft) to more than 30 m (100 ft) deep. The shape of the playa depressions is also highly variable; some playas are circular in plan, whereas others are distinctly elongated and oval in shape. Many large playas that lie within 40 km (25 mi) of the southern margin of the Canadian River Valley have extensive benches or flat bottoms.

A variety of processes has been suggested for the formation of playas, including deflation, caliche caprock solution, compaction, animal activity, and differential subsidence. It is probable that no single explanation for playa formation is sufficient to explain all playa relationships and that all of these processes may have had some influence on playa development at one time or another. Perhaps the earliest discussion of playa origins is by Gilbert (1895), who suggested that some of the lakes on the Great Plains were formed by deflation. Later Johnson (1901) hypothesized that most playas were formed by the compaction of Tertiary (Ogallala Formation) sediments and that at least some were formed by subsidence over areas of salt dissolution. Johnson denied that wind erosion played an important role in the formation of playas. Later workers, especially Evans and Meade (1944), Reeves (1966), and Reeves and Parry (1969), considered deflation to be the probable mechanism for the formation of most playas. Lee dunes occur on the east and southeast sides of many playas, indicating that deflation has contributed greatly to the formation of many or perhaps all playas. Price (1958) and Lotspeich and others (1971) suggested that solution of the caliche caprock may also be an important mechanism for creating certain playas.

Salt Dissolution and Playas

Two large playas that occur approximately 80 km (50 mi) northeast of Amarillo, Texas, were investigated in detail and show that dissolution of salt beds and collapse of overlying strata is a mechanism affecting both formation and size of playas. These playas are Lake McConnell, which lies 8.8 km (5.5 mi) west of Pampa, Texas, and an unnamed playa, which lies 6.8 km (4.2 mi) south of Pampa. Both playas are greater than 2,438 m (8,000 ft) wide and 6.1 m (20 ft) deep.

Structure-contour maps on the top of the Blaine (San Andres) Formation were prepared for the areas of both playas using gamma logs from oil and gas field development wells (figs. 10A and B). Beneath Lake McConnell are structural depressions on the top of the Blaine Formation that are more than 48 m (160 ft) deep. Immediately beneath the Lake McConnell depression, approximately 48 m (160 ft) of salt has been lost through dissolution from the salt-bearing intervals of the Blaine Formation and Flowerpot Salt interval (San Andres Formation) (fig. 10B) at a depth of approximately 240 to 300 m (800 to 1,000 ft). Dissolution of salt from this interval allowed the overlying strata to collapse into the cavity or cavities that were formed. Collapse was manifested at the surface by a large depression that was the forebear of Lake McConnell. Later modification by fluvial, lacustrine, and eolian processes resulted in the current morphology of the Lake McConnell area. Although it is apparent that salt dissolution has had an important role in the development of Lake McConnell, it is not possible to establish that salt dissolution created the Lake McConnell basin. There is insufficient evidence to determine which occurred first, the basin, followed and accentuated by salt dissolution, or the salt dissolution, followed by collapse to form the basin. On the other hand, it is possible that large permanent bodies of water like Lake McConnell create locally greater hydraulic heads and as a result either initiate or encourage salt solution beneath the lakes.

A second large playa occurs about 6.8 km (4.2 mi) south of Pampa (fig. 11). Gamma logs were available only for the northern half of the playa. A structural depression resulting from dissolution of salts within the Blaine Formation — Flowerpot Salt interval underlies the northern half of the playa basin. Dissolution is evident at depths of 400 to 525 m (1,200 to 1,600 ft). The data in this example are not as complete as in the Lake McConnell example; however, this playa was probably also greatly influenced or perhaps even begun by collapse of overlying strata into a solution cavity or cavities in bedded salts.

The relationship between salt dissolution at shallow to moderate depths in Lake McConnell and the unnamed playa is well established, but it is by no means applicable to all playas. A third playa containing several wells occurs in the Inbe Oil Field in eastern Lea County, New Mexico, approximately 8 km (5 mi) southeast of Lane Salt Lake. This playa differs significantly from the first two in that it is somewhat smaller (1.57 km or 5,100 ft in diameter) and the uppermost salts of the Salado Formation occur at a depth of approximately 700 m (2,100 ft). The topographic and stratigraphic cross sections in figure 12 illustrate both the playa morphology and the undisturbed nature of the Salado Formation and the overlying Alibates Lentil. From analysis of these and other wells in the immediate area there is no evidence of collapse owing to dissolution of Salado Formation salts beneath the playa; thus, in this case, salt dissolution has not contributed to playa development.

That two of three playas have been associated directly with salt dissolution raises the question of whether other playas owe their origin in part to collapse over areas of salt dissolution. With the exception of the three examples given above, the lack of playas that contain at least a few closely spaced oil wells hinders further exploration of the relationship between playas and salt dissolution. Therefore, another method was needed to determine if other playas are related to salt dissolution.

Populations of playas that occur above known salt dissolution zones were compared to populations of

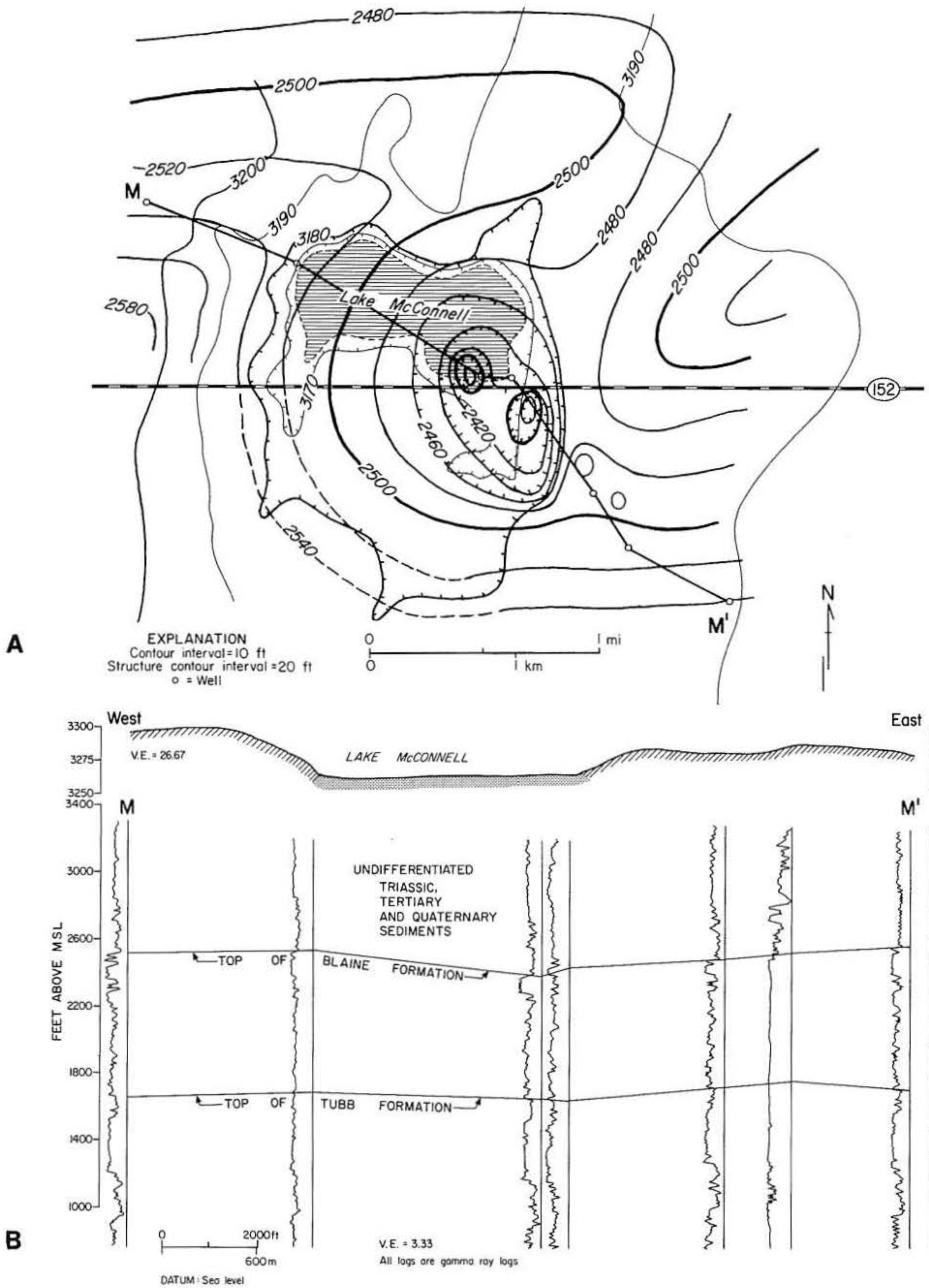

Figure 10. A. Topographic map of the Lake McConnell playa superimposed on a structure-contour map on the top of the Blaine Formation. The depression on the structure-contour surface (heavy contour lines) underlies the playa depression. B. Structural cross section through the Lake McConnell playa derived from gamma-ray logs. Lake McConnell is located in figure 14.

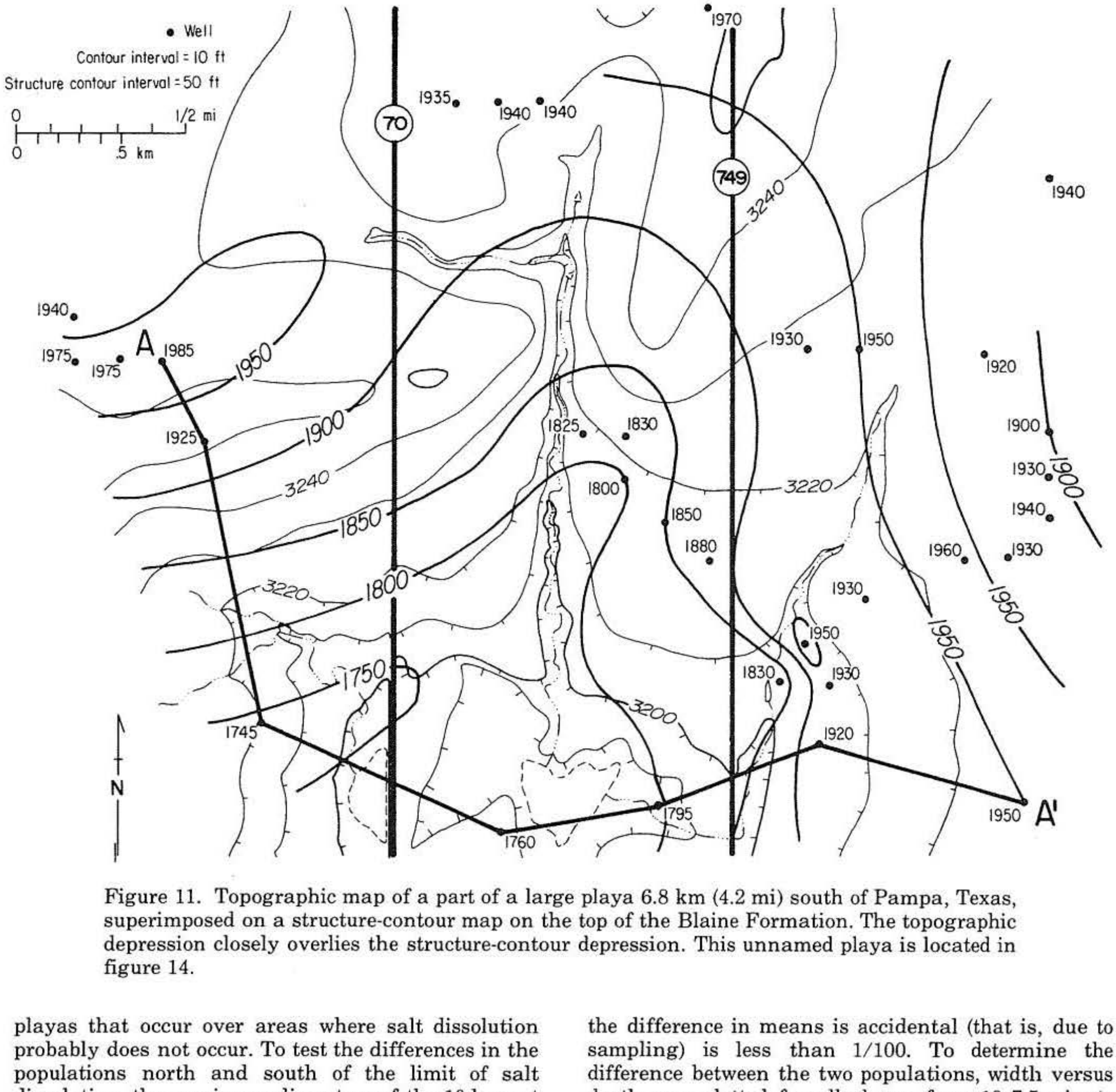

Figure 11. Topographic map of a part of a large playa 6.8 km (4.2 mi) south of Pampa, Texas, superimposed on a structure-contour map on the top of the Blaine Formation. The topographic depression closely overlies the structure-contour depression. This unnamed playa is located in figure 14.

playas that occur over areas where salt dissolution probably does not occur. To test the differences in the populations north and south of the limit of salt dissolution, the maximum diameters of the 10 largest playas on 91 7.5-minute U.S. Geological Survey quadrangle maps were measured. The maximum diameter of a playa was defined as the greatest distance across a playa within the highest 5-foot depression contour as shown on a USGS topographic quadrangle. Certain quadrangles within the 91-quadrangle test area had less than 10 playas; thus, only 725 playas were measured. Two hundred and eight playas comprised the playa population over the salt dissolution zone with a mean width of 1,577 m (5,173 ft). The population sample over the area of no dissolution comprised 517 playas with a mean depression width of 1,257 m (4,126 ft). The Student's T-test was performed to determine if the difference in means for the two samples was accidental and resulted in a T-value of 6.07, which is significant at the 0.01 level. This indicates that the probability that the difference in means is accidental (that is, due to sampling) is less than 1/100. To determine the difference between the two populations, width versus depth was plotted for all playas from 10 7.5-minute quadrangles lying within the salt dissolution zone and for all playas from 10 7.5-minute quadrangles lying outside of the salt dissolution zone (fig. 13). An important difference between these two populations is the number of playas within the salt dissolution zone with diameters larger than 2,440 m (8,000 ft). There is little if any difference in playa depth in the two population samples. Figure 14 shows the location of all playas in the Texas Panhandle that are 2,440 m (8,000 ft) or greater in diameter.

Most playas 2,440 m (8,000 ft) or larger in diameter lie within the active salt dissolution zone or close to the map boundary between the salt dissolution zone and the zone of no dissolution. Furthermore, in the area of older salt dissolution north of the Canadian River, large playas are also relatively more common than in the zone of no salt dissolution. That the large playas occur primarily in the salt dissolution zone and that two of these playas are underlain by salt dissolution basins indicate that the larger playas on the High Plains may be either the result of or strongly modified by salt dissolution.

Lotspeich and others (1971) have offered an explanation for variation in playa size. They suggested that regional variation in playa size is due to variation in soil texture; fewer larger playas occur in fine-textured soils, whereas smaller, more numerous playas occur in sandy soils. Their interpretation does not conflict with the preceding discussion of playa size distribution because both of the tested populations lie entirely within the fine-textured soil zone (Lotspeich and others, 1971; Godfrey and others, 1973).

Historical Examples of Playa Collapse[1]

Meade Salt Well, Meade County, Kansas

Historical examples of collapse forming large sinks have been reported in southwestern Kansas, along the western Caprock Escarpment in eastern New Mexico, and in Hall County east of the eastern Caprock Escarpment. Meade salt well in Meade County, Kansas, collapsed in 1878 (Johnson, 1901). The diameter of the sinkhole measured from the outermost ring fracture was more than 53 m (175 ft), whereas depth was approximately 18 m (60 ft). A striking feature of this collapse was that the basin was immediately filled with a hot brine (71°C, 159°F). The brine was apparently formation fluid forced out of the solution cavity when collapse occurred. This is strong evidence that upward vertical movement of Permian formation fluids to within a few feet of the ground surface can take place as a result of collapse owing to salt dissolution. The temperature of the brine represents the combined effects of formation fluid temperature and heat generated from friction between moving blocks of rock during collapse. Slumping and erosion of similar sinks could cause a depression similar to a modern playa depression.

Cunavea Basin, New Mexico

The Cunavea Basin is a large, flat-floored depression in Quay County, New Mexico (T7N R28E), that is approximately 3.2 km (2 mi) wide and 22 m (75 ft) deep (Judson, 1950). A small sinkhole about 91 by 45.5 m (300 by 150 ft) and 12 to 18 m (40 to 60 ft) deep formed in the northwest corner of the depression early this century. The most recent collapse occurred in 1934, about 10 to 15 years after initiation of the feature. Two additional sinkholes are present, located about 1.2 and 3.2 km (0.75 and 2 mi) east, respectively, of the 1934 sinkhole. Cunavea Basin occurs over an area of rapid thinning of Permian Bernal-Artesia Group strata in Quay and Curry Counties, New Mexico (Foster and others, 1972). Northeast of this area, thinning of stratigraphically equivalent salt-bearing units in Texas is attributed to large-scale salt dissolution (fig. 4). Thus, it is reasonable to infer, as Judson (1950) did, that the recent sinkhole and probably the Cunavea Basin are both collapse features caused by dissolution.

On the basis of the foregoing discussion, it appears that salt dissolution and collapse is responsible for the formation of sinkholes and certain playas. Following the formation of the sinkhole, the sides of the hole are immediately subject to slumping and erosion. As the sides of the hole are degraded, the floor of the depression is progressively infilled. Lake or pond sediments may be deposited during periods of higher precipitation. During protracted dry periods, deflation occurs. Erosion of playa sides and deflation are processes that are presently active. Gullies leading to small deltas are active in some playas during heavy rainstorms. When the waters of the playas totally evaporate, the fine sediments of the playa bottom dry and crack and are subject to deflation. As a result of these processes, a playa that originated as a sinkhole owing to salt dissolution and collapse would be difficult to distinguish from playas originating for other reasons.

Hall County, Texas

Hall County, east of the eastern Caprock Escarpment, is undergoing rapid karstification owing to salt dissolution and collapse (Gustavson and others, 1980). Over 400 collapse sinks and internally drained depressions occur within the county. When compared, four vintages of aerial photographs show that as many as 36 sinks and 2 depressions formed between 1940 and 1979. Collapse sinks are typically circular and range up to 100 m (333 ft) in diameter and 15 m (50 ft) in depth. Estelline Spring, a large sinkhole formed early this century, is the largest of several brine-producing sinkholes in the area. Collapse depressions are irregularly shaped, internally drained depressions up to 2.4 km (1.5 mi) long.

Salt Dissolution and Collapse Chimneys

Chimneys filled with collapse breccia are common in certain areas of the Texas Panhandle. These features formed by a process of natural stoping or roof fall into a void created by salt dissolution. Collapse in most cases was probably not a single event but rather a series of roof falls (see Landes, 1945, for a discussion of the process of chimney formation). In the Anadarko Basin along the boundary between Texas and Beaver Counties, Oklahoma, and 3.2 to 16 km (2 to 10 mi) north of the Texas-Oklahoma boundary, 36 breccia-filled collapse chimneys have been mapped by Barnes (1970). The chimneys occur in the Permian Cloud Chief Formation and are filled with sandstone and conglomerate of the Lower Cretaceous Dakota Group. Sixteen km (10 mi) west-northwest of Guymon, Oklahoma, sandstones and conglomerates of the Lower Cretaceous Dakota Group and Kiowa Formation occur

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[1]A modern example of collapse due to salt dissolution is a large sinkhole formed in Winkler County, Texas, north of the town of Wink on June 3, 1980.

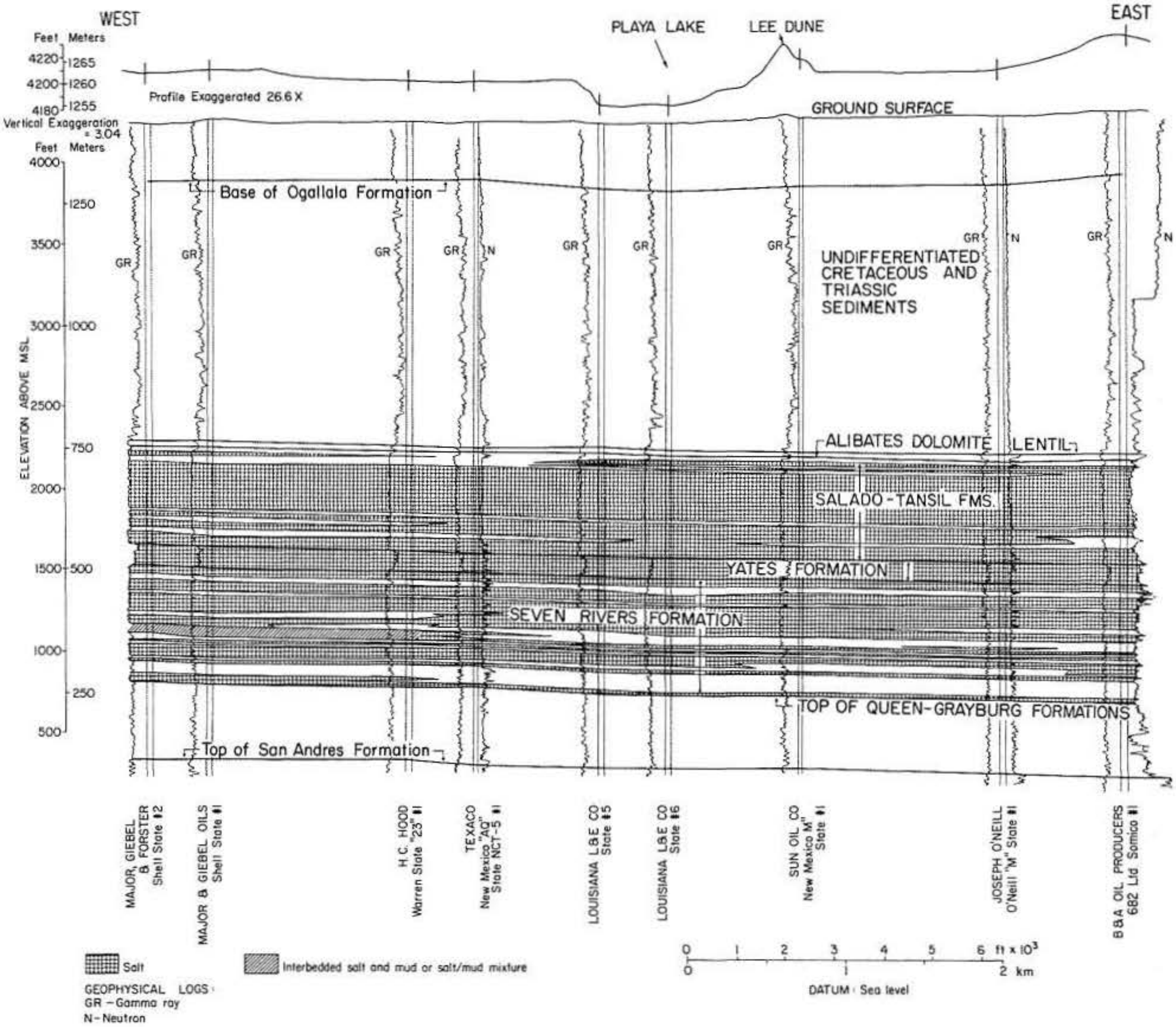


Figure 12. Structural cross section beneath a playa lake near Lane Salt Lake, New Mexico (NE 1/4 S22 T10S R33E to NW 1/4 S20 T10S R34E).

as collapse breccia infillings in 15 chimneys in Triassic Trujillo Formation clastic sediments (Barnes, 1970). Cretaceous rocks do not crop out in this region. Lower Cretaceous strata originally covered the area, but were eroded during the Late Cretaceous or early Tertiary, prior to deposition of Ogallala sediment. This suggests that these chimneys probably formed during the Late Cretaceous.

Twenty-seven filled collapse chimneys were discovered in the Permian Whitehorse Formation during construction of the Sanford Dam on the Canadian River (fig. 15) 64 km (40 mi) northeast of Amarillo (Eck and Redfield, 1963). They are circular to elliptical in cross section and are filled with slumped and brecciated sediments from the overlying Triassic Dockum Group, the Ogallala Formation, or the Canadian River terraces. The largest chimney exposed at the dam site is approximately 305 m (1,000 ft) in diameter. Characteristically, chimneys consist of slumped or downwarped Permian sediments, a collapse breccia of Permian sediments followed by a core of Triassic, Tertiary, or Quaternary sediments (figs. 16 and 17). The boundary between the competent Permian beds and the collapse chimney core is normally expressed as a zone of strong shearing with nearly vertical bedding and rare slickensides. In certain cases the cores of chimneys consist of near vertical beds of younger sediments. Certain chimneys have collapse breccias strongly cemented with $CaCO_3$; others are not cemented (figs. 17 and 18).

The writers have identified numerous additional collapse chimneys throughout most of the Permian exposures along the Canadian River from 4.8 km (3 mi) east of Highway 87 northeastward to the town of Phillips, Texas, a distance of approximately 48 km (30 mi). In exposures of Permian rocks east of the Caprock Escarpment, collapse chimneys are not common. Fifteen chimneys have been recognized in Donley County north of the Salt Fork of the Red River. One collapse chimney in the Permian Whitehorse Sandstone

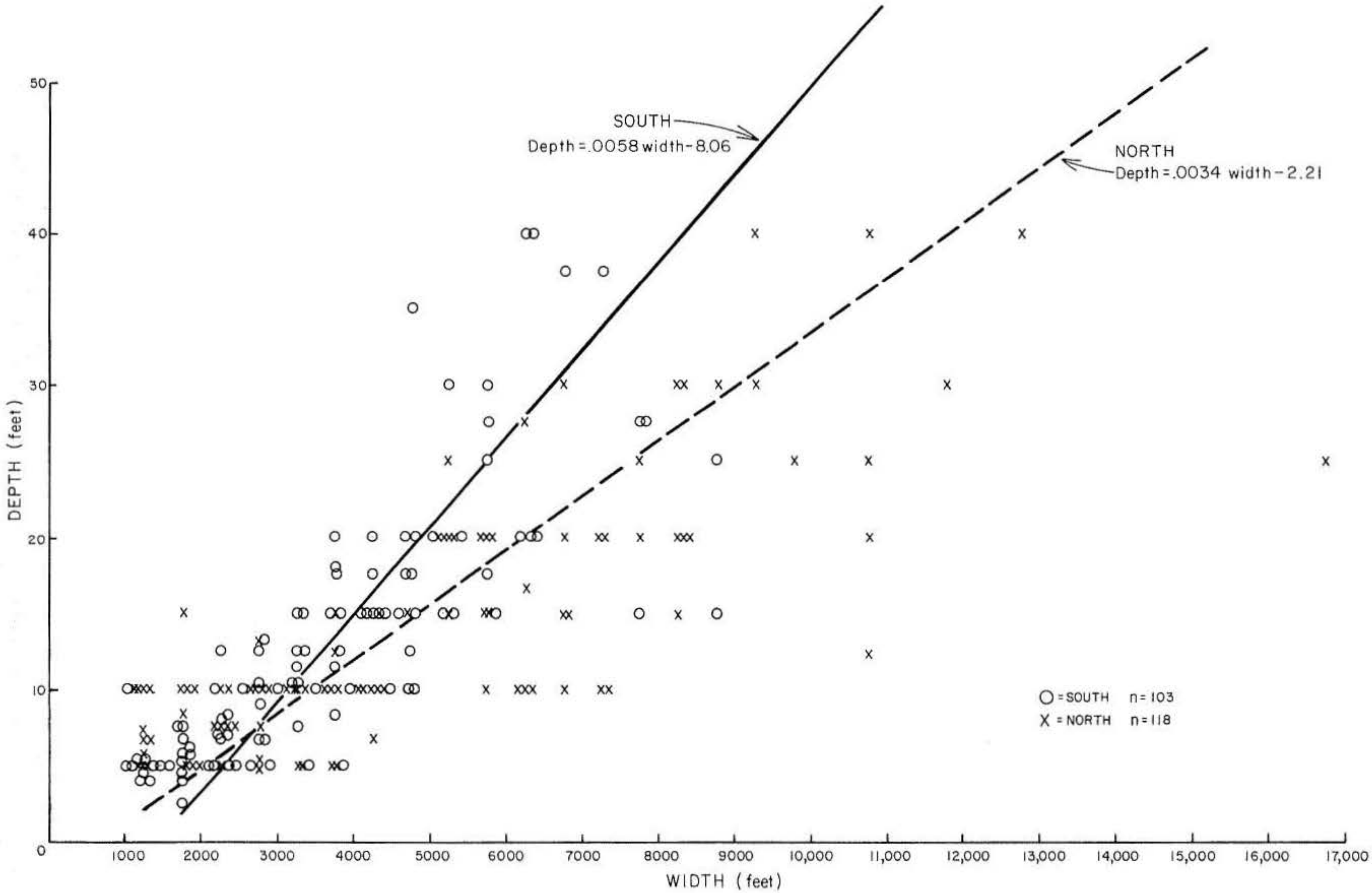


Figure 13. Width vs. depth plots of all playas from 10 selected 7.5-minute topographic quadrangles north of the limit of dissolution and from 10 selected quadrangles south of the dissolution limit. See figure 14 for playa locations.

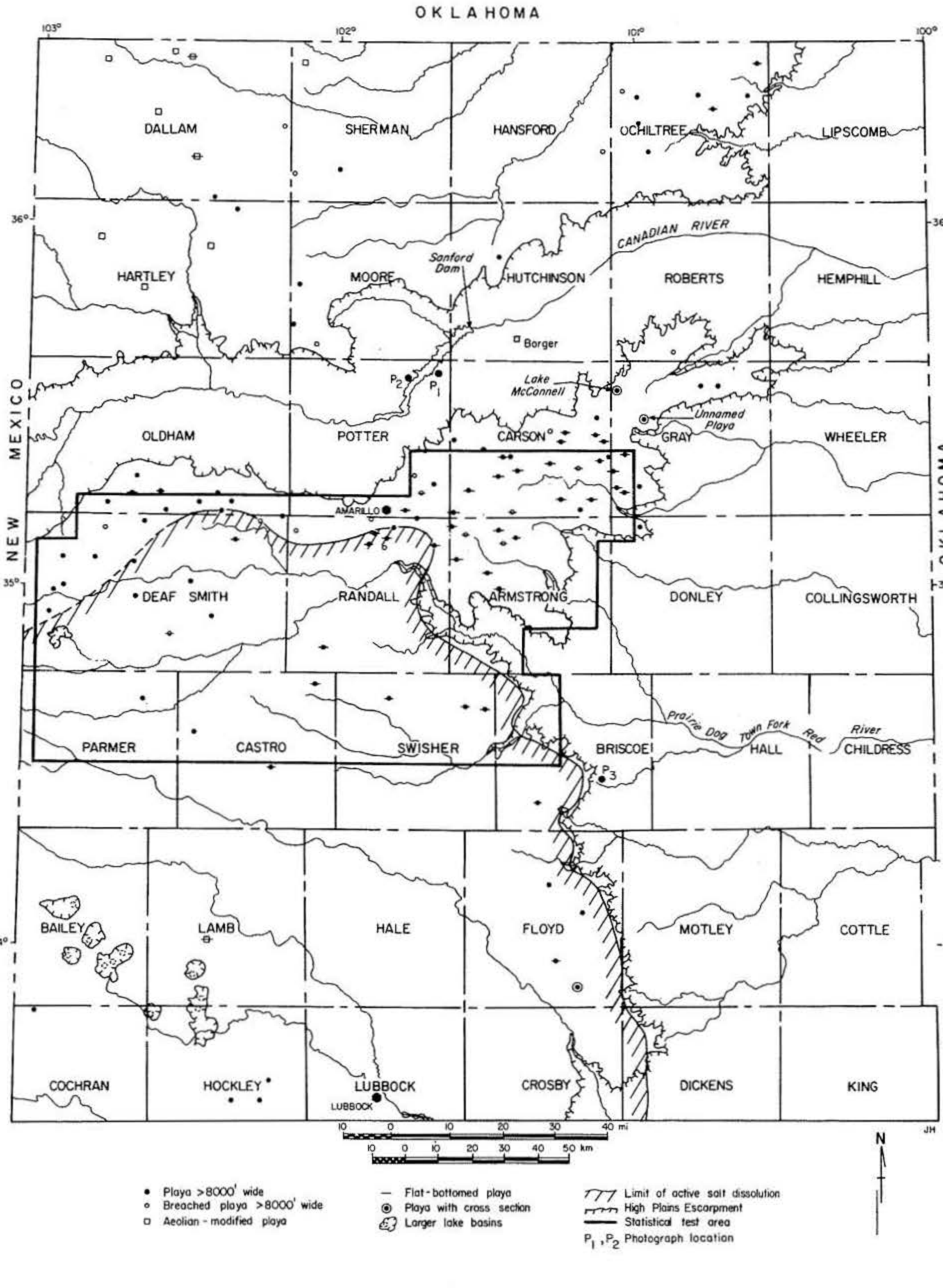


Figure 14. Distribution of playas greater than 242 m (8,000 ft) wide. Most large playas occur over the zone of salt dissolution that lies north and east of the hachured line. The outlined area contains the playas from which the data used in figure 13 were obtained.

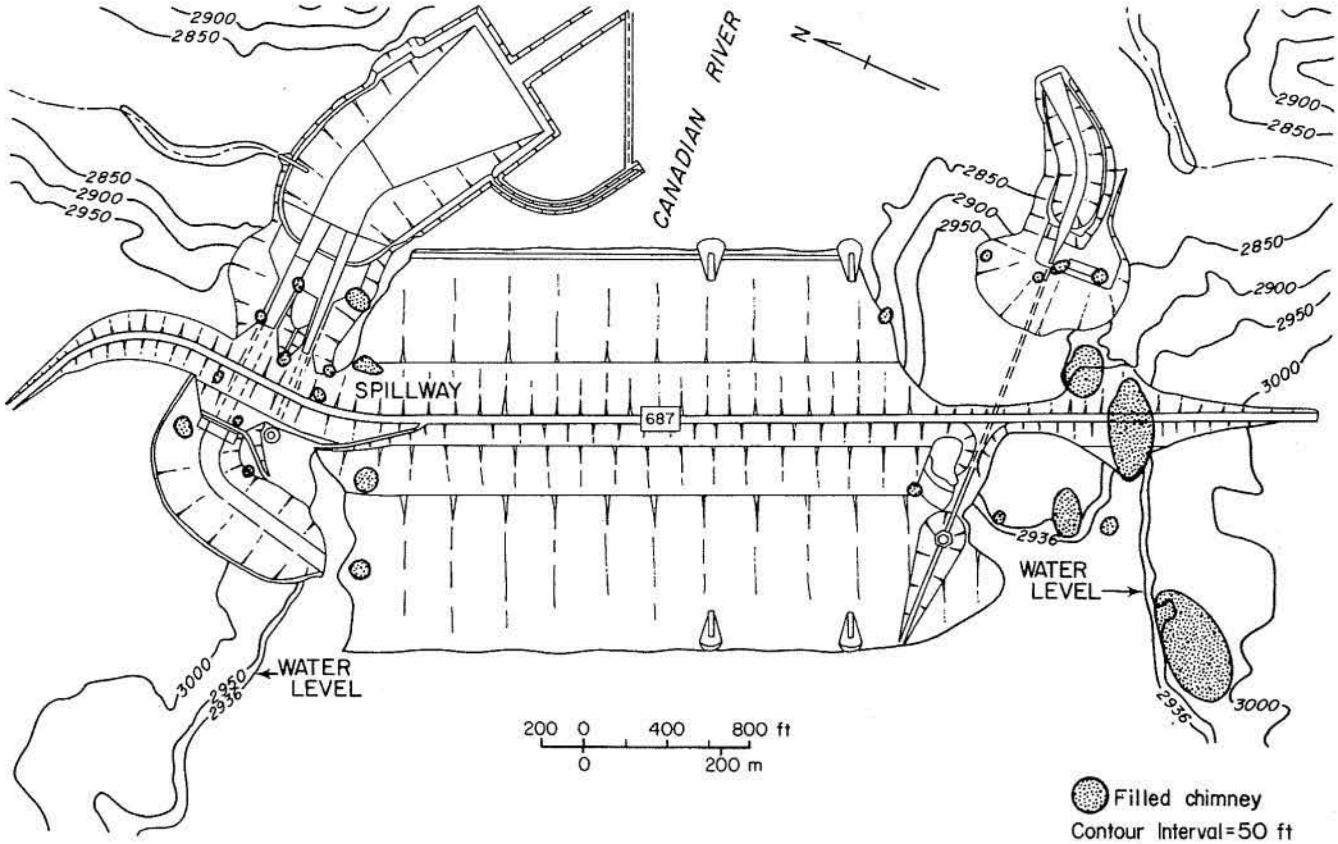


Figure 15. Distribution of chimneys in the vicinity of Sanford Dam, near Borger, Texas. See figure 14 for dam location. (From Eck and Redfield, 1973.)

filled with a breccia composed of Triassic Dockum Group sandstone and conglomerate occurs approximately 16 km (10 mi) east of the Caprock Escarpment adjacent to Texas Highway 256 in Briscoe County. Another possible collapse chimney in the Permian Quartermaster Formation is filled with Dockum Group sediments and occurs 14.5 km (9 mi) south of Quitaque, Texas, and 3.2 km (2 mi) east of Ranch to Market Road 1065 in Motley County.

All of the observed collapse chimneys occur within areas of active salt dissolution or within areas of possible paleodissolution of salt (fig. 4). The collapse chimneys and playas, as well as sink formations, are direct manifestations of subsurface salt dissolution.

Influence on Dissolution by Minor Streams (Draws) and Paleochannels

In the preceding discussion it was established that salt dissolution where it occurs at shallow to moderate depths is influenced by major surface streams such as the Canadian River (fig. 5), the Prairie Dog Town Fork (fig. 6), the Pecos River (Lee, 1923; Morgan, 1941), and by certain playas (figs. 10A, 10B, and 11). The question that remains to be answered is: do any of the draws draining the Southern High Plains or any of the ancient streams draining the pre-Ogallala erosion surface influence salt dissolution beneath the Southern High Plains? Providing an unequivocal answer to this question is not presently possible because of data limitations; only rarely are oil fields with closely spaced wells traversed by modern or ancient stream courses. An exception is the Yellow House oil field, which occurs a few miles south of Yellow House Lake in Hockley County, Texas. Here field wells occur within and to either side of Yellow House Draw, a major drainage feature on the High Plains. Yellow House Draw differs from the Pecos and Canadian Rivers and Prairie Dog Town Fork in that it is both ephemeral and substantially smaller. Depth to salt beneath the draw is approximately 700 m (2,100 ft), and no recognizable collapse owing to salt dissolution has occurred beneath this part of the Yellow House Draw valley (fig. 19). It should be noted, however, that this example is approximately 120 km (75 mi) east of the western Caprock Escarpment where dissolution processes are evident.

Figure 16. Collapse chimney breccia. Large blocks are Permian Alibates Dolomite Lentil. Other areas are a mixture of gravel (terrace ?) and smaller blocks of Permian material. Photograph is of the collapse chimney breccia shown in figure 18a.

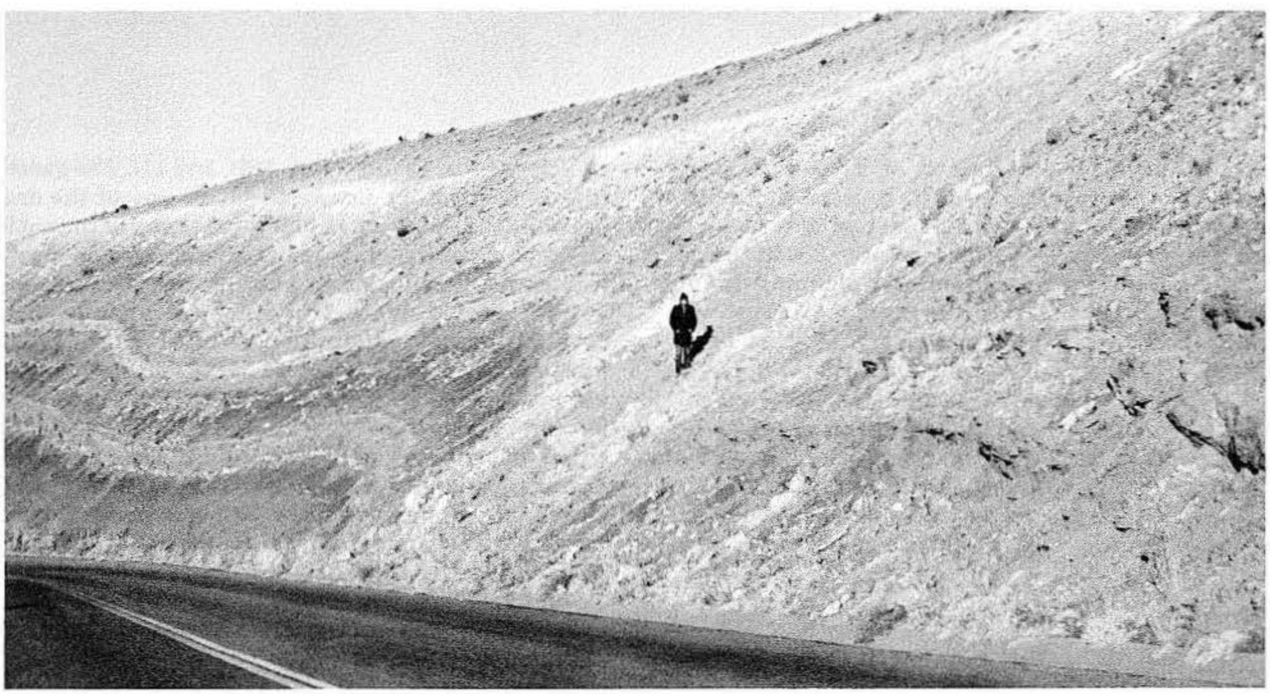
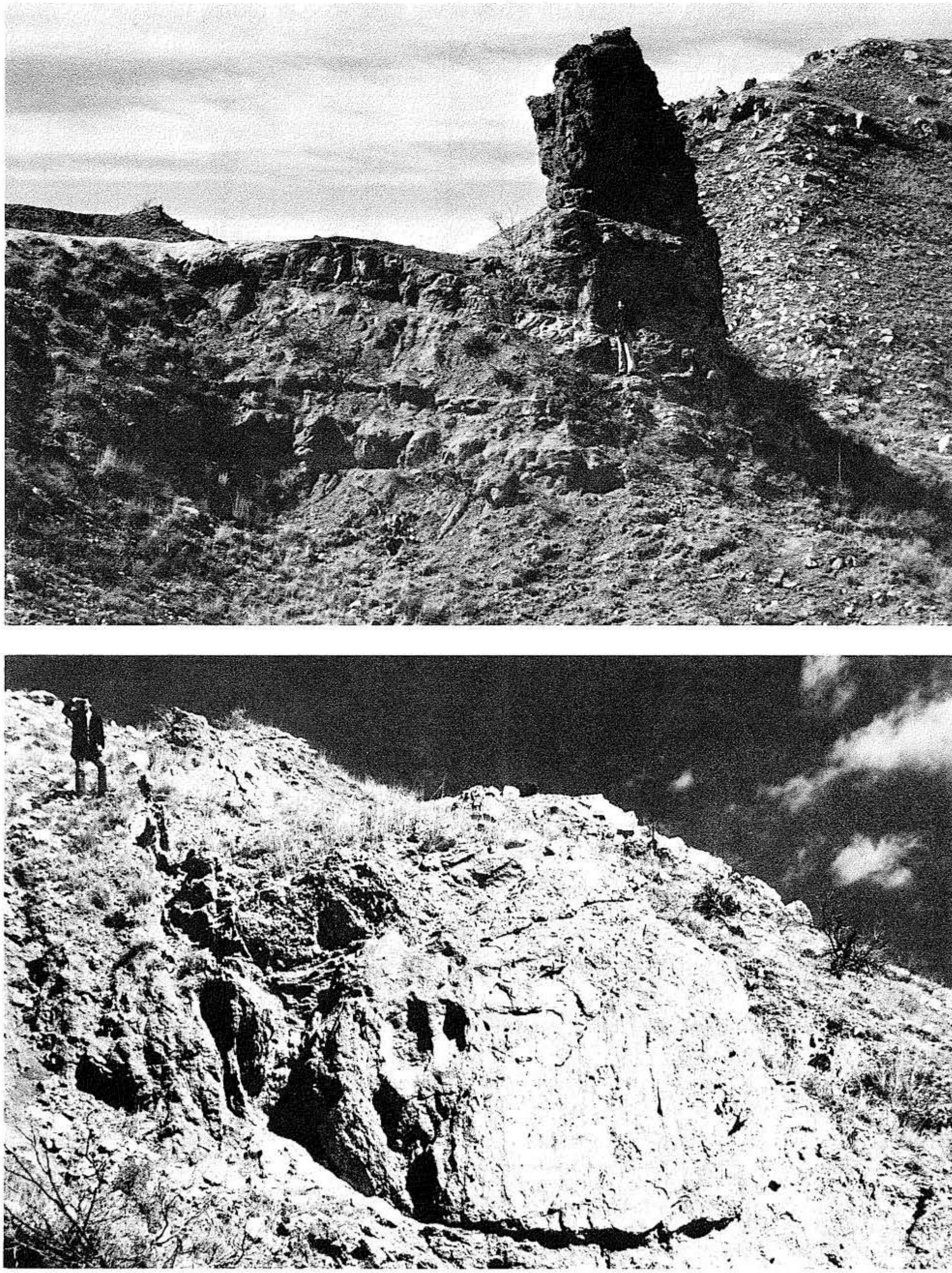


Figure 17. Oval collapse chimney in red Permian mudstones filled with Tertiary or younger fluvial sand and gravel. The collapse chimney filling is slightly cemented. Note the downwarping of the Permian enclosing beds. Figure on collapse chimney for scale. Photograph is of an area on Texas Highway 136 approximately 5 km (3 mi) north of Borger in Hutchinson County, Texas.



a

b

Figure 18. Erosionally resistant collapse chimney breccias in red Permian mudstones. Breccias are carbonate cemented and consist of a mixture of fluvial gravels (terrace ?) and blocks of Permian sediments. Photos from the Canadian River Valley. See figure 14 for locations; 18a is at P1; 18b, at P2.

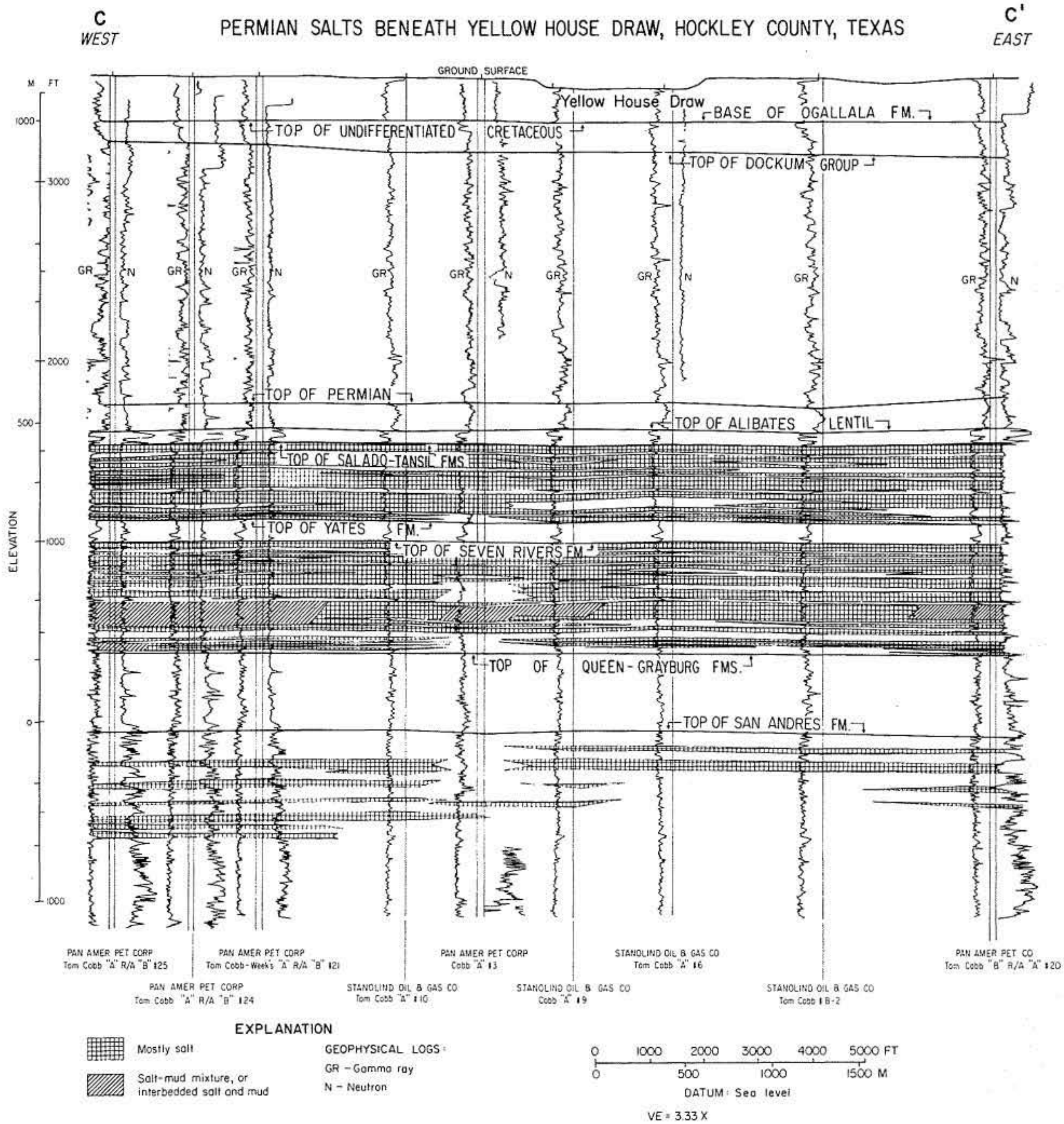


Figure 19. Structural cross section beneath Yellow House Draw. See figure 9 for location.

COLLAPSE SURFACES AND BRECCIA ZONES

Collapse breccias (breccia blankets) and the structure of the collapsed Permian surface are exposed locally along the northern and eastern margins of the Southern High Plains. In several areas in Palo Duro Canyon, in Caprock Canyon State Park, and in cores from the No. 1 White and No. 1 Grabbe wells, red Permian mudstones have been complexly fractured, and the fractures have been filled with white satinspar gypsum (fig. 20). The complex fracturing probably occurred as a result of collapse of strata over areas of salt dissolution. As salts were removed, roof collapse spread upward, and fractures that developed in the collapsing overburden were filled with gypsum (satinspar). As dissolution and collapse occurred at depth, precipitation of gypsum in the fractures helped to hold the fractures open. Close examination of fracture fillings in outcrops indicates that several episodes of fracturing occurred.

Collapse of overlying beds as a result of salt dissolution produced the structurally complex fold surface exposed near Borger, Texas. The fold surface is

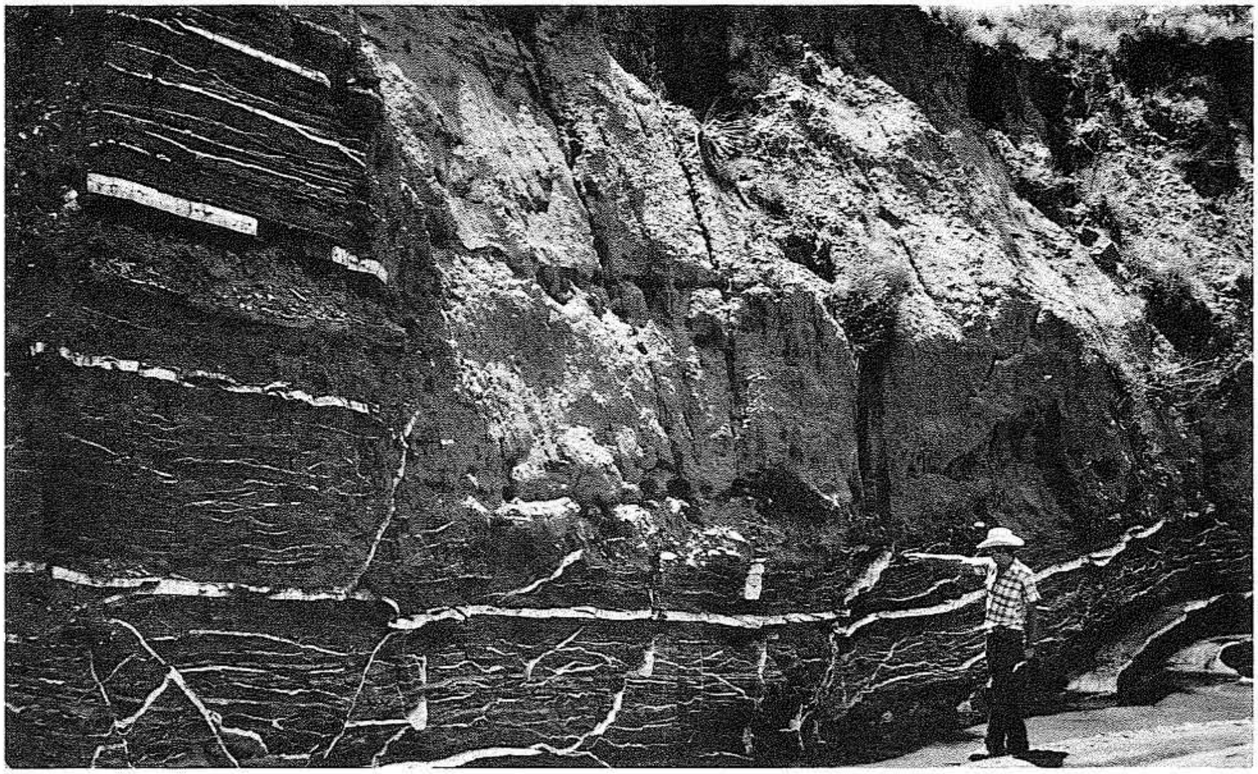


Figure 20. Fractures in red mudstones of Permian Quartermaster Formation filled with gypsum. Fractures result from collapse owing to solution of underlying salt beds. Photograph is from Caprock Canyons State Park. Photograph location is P3 in figure 14.

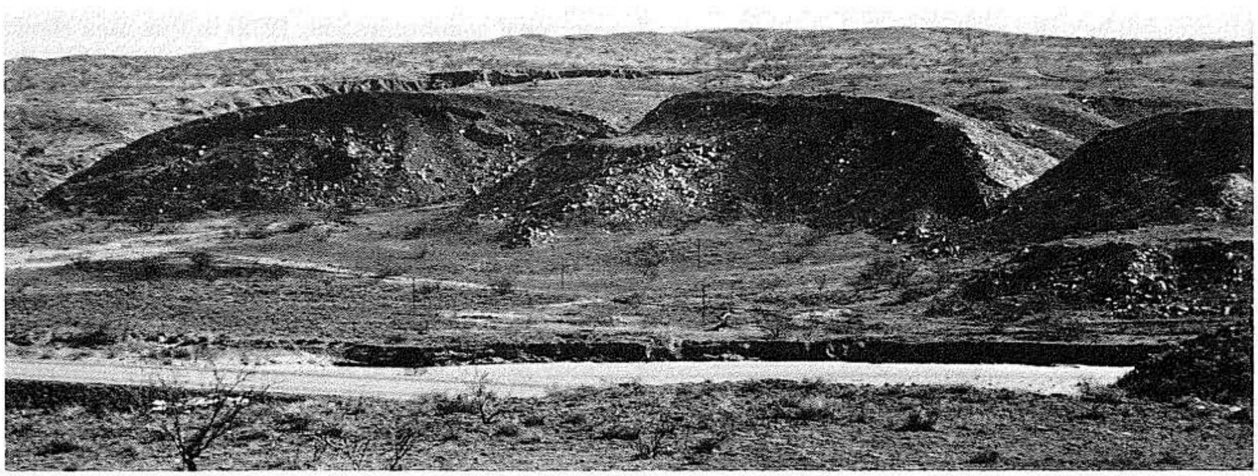


Figure 21. Folded red Permian mudstones capped by the Alibates Dolomite Lentil in the Canadian River Valley adjacent to Texas Highway 136 approximately 10 km (6 mi) north of Borger, Texas.

exposed where Triassic and younger sediments have been stripped from the Alibates Dolomite Lentil (fig. 21). The Alibates Dolomite is a resistant bed that protects the underlying mudstones from erosion. At the same time, the Alibates reflects the complex nature of the fold surface, consisting of anticlines, synclines, domes, and basins randomly pierced by collapse chimneys. Tributary valleys of the Canadian River have locally formed in Alibates synclines, and interfluves tend to be Alibates anticlines. Similar large-scale structural features were observed east of the eastern Caprock Escarpment in Caprock Canyon State Park.

In Palo Duro Canyon, small-scale warping of Permian beds — wavelength 100 m, amplitude 1 to 2 m (wavelength 300 ft, amplitude 3 to 6 ft) — has produced a series of minor folds. Nicholson (1960) attributes this structure to hydration and expansion of anhydrite to gypsum, although it too may have resulted from differential subsidence over zones of salt dissolution.

PALEODISSOLUTION OF SALT IN THE PALO DURO BASIN

Evidence of paleodissolution of salt is found in the Salado and Tansill Formations. In the southern Palo Duro Basin, the combined Salado-Tansill is a 90- to 150-m (300- to 500-ft) thick unit composed of salt with intercalated mudstone and broken by mudstone beds. To the north and east the salt grades into mudstone-siltstones and the formation thins to 18 to 30 m (60 to 100 ft) thick (fig. 22).

Major thinning of the Salado-Tansill is the result of progressive downsection disappearance of salt beds (fig. 23). Thick, massive salts in the south thin in the updip direction and are capped by progressively thicker mudstone-siltstones. Cores from No. 1 Grabbe and No. 1 Rex White (along strike from wells numbered Swisher 11 and Potter 44, respectively) show the mudstone-siltstones to be highly fractured. Fractures include crosscut as well as parallel bedding planes, and many are filled with satinspar gypsum. In figure 23, dissolution begins between wells Hale 6 and Swisher 11 and continues updip to Castro 9, where all salt has been dissolved.

The Salado-Tansill salt dissolution zone forms the northern and eastern boundaries of salt occurrence (fig. 22). South of the dissolution zone, a complete salt section is present; north and east of the zone, all salt has been dissolved. Salt dissolution is believed to be occurring at the present time at depths of 100 to 300 m (350 to 1,000 ft) within the eastern dissolution zone, which parallels ongoing dissolution trends in underlying salt-bearing units (fig. 4).

In contrast to the eastern margin, the dissolution zone along the northern margin of the Salado-Tansill salt trends northeast-southwest, counter to dissolution zones in underlying units and 67 to 133 km (40 to 80 mi) to the south of the nearest dissolution zone (fig. 4). Dissolution in the northern zone occurs at depths of 300 to 600 m (1,000 to 2,000 ft), well below depths of ongoing salt removal in the eastern zone. The northern arm of the Salado-Tansill dissolution zone is interpreted as a product of paleodissolution of salt; no dissolution is now occurring along that arm except in parts of Swisher County, where the eastern dissolution trend is being superimposed on the paleodissolution zone.

Evidence of paleodissolution appears in the Yellow House oil field in Lamb and Hockley Counties. Correlation of gamma logs indicates that approximately 15 ft (5 m) of salt are missing from the top of the Salado Formation in the Pan American Petroleum Corporation Tom Cobb A No. 5 well (fig. 24). In this well, the overlying Alibates Lentil, the Triassic Dewey Lake Formation, and the remainder of the lower part of the Triassic Dockum Group are structurally lower than in either adjacent well. The upper half of the Dockum Group, the Cretaceous Kiamichi Shale, and the Ogallala Formation are unaffected. Furthermore, the magnitude of bed displacement seems to decrease upward. The missing salt and structural displacement of overlying sediments are attributed to salt dissolution and collapse of overlying sediments. Salt dissolution and collapse took place following deposition of the lower part of the Triassic Dockum Group because these sediments are displaced by collapse. An unpublished isopach map of Cretaceous sediments (S. J. Seni, personal communication, 1979) in this area shows an anomalous thickened section; the thickened Cretaceous sequence could have resulted from Cretaceous salt dissolution and collapse of the underlying Dockum Group.

FAULTING AND SALT DISSOLUTION

Bonita and Alamosa Faults

Two northeast-trending fault systems occur along the western Caprock Escarpment in eastern New Mexico. The Bonita Fault extends over 16 km (10 mi) from S25 T8N R32E to S35 T9N R33E. Another unnamed fault lies to the southwest along Alamosa Creek and extends over 11 km (7 mi) from S12 T3N R29E to S24 T4N R30E. Both fault systems are grabens consisting of normal faults dipping to the northwest with one or more southeasterly dipping antithetic faults. To delineate their extent, stratigraphic cross sections based on geophysical and lithologic logs were constructed across both faults (figs. 25 and 26).

The fault system that lies along the floor of the valley of Alamosa Creek, herein referred to as the Alamosa Fault, extends about 11 km (7 mi) along Alamosa Creek (Barnes, 1977). However, the differences in surface elevation of stratigraphic units on either side of the Alamosa Creek Valley and the alignment of the creek along the fault both suggest that the Alamosa Fault may extend several kilometers farther southwestward beneath a cover of Quaternary alluvium. A structural cross section was constructed across the lower reach of Alamosa Creek and across the extension of the Alamosa Fault that is presumed to lie beneath the alluvium of the creek (fig. 25). As illustrated on the cross section, the San Andres Formation is stratigraphically continuous beneath the fault projection. The overlying Artesia Group thins approximately 55 m (180 ft) in the vicinity of the fault between the Franklin No. 1 Gephart Well and the Shell No. 1 Swink et al. well. The thinning can be entirely accounted for by the loss of salt beds in the Artesia Group sediments. Detailed correlations between the Southern Petroleum Exploration well and the Shell No. 1 Swink well indicate that other lithologic units are continuous between the two wells, whereas salts have been selectively removed to the west. Thinning of the Artesia Group in the Shell No. 1 Swink well has allowed collapse of the overlying strata

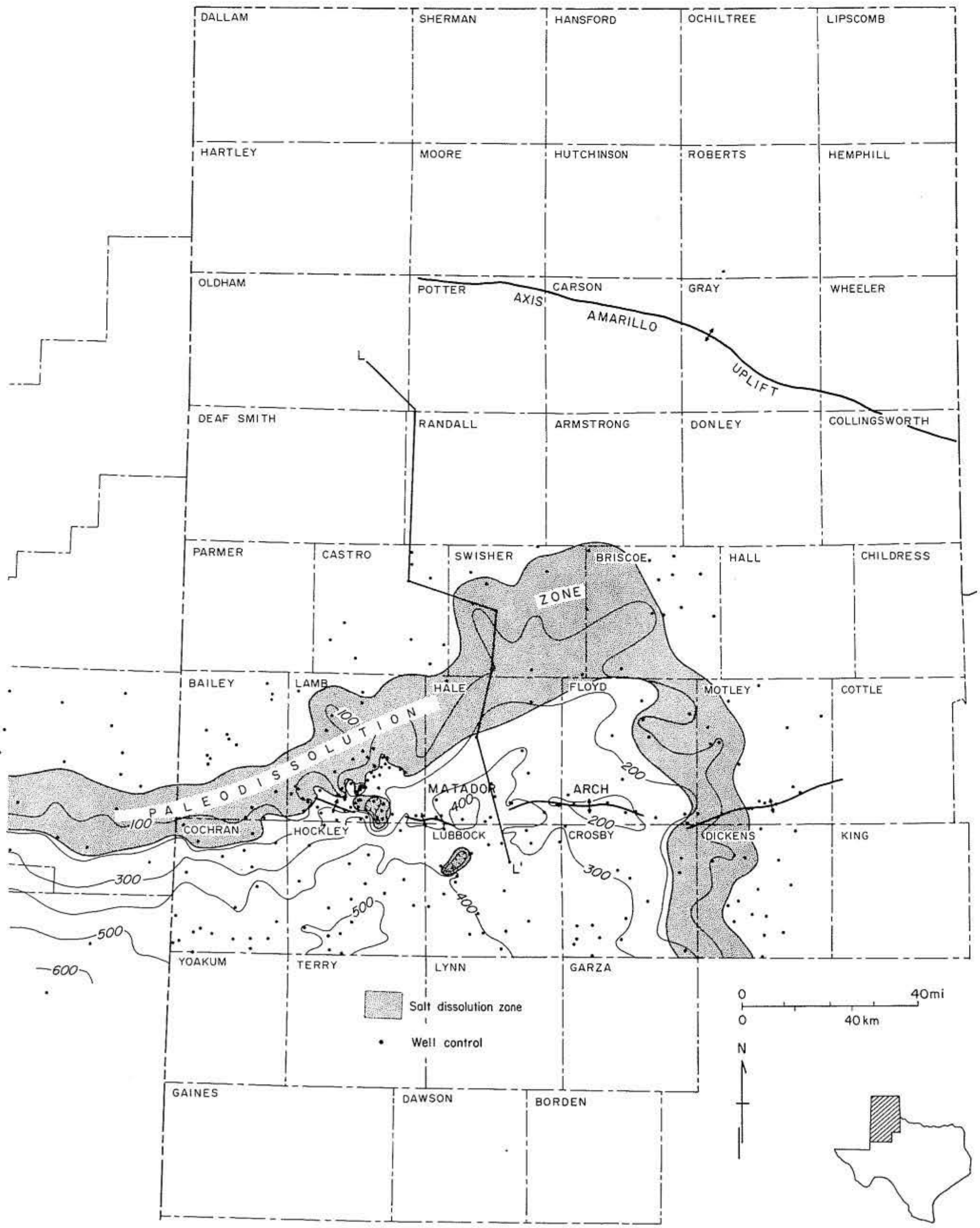


Figure 22. Net salt and salt dissolution zone of Salado-Tansill Formations. Line from Hale to Oldham Counties indicates the location of the cross section illustrated in figure 23.

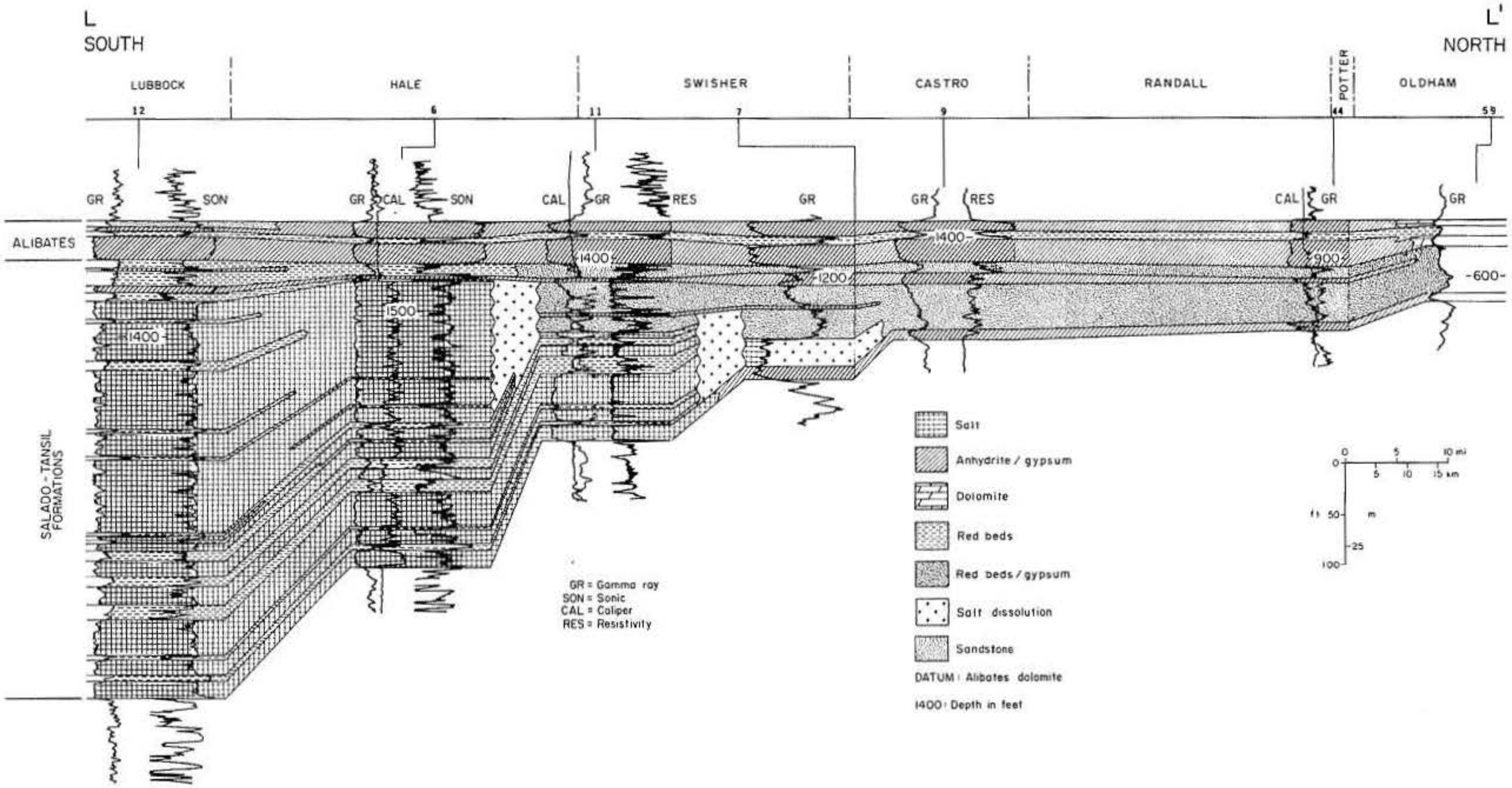


Figure 23. Stratigraphic cross section of Salado-Tansill Formations and the Alibates Lentil. Line of section shown in figure 22.

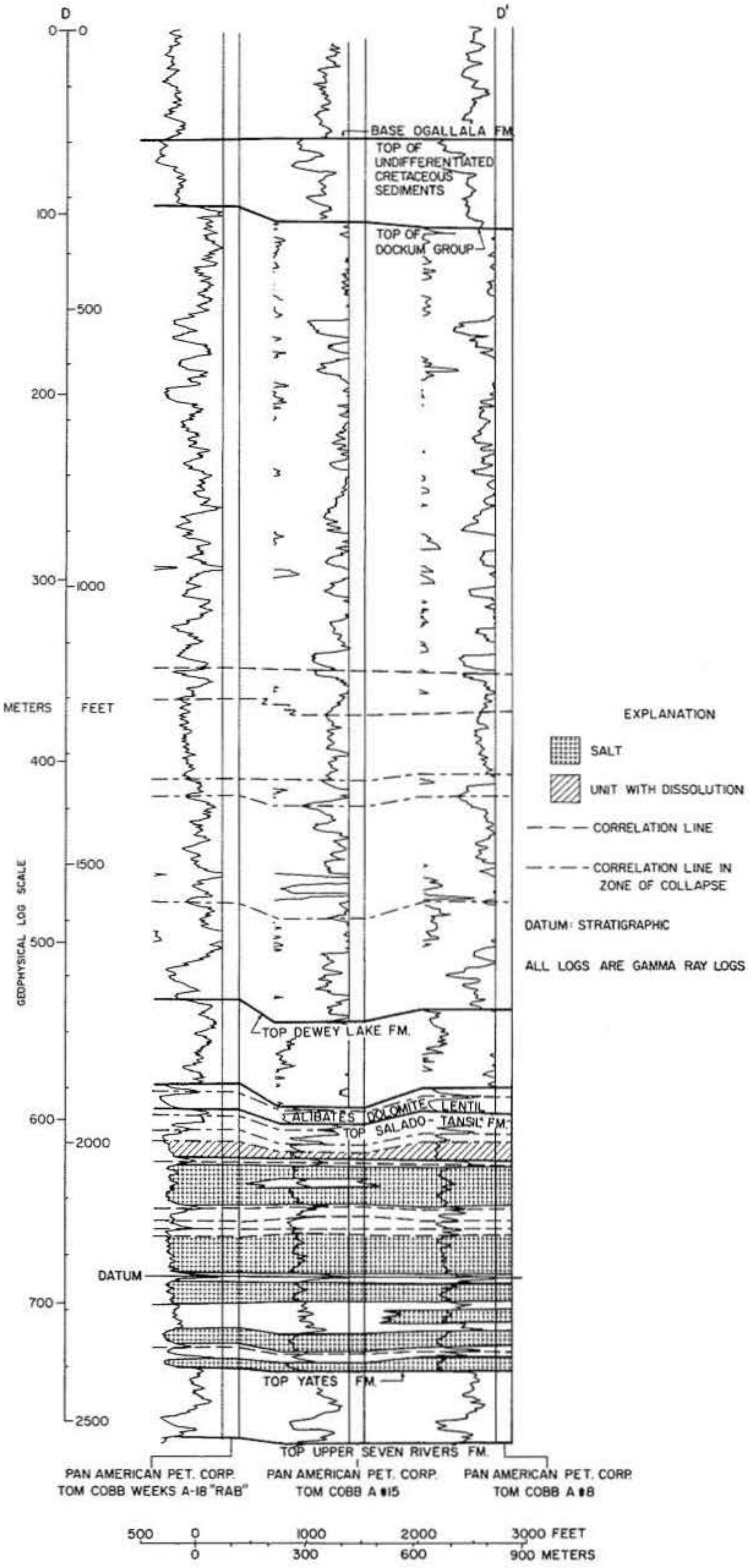


Figure 24. Stratigraphic cross section showing Salado Formation salt dissolution and collapse of overlying strata in the Tom Cobb A No. 5 well. Cross section D-D′ is located in figure 9.

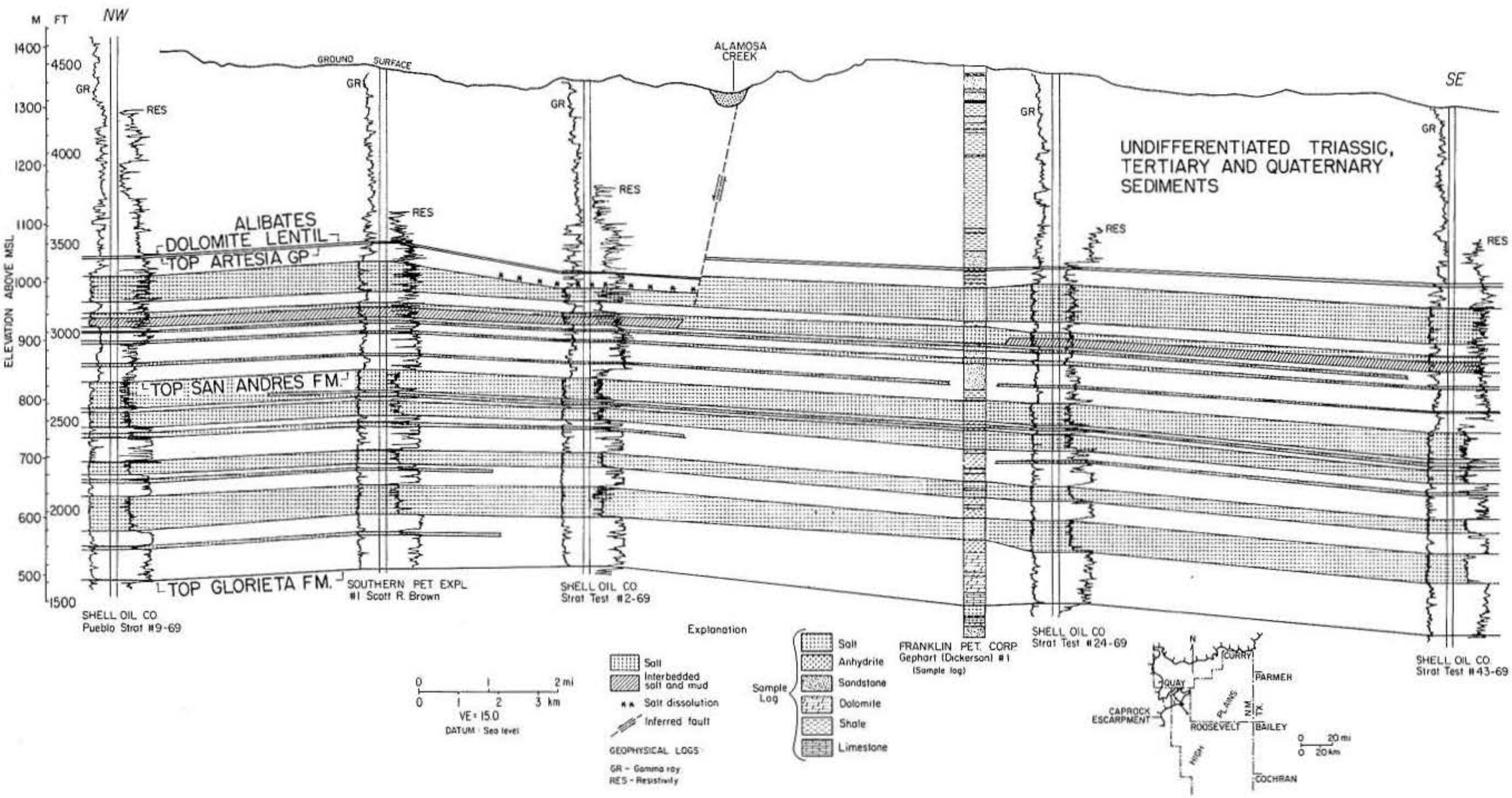


Figure 25. Structural cross section showing thinning of Artesia Group. Thinning and resultant faults are probably due to salt dissolution in the Artesia Group northwest of the fault. Cross section location is given in the inset map in this figure.

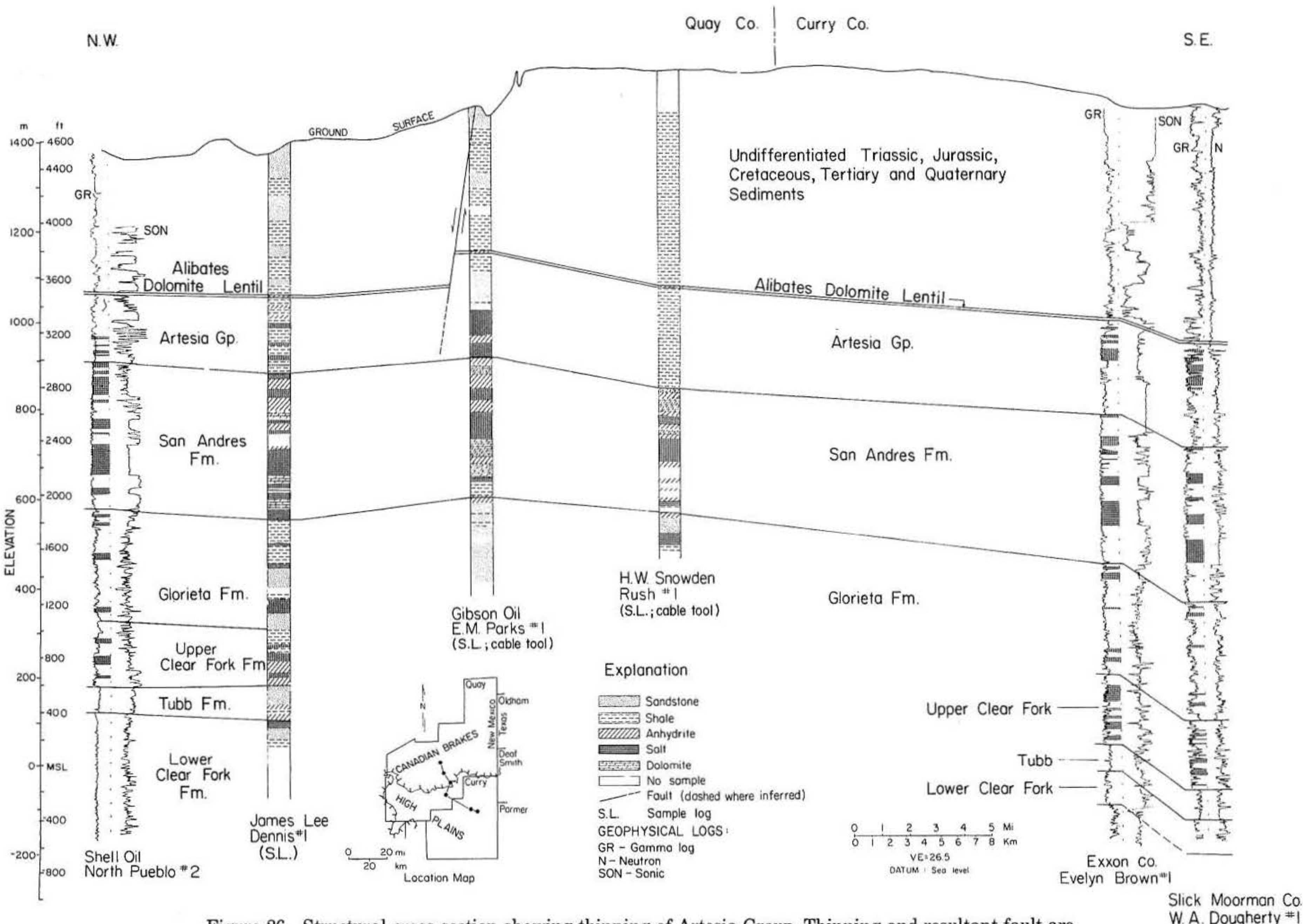


Figure 26. Structural cross section showing thinning of Artesia Group. Thinning and resultant fault are probably due to salt dissolution in Artesia northwest of the fault. Cross section location is given in the inset map in this figure.

including the Alibates Dolomite Lentil. The apparent lack of displacement in the San Andres Formation and selective removal of salts in the Artesia Group, coupled with collapse of overlying sediments, suggests that salt dissolution occurred in the region northwest of Alamosa Creek and that the structural collapse that followed is manifested by faulting along the creek valley. The Alamosa Fault system involves both Triassic Dockum Group and Tertiary Ogallala Formation sediments at the surface, indicating that the fault is at least late Tertiary and possibly Pleistocene in age. The age of the fault and the character of the subsurface displacement both suggest that regional salt dissolution in the Artesia Group was the mechanism for faulting. According to Lee (1923) and Morgan (1941), the Pecos River Valley is a late Tertiary-Pleistocene feature that developed in part by occupying salt dissolution subsidence basins in eastern New Mexico. The Alamosa Creek Valley is a tributary of the Pecos River Valley, and thus salt dissolution along Alamosa Creek may have followed salt dissolution along the Pecos River.

Stearns (1972) considered the Alamosa Fault to be a southeasterly extension of the Bonita Fault. However, it appears that the Bonita Fault is significantly older and not directly related to the Alamosa Fault system. The Bonita Fault displaces rocks as young as Cretaceous, but Tertiary Ogallala sediments overlying the fault are not involved (Barnes, 1977). A stratigraphic section between the two faults shows no evidence of abrupt structural displacement, although salt dissolution is present and increases northwestward (fig. 27). Stearns (1972) also related the Bonita Fault system to the Laramide deformation. However, analysis of a geophysical and lithological stratigraphic section across the fault suggests that an alternative interpretation is possible. Interpretation of the cross section is hindered from the outset because the three logs that lie closest to the fault are lithologic logs and are subject to errors in interpretation. Nonetheless, correlations through the San Andres Formation show good continuity of thickness and lithology. In the overlying Artesia Group, the lithologic logs are less clear, but the position of the Alibates Dolomite Lentil is well marked. Between the Gibson Oil Company No. 1 Parks well on the southeast side of the fault and the Lee No. 1 Dennis well on the northwest side, approximately 75 m (250 ft) of thinning occurs. Thinning can be explained by dissolution of salts in the Artesia Group and the subsequent collapse of overlying strata including the Alibates. Subsurface collapse is manifested at the surface by the Bonita Fault system, where surface displacements along the line of section are also approximately 75 m (250 ft).

An alternative explanation is that movement along the Alamosa and Bonita Faults was initially tectonic in origin, but with very small displacements. This explains the relatively straight fault lines. At a later time salt dissolution occurred preferentially along the faults and has accounted for most of the offset.

Modern Faults

Microfaulting has occurred in Hall County south of the Prairie Dog Town Fork of the Red River approximately 19 km (12 mi) west of Estelline, Texas. Six microfaults were recognized as freshly repaired separations in a paved secondary road (fig. 28). Faults across the road were continuous with open fractures in cultivated fields that were up to 10 cm (4 inches) across. Vertical displacement, measured across faults on the road surface, ranged from 1 to 4 cm (0.4 to 1.6 inch). All the faults were aligned from N25° to N60° E and are associated with a series of undrained depressions oriented N50° E (fig. 28). This area of Hall County lies within the zone of active salt dissolution (fig. 4) and Estelline Spring; the largest saline spring in this region lies only 20 km (13 mi) east of the fault area. Coupled with the evidence of regional salt dissolution previously described, the undrained depressions, saline spring, and faults indicate that active salt dissolution and collapse are occurring beneath the fault area.

TIMING OF REGIONAL SALT DISSOLUTION IN THE ANADARKO, DALHART, AND PALO DURO BASINS

Sufficient information is available to trace the history of salt dissolution in the Texas and Oklahoma Panhandles. Several collapse chimneys occur in two localities in the Oklahoma Panhandle Upper Cretaceous to Lower Tertiary (Barnes, 1970). Approximately 48 km (30 mi) north-northeast of Spearman, Texas, 39 collapse chimneys occur in the Permian Cloud Chief Formation and the overlying Doxey Shale and are filled with brecciated sandstones and conglomerates of the Cretaceous Dakota Group. A second area of collapse-breccia-filled chimneys occurs to the west about 24 km (15 mi) northeast of Texhoma, Texas. In this area, sandstones and conglomerates of the Lower Cretaceous Dakota Group and shales of the Kiowa Formation fill collapse chimneys in the Triassic Trujillo Formation. Dakota Group sediments were deposited before the collapse of chimneys into underlying Triassic and Permian strata. That dissolution and collapse took place before the deposition of the Ogallala Formation is indicated by a regional unconformity between the Permian Doxey Shale and the Tertiary Ogallala Formation at one locality and between the Cretaceous Kiowa Formation and the Ogallala at the other locality. The unconformity also truncates the chimneys. Thus, collapse of Dakota Group sediments into Permian strata at one locality and into Triassic strata at the other locality occurred during the Late Cretaceous or Early Tertiary. Following or

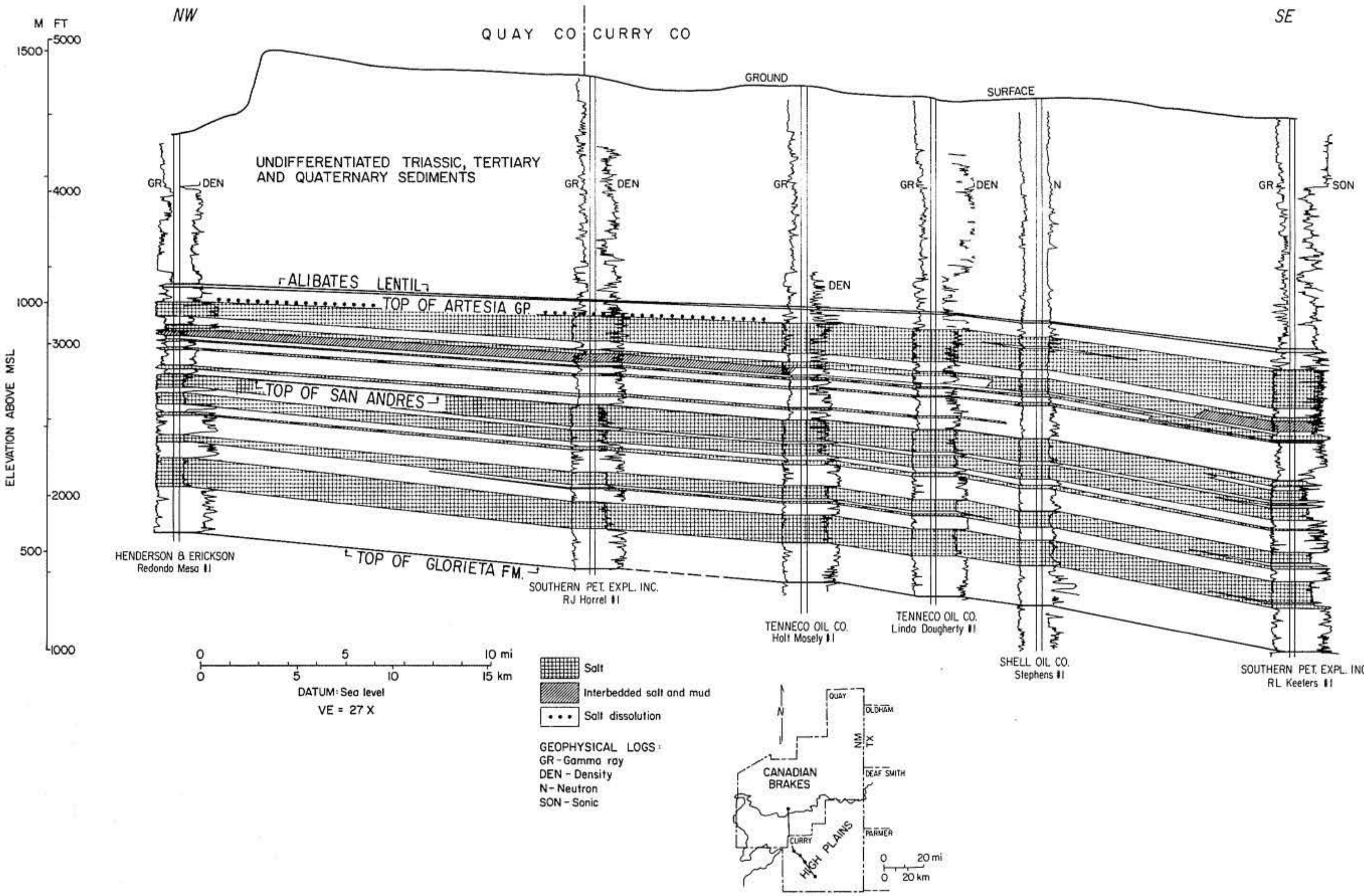


Figure 27. Cross section between the Bonita Fault (fig. 26) and the Alamosa Creek Fault (fig. 25) showing no evidence of displacement. This suggests that the two faults are not continuous. Cross section location is given in the inset map in this figure.

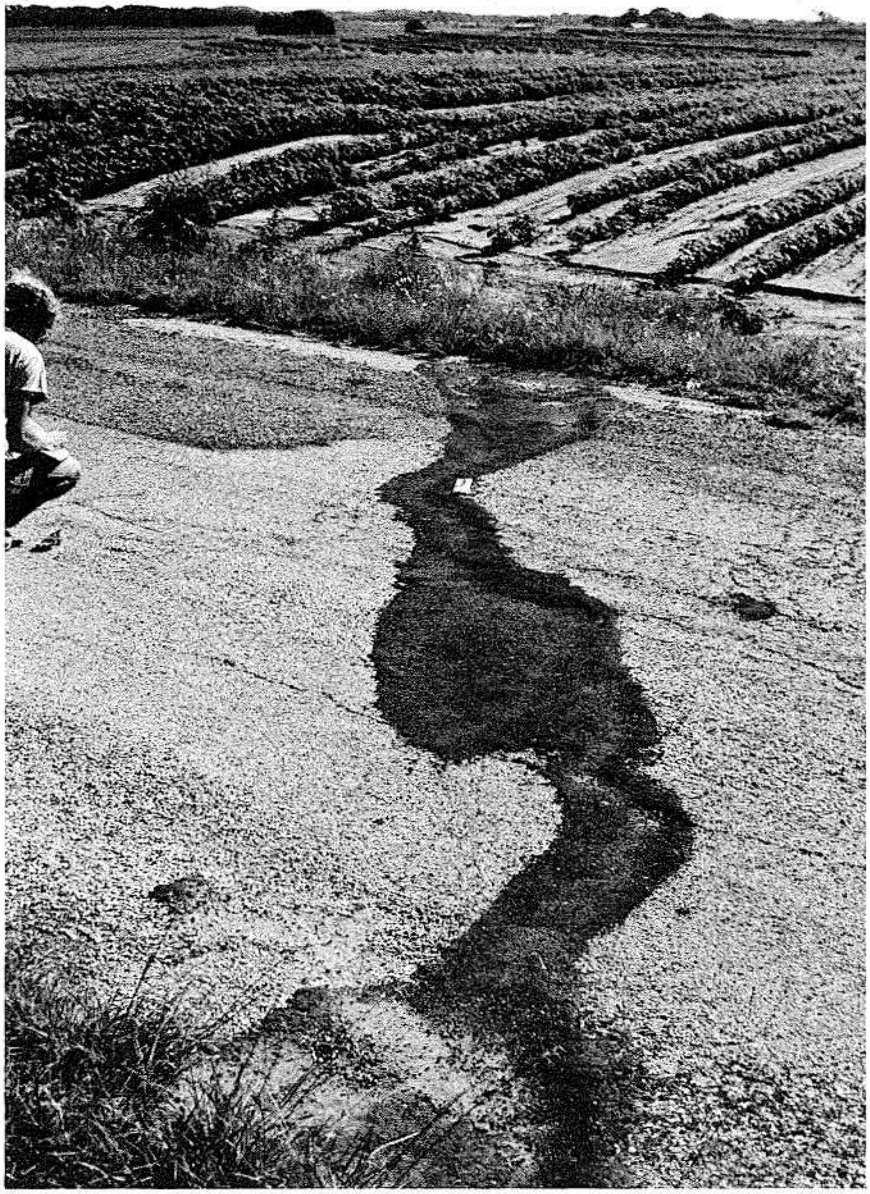


Figure 28. Microfault across County Road 2639 in central Hall County. Left side of the fracture is depressed 3 to 4 cm relative to right side. Fault continues about 30 m into cultivated field.

perhaps during dissolution and collapse, an interval of profound erosion occurred, during which Cretaceous and Triassic sediments were stripped away from parts of the Anadarko, Dalhart, and Palo Duro Basins, leaving indurated plugs of brecciated Cretaceous clastic sediments preserved locally as collapsed chimney fillings.

Dissolution probably continued throughout the Tertiary. Structure-contour maps of the base of the Ogallala Formation reveal chaotic structures in the Anadarko Basin, in the eastern Dalhart Basin, and north of the salt dissolution limit in the Palo Duro Basin (fig. 7). The structure-contour surface is characterized by numerous closed basins, the largest of which are up to 310 km^2 (120 mi^2) in area and as much as 107 m (350 ft) deep. These basins contain only Miocene-Pliocene Ogallala Formation sediments and thus formed after the onset of Ogallala deposition. Had they been closed basins on the Permian surface prior to Ogallala deposition, the basins would contain some record of pre-Ogallala but post-Permian sedimentation.

The base of the Ogallala Formation north of the dissolution zone lies locally more than 180 m (600 ft) below the base of the Ogallala Formation south of the dissolution zone, which suggests that several tens of meters of dissolution took place during or before deposition (figs. 5 and 6). Salt dissolution that occurred during the Tertiary probably resulted in a structural escarpment along the line of, or slightly northeast of, the present salt dissolution zone. The structurally depressed area north of the Tertiary salt dissolution zone is where the oldest and thickest Ogallala sediments are preserved. Frye and Leonard (1957 and 1959) report sections within this area that contain as much as 75 m (250 ft) of Valentine floral zone sediments.

South of the salt dissolution zone, much thinner sections of younger sediments of the Ash Hollow floral zone representing mid-Ogallala deposition normally rest directly on pre-Ogallala bedrock. Furthermore, on the basis of an analysis of the distribution of facies types and sand thickness, Seni (1980, p. 23, p. 25, fig. 17) states that Ogallala sedimentation first infilled the structurally depressed region north of the present-day dissolution zone. Later Ogallala depositional trends are to the south and southeast across the dissolution zone and are responsible for Ash Hollow sediments that compose much of the Ogallala beneath the Southern High Plains (Frye and Leonard, 1957 and 1959).

The interpretation poses a difficult problem because the present surface of the Ogallala north of the dissolution zone and the Canadian River is 75 m (250 ft) lower in elevation than the Ogallala surface south of the dissolution zone. The problem is resolved by suggesting that salt dissolution occurred throughout the Tertiary and into the Pleistocene. Subsidence of the area north of the Southern High Plains during the Tertiary and the Pleistocene accounts for (1) the otherwise unexplained differences in elevation between the Northern and Southern High Plains, (2) the different ages in basal Ogallala sediments, and (3) the elevation differences in segments of Ogallala depositional trends from north to south across the dissolution zone.

That dissolution has continued through the Pleistocene to the present is supported by three lines of evidence. Both the Canadian River and the Pecos River, whose valley marks the westward limit of the Southern High Plains, were developed entirely during the Pleistocene. The headward extension of the Pecos River beheaded all the streams that flowed across the High Plains surface south of the present Canadian River drainage (Thomas, 1972; Byrd, 1971; and Epps, 1973). The northward expansion of the Pecos drainage appears to have been encouraged by solution of evaporites along its path (Lee, 1923; Morgan, 1941). During the Pleistocene, the Canadian River also cut a deep valley that separates the Northern and Southern High Plains. Development of the western part of the Canadian River probably postdates the development of the Pecos River because the upper part of the Canadian River drainage appears to have pirated the Pecos River in the vicinity of the Conchas Reservoir in New Mexico (Kessler, 1972). The structure contours on the base of the Ogallala Formation also show that the Canadian River directly overlies or is slightly offset from a series of solution depressions or troughs (fig. 7). Taken collectively, however, all the basins and troughs underlie the lower part of the Canadian River Valley.

Mapping of Pleistocene terrace distribution along the Canadian River led to the recognition of numerous collapse chimneys filled with brecciated gravels. In one area, terrace gravels south and approximately 75 m (250 ft) above the present stream were observed to overlie a 1-m-thick ash bed. The ash has been tentatively identified as being in the Pearlette Type O family (G. Izett, personal communication, 1979), which would indicate a late Kansan age (600,000 years B.P.). A collapse chimney is exposed about 20 m (65 ft) downslope from the terrace (fig. 17, top photo). Gravels that fill the chimney are similar in lithology and size distribution to the gravels that make up the terrace. The close relationship of the terrace and collapse chimney and the Pearlette Ash suggests that collapse forming this chimney took place following deposition of the terrace or during post-Kansan time.

Salt dissolution has probably been active in the vicinity of the Texas Panhandle since at least the Late Cretaceous. That dissolution is still active in the Southern High Plains is reflected by historic collapse events and by the large volumes of brines discharged by all the major streams draining the Texas and New Mexico part of the High Plains.

RATES OF SALT DISSOLUTION ALONG THE EASTERN ESCARPMENT OF THE SOUTHERN HIGH PLAINS

The average annual solute discharge for the Southern High Plains from 1969 to 1974 was 2.7572×10^6 tons of dissolved solids per year, including 1.1343×10^6 tons of chloride and 0.513×10^6 tons of sulfate (U.S. Geological Survey, 1969-1977). Nearly half of this load was supplied by the Prairie Dog Town Fork of the Red River, whose average load for the same period was 1.0335×10^6 tons of dissolved solids, including 0.4253×10^6 tons of chloride and 0.1558×10^6 tons of sulfate. It is assumed that the main source for this solute load is bedded Permian evaporites and that dissolution of Permian salts and other evaporites in the Palo Duro Basin is an active process.

Swenson (1974) discussed salt dissolution rates for the same general area in terms of thickness of salt dissolved per thousand years per drainage basin. He found that for the drainage basin of Croton Creek, a small subbasin of the Salt Fork of the Brazos River, the vertical dissolution rate was 0.15 mm (0.006 inch) per year for the entire 6.55-km^2 (253-mi^2) drainage basin (fig. 29). Swenson described rates of salt dissolution expressed both as a rate of backwasting toward the basin and as a rate of vertical dissolution.

To develop rates for salt dissolution by backwasting, two figures must be compared: (1) an estimate of the cross-sectional area of the body of salt undergoing dissolution and (2) an estimate of the volume of salt removed from the dissolution surface during a known period of time. The volume of salt exported from the active dissolution zone on the eastern and northern sides of the Palo Duro Basin can be approximated from annual solute load data. Annual solute load in terms of

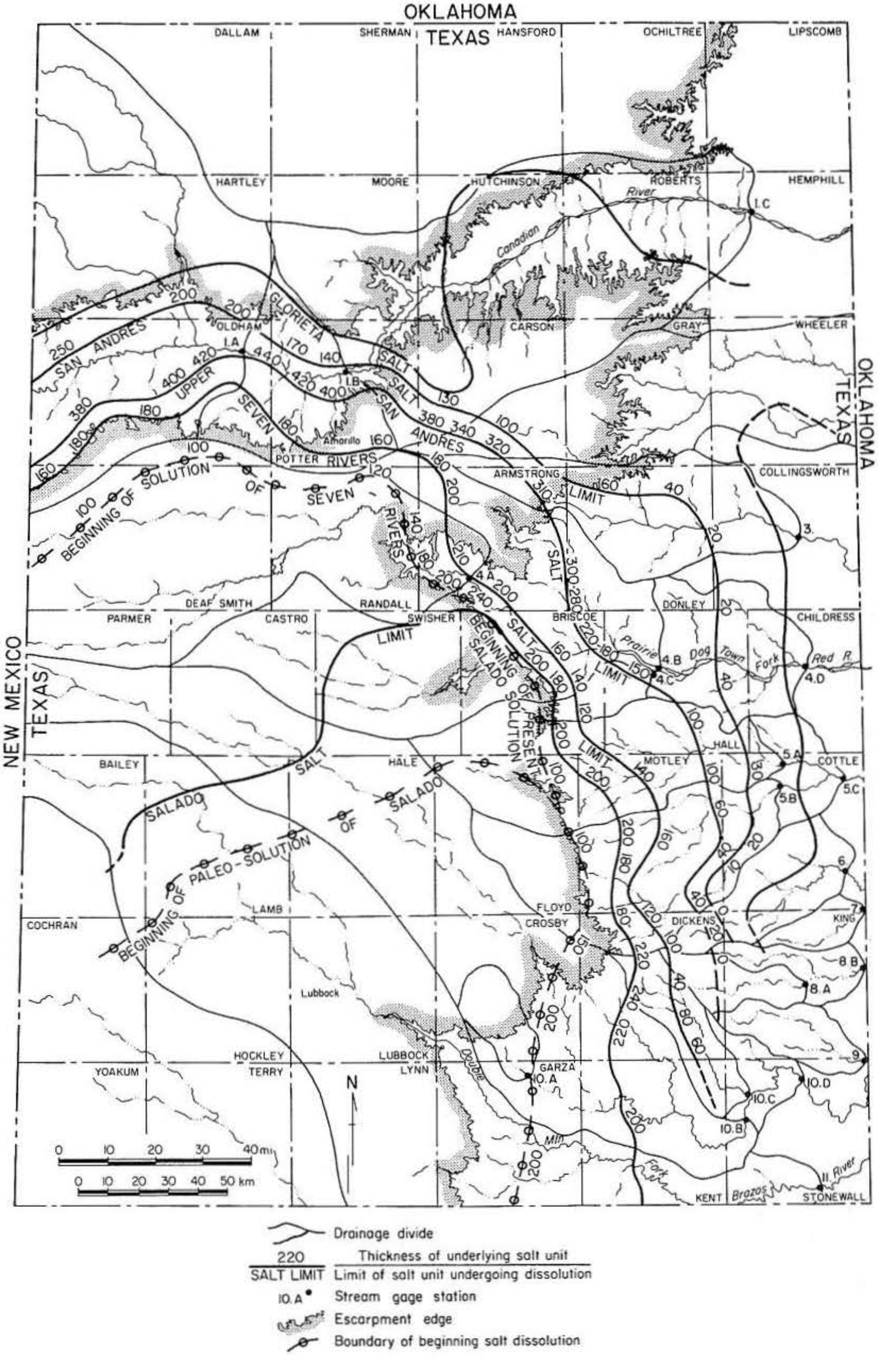


Figure 29. Watersheds and associated water quality sampling stations. Lines marked "beginning of dissolution" indicate the limit of the complete salt section for the Salado and Seven Rivers Formations. Salt dissolution occurs north and east of these lines.

tons of total dissolved solids, chloride, sulfate, sodium, and calcium is known for all the major and several minor drainage basins along the northern and eastern margins of the Southern High Plains (table 1, fig. 29). Surface drainage divides are approximate boundaries for ground-water systems that provide base flow to surface streams. Data on dissolved load of the surface streams then serve as a minimum approximation of the dissolved load of the ground water beneath each drainage basin. It is assumed, however, that brines discharging to the streams flow primarily parallel to bedding, and thus only those salts at the same stratigraphic horizon or higher than the recording station are considered in the estimate of cross-sectional area of salt undergoing dissolution. It is also assumed that only a relatively small amount of ground water leaves each basin by subsurface flow, and that surface discharge accounts for all but a small part of the total discharge from a basin.

The depths of the salt beds exposed along the dissolution front and the areas where these strata are undergoing dissolution are mapped in figure 29. Examination of closely spaced geophysical logs indicates that for each major salt-bearing unit the salt dissolution surface is a relatively abrupt inclined surface at the updip limit of a bed. This is consistent with the assumption that salt dissolution is predominantly backwasting rather than vertical downwasting over a large geographic area. By multiplying the length of the dissolution front for each salt unit by the thickness of the salt unit, a figure approximating the cross-sectional area of the salt undergoing dissolution is obtained for each drainage basin. Thus, by dividing the export volume by the cross-sectional area of all the salt units within a drainage basin, a figure for the mean annual dissolution rate is obtained (table 1). A rate of vertical salt dissolution was also determined by dividing the annual solute load by the geographic area of each basin underlain by a part of the salt dissolution zone.

Maximum rates of horizontal and vertical salt dissolution are those of the drainage basins of the Prairie Dog Town Fork of the Red River, the Little Red River, and of tributaries of the Wichita and Brazos Rivers. Rates comparable to those in table 1 are sufficient to account for the amount of salt dissolution that occurred in the Anadarko, Dalhart, and Palo Duro Basins since the onset of Ogallala deposition. From this analysis of salt dissolution rates, it is evident that salt dissolution currently is more rapid along the eastern Caprock Escarpment than it is along the Canadian River Breaks.

Preliminary Process Model of Salt Dissolution

Depths to the top of the salt dissolution zone along the southern margin of the Canadian River and along the eastern escarpment of the Southern High Plains are variable. Maximum depths to salt dissolution beneath the High Plains occur in Swisher County and exceed 460 m (1,500 ft). Beneath the Canadian River in Potter County, salt dissolution occurs at a depth of 210 m (700 ft) to 305 m (1,000 ft). Eastward of the Caprock Escarpment, where Ogallala and Dockum sediments have been removed, salt dissolution occurs at increasingly shallow depths. Depths range from 290 m (950 ft) in Donley County to 120 m (385 ft) in southeastern Hall County. Beneath the High Plains, depths to salt dissolution increase southward and range from 160 m (530 ft) to 468 m (1,534 ft).

The formations that are undergoing dissolution — Salado, Seven Rivers, San Andres, Glorieta, and upper Clear Fork — retain salt increasingly farther to the north and east with depth. The Salado dissolution zone occurs nearest to the High Plains Escarpment, and the dissolution zones of older salt-bearing units occur farther to the north and east beneath the Canadian River Valley and the Rolling Plains (fig. 4).

Salt seeps, salt pans, and salt springs occur in numerous areas along the Prairie Dog Town Fork of the Red River, Little Red River, Pease River, Salt Creek, and Wichita River. Estelline Spring, the largest single source of salt water in the vicinity of the High Plains, occurs in central Hall County in the salt dissolution zone and is apparently a sinkhole that extends down to Permian salts (Ward, 1963). Water discharges at a rate of 0.11 m^3 (4 ft^3) per second and at a salinity of 28,000 ppm. Temporary salt pans occur along the Prairie Dog Town Fork of the Red River and along the Little Red River (fig. 30). Salt pans form by evaporation of waters contributed to these creeks as base flow from Permian sediments. Waters within the alluvium are drawn upward by capillary action to be evaporated at the surface.

The age of the brines that are flowing from springs and seeps is not well known. Ward (1963) completed tritium age determinations for spring water from Estelline Spring in Hall County, from Salt Creek in Cottle County, and from the Wichita River in King County. He gave no numerical data but stated that "the analyses' data indicate that each spring contains water younger than 20 years. The samples from Cottle and King Counties, Texas, contain considerable amounts of post-1954 water." Ward did not speculate on the degree of brine dilution by younger, shallower, and fresher ground water.

The pattern of ground-water movement necessary to account for salt dissolution patterns, the variations in depths of salt units undergoing dissolution, and the position of salt seeps, pans, and springs is shown in a conceptual flow-distribution diagram (fig. 31). The conceptual diagram requires an input of fresh water at topographically high points to provide the necessary hydrostatic head. Since there is evidence of dissolution beneath the High Plains, a source of fresh water must be available for this process to have occurred. Clearly, the overlying Ogallala Formation is the most likely source. Downward percolation of waters through the upper part of the Dockum Group is reflected by the large number of springs that occur along the base of the upper Dockum fluvial sandstones along the outcrop in the Canadian River Breaks and along the Caprock Escarpment.

Table 1. Salt dissolution expressed as rates of horizontal and vertical dissolution. (Solute load data from U.S. Geological Survey, 1968-1977)*

Basin	Mean annual solute load	Annual rates of horizontal dissolution				Annual rates of vertical dissolution			
	$x\ 10^5 ft^3$	Mean		Max	Min	Mean		Max	Min
		ft/yr	cm/yr	ft/yr	ft/yr	$x\ 10^{-5}$ft/yr	$x\ 10^{-3}$cm/yr	$x\ 10^{-5}$ft/yr	$x\ 10^{-5}$ft/yr
1A Canadian River (Tascosa)	(5 years)** 4.460	0.00189	0.0576	0.00246	0.00132	1.0499	3.2001	1.367	0.735
1B Canadian River (Amarillo)	(5 years) 6.9542	0.00188	0.0575	0.00239	0.00081	1.0312	3.1431	1.306	0.452
1C Canadian River (Canadian)	(3 years) 7.9221	0.00186	0.0568	0.00261	0.00118	0.7665	2.3362	1.072	0.484
3 Salt Fork of the Red River (Wellington)	(9 years) 2.119	0.00621	0.1893	0.01265	0.00154	0.7405	2.2571	1.509	0.183
4A Prairie Dog Town Fork of the Red River (Lakeview)	(9 years) 24.1188	0.00963	0.2935	0.02337	0.00376	5.6674	17.2742	11.926	2.637
4C Little Red River (Turkey)	(9 years) 12.851	0.25353	7.7276	0.47850	0.13238	27.1130	82.6404	51.172	14.157
4D Prairie Dog Town Fork of the Red River (Childress)	(9 years) 119.5366	0.08485	2.5862	0.01925	0.00564	17.7560	54.1203	29.142	11.816
5A North Pease River (Childress)	(5 years) 4.3677	0.01077	0.3283	0.01607	0.00758	1.7911	5.4593	2.672	1.261
5B Middle Pease River (Paducah)	(5 years) 0.5515	0.00100	0.0305	0.00248	0.00018	0.2027	0.6177	0.500	0.037
5C Pease River (Childress)	(8 years) 32.5842	0.02408	0.7339	0.03318	0.01737	5.8465	17.8200	8.056	4.216
6-10 Area includes basins 6-10	(5-9 years) 115.5136	0.1249	3.8070	0.1735	0.0846	30.8860	94.1405	42.910	20.926
6 North Fork Wichita River (Paducah)	(8 years) 19.8165	2.6808	81.7108	3.2283	2.1093				
8A South Fork Wichita River (Guthrie)	(6 years) 13.6156	0.2686	8.1870	0.3115	0.2229				
10B Salt Fork Brazos River (Peacock)	(9 years) 25.0487	0.0327	0.9967	0.0672	0.0087				
10C Croton Creek (Jayton)	(9 years) 6.3678	0.0635	1.9355	0.1352	0.0218				
10D Salt Fork Brazos River (Aspermont)	(9 years) 70.1657	0.07216	2.1994	0.1061	0.0447				

*Preliminary horizontal rates in Gustavson and others (1979c) are lower due to a difference in procedure. All dissolution zones beneath a basin were considered to contribute to solute load for the basin.

**Number of years of data.

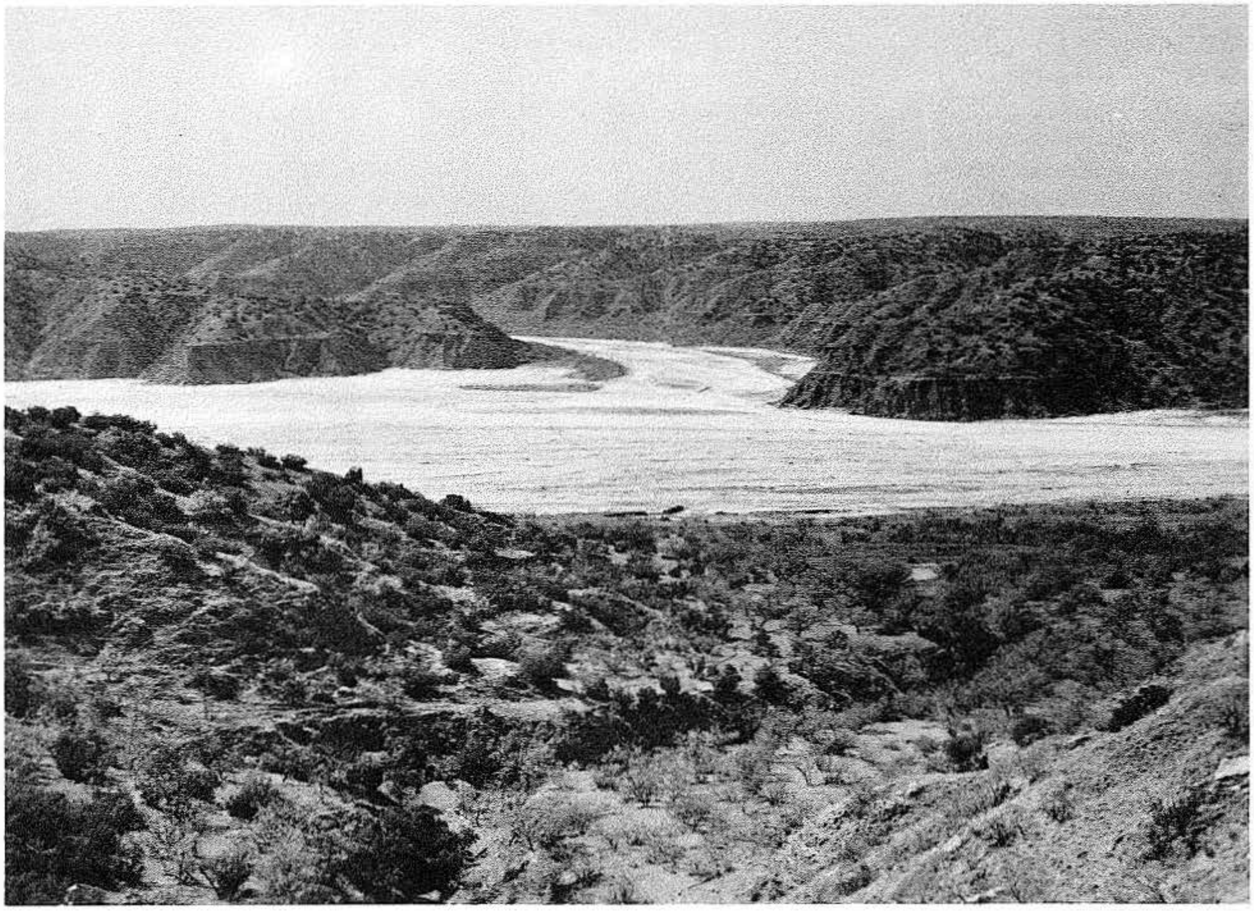


Figure 30. Salt pans developing along the Little Red River and the Prairie Dog Town Fork of the Red River at their confluence east of Quitaque, Texas.

Lacustrine claystones and mudstones compose the lower Dockum. At best this material is only slightly permeable and would prevent the downward percolation of ground water from the upper Dockum and from the Ogallala. Lacustrine sediments are easily erodable and are subject to rapid slaking and expansion at the surface; thus, fractures are not readily observed. Fractures are very common in both overlying and underlying rocks and probably extend through the poorly permeable lacustrine beds. Fractures through the lacustrine beds would provide a pathway for relatively fresh ground water to move downward toward the observed dissolution zone in Permian salts. Collapse over areas of dissolution would further accentuate fracturing and thus increase the potential for ground-water movement. If it is true that large playas (≥2,440 m [≥8,000 ft]) are the result of or were at least influenced by salt dissolution, then this is additional indirect evidence that vertical movement of fresh ground water downward through Tertiary and Triassic sediments to Permian salts does occur. Most of the large playas discussed in this paper occur above the subcrop of the Triassic Dockum Group.

Eastward of the Caprock Escarpment, Permian sediments are structurally disturbed as a result of collapse. Numerous fractures provide routes for the downward percolation of fresh ground water. Depth to the tops of salt units where salt dissolution is underway is generally less than 245 m (800 ft). Downward-percolating fresh water dissolves the salt and migrates laterally or slightly upward to reappear at the surface as salt springs, seeps, or pans in a major stream valley. The pattern of ground-water flow is recharge on the Rolling Plains and High Plains, the hydrostatic head causing flow downward through fracture systems to the salt. Relatively fresh water dissolves the salt and moves laterally along fractures and bedding planes to discharge points.

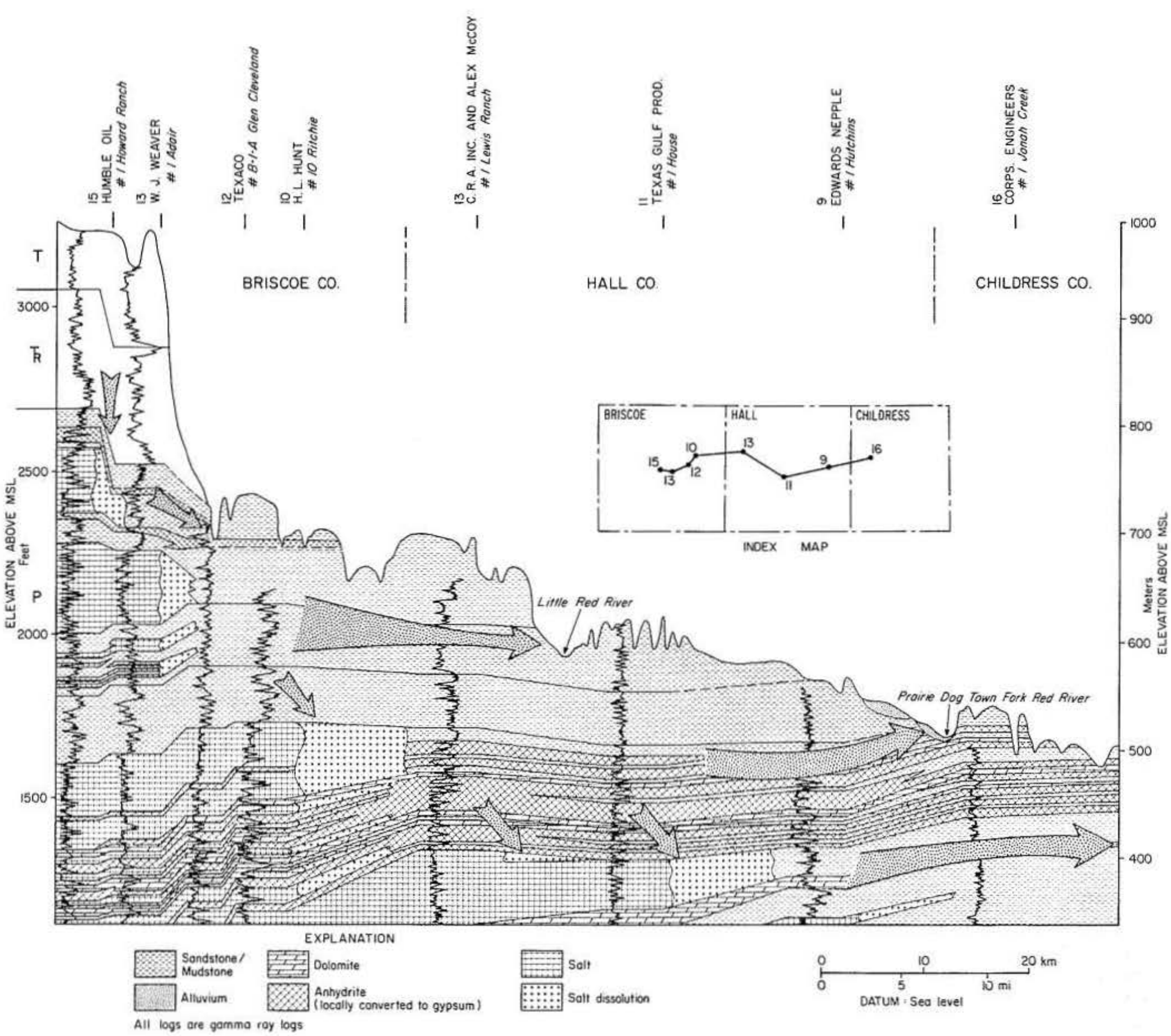


Figure 31. Conceptual model of ground-water movement and its impact on Permian salt units beneath the eastern Caprock Escarpment. Inferred movement paths are indicated by the arrows. Stratigraphic units are identified in figure 6.

SUMMARY

Salt dissolution is an active process in the Texas Panhandle and results in numerous salt seeps, springs, and pans along the streams that drain the Southern High Plains. These streams carry a cumulative solute load that exceeds 2.8×10^6 tons of dissolved solids per year. Approximately 66 percent of the solute load is derived from the dissolution of salt, and the remainder is from the dissolution of gypsum or anhydrite.

The effects of salt dissolution are manifested by regional subsidence and structural deformation of Permian and younger sediments throughout the eastern and northern parts of the Texas Panhandle. Cumulative salt dissolution probably exceeds 180 m (600 ft). Subsidence following salt dissolution has resulted in (1) as much as 75 m (250 ft) of regional lowering of the High Plains surface north of the Canadian River, (2) complex folding and brecciation of Permian sediments that lie above the zones of salt dissolution, (3) chimneys filled with collapse breccias, and (4) ancient and modern sinkholes.

Salt dissolution began in the Oklahoma Panhandle in the Late Cretaceous to early Tertiary prior to deposition of the Ogallala Formation. Dissolution in the Texas Panhandle was probably active more or less continuously from the late Tertiary to the present. The base of the Ogallala Formation north of the Canadian River was disturbed by subsidence while deposition was underway. Furthermore, the surface of the Ogallala north of the Canadian River has subsided 75 m (250 ft) since deposition ceased. The Canadian River, which developed following deposition of the Ogallala Formation, overlies a series of dissolution basins or troughs that locally exceed 75 m (250 ft) in depth. Terrace deposits (Kansan) along the margin of the Canadian River Valley appear to have been incorporated in collapse chimneys. In conjunction with the fact that salt dissolution is presently active, this evidence suggests that salt dissolution in the Texas and Oklahoma Panhandles has been continuous since the Late Cretaceous.

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