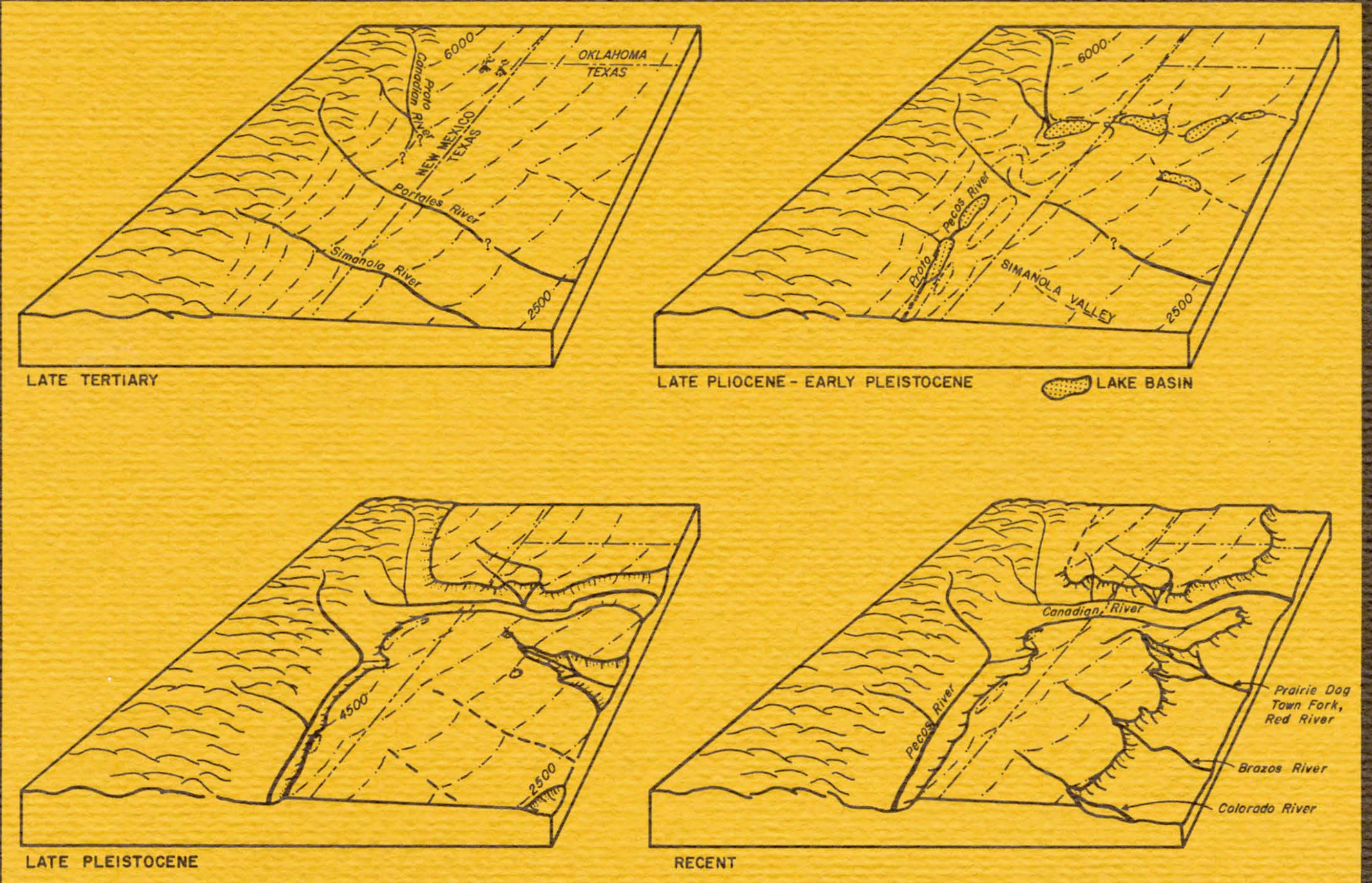
Report of Investigations No. 148

Late Cenozoic Geomorphic Evolution of the Texas Panhandle and Northeastern New Mexico—
Case Studies of Structural Controls on Regional Drainage Development

Thomas C. Gustavson and Robert J. Finley



Bureau of Economic Geology
W. L. Fisher, Director
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ABSTRACT

Salt dissolution has affected parts of the Upper Permian Salado, Seven Rivers, San Andres, Glorieta, and upper Clear Fork Formations beneath the Pecos River valley in eastern New Mexico and has been active beneath the Canadian River valley and the Rolling Plains of the Texas Panhandle. Extensive dissolution of the salts of the Salado and Seven Rivers Formations has also occurred beneath the Southern High Plains. Cumulative thickness of salt lost to dissolution exceeds 150 m (500 ft) along the western, northern, and eastern margins of the Palo Duro Basin.

Dissolution and subsidence occurred during deposition of the Tertiary Ogallala Formation, but Ogallala deposition kept pace with subsidence. After Ogallala deposition during the late Pliocene, surface subsidence created lacustrine basins along trends of relatively rapid dissolution. Preserved lacustrine sediments contain Blancan faunas (which confirm a basin age of at least late Pliocene).

Continued subsidence along trends of relatively rapid dissolution overlying the structural margins of the Palo Duro and Anadarko Basins during the late Tertiary and early Quaternary formed a series of subsidence basins that diverted many of the streams that flowed southeasterly across the Southern High Plains. As a result of subsidence, the headwaters of the ancestral Brazos River were diverted during the middle to late Pleistocene from a southeastern drainage through the Portales paleovalley to a southern drainage through the Pecos Valley. The present headwaters of the Canadian River are probably a former tributary of the Pecos-Portales-Brazos River system that was diverted to the northeast along a subsidence trough caused by dissolution during the late Pliocene or early Quaternary.

On the High Plains surface, several lacustrine basins (Frio Draw, Tierra Blanca Creek, and Yellow House Draw) lie above areas where accelerated salt dissolution has apparently occurred. These features overlie apparent structural depressions of the Alibates Formation, which is stratigraphically above the salt-bearing units. Most of the features also overlie either paleostream valleys or closed depressions on the middle Tertiary erosional surface. Faunal evidence suggests that the present stream valleys formed as early as the late Pliocene. Lacustrine basins probably formed between the late Pliocene and the early Pleistocene. The basins and stream valleys probably owe most of their form to normal fluvial and eolian erosion. Their location, however, is most likely the result of dissolution-induced subsidence.

A large system of late Quaternary alluvial fans that built eastward from the Caprock Escarpment is being extensively dissected. This suggests that much of the drainage on the Rolling Plains in the Texas Panhandle developed during the late Pleistocene and Holocene. The parallelism between major stream segments and the dissolution fronts of Permian salt-bearing units indicates that much of the drainage is controlled by dissolution-induced subsidence. Furthermore, minor stream segments parallel the preferred orientations of numerous subsidence basins that are on the surface of the alluvial fans. Both straight segments of minor streams and long axes of subsidence basins are aligned parallel to the preferred orientations of the regional fracture system. Dissolution was probably accelerated along fracture trends, resulting in the development of subsidence basins that parallel fracture trends and, in turn, leading to the alignment of drainage when subsidence basins were incorporated into the drainage network.

Keywords: geomorphology, physiography, salt dissolution, Cenozoic, Texas Panhandle, northeastern New Mexico

INTRODUCTION

The Palo Duro and Dalhart Basins of the Texas Panhandle and eastern New Mexico (fig. 1) contain bedded Permian salts that are thick enough and deep enough to be considered as potential sites for long-term storage and isolation of high-level radioactive nuclear waste (Johnson, 1976). Salt (primarily halite), because of its low permeability, low moisture content, and high gamma-ray-shielding properties, is a desirable host rock for the waste.

Zones of active salt dissolution have been identified along the eastern and western Caprock Escarpments of the Llano Estacado, or Southern High Plains, along the southern margin of the Canadian River valley, and beneath the Canadian River west of Amarillo (Gustavson

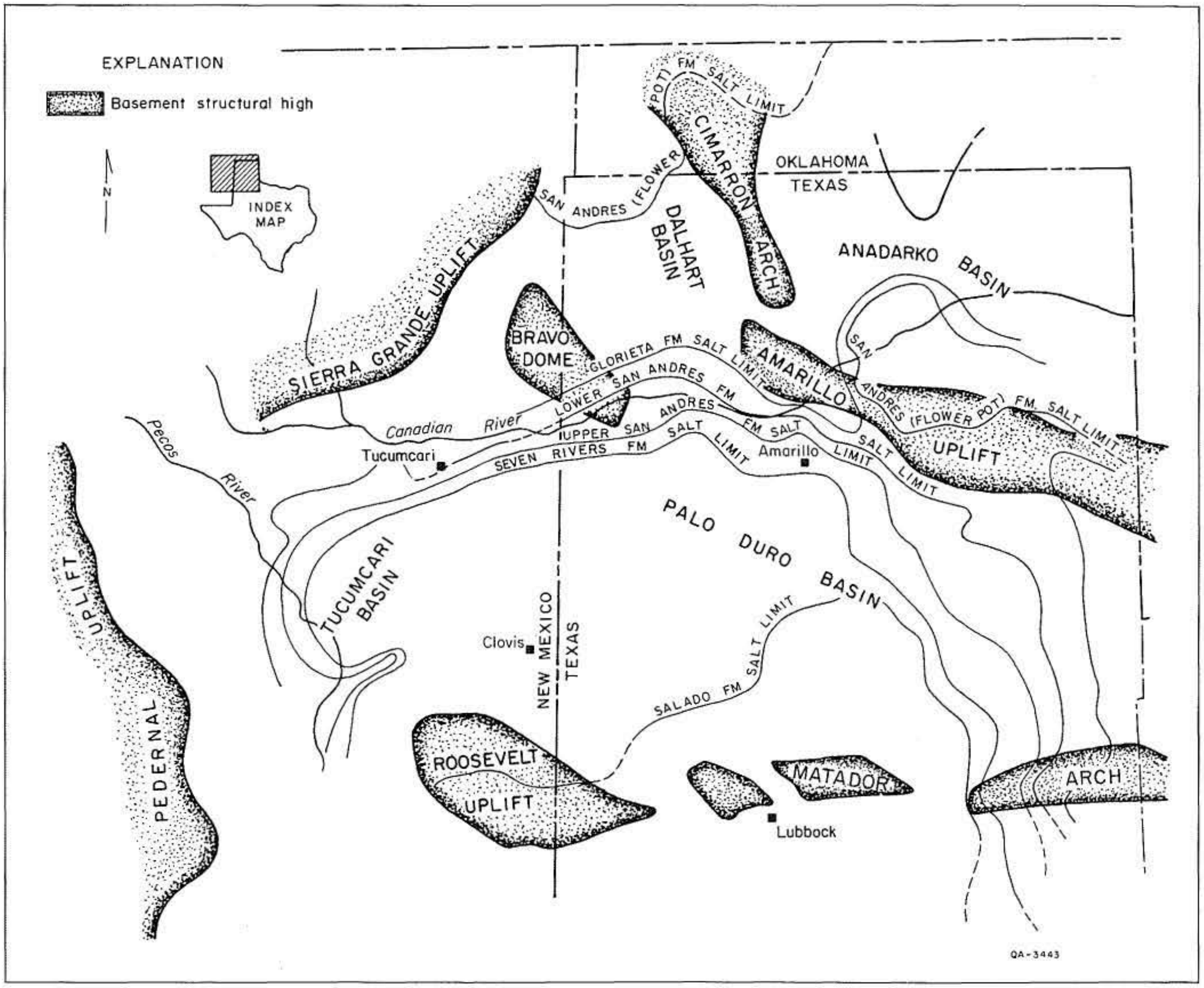

Figure 1. Major structural elements, Texas Panhandle and surrounding areas (after Nicholson, 1960). Limits of Permian bedded salts are closely associated with the structural margins of the Palo Duro Basin. Structurally high salt units are most likely to be affected by dissolution.

and others, 1980a; Presley, 1980a, 1980b; Johnson, 1981). The general coincidence of these dissolution zones, escarpments, and major stream segments strongly suggests that the processes of dissolution and subsidence have influenced the development of both drainage systems and erosional scarps. Because dissolution zones locally extend beneath the High Plains surface, it is clear that dissolution precedes backwasting of the escarpments. In addition, evidence of widespread dissolution beneath the Southern High Plains has been recognized in salts of the Upper Permian Salado and Seven Rivers Formations (Gustavson and Budnik, 1985; McGookey and others, 1985). To determine whether the continued development of drainage systems in the Texas Panhandle and eastern New Mexico could adversely affect potential waste isolation sites, the geologic characteristics and processes that affect drainage development must be understood. This report describes certain structural and topographic controls on drainage development in the Texas Panhandle and in eastern New Mexico.

Orientations of many drainage elements in eastern New Mexico, the Texas Panhandle, and western Oklahoma have been attributed to the adjustment of drainage segments to bedrock structure. Spiegel (1972) ascribed the morphology of the present Canadian River in eastern New Mexico to the river's adjustment to middle Pleistocene normal faults. Fay (1959) suggested that the present course of the Canadian River in western Oklahoma is caused by the river's adjustment to the strike of Permian outcrops exposed across the regional surface slope and to stream piracy. Brown (1967) offered an alternative explanation, suggesting that the river has adjusted to deep-basin structure, forming a series of three large loops. The loops overlie a group of synclines attributed in part to solution and collapse of the Blaine and Cimarron Anhydrites. Gustavson and Finley (1982a, 1982b) suggested that the path of the Canadian River in eastern New Mexico and in the Texas Panhandle is strongly influenced by dissolution of Permian salt and subsidence. Dolliver (1984) synthesized much of the literature pertaining to the development of the Canadian River basin.

The development of the Pecos River in New Mexico where it parallels the western Caprock Escarpment of the Southern High Plains has been attributed to dissolution and collapse along the strike of Permian evaporites (Morgan, 1941; Kelley, 1972; Thomas, 1972; Gustavson and Finley, 1982a, 1982b). According to these interpretations, streams flowing southeasterly across the Ogallala surface became ponded along the trend of the dissolution-collapse zone. Progressive headward piracy by the Pecos River ensued, culminating in piracy of the headwaters of the Brazos River. Thomas (1972) and Kessler (1972) suggested that a part of the headwaters of the Pecos River system were then beheaded by the Canadian River.

Fenneman (1931) classified streams draining the High Plains as "consequent"; that is, they are adjusted only to the surface slope of the High Plains. Reeves (1970) and Finch and Wright (1970) related the rectilinear draws, which are the major drainage features on the Southern High Plains surface, to a system of inferred northwest-southeast and northeast-southwest fractures. They differed, however, in their interpretations of the origin of the fractures. Finch and Wright proposed a structural flexure or fault along the Running Water Draw/White River. Reeves, on the other hand, suggested that the fractures relate to the "regmatic shear pattern" of basement rocks. Woodruff and others (1979) attributed the development of draws to ponding in playas and to the overtopping of playa divides resulting in discharge of waters into the next playa downslope. In the area that they considered, playa density was so great that no preferred alignment of playas was recognizable. Finley and Gustavson (1979, 1981) related regional drainage development and playa alignment to major joint trends and suggested that joint development reflected major basement structural trends.

The following discussion of the regional relation of Permian salt dissolution and the present drainage systems of eastern New Mexico and the Texas Panhandle is in part a synthesis of previous work, in particular discussions by Gustavson and others (1980b, 1981a, 1981b), Gustavson and Finley (1982a, 1982b), and Gustavson and Budnik (1985) on dissolution zones, collapse features, and the association of dissolution-induced collapse features with fractures. In addition, significant new data describing the relation between drainage development and dissolution are presented in this report.

GEOLOGIC SETTING OF THE PALO DURO BASIN

Structural Development

In the late Paleozoic, but perhaps as early as the Late Cambrian, rocks of the Wichita igneous province and the Red River mobile terrane were faulted and uplifted to form the Amarillo Uplift and the Matador Arch (Birsa, 1977). These features are the major positive tectonic elements bounding the Palo Duro Basin (fig. 1).

Movement along the Amarillo Uplift, Matador Arch, and Cimarron Arch controlled sedimentation and facies distribution during the Pennsylvanian and apparently continued into the Permian (Dutton and others, 1979). Recent work by Budnik (1983) and by McGookey and others (1985) suggests that tectonic movement continued throughout the Texas Panhandle as late as the Tertiary and possibly as late as the Quaternary.

Sedimentation

During the early Paleozoic, periods of erosion alternated with episodes of shallow marine-shelf deposition in the Texas Panhandle. During the Mississippian, marine-shelf carbonates were deposited across the area. Major tectonic activity, which began in the Late Mississippian and continued through the Pennsylvanian, formed the bounding elements of the Anadarko, Dalhart, and Palo Duro Basins. Deposition of terrigenous clastic sediments, informally called granite wash, was prevalent during the Pennsylvanian and Early Permian. Granite wash was derived from and deposited near the principal uplifts (Handford and Dutton, 1980). Distal from principal uplift, Late Pennsylvanian sedimentation was dominated by shelf carbonates. Finegrained clastic sediments filled deeper parts of the basin. Salt, anhydrite, dolomite, limestone, and red beds compose middle and Upper Permian strata in the Anadarko, Dalhart, and Palo Duro Basins (Presley, 1979a, 1979b, 1980a, 1980b). These rock types were probably deposited in a range of subtidal to supratidal environments on an extensive, very low relief marine shelf.

The Triassic Dockum Group consists of fluvial, deltaic, and lacustrine sandstones and mudstones that accumulated in a large fluvial-lacustrine basin south of the Amarillo Uplift (McGowen and others, 1979). Dockum Group strata are overlain unconformably by the Upper Jurassic Exeter Sandstone in certain areas and by the Lower Cretaceous Kiamichi Formation (Fredericksburg Group), Dakota Group sandstones and conglomerates, and Kiowa Shale in other areas. After a period of extensive erosion, producing the middle Tertiary erosional surface, the Miocene-Pliocene Ogallala Formation was deposited in northwestern Texas, western Oklahoma, and eastern New Mexico. Ogallala sediments are primarily fluvial deposits that were deposited in an alluvial-fan environment (Seni, 1980; Winkler, 1984). Locally, upper Ogallala sediments are largely eolian. Several calcretes occur within the Ogallala, and the upper part of the Ogallala was extensively calichified to form the Caprock caliche.

The end of Ogallala deposition has not been precisely dated, but deposition probably had ceased by the late Pliocene (approximately 3.5 mya). In northeastern Union County, New Mexico, basalt flows cap the Ogallala Formation (Baldwin and Muehlberger, 1959). These rocks, called the late Raton basalt, have been dated by analyses of potassium-argon isotopes in whole-rock samples (Stormer, 1972) as being $3.5 \pm 0.2 \times 10^6$ years old. The Clayton basalt, which is similar in composition to the Raton basalt, occupies paleostream valleys incised into the Ogallala surface and has potassium-argon ages of $2.5 \pm 0.8 \times 10^6$ and $2.2 \pm 0.3 \times 10^6$ years for two samples analyzed (Stormer, 1972). These dates indicate that Ogallala fluvial sedimentation in northeast New Mexico probably had ceased 3.5×10^6 years ago and certainly by 2.5×10^6 years ago.

Schultz (1977) discussed the age of the Blanco Formation and Blancan-age local faunas, which locally unconformably overlie the Ogallala Formation. He pointed out that Boellstorff (1976) obtained a fission track age of 2.8 ± 0.3 m.y. for the Blanco ash, which overlies the fossil-bearing beds of the Blanco Formation. Lindsey and others (1975) determined that the entire Blanco Formation section exposed at Mount Blanco (Crosby County, Texas) is reversely magnetized. The 1.4 m.y. old Guaje ash rests unconformably on a paleosol developed in post-Blanco Formation eolian sediments. In conjunction with a 1.4 m.y. age of the Guaje ash, which lies 8 m (25 ft) above the Blanco ash, the lack of a normal magnetic polarity zone beneath the Guaje ash indicated to Lindsey and others (1975) that the section at Mount Blanco is in the lower Matuyama (reversed) magnetic interval and is 1.4 to 2.4 m.y. old. Lindsey and others (1975) also recognized that the Cita Canyon Local Fauna, which is typically correlated with the Blanco Local Fauna, occurs in a normally polarized zone. They included these strata in the Gauss Epoch and thus considered them to be older than the type Blanco fauna. Regardless of the dating inconsistencies, the Blanco Formation unconformably overlies the Ogallala Formation and is probably at least 2.8 m.y. old. Furthermore, the Blanco Formation contains boulders of Caprock caliche, a caliche that took considerable time to form after the end of Ogallala deposition. This suggests that the age of the end of Ogallala Formation deposition in the area of Mount Blanco and Cita Canyon overlaps or is slightly younger than the age of the end of Ogallala deposition in northeastern New Mexico. The Pleistocene Blackwater Draw Formation forms an eolian mantle (cover sands) on most of the Southern High Plains and overlies the Ogallala and Blanco Formations (Reeves, 1972; Machenberg and others, 1985).

Physiography of the Texas Panhandle and Central-Eastern New Mexico

The Texas Panhandle lies within the Great Plains physiographic province (Fenneman, 1931, 1938) (fig. 2). The surface of the Great Plains is broken by the valley of the Canadian River, which is also known as the Canadian Breaks. South of the Canadian Breaks and east of the Pecos River valley, the Great Plains are known as the Southern High Plains, or the Llano Estacado. The central part of the High Plains is north of the Canadian River valley. The Southern High Plains are truncated to the east and west at the Caprock Escarpment, an erosional scarp where relief locally exceeds 265 m (900 ft). Drainage is poorly developed on the Southern High Plains; most discharge is internal into thousands of playa lake basins that cover its surface (Woodruff and others, 1979). Integrated drainage is mainly by extremely elongated, narrow, rectilinear valleys, or draws. The Caprock Escarpment is supported by the massive Caprock caliche that marks the top of the Ogallala Formation and by well-indurated sandstones that are in the upper part of the Triassic Dockum and Permian Whitehorse Groups. East of the Caprock Escarpment, the Rolling Plains are developed on structurally disturbed Permian red beds. The Pecos Plains and the Pecos River valley, developed primarily on Permian, Triassic, and Tertiary clastic sediments, lie west of the Southern High Plains.

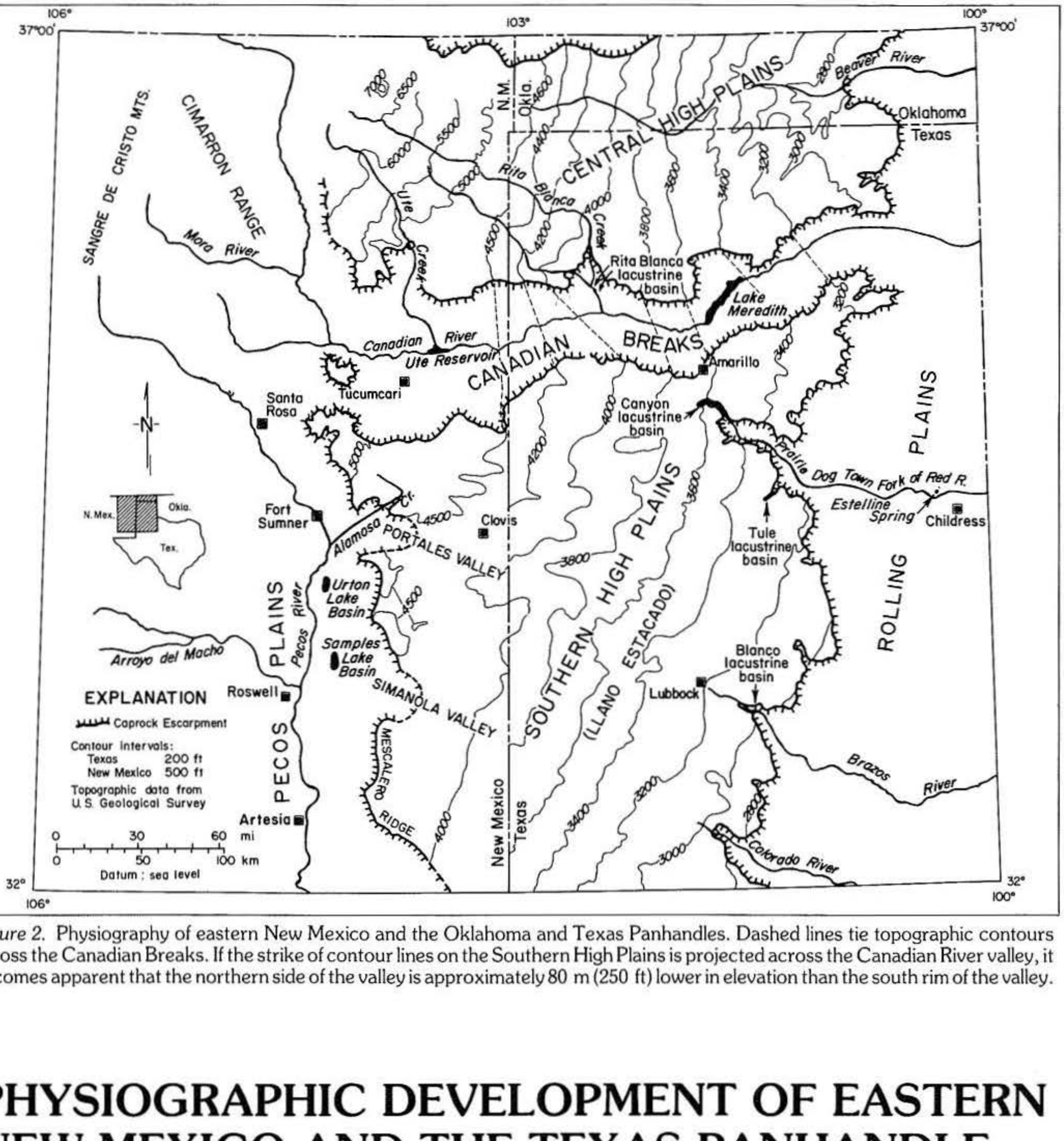

Figure 2. Physiography of eastern New Mexico and the Oklahoma and Texas Panhandles. Dashed lines tie topographic contours across the Canadian Breaks. If the strike of contour lines on the Southern High Plains is projected across the Canadian River valley, it becomes apparent that the northern side of the valley is approximately 80 m (250 ft) lower in elevation than the south rim of the valley.

PHYSIOGRAPHIC DEVELOPMENT OF EASTERN NEW MEXICO AND THE TEXAS PANHANDLE

Methods

The following discussion of the geomorphic evolution of eastern New Mexico and the Texas Panhandle is presented as case studies of drainage systems including the Pecos, Canadian, and Prairie Dog Town Fork Rivers, Tierra Blanca Creek, and other streams draining the Southern High Plains and the Rolling Plains. For each of these areas, field studies were integrated with subsurface studies based on interpretation of geophysical logs and seismic reflection profiles, hydrologic and water quality data obtained from stream-gauging stations, interpretations of aerial photographs and Landsat images, and topographic maps.

Evidence of Dissolution

Regional salt dissolution and the subsequent collapse of overlying strata affected substantial parts of the Texas and Oklahoma Panhandles (Gustavson and others, 1980a) and eastern New Mexico (Gustavson and Finley, 1982a, 1982b). Seven salt-bearing units lie within the Permian System of the Texas Panhandle and eastern New Mexico. With the probable exception of the lower Clear Fork Formation, all the younger salt-bearing units (the upper Clear Fork, Glorieta, Flowerpot, San Andres, Seven Rivers, and Salado Formations) are locally undergoing dissolution.

Several lines of evidence support the conclusion that zones of salt dissolution underlie the Southern High Plains and adjacent areas (fig. 3):

(1) Streams draining the region surrounding the Southern High Plains carry high solute loads, indicating that dissolution is active. For example, the Prairie Dog Town Fork of the Red River carries a mean annual solute load of 1,003.5 x 10^3 short tons of dissolved solids, including 425.3 x 10^3 short tons of chloride (U.S. Geological Survey, 1969–1977). Brine springs, salt springs, and salt pans appear along several stream valleys and especially in the vicinity of Estelline, Texas (fig. 2).

High chloride contents in both the Canadian and Pecos Rivers and their tributaries indicate that salt dissolution is an active process in eastern New Mexico and along the Canadian River valley in Texas (fig. 2). Downstream from the Ute Reservoir in Quay County, New Mexico, the solute load of the Canadian River can exceed 3,000 parts per million (ppm) chloride, and waters within the alluvium can exceed 30,000 ppm chloride (U.S. Geological Survey, 1969–1977; U.S. Bureau of Reclamation, 1979). The Bureau of Reclamation (1979) estimates that more than 55.0 x 10^3 metric tons of sodium chloride are carried annually by the Canadian River to Lake Meredith, Texas.

The chloride content of the Pecos River between Santa Rosa and Carlsbad, New Mexico, varies from several tens to several thousands ppm. Morgan (1941) estimated that 266.0 x 10^3 short tons of sodium chloride are transported annually by the Pecos River at Artesia, New Mexico. Brine springs are common, and collapse features have been observed in many places along the Pecos valley (Morgan, 1941; Reeves, 1972). By comparison, the Pecos River north of Santa Rosa, New Mexico, which is in an area not underlain by Permian salt, has a chloride load of less than 100 ppm.

(2) The abrupt loss of salt sequences between relatively closely spaced oil and gas exploration wells can be interpreted from geophysical logs. Where structural collapse of overlying strata is evident in the wells that are missing salt, dissolution and not facies change has probably occurred (figs. 4 through 7) (McGookey and others, 1985). Areas of salt dissolution are shown graphically on stratigraphic cross sections (figs. 4 through 7), but neither insoluble residues nor the original extent of salt can be interpreted from geophysical logs. Thus, the original extent of salt before it was subjected to dissolution is not shown on cross sections.

(3) Brecciated zones, fractures with slickensides, extension fractures filled with gypsum, and insoluble residues composed of soft mudstone, anhydrite, or dolomite overlie the uppermost salts in cores from the U.S. Department of Energy (DOE)-Gruy Federal Rex H. White No. 1 well and the Stone and Webster Engineering Corp. Holtzclaw No. 1 well in Randall County, the DOE-Gruy Federal D. N. Grabbe No. 1 well and the Stone and Webster Engineering Corp. Zeeck No. 1 and Harman No. 1 wells in Swisher County, the Stone and Webster Engineering Corp. Sawyer No. 1 well in Donley County, the Stone and Webster Engineering Corp. G. Friemel No. 1, J. Friemel No. 1, and Detten No. 1 wells in Deaf Smith County, and the Stone and Webster Engineering Corp. Mansfield No. 1 well in Oldham County (fig. 3).

(4) Permian outcrops along parts of the Canadian River valley and east of the Caprock Escarpment display folds, systems of extension fractures, breccia-filled chimneys, breccia beds, and caverns, all of which are interpreted to result from dissolution of salt and collapse of overlying sediments.

(5) Hydrologic testing of strata immediately above uppermost salts in the Stone and Webster Engineering Corp. Mansfield No. 2 well in Oldham County and the Sawyer No. 2 well in Donley County (Dutton and others, 1985) suggests that dissolution in these areas is active (fig. 3). In the Mansfield No. 2 well, dissolution of the Seven Rivers salt is probably underway at a depth of 247 m (811 ft). In the Sawyer No. 2 well, dissolution of the San Andres salt is probably occurring at a depth of 252 m (830 ft). Sodium chloride brines have been pumped from permeable intervals a few meters above the uppermost salt in each well.

Dissolution Along the Margins of the Southern High Plains

Salt dissolution zones that occur in Permian strata east of and beneath the Caprock Escarpment on the eastern margin of the Southern High Plains also underlie the Canadian Breaks, the northern edge of the Southern High Plains (Presley, 1979a; Gustavson and others, 1980a), and the Pecos River valley to the west. Because this area is around the margin of the Southern High Plains, it is called the peripheral salt dissolution zone. In the peripheral salt dissolution zone, younger, or stratigraphically higher, salt units have undergone more extensive dissolution than have lower units, and intervals of salt dissolution in the upper units lie nearer the center of the Palo Duro Basin. The steplike character of peripheral salt dissolution zones and their relation to major physiographic features, such as the Canadian

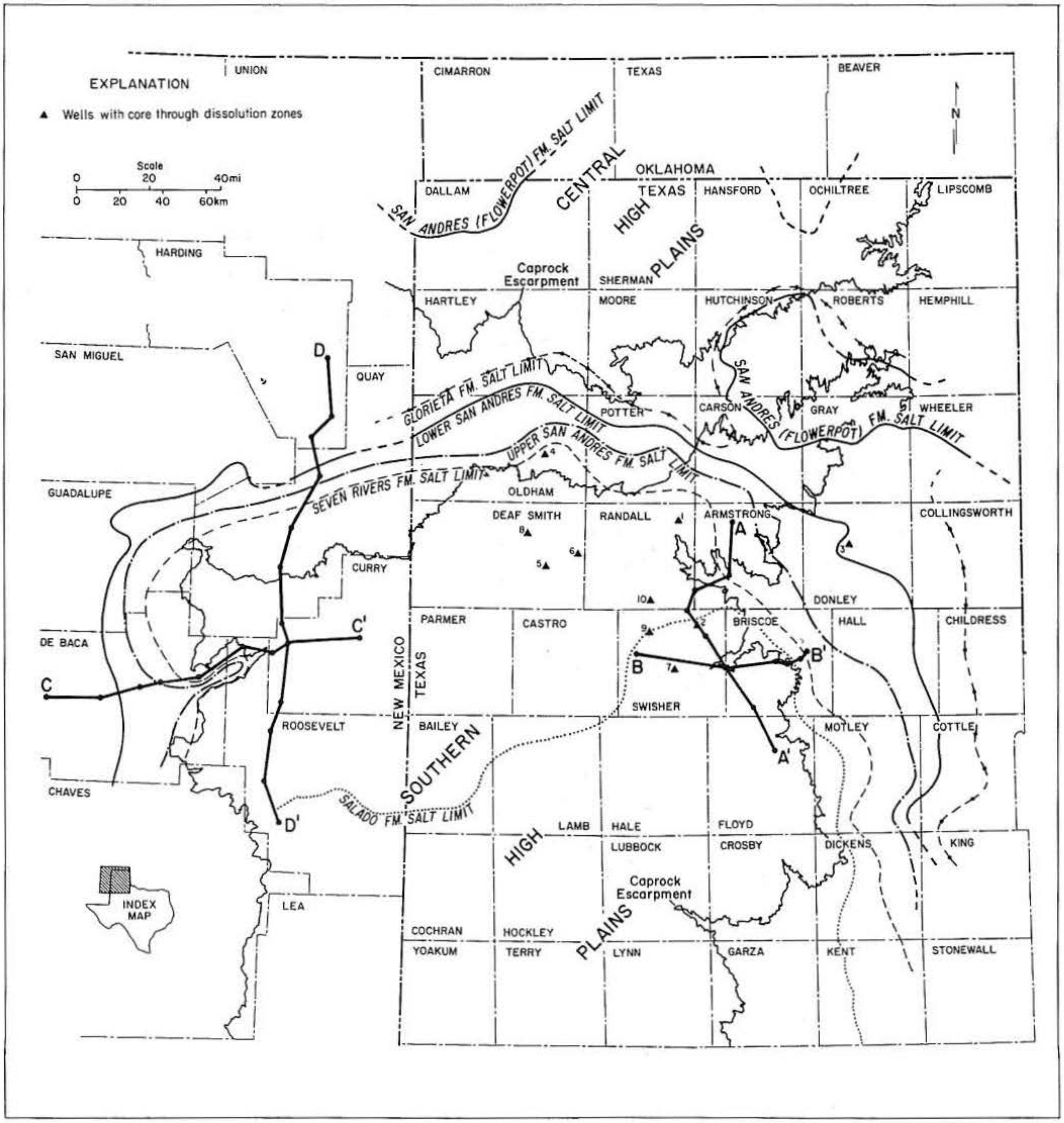

Figure 3. Zones of salt dissolution in eastern New Mexico and the Texas and Oklahoma Panhandles. Lines indicate the present extent of salt in the study region. In stratigraphic succession upward from the Glorieta to the Salado Formation, increasing amounts of salt are preserved toward the southwest corner of the Texas Panhandle. Some San Andres Formation salts are preserved in northwestern Dallam County, and some Glorieta and San Andres Formation salts are preserved near Hutchinson County. A peripheral dissolution zone is approximately located by salt-limit lines of the Seven Rivers, San Andres, and Glorieta Formations. An interior dissolution zone is approximated by the area overlain by the Southern High Plains. Wells with core through strata from which salt has been dissolved are indicated by numbered triangles: (1) DOE-Gruy Federal Rex H. White No. 1. (2) DOE-Gruy Federal Grabbe No. 1. (3) Stone and Webster Engineering Corp. Sawyer No. 1. (4) Stone and Webster Engineering Corp. Mansfield No. 1. (5) Stone and Webster Engineering Corp. Detten No. 1. (6) Stone and Webster Engineering Corp. G. Friemel No. 1. (7) Stone and Webster Engineering Corp. Zeeck No. 1. (8) Stone and Webster Engineering Corp. J. Friemel No. 1. (9) Stone and Webster Engineering Corp. Harman No. 1. (10) Stone and Webster Engineering Corp. Holtzclaw No. 1. Line A-A′ is figure 7, line B-B′ is figure 6, line C-C′ is figure 4, and line D-D′ is figure 5.

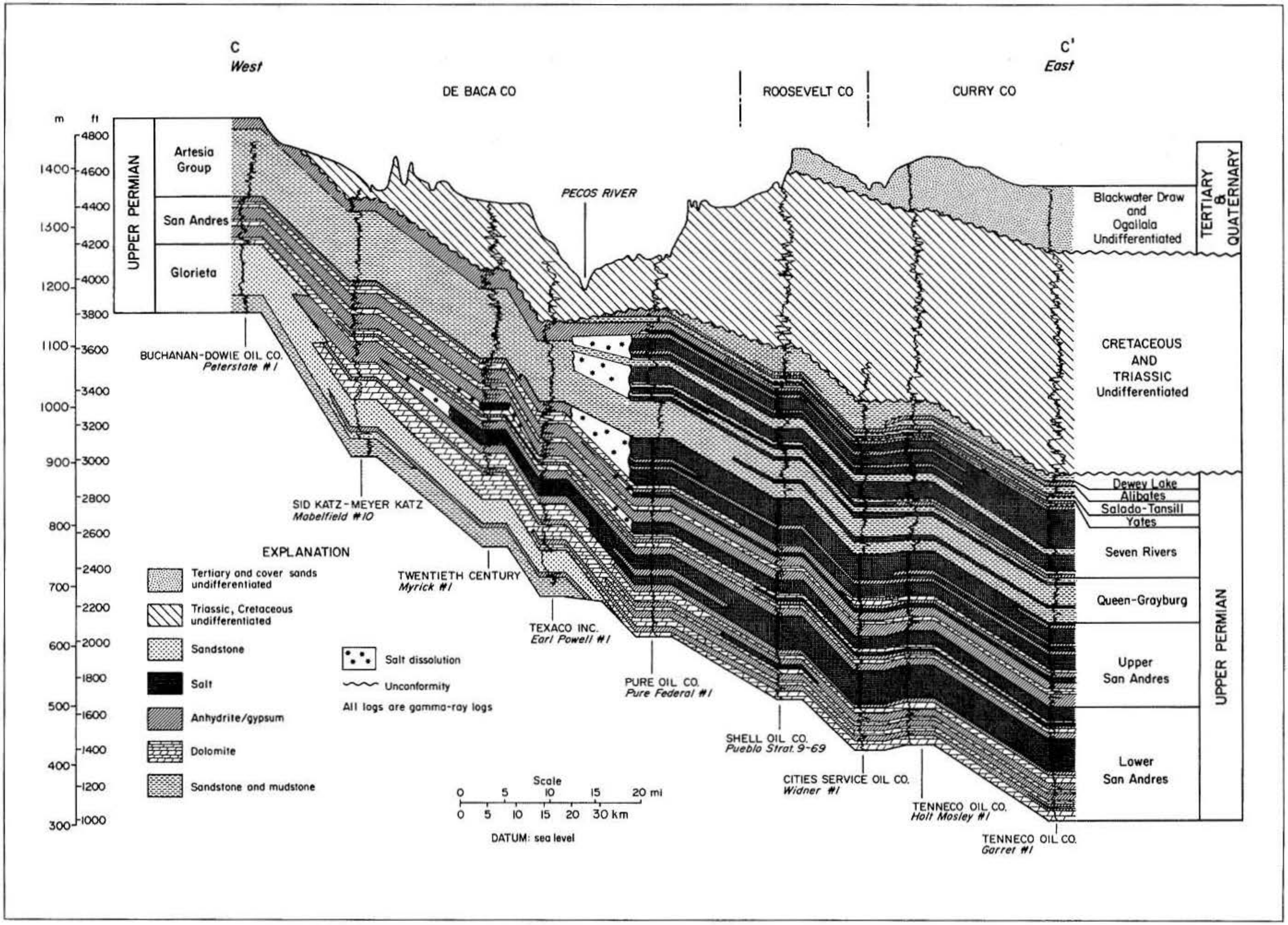

Figure 4. Stratigraphic cross section illustrating salt dissolution and collapse of strata beneath the Pecos River. See figure 3 for the location of section C-C′.

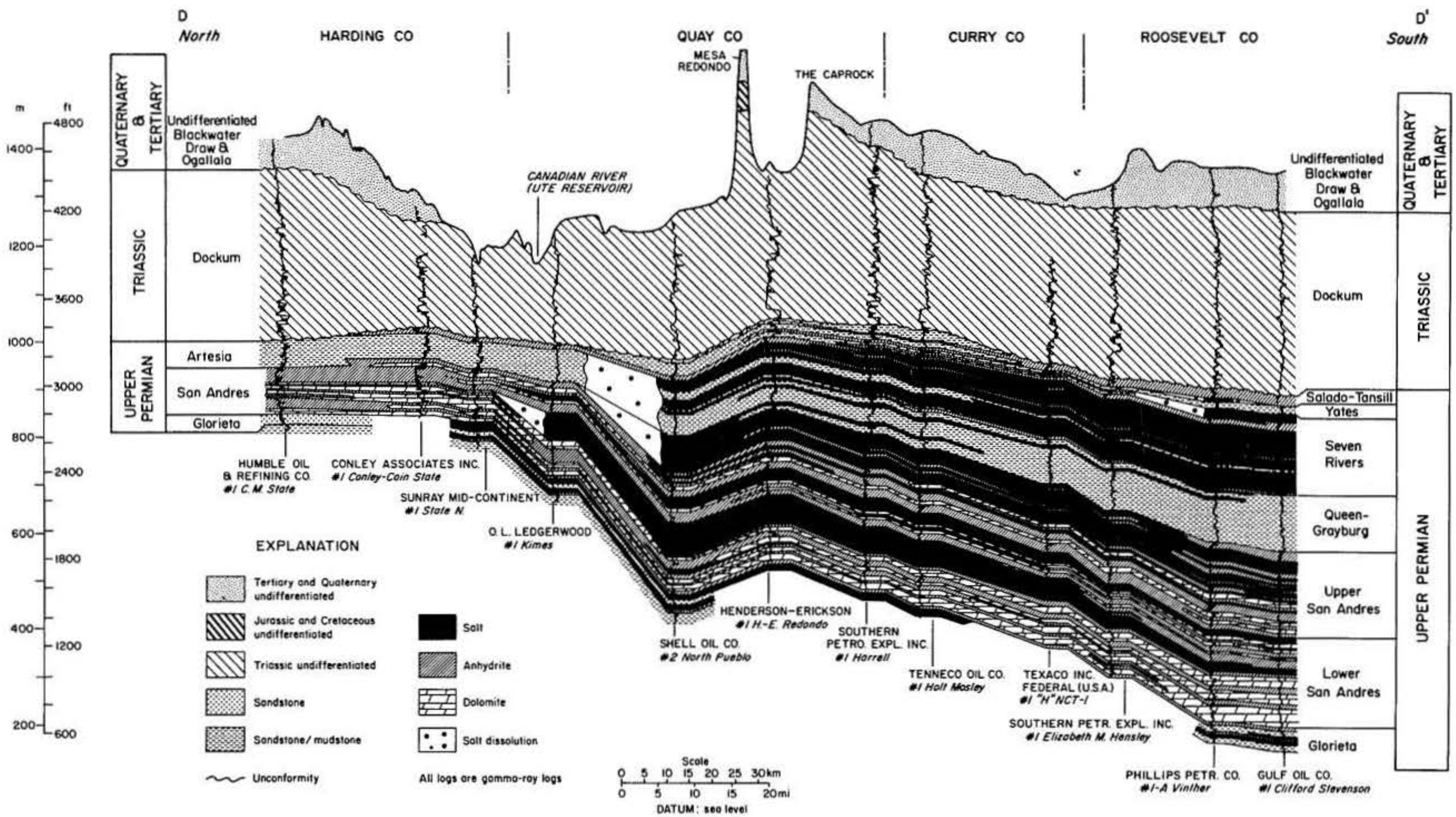

Figure 5. Stratigraphic cross section illustrating salt dissolution and collapse of strata beneath the Canadian River. See figure 3 for the location of section D-D'.

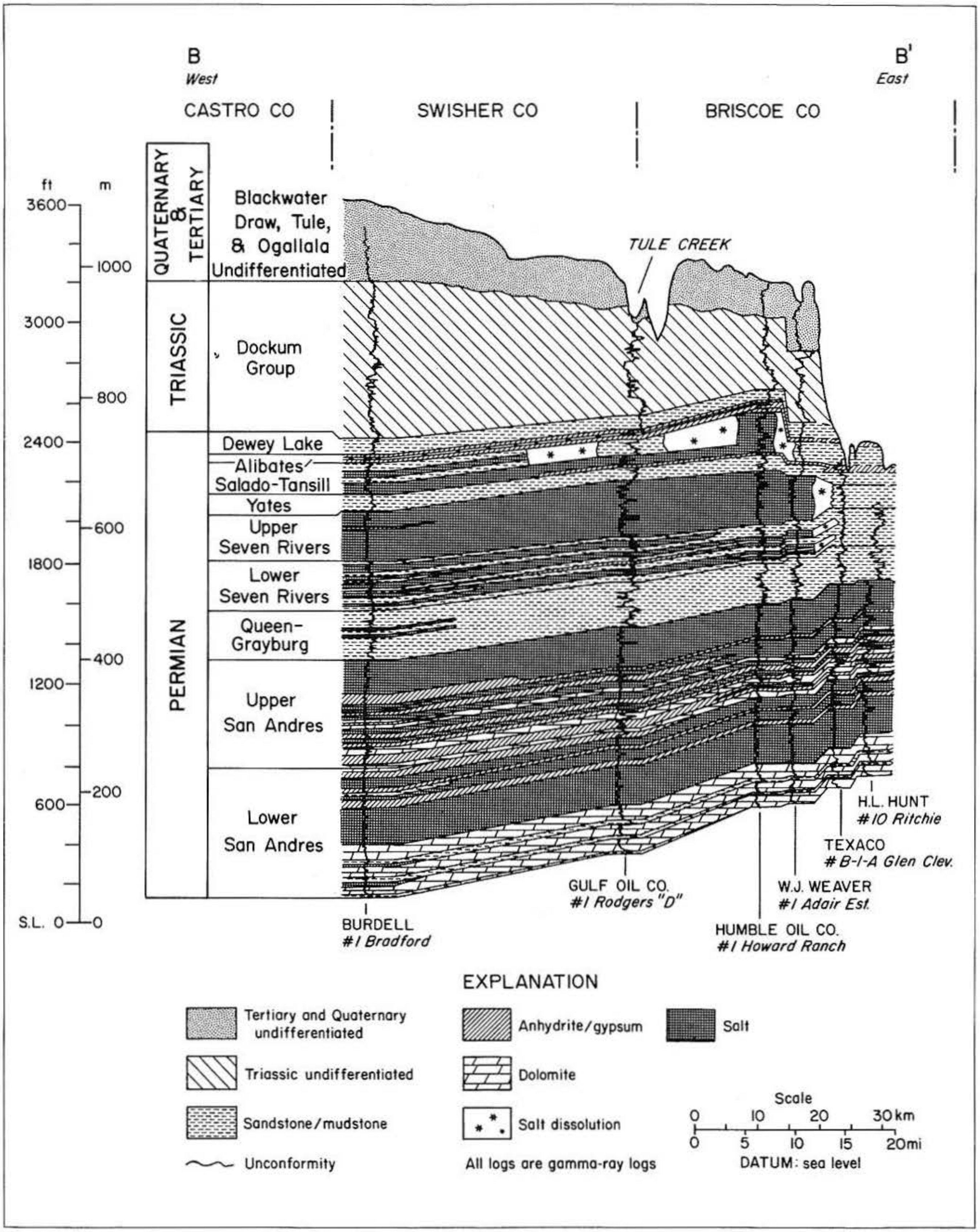

Figure 6. Stratigraphic cross section illustrating salt dissolution and collapse of overlying strata beneath Tule Creek. Tule Formation lacustrine beds, not shown on the cross section, crop out along the valley sides of Tule Creek. See figure 3 for the location of section B-B′.

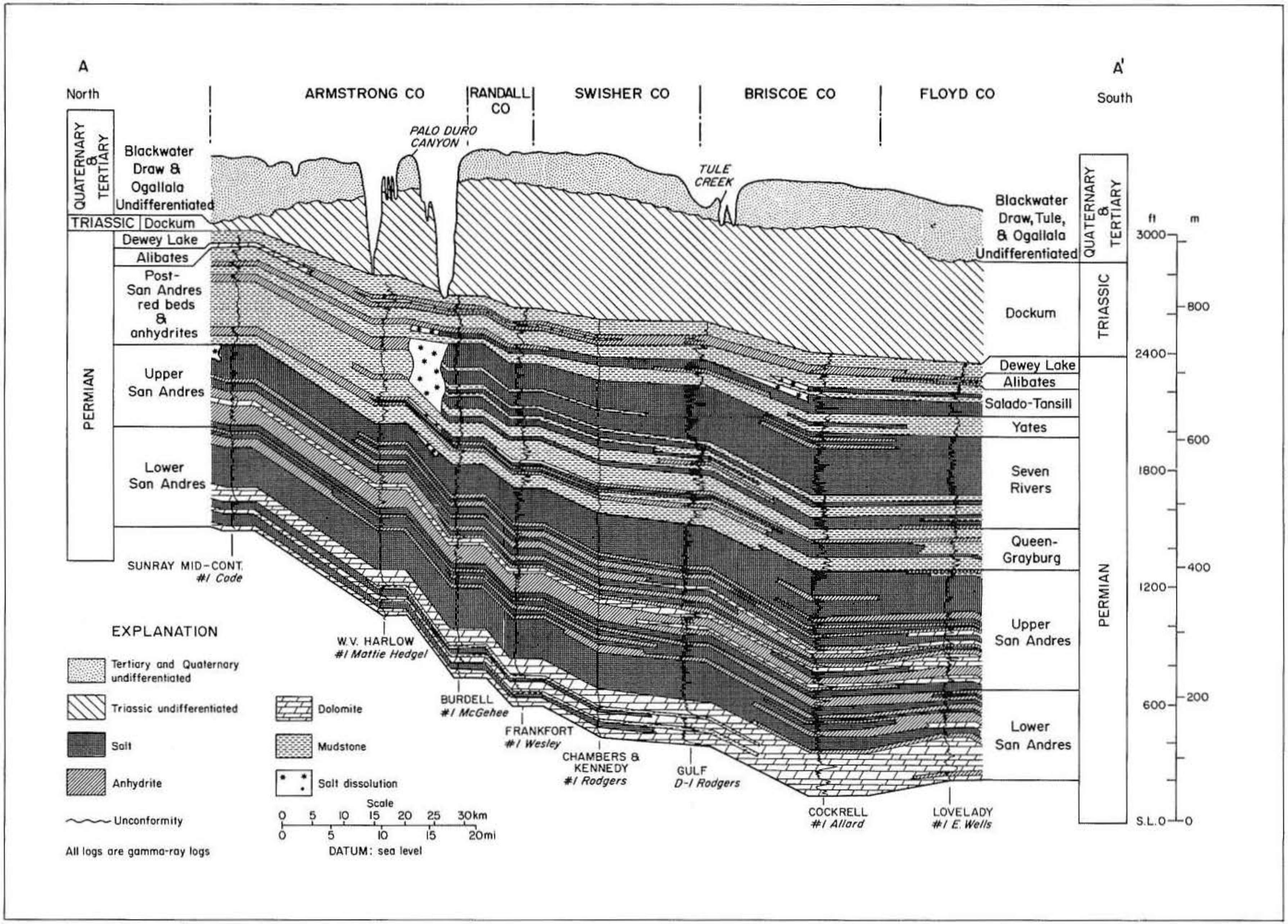

Figure 7. Stratigraphic cross section illustrating salt dissolution and collapse of overlying strata beneath the Palo Duro Canyon (Prairie Dog Town Fork of the Red River). See figure 3 for the location of section A-A'.

River valley, the Caprock Escarpment, and the Palo Duro Canyon, are illustrated by stratigraphic cross sections (figs. 4 through 7). In these cross sections, Glorieta Formation salts and younger salts are interpreted to be undergoing dissolution.

The peripheral salt dissolution zone noted in the Texas Panhandle extends into eastern New Mexico (fig. 3). Interpretation of stratigraphic cross sections based on gamma-ray logs indicates that dissolution of salt-bearing units has allowed collapse of overlying strata (figs. 4 and 5) (McGookey and others, 1985). Local dip reversals occur, such as those in Quay County, New Mexico, where more than 122 m (400 ft) of salt have been removed (fig. 5).

Gustavson and others (1980a, 1981a, 1981b, 1982a) described the relation of elements of the salt dissolution zone to the physiography of the Southern High Plains and the Rolling Plains in the Texas Panhandle (figs. 2 and 3). As in the Texas Panhandle, elements of the salt dissolution zone in eastern New Mexico parallel the western escarpment of the Southern High Plains. The Pecos River parallels the salt dissolution zone from Guadalupe County to Chaves County, New Mexico.

Dissolution Beneath the Southern High Plains

Salado Formation

Extensive post-Permian dissolution has apparently occurred beneath the Southern High Plains. Salt within the Salado Formation originally extended to southern Oldham County, 96 km (60 mi) northwest of the present subcrop limit of the formation in Swisher County (McGillis and Presley, 1981). Insoluble residues and collapse breccias in core from the Stone and Webster Engineering Corp. Mansfield No. 1 well in southern Oldham County indicate the former presence of salt in the Salado Formation (fig. 3). Figures 6 and 7 show the salt-bearing units within the Salado Formation, thinning from 50 to 65 m (150 to 200 ft) to no salt. Examination of the net-salt map of the Salado Formation (fig. 8) and of the structure-contour map of the Alibates Formation (fig. 9) suggests that as much as 80 m (250 ft) of salt have been lost to dissolution in northern Hockley County, southern Lamb County, and northwestern Lubbock County. The coincidence of structural lows over areas of thin salt is indicative of dissolution because interpretation of geophysical logs shows that strata beneath the Salado Formation are not structurally disturbed and that overlying strata have collapsed into the section from which salt was removed.

Dissolution of Salado Formation salts and subsidence beneath the Tule lacustrine basin along the Swisher/Briscoe county line can also be inferred from stratigraphic and outcrop structural data. Salt in the Salado Formation thins approximately 30 m (150 ft) beneath the topographic basin that contains the Tule Formation exposures along Tule Creek (fig. 8). The overlying Upper Permian Alibates Formation is structurally low over the area of thin salt (fig. 9). An extensive system of inclined and bedding-plane fractures occurs in outcrops of mudstone of the Triassic Dockum Group above the area of thin Salado salt and the structural low on the Alibates. These fractures are gypsum-filled and are similar to brittle-fracture systems interpreted by Goldstein (1982) and Goldstein and Collins (1984) to have resulted from subsidence after salt dissolution. The vertical stacking of thin salt, the structural low on the Alibates Formation, and the extension fractures in the Dockum Group all suggest that dissolution and subsidence have occurred near Tule basin. Evans and Meade (1945) reached a similar conclusion from their observations of structurally disturbed sections of the Dockum Group exposed in The Narrows of Tule Creek canyon east of the Tule basin.

Along the trace of the White River in Blanco Canyon in Crosby County, Salado Formation salts thin by as much as 30 m (100 ft) (fig. 8). The structure-contour map on the top of the Alibates Formation in this area shows a broad structural low with approximately 30 m (100 ft) of relief (fig. 9). The middle Tertiary erosional surface is also deeply incised in this area (fig. 10). Farther southwest, a similar relation exists along the Yellow House Draw in Lubbock, Hockley, and Lamb Counties. Here structural lows shown on the structure-contour map of the Alibates Formation overlie sharply defined areas of thin salt of the Salado Formation (figs. 8 and 9). A paleodrainage system that developed on the middle Tertiary erosional surface parallels and nearly underlies the northwest-trending zone of thin salt. In both of these areas, the relation between thin salt and structural lows in the overlying Alibates Formation suggests that dissolution and subsidence have occurred. Thus, the widespread evidence of dissolution indicates that the uppermost salts of the Salado Formation have been subject to dissolution beneath the Southern High Plains.

Seven Rivers Formation

Extensive dissolution of the Seven Rivers Formation salts has also apparently occurred beneath the Southern High Plains. Net-salt thickness of the part of the Seven Rivers Formation that is not overlain by salt within the Salado Formation is shown in figure 8.

Examination of core from the Stone and Webster Engineering Corp. Detten No. 1 and the G. Friemel No. 1 wells indicates that the remaining upper Seven Rivers salt is overlain in each well by insoluble residues, fractures with slickensides, and tension fractures filled with fibrous gypsum (var. selenite). The Stone and Webster Detten No. 1 and G. Friemel No. 1 wells occur within the northeast-trending zone of thin Seven Rivers salt in eastern Deaf Smith County (fig. 8). This zone of

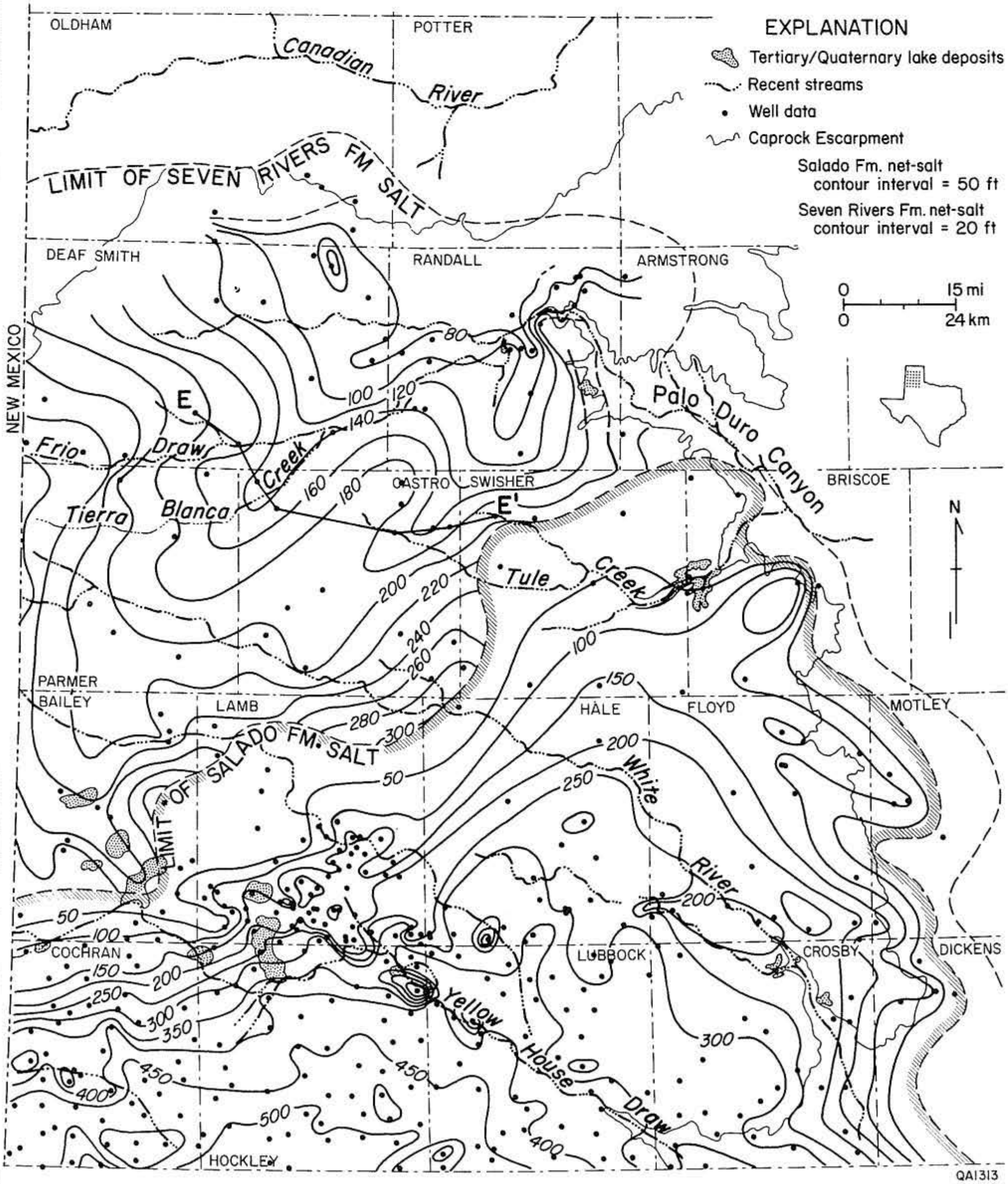

Figure 8. Net-salt map of parts of the Salado and Seven Rivers Formations. Net-salt thickness of the Seven Rivers Formation is shown only where Seven Rivers salts are not overlain by salts of the Salado Formation. Adapted in part from Gustavson and others (1981b).

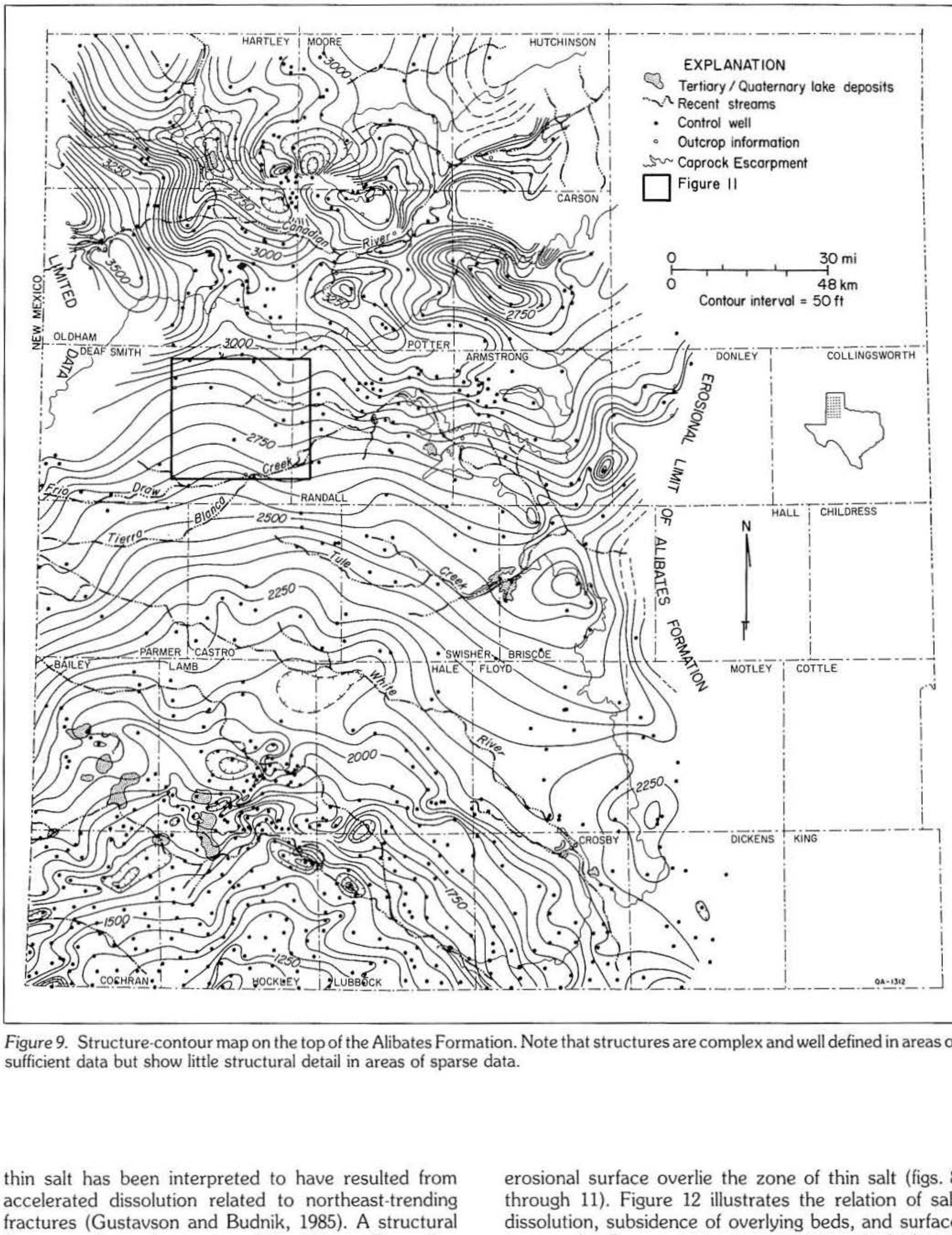

Figure 9. Structure-contour map on the top of the Alibates Formation. Note that structures are complex and well defined in areas of sufficient data but show little structural detail in areas of sparse data.

thin salt has been interpreted to have resulted from accelerated dissolution related to northeast-trending fractures (Gustavson and Budnik, 1985). A structural flexure or depression on top of the Alibates Formation and depressions on the base of the middle Tertiary erosional surface overlie the zone of thin salt (figs. 8 through 11). Figure 12 illustrates the relation of salt dissolution, subsidence of overlying beds, and surface topography. Basement structure, variations in thickness of Paleozoic units, and fractures all trend to the northeast

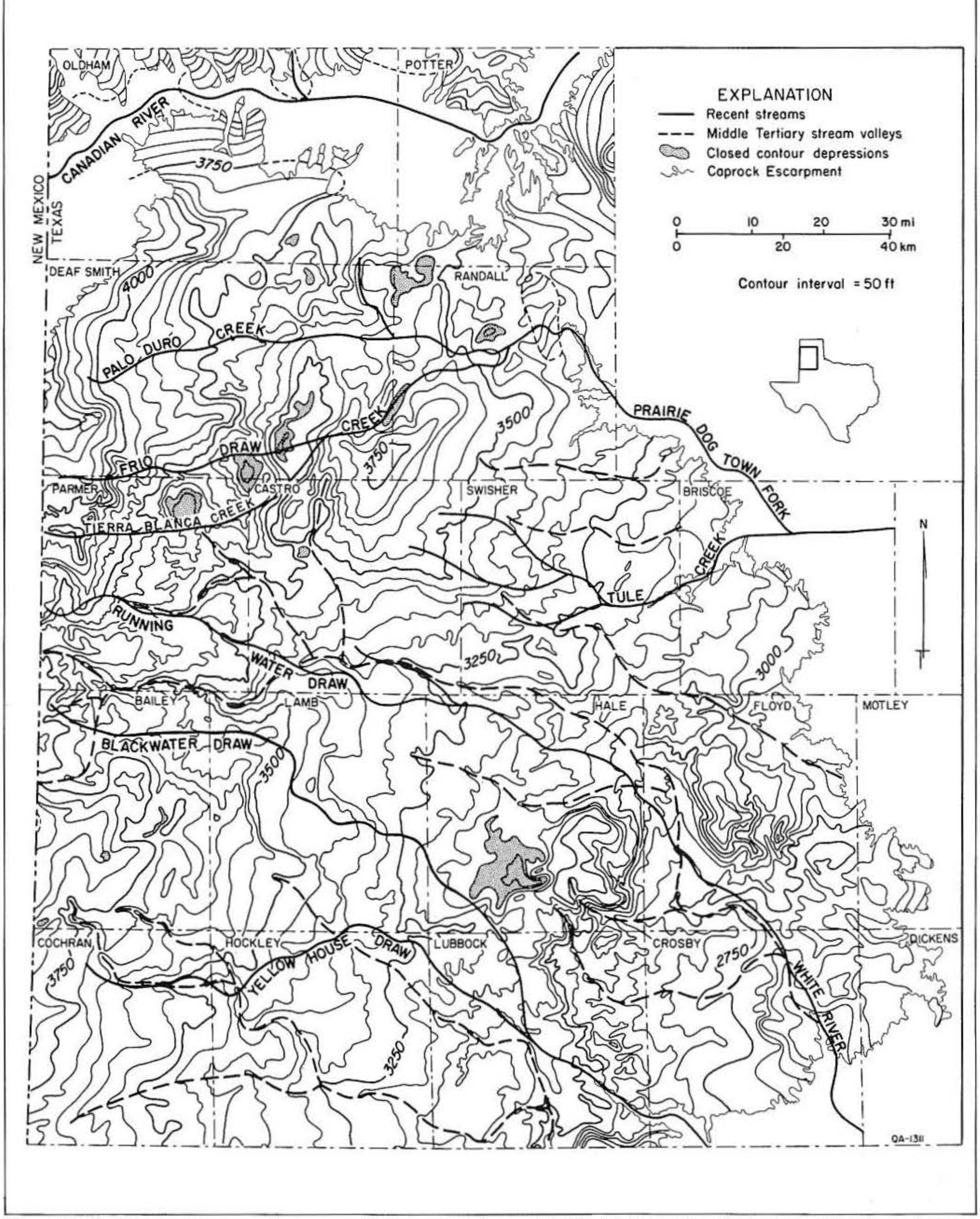

Figure 10. Structure-contour, or paleotopographic, map on the base of the Ogallala Formation (derived from Knowles and others, 1982). Paleostreams are interpreted from contour V's pointing upslope. Modern drainage is superimposed to show the relation between modern drainage and structure and between modern drainage and paleodrainage.

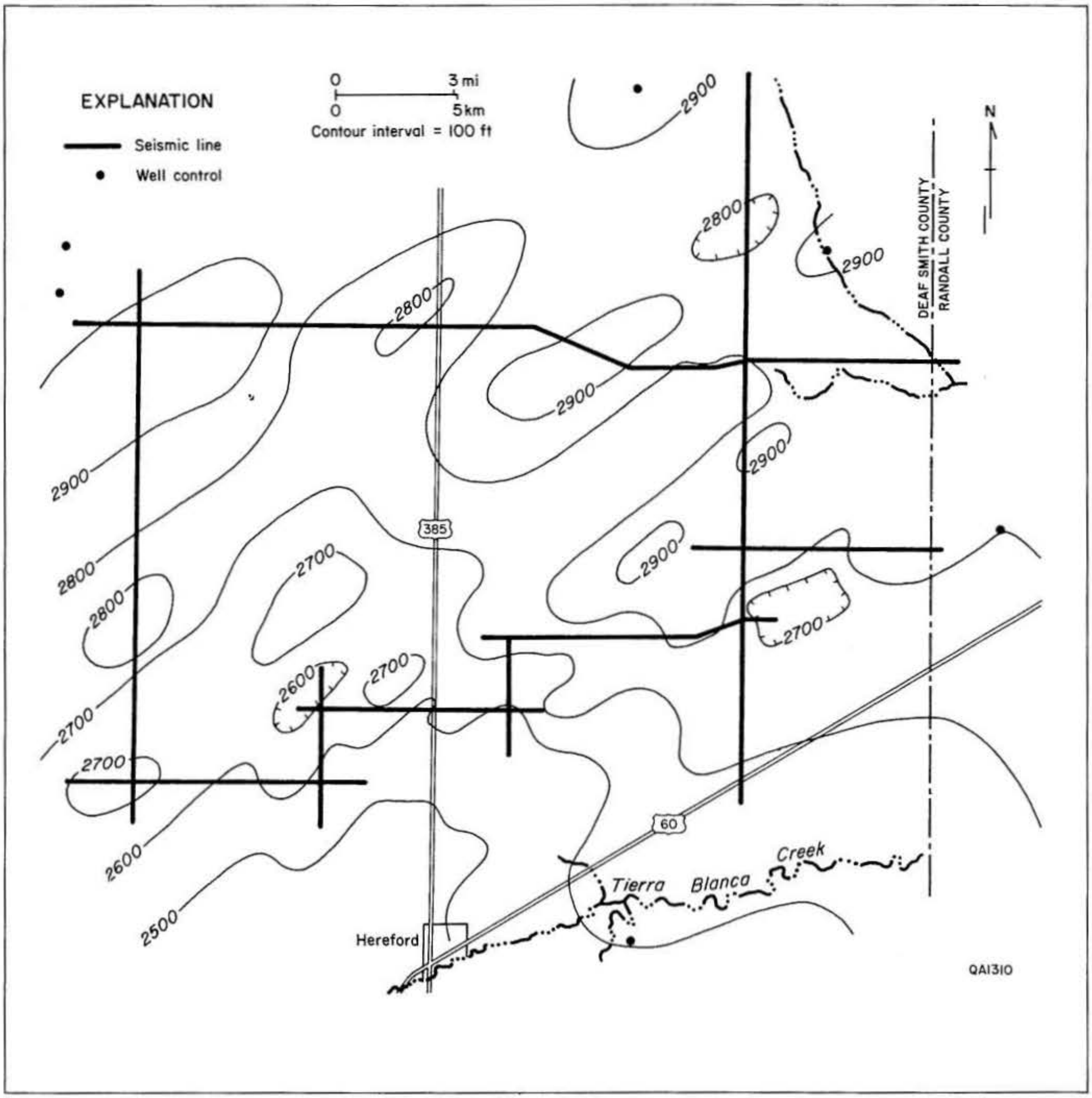

Figure 11. Structure-contour map on the top of the Alibates Formation, interpreted from seismic reflection velocity data. See figure 9 for location.

in this area. Core, stratigraphic, and structural data suggest that dissolution and subsidence have occurred preferentially along the northeast trend here.

Salts of both the Seven Rivers and Salado Formations are missing from beneath the Palo Duro Canyon along the Prairie Dog Town Fork of the Red River in eastern Randall and southwestern Armstrong Counties (fig. 8). A structural depression is indicated on the structure-contour map of the Alibates Formation (fig. 9) in the area underlying the Palo Duro Canyon. Exposures of Upper Permian strata in the Palo Duro Canyon contain numerous gypsum-filled fractures (satin spar), minor folds, and normal faults (Collins, 1984). The vertical juxtaposition of thin or missing salt in the Seven Rivers and Salado Formations, a structural trough in the Alibates Formation, and outcropping signs of fracturing caused by extension and folding suggest that dissolution and subsidence have been active beneath the Palo Duro

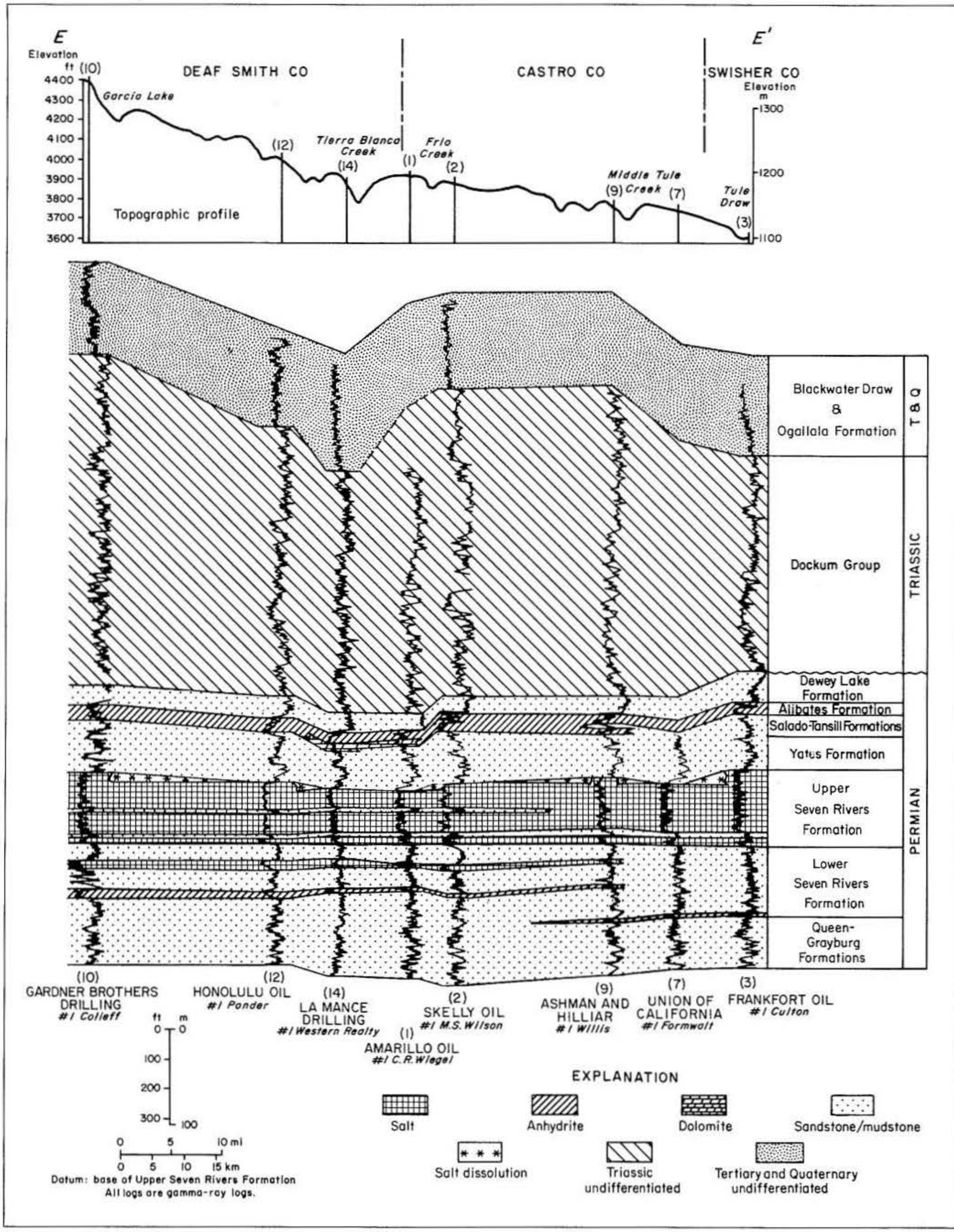

Figure 12. Stratigraphic section showing dissolution of Seven Rivers Formation salts and collapse of overlying strata beneath Tierra Blanca Creek (datum is base of the Seven Rivers Formation). See figure 8 for the location of section E-E'.

Canyon. This evidence supports the interpretation that Seven Rivers salts have undergone dissolution beneath the Southern High Plains wherever these salts are not overlain by Salado Formation salts.

Although cores from DOE stratigraphic test wells (fig. 3) through the upper parts of the Salado or the Seven Rivers Formations beneath the Southern High Plains contain evidence of the former presence of salt, no large-scale collapse breccias were recognized. This suggests a relatively slow dissolution and subsidence process.

Age of Dissolution

Dissolution beneath the Rolling Plains, Canadian Breaks, and Pecos Plains is active and causes the high chloride loads in streams draining the area surrounding the Southern High Plains as well as the collapse features that have formed (Gustavson and others, 1980a; Gustavson and Finley, 1982a, 1982b). The exact age of dissolution beneath the Southern High Plains is not known. There is no evidence to suggest whether dissolution beneath the Southern High Plains is currently active or inactive. The timing of past local dissolution events, however, can be dated in relative terms.

Beneath the Southern High Plains, structural depressions appearing on the Alibates structure map tend to occur over areas of thin salt, as shown on the net-salt map of the Salado and Seven Rivers Formations (figs. 8 through 10). The combinations of structural lows and salt thins are in eastern Deaf Smith and western Randall Counties, in central and southeastern Randall County (Palo Duro Canyon), midway along the border of Swisher and Briscoe Counties (Tule lacustrine basin), in northeastern Crosby County (Blanco Canyon), and along a line from central Bailey County to northeastern Hockley County. These areas occur beneath paleotopographic lows on the middle Tertiary erosional surface that marks the base of the Ogallala Formation. Each of these areas of thin salt and structural depression on the Alibates Formation is also overlain by Pliocene-Pleistocene lacustrine basins. Elements of late Pliocene Blancan faunas appear in lacustrine basins that contain outcrops of the Blanco Formation in Deaf Smith County, in southeastern Randall County (Cita Canyon beds), and in northeastern Crosby County (Blanco beds) (Schultz, 1977). Because these basins contain late Pliocene sediments, basin formation must have been initiated earlier. Owing to the presence of caliche boulders in the floor of the Blanco lacustrine basin, Evans and Meade (1945) suggested that the Blanco basin formed after the development of the Caprock caliche of the Ogallala Formation. In turn, this suggests that the other lacustrine basins containing Blancan faunas in the Texas Panhandle formed after the development of the Caprock caliche.

Schultz (1977) reviewed radiometric age dates obtained from volcanic ash associated with the Blancan Local Fauna at Mount Blanco. Using data from Boellstorff (1976) and Izett and others (1972), Schultz indicated that the Blanco Formation is probably more than 2.8 ± 0.3 m.y. old. Thus, the basins that contain Blancan-age sediments and the processes of dissolution and subsidence that led to their development began at least before 2.8 mya and are most likely late Pliocene in age.

Lake basins at Canyon, Texas, in Randall County and midway along the Swisher/Briscoe county line (Tule Formation) have also formed over areas of thin salt, structural lows on the Alibates Formation, and paleotopographic lows on the middle Tertiary erosional surface (figs. 8, 10, and 11). Both of these basins contain Pleistocene lacustrine sediments (Evans and Meade, 1945; Frye and Leonard, 1957; Hawley and others, 1976; Schultz, in press). The relation among thin-salt areas, structural lows on the Alibates Formation, and overlying lacustrine basins suggests that these basins, and the processes of dissolution and subsidence that led to their development, probably began to form in the Pliocene and early Pleistocene.

Formation of large lake basins in the Texas Panhandle, excluding the thousands of small playa-lake basins, has been attributed to several processes, including subsidence, deflation, and blockage of previously existing valleys. Baker (1915) suggested that the larger, partly filled basins formed as a result of subsidence over areas of dissolution of Permian evaporites. Evans and Meade (1945) recognized the presence of sizable lee dunes on the downwind side of many lake and playa-lake basins on the Southern High Plains and thought that deflation was far more effective in forming these basins than were dissolution and subsidence. Reeves (1966) and Reeves and Parry (1969) suggested that large pluvial lakes formed along drainage channels crossing Cretaceous highs. Later Reeves (1970) suggested that these large lakes resulted from accelerated erosion at intersections of lineaments related to the Earth's regmatic shear pattern.

Field and subsurface evidence, summarized as follows, suggest that both dissolution-induced subsidence and deflation greatly influenced the development of some of the larger lake basins that occur in the Texas Panhandle. As a result of locally accelerated dissolution, overlying strata subsided, forming small depressions that later became lake basins. Depressions accumulated water and sediment, which killed vegetation in the center of the depression. During dry times, sediment in the central part of the depressions, not being bound by vegetation, was subject to wind deflation. Although dissolution and subsidence were important in determining the location of large lake basins, deflation accounted for the removal of large volumes of sediment from the basins; sheetwash, rillwash, and gullying supplied sediment from the sides of the basin to the basin floor.

Salt dissolution and collapse probably have been active north of the Canadian River valley in the Oklahoma and Texas Panhandles since the Late Cretaceous (Gustavson and others, 1980a). Schultz (1977) attributed sinkholes containing Miocene Ogallala sediments in Donley County, Texas, to collapse as a result of evaporite dissolution. Bachman (1974, 1980, 1984) suggested that dissolution has occurred intermittently since the Triassic in the Delaware Basin of Texas and in southeastern New Mexico. Pre-Ogallala dissolution and the presence of a north-south-trending pre-Ogallala paleovalley near the modern Pecos River in New Mexico have been suggested (Bretz and Horberg, 1949; Kelley, 1972; Reeves, 1972). This evidence, coupled with current evidence of salt dissolution, makes it reasonable to infer that salt dissolution has been active, at variable rates, in the Permian salt basin since the Triassic and possibly since deposition of the salts.

MIDDLE TERTIARY EROSIONAL SURFACE

Permian, Triassic, Jurassic, and Cretaceous strata underlie the middle Tertiary erosional surface beneath the Southern and Central High Plains. Figure 10, a structure-contour map of the base of the High Plains aquifer, closely approximates this surface because in most areas the base of the High Plains aquifer is the base of the Ogallala Formation. Locally, small parts of the Triassic Dockum Group are included in the High Plains aquifer.

The presence of a system of major valleys as part of the middle Tertiary erosional surface is indicated by aligned groups of V-shaped contour lines, which point upslope (fig. 10). Paleostream segments appear to have flowed southeastward over most of the paleosurface. In northern Hale and Lamb Counties, a major paleodrainage segment flowed west to east. Reeves (1972) suggested that this valley is middle Pleistocene in age and was incised through Ogallala sediments. Clear evidence of the paleodrainage pattern is not recognizable north of central Parmer County and southern Castro and Swisher Counties.

The middle Tertiary erosional surface is markedly different northwest of a line that extends from central Parmer County northeast to central Randall County and southern Armstrong County (fig. 10). North of this line, the middle Tertiary erosional surface is characterized by numerous large closed basins that are thought to have resulted primarily from late Tertiary to Quaternary salt dissolution and collapse (Gustavson and others, 1980a; Gustavson and Budnik, 1985). Several of these basins exceed 75 m (250 ft) in depth. Because of the extensive collapse, no significant trace of the middle Tertiary paleodrainage system exists.

Seni (1980) noted that Ogallala sediments as thick as 160 m (500 ft) completely cover all older strata but for a few small Cretaceous outliers in the Southern High Plains (Floyd County). In most of the map area, data on depositional trends derived from sand-percent values and paleocurrent measurements suggest south or southeasterly drainage (fig. 13). Local sand trends are more southerly in eastern Oldham and central Hutchinson Counties. Nonetheless, thick net-sand areas appear to be oriented to the southeast and to be substantially parallel to paleodrainage on the pre-Ogallala erosional surface where paleodrainage is preserved. Both pre-Ogallala and Ogallala drainage flowed generally in the same directions.

Southern High Plains (Middle Tertiary) Paleotopography

The topography of the High Plains as it existed at the end of Ogallala time in western Oklahoma, the Texas Panhandle, and eastern New Mexico can be reconstructed with reasonable certainty. This reconstruction, which is necessary for understanding the development of post-Ogallala drainage, requires a series of assumptions. It is assumed that the Southern High Plains surface, which reflects the pre-Ogallala depositional surface, has not been significantly tilted since deposition although the region has been uplifted during the past 10 million years (Gable and Hatton, 1983). Long axes of pebbles in Ogallala gravels near the eastern Caprock Escarpment commonly range from 2 to 10 cm (0.75 to 4 inches). Slopes of stream channels on both the Southern High Plains surface and the pre-Ogallala surface range from approximately 2 to 4 m/km (7 to 13 ft/mi). Gole and Chitale (1966), Boothroyd and Ashley (1975), Nummedal and Boothroyd (1976), and Gustavson (1978) observed that slopes of 1 to 4 m/km (3 to 13 ft/mi) are required to transport 2- to 10-cm- (0.75- to 4-inch-) long pebbles. Therefore, slope values of Holocene and paleostream channels are sufficient to transport gravel in the 2- to 10-cm (0.75- to 4-inch) size range, indicating that if tilting of the Ogallala surface has occurred since its deposition,

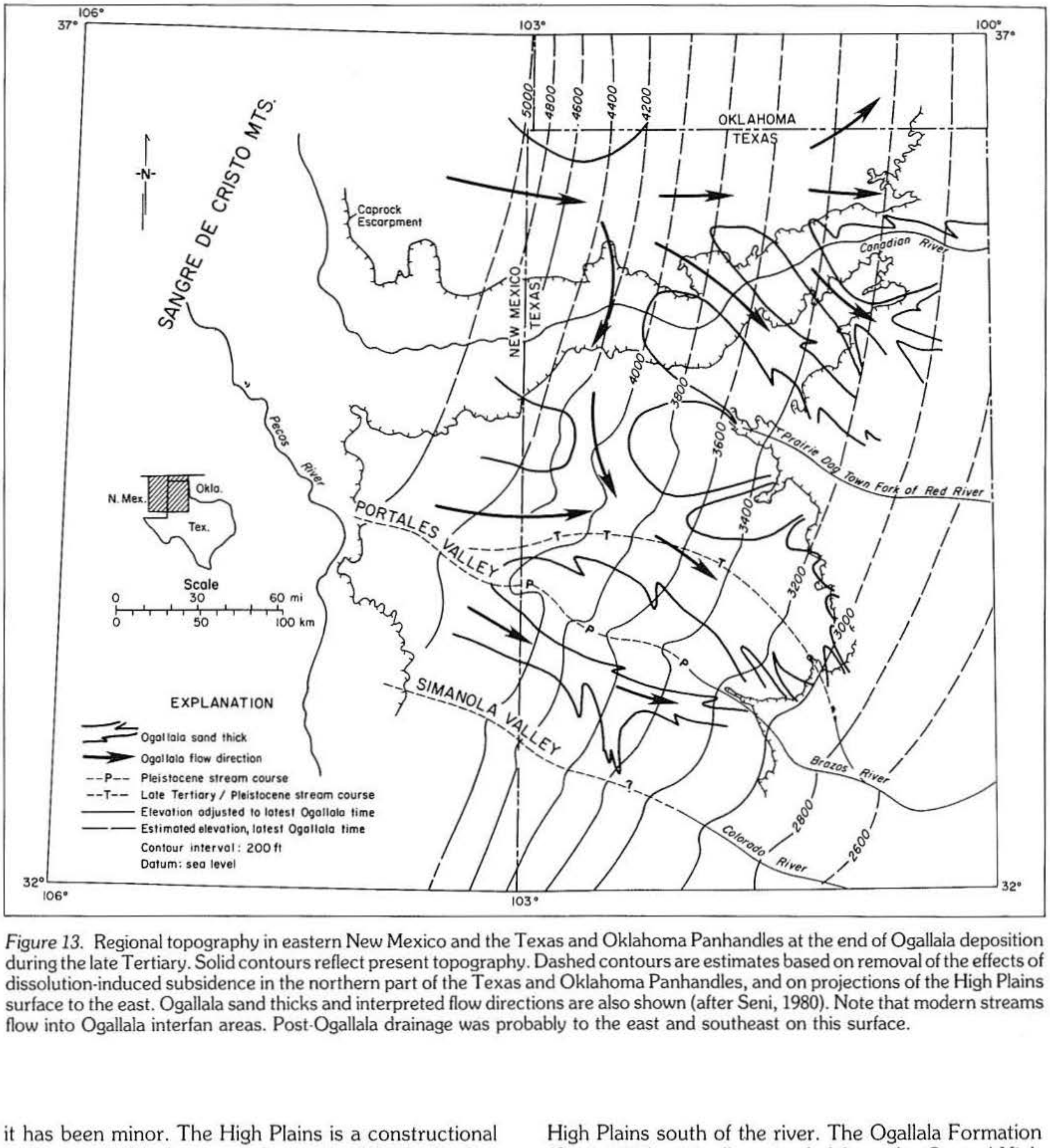

Figure 13. Regional topography in eastern New Mexico and the Texas and Oklahoma Panhandles at the end of Ogallala deposition during the late Tertiary. Solid contours reflect present topography. Dashed contours are estimates based on removal of the effects of dissolution-induced subsidence in the northern part of the Texas and Oklahoma Panhandles, and on projections of the High Plains surface to the east. Ogallala sand thicks and interpreted flow directions are also shown (after Seni, 1980). Note that modern streams flow into Ogallala interfan areas. Post-Ogallala drainage was probably to the east and southeast on this surface.

it has been minor. The High Plains is a constructional surface underlain by as much as 25 m (75 ft) of eolian sands and silts of the Blackwater Draw Formation, and post-Ogallala erosion has not significantly altered the regional topography. Thus, projection of contours from stream divides across valleys will provide a reasonable approximation of regional paleotopography as it existed immediately after the Ogallala Formation was deposited.

Regional topography (fig. 2) indicates that the present High Plains surface north of the Canadian River is as much as 80 m (250 ft) lower than that of the Southern High Plains south of the river. The Ogallala Formation (Seni, 1980) originally extended from the Central High Plains north of the Canadian River valley south to the northern edge of the Southern High Plains. Field observations confirm southeasterly paleoflow directions in Ogallala sediments exposed along the south flank of the Canadian River valley. These data indicate that the surface of the Dalhart-Amarillo fan lobe of the Ogallala Formation originally sloped to the south and southeast across the trend of the present Canadian River valley. Gustavson and others (1980a) suggested that the topographically lower elevation of the High Plains surface north of the Canadian River valley is the result of post-Ogallala subsidence caused by regional salt dissolution.

From these assumptions and by deleting the effects of dissolution-induced subsidence north of the Canadian River, we developed a generalized map of post-Ogallala topography. The topographic reconstruction (fig. 13) shows that the Ogallala surface sloped directly east in the northern part of the Texas Panhandle and in the Oklahoma Panhandle. Further south, slope direction became progressively more southeasterly. This topographic configuration is consistent with Seni's (1980) conclusions about sediment transport across the ancient Ogallala fan surface (fig. 13).

COMPARISON OF HOLOCENE SOUTHERN HIGH PLAINS DRAINAGE TO TERTIARY DRAINAGE

The Southern High Plains are drained by a series of narrow elongate draws, or valleys, that slope mostly to the southeast. A substantial part of the surface of the Southern High Plains has not developed an integrated drainage system, so adjacent draws do not share common drainage divides. Major through-flowing draws may be separated by as much as 50 km (30 mi) of plains without integrated drainage.

The pre-Ogallala drainage system is similar to the present drainage system (fig. 10) although they are separated by approximately 100 m (330 ft) of sediment and by 10 to 12 million years. Major segments of both drainage systems are roughly parallel, and modern streams tend to occur near the paleostreams in some areas. Because both the pre-Ogallala erosional surface and the present surface are in part parallel, both the modern and the pre-Ogallala drainage systems cross these surfaces at similar angles. In the west-central part of the Southern High Plains, both modern drainage and paleodrainage are aligned easterly and east-southeasterly. Both drainages are aligned more south-easterly in the east-central part. In the southern part of the Southern High Plains, both sets of drainages are aligned southeasterly.

Parallelism, or stacking of drainage elements, is common in the geologic record; Fisher and McGowen (1967) recognized this phenomenon in their study of the Wilcox Formation of the Texas Gulf Coast, and Brown (1975) noted similar relations in fluvial-deltaic systems in the Permian Basin of North-Central Texas. What is significant is that associated pairs of present streams and paleostreams flowed across their respective regional slopes and, thus, are not consequent streams in the strict sense. The parallelism and the tendency toward superposition of these streams suggest that the controls or influences on the development of pre-Ogallala drainage also controlled or influenced the development of the Holocene drainage on the Southern High Plains.

STRUCTURAL CONTROLS ON REGIONAL DRAINAGE DEVELOPMENT

Four distinctly different drainage systems impinge upon the Southern High Plains: the Pecos River on the west, the Canadian River on the north, the tributaries of the Red and Brazos Rivers that drain the Rolling Plains and Caprock Escarpment to the east, and tributaries of the Red and Brazos Rivers that drain a small part of the surface of the Southern High Plains (fig. 14). Two of these systems, the Pecos and Canadian Rivers, flow across regional basement structural trends and at high angles to the regional southeasterly topographic slope. Tributaries of the Red and Brazos Rivers, conversely, contain many parallel segments and are aligned parallel to regional and local structural elements.

Pecos and Canadian Rivers

The headwaters of the Pecos River are in north-central New Mexico in the Sangre de Cristo Mountains. The Canadian River also begins in the Sangre de Cristo Mountains and partly in the Cimarron Mountains of north-central New Mexico. Both streams initially flow southeast. In central-eastern New Mexico, both streams turn abruptly from the southeasterly flow direction that prevailed at the end of Ogallala deposition (fig. 13). The Pecos River turns southward approximately 70° to parallel the western Caprock Escarpment, or the

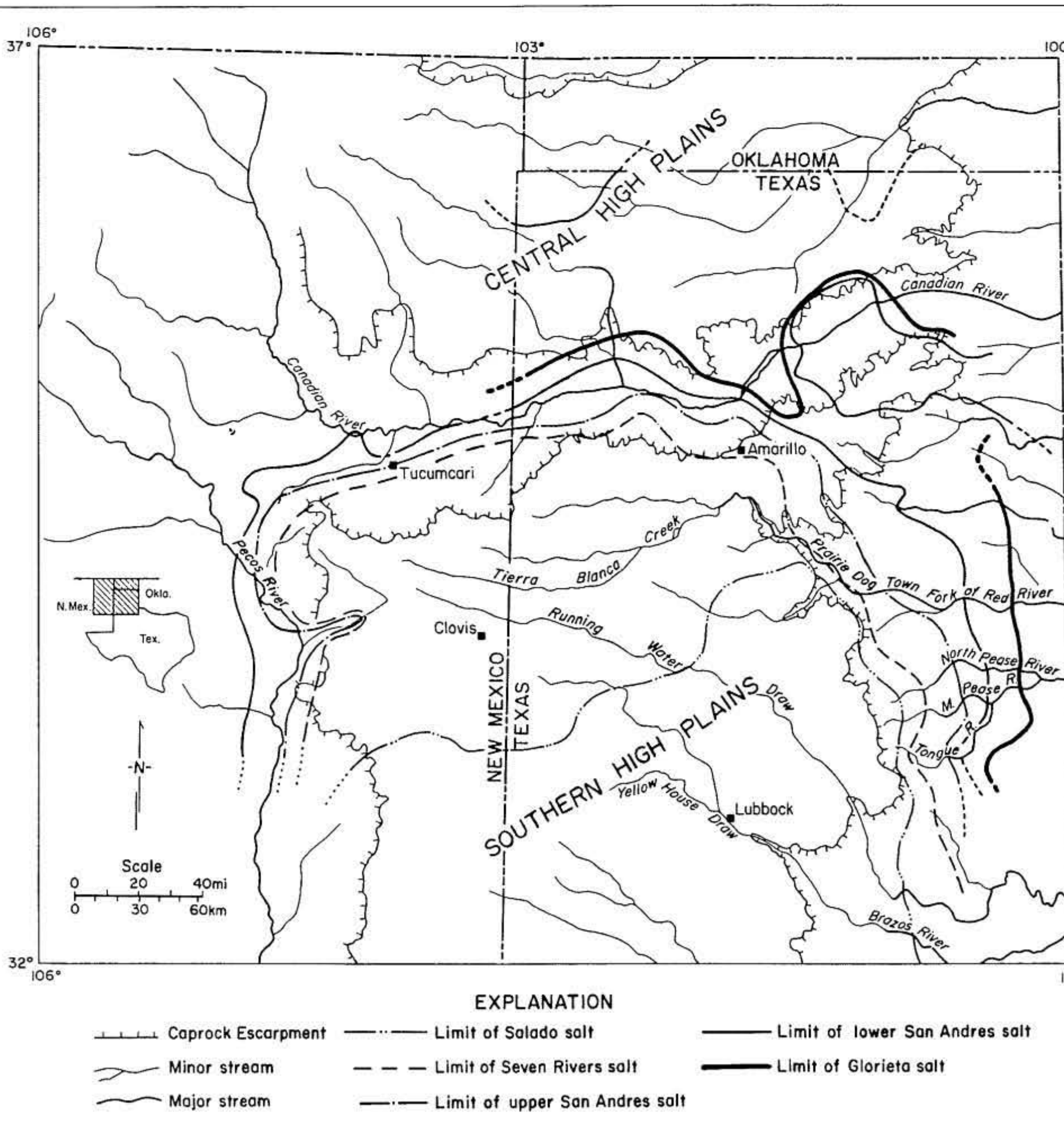

Figure 14. Regional drainage of eastern New Mexico and of the Texas and Oklahoma Panhandles. Notice that the Pecos River turns south to flow along the western margin of the salt dissolution zone; the Canadian River turns east along the eastern margin of the dissolution zone. Both the Pecos and Canadian Rivers flow at very high angles to the regional southeasterly slope and to streams such as Running Water and Yellow House Draws that are essentially flowing parallel to regional slope.

Mescalero Escarpment, of the Southern High Plains (fig. 2). The Canadian River turns 90° eastward to flow east-northeastward and to separate the Southern and Central High Plains (fig. 2).

Field observation of valleys of the Canadian River in the Texas Panhandle and of the Pecos River in eastern New Mexico indicates that the present Canadian and Pecos Rivers are small streams flowing in large valleys. In Texas, the Canadian River valley is approximately 48 km (30 mi) wide, and the floor of the valley lies from 185 to 305 m (600 to 1,000 ft) below the Southern High Plains surface. In eastern New Mexico, the Pecos River lies from 305 to 370 m (1,000 to 1,200 ft) below the western margin of the Southern High Plains. The valley floor is 24 to 32 km (15 to 20 mi) west of the rim of the Southern High Plains. The western side of the Pecos River valley cannot be easily defined. These two valleys are all the more impressive when one realizes that both were formed after the end of deposition of the Ogallala Formation, approximately 3.5 million years ago.

Any discussion of the origin of the Canadian and Pecos River valleys must account not only for the development of the valleys across regional slopes and structures but also for the processes by which or conditions under which these valleys formed. In relatively arid climates and in areas having small drainage basins, these large valleys were formed during a geologically short time.

During the late Pliocene to early Pleistocene, the upper part of the Pecos River system drained southeast across the Southern High Plains through the Portales Valley and was part of the system that evolved into the Brazos River (fig. 13). In the eastern part of the Southern High Plains, two paleovalleys have been recognized as possible eastward extensions of the Portales Valley: a southern valley now containing Yellow House Draw and a more northerly valley along the trend of Running Water Draw/White River. The literature describing the geomorphic evolution of the Pecos River system was reviewed by Kelley (1972, 1980), Reeves (1972), Thomas (1972), and Hawley and others (1976).

A subtle topographic notch in the western Caprock Escarpment at the northern limit of the Mescalero Ridge suggests the presence of an additional paleovalley, the Simanola Valley (fig. 13). Definition of the valley on the Ogallala surface is obscured by an infilling of windblown cover sand. A wide band of sand dunes parallels the valley on its north side. Farther north, the Portales Valley is also paralleled on its north side by a wide band of sand dunes.

Using recent topography and Seni's (1980) interpretation of the placement of Ogallala distributaries and fan lobes, we developed an approximation of the topography at the end of Ogallala time in eastern New Mexico and in the Texas Panhandle (fig. 13). Clearly, the major drainage systems at the end of Ogallala time flowed to the southeast and east.

Parts of the upper reaches of the Pecos and Canadian Rivers, the major drainage elements in the region, now flow nearly normal to both recent flow and paleoflow directions on the Southern High Plains surface (compare figs. 13 and 14). To interpret the evolution of drainage in this region, the mechanism that caused these diversions as well as the timing of the diversions must be clearly understood.

Diversions of Regional Paleodrainage

The eastward shift of the Canadian River and the southward diversion of the Pecos River to their present drainages most likely resulted from surface subsidence following dissolution of Permian salts, a hypothesis supported by varied but compelling evidence. Kelley (1972) described the formation of the Pecos River valley; parts of this explanation are elaborated on or modified in the following discussion of the origin of both the Pecos and the Canadian River valleys.

Pecos River Valley

The Pecos River valley is thought to have resulted from a series of subsidence basins that developed along the western margin of the Palo Duro Basin in post-Ogallala time over the north-south-trending (Gustavson and Finley, 1982a, 1982b) dissolution zone. Bachman (1980, 1984) reached similar conclusions for parts of the Pecos Valley south of this study area. The valley parallels the dissolution limits of Permian salts in eastern New Mexico (fig. 14) and lies above anhydrite/gypsum beds that appear to have subsided approximately 120 m (400 ft) (fig. 4) (McGookey and others, 1985). The form of the subsidence basins was probably similar to the large, internally drained basins that exist on the eastern flank of the Pecos River valley near Urton Lake in De Baca County and Samples Lake in Chaves County, New Mexico (fig. 2). Nash Draw (Vine, 1973) and San Simon Swale (Bachman and Johnson, 1973) are two additional examples of large topographic basins that have been previously attributed to dissolution and subsidence east of the Pecos River but south of this study area. All these basins are shallow and elongate and are roughly parallel to the trend of the western dissolution zone.

Dissolution and subsidence influence or control a series of surface processes (Kelley, 1972). Initially, surface subsidence would have resulted in a locally diminished gradient and the deposition of bed load. Collapse would have increased fracture permeability. As ponding expanded along stream courses, drainage probably would have continued to the southeast, for a short time at least. Once subsidence ponding was established, two processes would have resulted in drainage diversion to the south. Because of either further collapse or flooding, waters could have overtopped divides between basins. Overtopping within a series of basins aligned north-south on a surface that slopes to the southeast would have resulted in diversion to the south. Eventually, divides were eliminated between subsidence basins either by overtopping and incision of a channel, by further subsidence, or by a combination of these two processes. The process described here is a diversion of what were probably many southeasterly flowing streams (including streams that occupied the Portales and Simanola Valleys) caused by regional subsidence resulting from salt dissolution (figs. 13 through 15). This model differs from those suggested by Morgan (1941), Kelley (1972), Reeves (1972, 1976), and Thomas (1972) in that it eliminates the progressive headward capture by piracy of a succession of southeasterly flowing streams, perhaps ending with the paleo-Brazos-Portales river

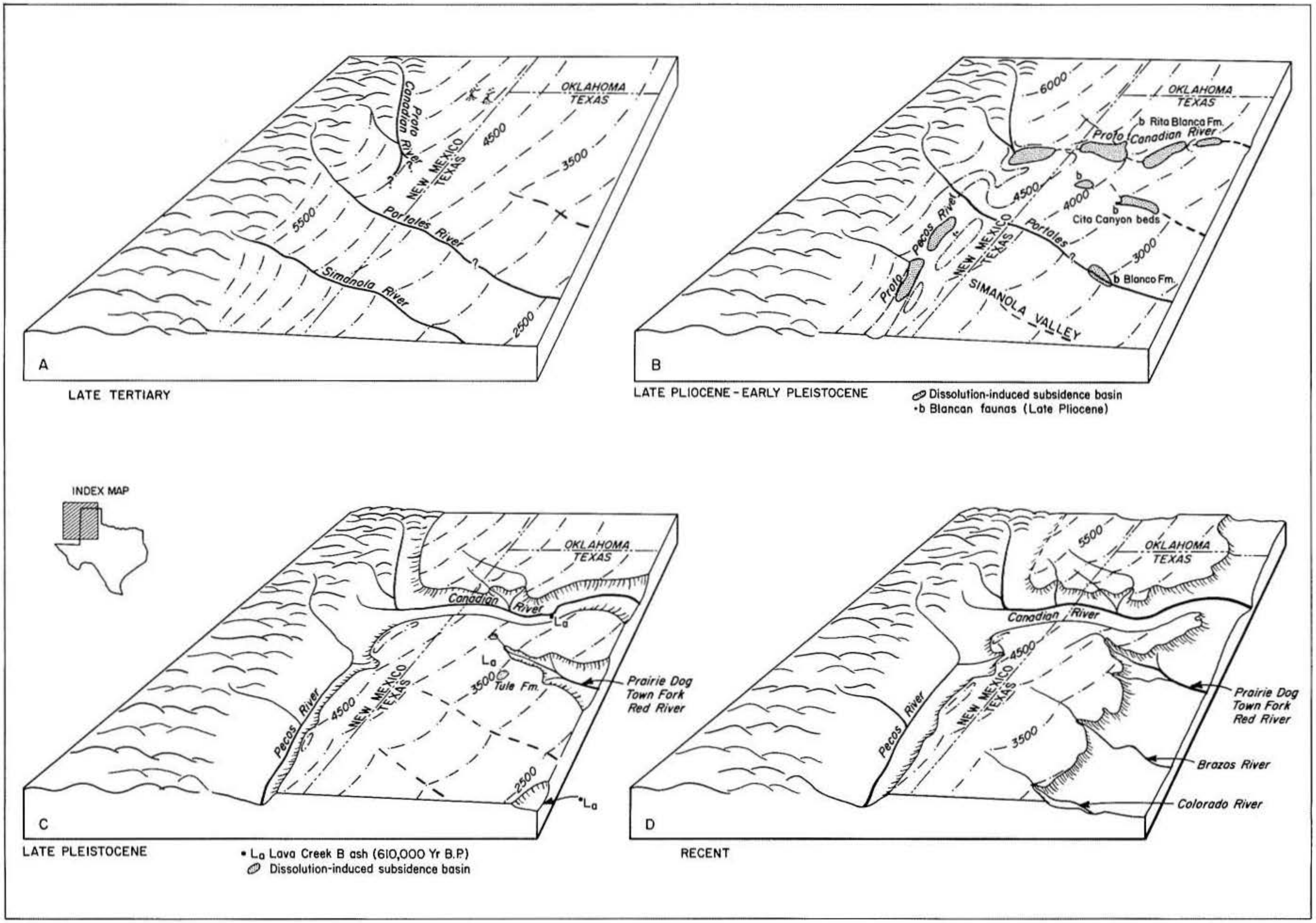

Figure 15. Evolution of drainage of eastern New Mexico and the Texas and Oklahoma Panhandles since the end of Ogallala deposition. Sizes of dissolution-induced subsidence basins are speculative because only remnants of these features were preserved. Rather than a few large basins, there may have been numerous small basins.

system. The advantage of our model is that it is consistent with the processes of dissolution and collapse that are currently active and were undoubtedly active during early development of the Pecos River.

Canadian River Valley

The path of the Canadian River from southeastern San Miguel County, New Mexico, is at a wide angle to the regional slope of the Southern High Plains. The valley is also normal to several southeasterly trending paleodistributaries within the Ogallala Formation (compare figs. 13 and 14). Flowing east-northeasterly across the Texas Panhandle, the Canadian River is the only major stream within the Texas Panhandle since pre-Ogallala time that has not flowed eastward or southeastward. The Canadian River valley, where it impinges on the salt dissolution zone in eastern New Mexico, turns abruptly eastward and then northeastward to nearly parallel the northern limit of salt in the Seven Rivers, San Andres, and Glorieta Formations (fig. 14). Approximately 105 m (350 ft) of subsidence has occurred beneath the Canadian River (fig. 5) (McGookey and others, 1985).

When Ogallala deposition ceased during the Pliocene near the present Canadian River valley, a broad low-relief alluvial plain stretched from eastern New Mexico across the Texas and Oklahoma Panhandles (fig. 15A). Dissolution and subsidence, which were probably active during Ogallala deposition, continued along the trend of the current peripheral dissolution zone. As subsidence occurred, a series of broad basins formed above the dissolution zone. The Pliocene Rita Blanca lakebeds (Anderson and Kirkland, 1969; Lindsey and others, 1975), which occur along Rita Blanca Creek north of the Canadian River, may be a remnant of these basins (fig. 15B). Subsidence basins along the trend of the Canadian River valley would have diverted or ponded southeasterly flowing streams. Assuming that the depressions formed parallel to the northeast trend of the northern margin of dissolution, water trapped in the depressions could have drained only to the northeast. As for the Pecos River, once the subsidence ponding had occurred, two processes would have resulted in diversion of the Canadian River to the northeast. Because of either flooding or additional subsidence, waters would have overtopped divides between adjacent basins. Overtopping between basins that were aligned east-northeast on a surface that sloped to the east-southeast would have resulted in flow to the east-northeast. Eventually divides between basins were eliminated either by overtopping and incision or by further subsidence (fig. 15C). The process described here is diversion of preexisting streams rather than headward erosion and piracy.

Regional subsidence over the peripheral salt dissolution zone accounts both for the position of the Canadian River valley and for the disparity of elevation of the High Plains surfaces on either side of the Canadian River valley. The northwest side is approximately 75 m (250 ft) lower than the southeast side (fig. 2).

Diversion of drainage of the Ogallala fan surface to the Pecos and Canadian Rivers probably began in the early Pliocene and was not complete until the Pleistocene, but it resulted in a fundamental change in the style of deposition on the Ogallala fan surface. Older Ogallala sediments are primarily fluvial, having secondary amounts of eolian sediment (Evans and Meade, 1945; Winkler, 1984). Increasing amounts of eolian material are present in younger Ogallala sediments. In numerous areas, the Ogallala is capped by as much as 10 to 15 m (30 to 45 ft) of eolian sediment. The diversion of southeasterly flowing streams to the Pecos and Canadian drainages prevented through-flowing streams from crossing the Ogallala fan surface. As the Canadian and Pecos Rivers incised their valleys into easily erodible Ogallala and older sediments, broad expanses of alluvium were exposed in valley walls and floors.

McCauley and others (1981) showed that the area between the Pecos River and the Texas and New Mexico border is an important contemporary source for eolian sediment carried eastward by dust storms. The combination of periodic drought, dry soils, high winds, sparse vegetation, and erodible soils makes this area ideal for eolian erosion. Conditions similar to this have probably existed periodically in this region since the middle Tertiary. It seems likely, therefore, that the eolian sands and silts that compose the upper part of the Ogallala Formation were eroded from the Pecos River valley and the western reaches of the Canadian River valley by wind and deposited on the Ogallala fan surface. Although interrupted during the Pliocene when the Caprock caliche was formed, eolian deposition continued throughout most of the Quaternary to form the Blackwater Draw Formation (Machenberg and others, 1985).

Prairie Dog Town Fork of the Red River

The Prairie Dog Town Fork of the Red River, which extends from northern Briscoe County to southeastern Randall County, or a distance of approximately 65 km (40 mi), parallels the northeastern limit of salts of the Salado and Seven Rivers Formations (fig. 14). Where the river has incised the Southern High Plains, its valley is called the Palo Duro Canyon. Cross section A-A′ shows that, between the Burdell well on the southern edge of the canyon and the Harlow well within the canyon, approximately 60 m (200 ft) of salt have been lost to dissolution (fig. 7). Many of the folds, faults, and veins exposed within the canyon are similar to the features described by Goldstein and Collins (1984) as examples of brittle deformation of strata overlying salt dissolution zones and resulting from subsidence related to salt removal. Veins are mostly filled with fibrous gypsum (satin spar).

The depth of the canyon as well as its location is thought to be at least partly due to subsidence along the northeastern margin of salt beds within the Seven Rivers and Salado Formations. In addition, the rocks undergoing subsidence were extensively fractured, which probably increased their susceptibility to weathering and erosion. Thus both subsidence and the physical breakup of strata in this area probably contributed to the development of the canyon.

Development of subsidence basins in this area as a result of dissolution during the late Pliocene may also be suggested by Blancan-age lacustrine sediments (Lindsey and others, 1975; Schultz, 1977) that are preserved in Cita Canyon, a short tributary on the southwest side of Palo Duro Canyon in Randall County (fig. 8). This lacustrine basin may be a remnant of a system of subsidence basins that formed before incision of the Palo Duro Canyon.

Rolling Plains Drainage

Numerous small streams drain the eastern Caprock Escarpment of the Southern High Plains. Several larger streams, including the larger tributaries of the Red, Brazos, and Canadian Rivers, drain small parts of the Southern High Plains. The many small streams that arise below the Caprock Escarpment compose a substantial part of the headwaters of these three major rivers. In contrast to the Canadian and Pecos River systems, which formed their valleys primarily by incision, the streams east of the Caprock Escarpment are enlarging their drainage basins by headward erosion. Gustavson and others (1981b) have suggested scarp retreat rates of about 11 to 18 cm/year (4.3 to 7 inches/year). As a stream system evolves, the valley reflects the adjustment of the stream not only to the prevailing hydrodynamic conditions but also to the climate and to the structure of the rocks over which the stream flows. The following is a discussion of the possible structural controls on stream development on the Rolling Plains of the Texas Panhandle.

Several authors have attributed the development of linear segments of the Rolling Plains drainage to adjustment to prevailing sets of fractures. These authors differ widely in their speculations on the origins of fracture patterns or inferred fracture patterns. Reeves (1971a) observed that linear segments of the valleys of the Salt Fork and the Double Mountain Fork of the Brazos River had preferred orientations of north-south, northeast-southwest, and northwest-southeast. He did not observe any regional fractures but inferred that the streams had responded to the "Earth's regmatic fracture pattern." The U.S. Army Corps of Engineers (1975), using side-looking airborne radar (SLAR) imagery, recognized that linear valley segments occur along the Middle and North Pease Rivers and the Prairie Dog Town Fork of the Red River. They provided no data on the preferred orientations of the stream segments or of fractures within the area, but they attributed the linearity of stream segments to the influence of a system of fractures. The U.S. Army Corps of Engineers suggested that fracturing is a near-surface phenomenon and that it results from the dissolution of salt, gypsum, and possibly dolomite and the collapse of overlying strata. Finley and Gustavson (1979, 1981) analyzed lineaments, shown by linear streams, topographic elements, and tonal anomalies, recognized from Landsat imagery of the Southern High Plains and the Rolling Plains of the Texas Panhandle. Finley and Gustavson noted a similarity in the orientations of lineaments and major joint trends. They also noted that the major joint trends were similar to subsurface structural trends and suggested that linear physiographic features were probably structurally controlled. Gustavson and others (1982b) observed the development of elements of karst topography caused by salt dissolution and associated collapse. These subsidence basins, or dolines, developed with preferred orientations of their long axes. The long axes tend to parallel the preferred orientations of linear stream elements, and both tend to parallel preferred orientations of joint systems in the region. Gustavson and others (1982b) did not speculate on the origin of the joints.

This review of the literature indicates implied agreement that the streams draining the Rolling Plains of the Texas Panhandle contain linear segments and that these streams are at least in part structurally controlled. Although investigators also agree that aligned stream segments appear to be related to fracture systems, they disagree on the origin of the fracture systems.

Subsidence Basins, Sinkholes, and Fractures

A large study area encompassing all of Hall County, Texas, was selected to be examined for the relation between the processes of dissolution and subsidence or collapse and the karst topography that is developing in the Rolling Plains (Gustavson and others, 1982b). In addition to numerous sinkholes, more than 200 internally drained, closed depressions (dolines) were recognized (fig. 16). These are broad, shallow, typically oblong depressions that are as long as 3.5 km (2 mi) and as deep as 10 to 15 m (30 to 45 ft). Many of these elongate depressions show preferential northwesterly, northerly, and northeasterly alignments (fig. 17). Two new collapse depressions, as well as at least 36 new sinkholes, formed in the study area between 1940 and 1972.

The physiography of Hall County is characteristic of much of the rest of the Rolling Plains in the Texas Panhandle. Two major physiographic units are distinguished: (1) dissected areas of low to moderate relief underlain primarily by Permian strata and (2) areas underlain by low-relief, relatively undissected Quaternary fluvial and eolian deposits. Landforms

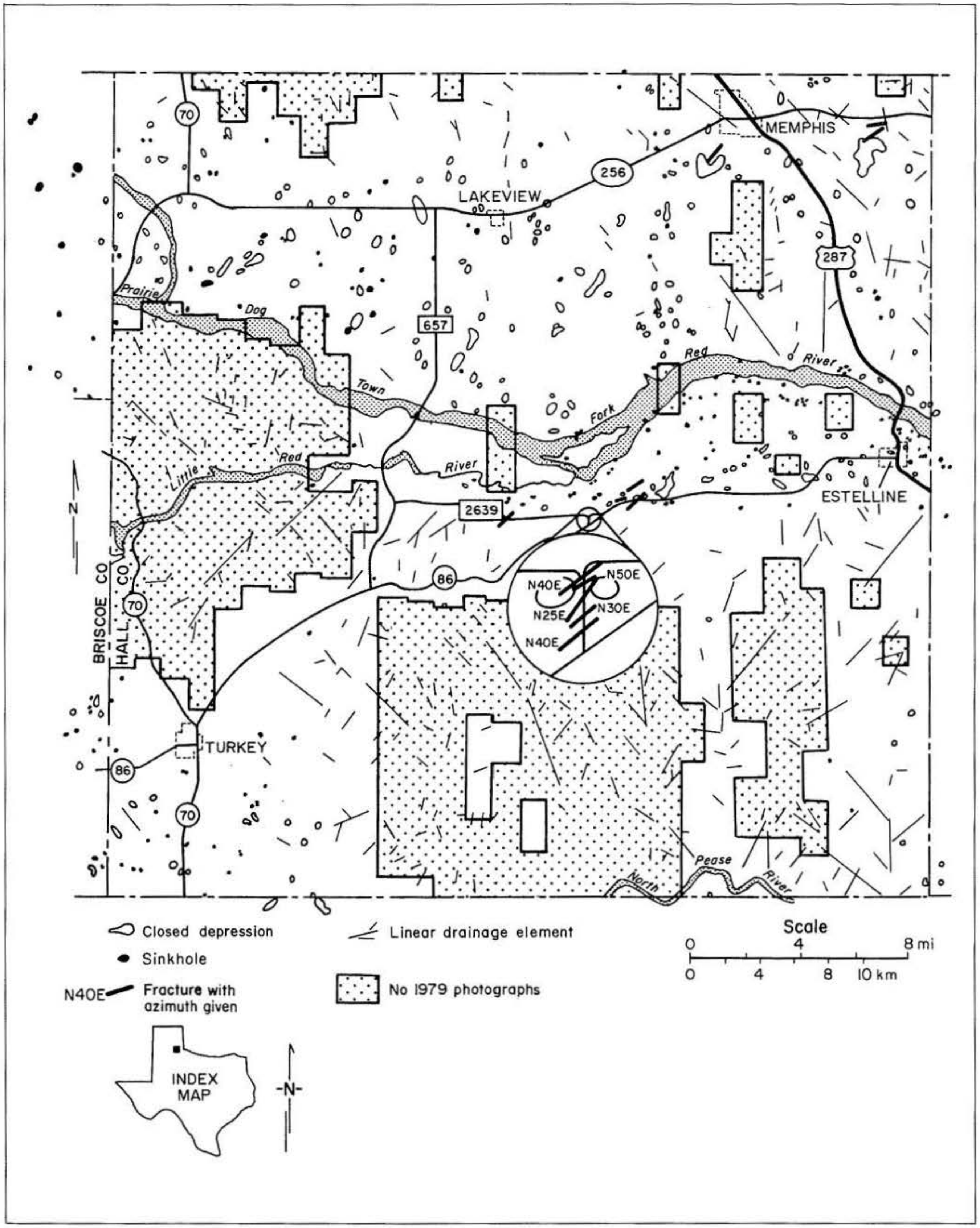

Figure 16. Location of sinkholes, closed depressions (dolines), and fractures in Hall and eastern Briscoe Counties, Texas. Dolines are drawn to scale; sinkholes, which are much smaller, are not drawn to scale. Dolines and sinkholes were recognized from color aerial photographs taken in 1979.

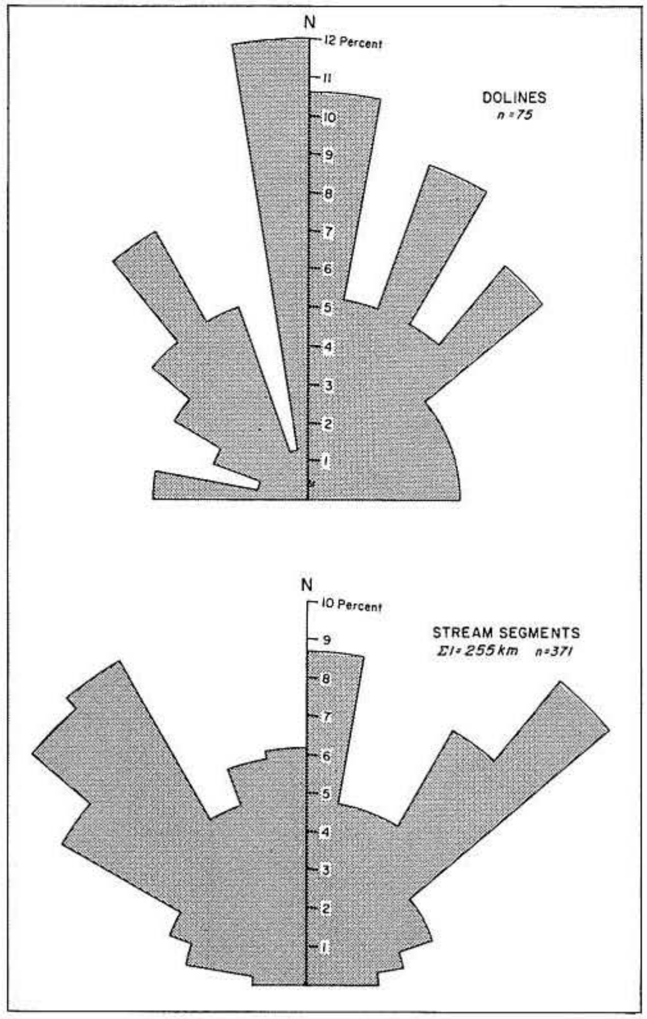

Figure 17. Diagrams indicating orientations of long axes of dolines and linear stream segments in Hall County, Texas. For each 10° sector, linear data are plotted as a percentage of the total number of closed depressions and as a percentage of total length of linear stream segments.

resulting from dissolution and collapse are recognized primarily in the undissected areas underlain by Quaternary deposits. Linear stream segments are observed primarily in the dissected areas.

The shapes of the depressions depicted in figure 16 clearly illustrate preferred orientations of northwest-southeast, north-south, and northeast-southwest (fig. 17). These orientations correspond closely to the orientations of fractures within Triassic and Permian Systems exposed to the west along the western margin of the Rolling Plains and along the Caprock Escarpment (Finley and Gustavson, 1981; Collins and Luneau, 1985). In areas of exposed Permian bedrock in Caprock Canyons State Park, a few kilometers west of the area covered by the Hall County study, Collins (1983) described the relation between joints and synclinal depressions. He concluded that dissolution and collapse developed preferentially along joint paths and caused the synclines. It is thought that the depressions (dolines) observed on Quaternary surfaces are underlain by synclines similar to those observed by Collins. Furthermore, analysis of Schlumberger Fracture Identification Logs from DOE wells (fig. 18) and outcrop measurements of fractures indicate that the preferred orientations for fractures in this area are northwest-southeast, north-south, and northeast-southwest, similar to the orientations of closed depressions on the Rolling Plains.

Open fractures at the surface are difficult to observe over a large region because they tend to be covered by natural processes or are infilled by landowners in agricultural areas such as the Rolling-Plains. However, evidence of six surface fractures was noted along State Highway 2639 in Hall County (fig. 16). Two of the six surface fractures observed in Hall County were open intermittently between 1979 and 1984 to widths of 30 cm (12 inches) where they crossed cultivated fields. The locations of four previously open tension fractures were indicated by diagonal patches across State Highway 2639; the open parts of these fractures in adjacent fields had been filled by the landowners. Fractures that cross State Highway 2639 are oriented from N.25°E. to N.50°E. and closely parallel an adjacent series of closed depressions that are aligned N.40°E.

To determine the region outside Hall County where karst features were being formed, questionnaires with photographs of sinkholes and open fractures were sent to soil scientists of the U.S. Department of Agriculture, Soil Conservation Service, to the Agricultural Stabilization and Conservation Service, and to State highway maintenance supervisors. This was done in each county in the Texas Panhandle and in the two eastern tiers of counties in New Mexico. Soil scientists from 21 of the counties within the Pecos Plains, Canadian Breaks, and Rolling Plains reported that sinkholes had formed in their county (fig. 19). Highway maintenance supervisors from 9 of the 21 counties also reported that sinkholes or fractures had formed in the highway rights-of-way in their areas of jurisdiction (Simpkins and others, 1981). Neither sinkholes nor fractures were reported for counties in Texas and New Mexico that lie entirely within the Southern High Plains.

This absence of sinkholes and fractures in the Southern High Plains indicates that recent catastrophic subsidence or collapse as reflected by the formation of sinkholes and open surface fractures is restricted to lands overlying an area of relatively rapid salt dissolution, the peripheral dissolution zone. Gustavson and others (1980a) previously thought that the lack of development of sinkholes and fractures on the Southern High Plains indicated that salt dissolution was inactive there. However, additional analyses of core from the Stone and

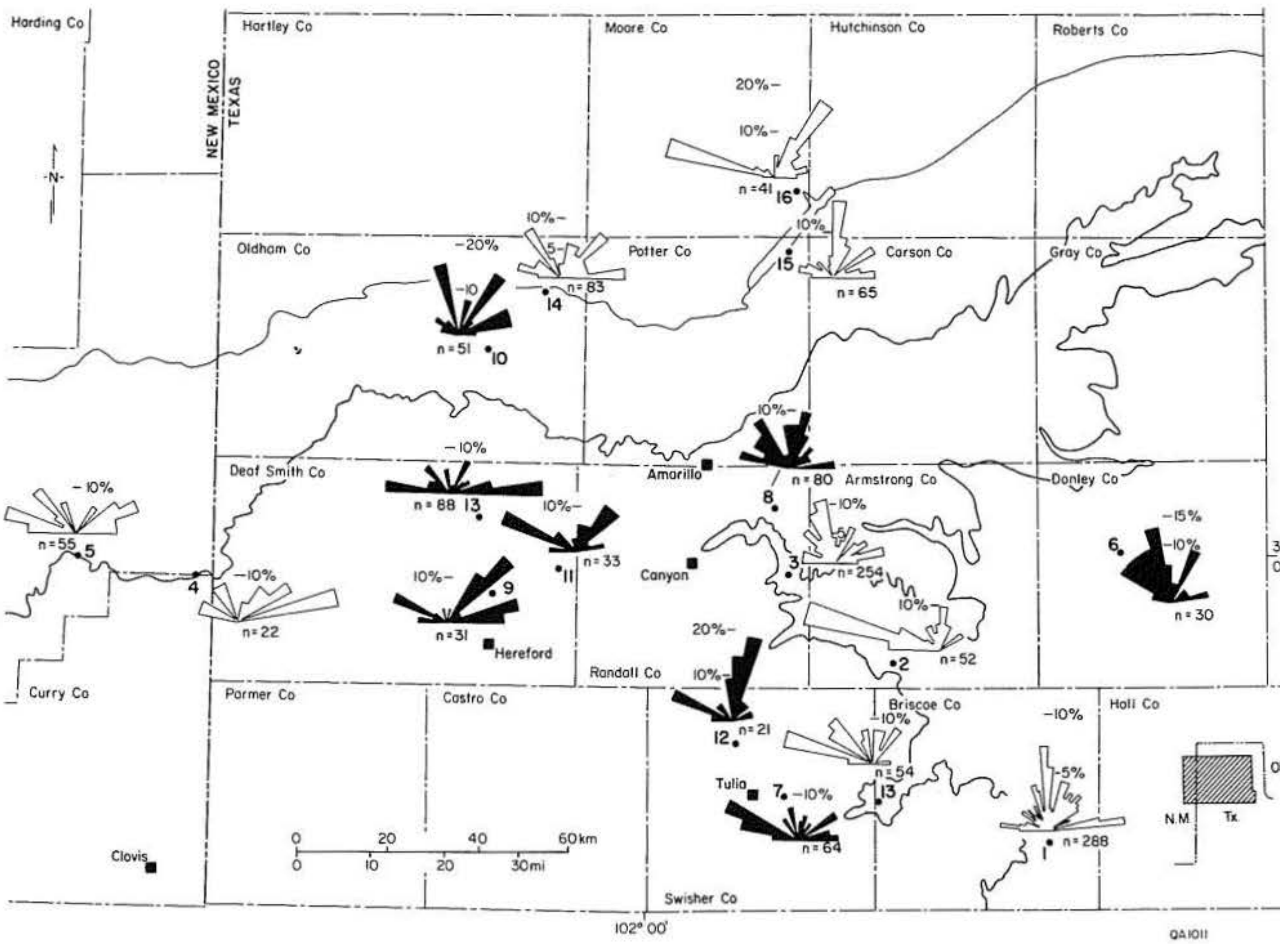

Figure 18. Fracture orientations from nine surface locations (open roses) in the Texas Panhandle and eastern New Mexico and from Schlumberger Fracture Identification Logs from eight test wells (filled roses) in the Texas Panhandle.

Webster Zeeck No. 1, Harman No. 1, J. Friemel No. 1, G. Friemel No. 1, and Detten No. 1 wells, all of which occur on the Southern High Plains, show clearly that dissolution of Upper Permian salt has been widespread. In core from these wells, salts of the Salado and Seven Rivers Formations are overlain by insoluble residues composed of anhydrite, dolomite, and soft mudstone, as well as complexly fractured rock with slickensides on fracture surfaces and extension fractures filled with fibrous gypsum. It seems that the absence of sinkhole development suggests only that dissolution beneath the Southern High Plains has not resulted in cavernous conditions or catastrophic collapse.

Linear Drainage Elements

Analyses of linear drainage elements were made using both small-scale black-and-white aerial photographs and specially processed false-color composite Landsat

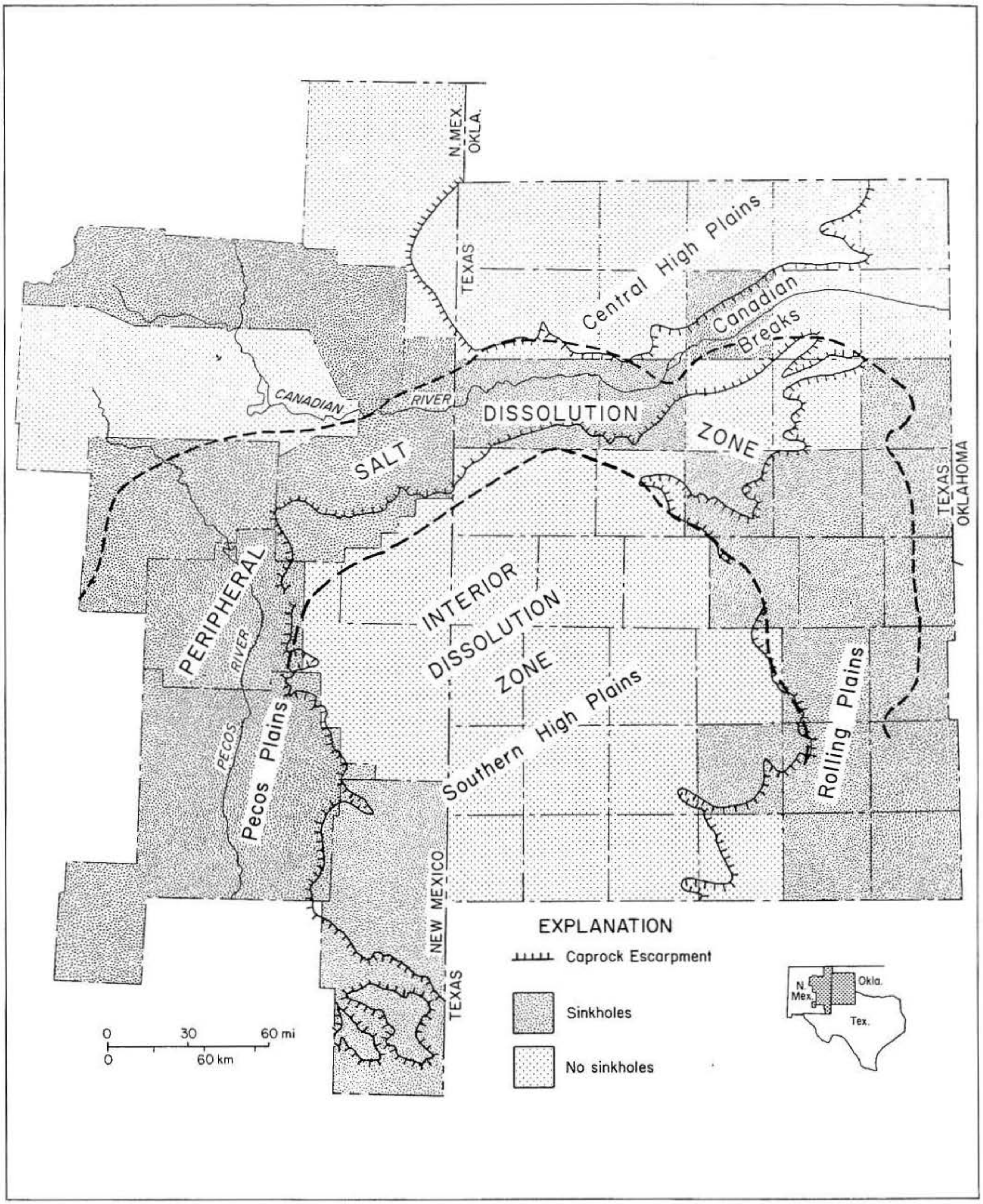

Figure 19. Texas and New Mexico counties, from which sinkholes and fractures have been reported, lying mostly within a peripheral dissolution zone that encompasses the Pecos Plains, the Canadian River Breaks, and the Rolling Plains. Sinkholes and open fractures have not been reported from the Southern High Plains or the Central High Plains within eastern New Mexico or the Texas Panhandle.

imagery (Finley and Gustavson, 1979; Gustavson and others, 1982b). Linear stream segments in Hall County were identified from black-and-white aerial photographs (fig. 16) and appear primarily in dissected areas. Undissected areas or slightly dissected areas have few linear streams but contain most of the closed depressions.

Linear stream segments have preferred orientations that are northwest-southeast, north-south, and northeast-southwest and are generally comparable to the preferred orientations of closed depressions (figs. 16 and 17). The orientations of open fractures within the county are also similar to preferred orientations of linear stream segments.

Many segments of major streams and tributaries are oriented in a way that is similar to the trends of dissolution zones beneath the Rolling Plains. Approximate limits of Permian bedded salts undergoing dissolution beneath the Rolling Plains have been identified (Presley, 1979a, 1979b; Gustavson and others, 1980a). Placement of the limits of each salt unit, as shown in figure 3, is directly dependent on available well control. For example, if a remnant of the lower San Andres salt is present in one well but absent in a well 8 km (5 mi) to the east, the actual salt limit could occur anywhere within that 8-km (5-mi) distance. Salt-limit lines on the map have been placed approximately midway between the last salt-bearing well penetrating a salt unit and the first nonsalt-bearing well to the east. Even with this potential source of error, a strong relation exists between the trends of dissolution and the position and orientation of segments of major streams and tributaries on the Rolling Plains. Approximately 40 percent of the total length of the streams shown on figure 20 lies nearly parallel to or within 20° of the orientation of the limits of adjacent bedded salt.

A relation between regional fracture trends, open surface fractures, closed depressions, linear stream segments, and trends of salt dissolution surfaces has been illustrated by showing that they all have broadly similar orientations. This suggests that a causal relation exists among tectonically induced deep fracture systems, the processes of salt dissolution and collapse, and the orientation and possibly the location of surface streams.

Relation between Aligned Surface Elements and Salt Dissolution

Dissolution of progressively younger Permian bedded salts occurs from east to west across the Rolling Plains. Each stratigraphically higher salt-bearing unit has undergone more dissolution than the next underlying salt unit. The salt dissolution fronts beneath the Rolling Plains are subparallel to each other and to the margin of the Southern High Plains. Although this pattern suggests that dissolution of different salt-bearing units has occurred at similar rates across the eastern part of the dissolution zone on a geologically long-term basis, it is not true at present. Mean annual dissolution rates for salts that are within the 12 drainage basins covering the Rolling Plains vary by as much as four orders of magnitude (vertical, 0.062×10^{-3} to 94.14×10^{-3} cm/year [0.024×10^{-3} to 3.71×10^{-2} inches/year]; horizontal, 0.3 to 81.71 cm/year [0.18 to 32.2 inches/year]; Gustavson and others, 1980a). In addition to the differential dissolution suggested by landforms, the range of observed dissolution rates indicates that dissolution varies over relatively short time periods from drainage basin to drainage basin and from place to place within drainage basins. The roughly parallel nature of the dissolution trends (fig. 3), however, implies that the spatially variable rates of dissolution may average out over geologic time, so that regional dissolution of different salt units occurs at similar long-term rates.

Regional dissolution is thought to occur from the upper surface of a salt bed downward. The amount of salt that has been removed from any bed decreases to the west. If this is true on a regional scale, then as dissolution occurs and the salt wedge retreats to the west, progressive collapse of overlying strata will also occur. As dissolution and collapse occur, subsidence depressions parallel to dissolution trends develop at the surface. These depressions also tend to be aligned with the regional fracture trends because of accelerated dissolution along fracture trends. During collapse, tension fractures, which are also parallel to regional fracture trends or to the trend of the dissolution zone, open at the surface (Goldstein, 1982; Goldstein and Collins, 1984). Closed subsidence depressions and open surface fractures are similar to regional fracture trends and, in turn, have influenced the orientation and location of aligned stream segments.

Southern High Plains Drainage

Two different styles of drainage characterize the Southern High Plains. Most of the surface drains internally into thousands of small lake basins; this constitutes the first type of drainage pattern. Except after periods of heavy rainfall, little interconnecting drainage exists between these lake basins, known by various terms including small lake basins, playas, and buffalo wallows. The possible origins and ages of these enigmatic features have been described by Gilbert (1895), Evans and Meade (1945), Judson (1950), Price (1958), Reeves (1965, 1966, 1970, 1971b), Woodruff and others (1979), Gustavson and others (1980a), and Wood and Osterkamp (1984). These researchers attributed the origins of these features to deflation, solution and subsidence, and animal activity. Although lake basins on the Southern High Plains surface receive much of the runoff of the area, they will not be discussed further in this

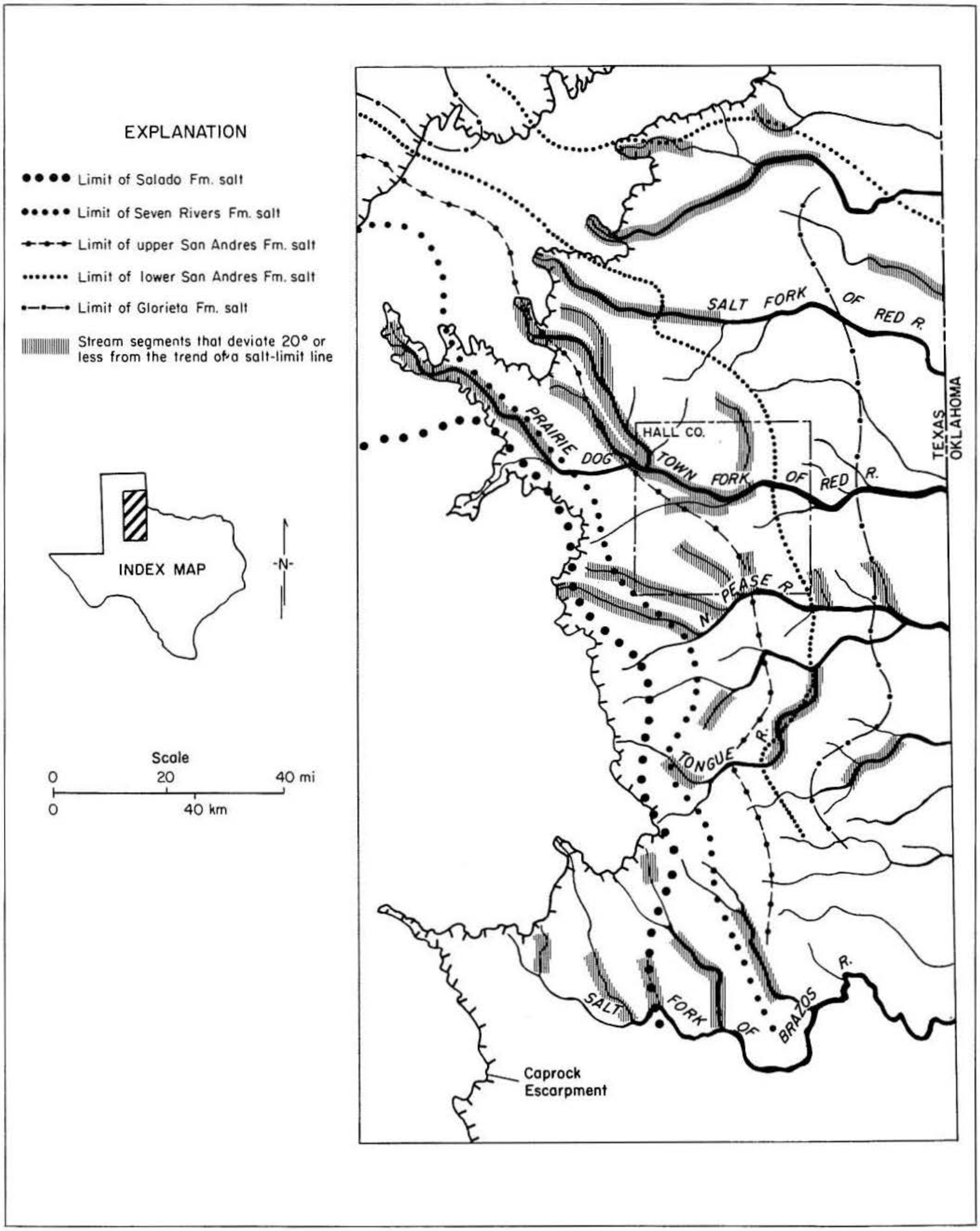

Figure 20. Comparison of stream segments to trends of the eastern limits of Permian salts. Approximately 40 percent of the total length of major streams within the Rolling Plains of the Texas Panhandle lies within 20° of the orientation of one or more of these salt limits. For comparison, a random stream pattern would yield a value of only 22 percent.

report because they only rarely contribute runoff to the regional drainage system.

The second type of drainage on the Southern High Plains is composed of a series of elongate stream valleys having narrow drainage basins. These include Yellow House Draw, Blackwater Draw, Running Water Draw, Tule Creek, Quitaque Creek, and Tierra Blanca Creek. Of these, all except the eastern half of Tierra Blanca Creek and Palo Duro Creek drain primarily to the southeast. Tierra Blanca Creek and Frio Draw, a major tributary, drain to the northeast across the regional southeast slope.

Influence of Salt Dissolution and Subsidence on Frio Draw and Tierra Blanca Creek

Tierra Blanca Creek and Frio Draw begin in eastern New Mexico, where both streams flow to the southeast. In the western part of the Texas Panhandle, both streams flow first eastward then northeastward (fig. 8). These streams probably could not have developed where they are simply by adjustment to regional southeast slope. Furthermore, these streams cross the southeast-trending Ogallala distributaries at high angles (fig. 13). The position of this stream system is apparently neither related to regional slope nor inherited from Ogallala deposition.

Figures 8, 9, and 11 illustrate a zone of thin salt in the Seven Rivers Formation overlain by structural lows or flexures on the Alibates Formation beneath the valleys of these streams. The structure-contour map on the base of the Ogallala Formation (the High Plains aquifer described by Knowles and others, 1982) (fig. 10) shows a series of closed structural depressions, which tend to overlie depressions or flexures on the Alibates surface, and a northeast grain to the paleotopography. The deepest depressions lie along the axis of thin salt. The valley of Tierra Blanca Creek and the parts of other streams in the area overlie and parallel structural depressions on the middle Tertiary erosional surface. This broad topographic low overlies and parallels the paleotopographic low on the middle Tertiary erosional surface, the structural low on the surface of the Alibates Formation, and the area of thin Seven Rivers Formation salt (fig. 12). This evidence leads to the interpretation that Tierra Blanca Creek and Frio Draw developed in an area of regional subsidence that trends to the northeast from northeast Parmer County through eastern Deaf Smith and western Randall Counties.

However, the topographic low in eastern Deaf Smith and adjacent counties, as well as the paleotopographic low, is not entirely the result of dissolution and subsidence. Surface erosion by wind and streams has probably contributed greatly to lowering the Southern High Plains surface along Tierra Blanca Creek because the loss of approximately 30 m (100 ft) of salt cannot account for a valley that is more than 45 m (150 ft) deep and a paleovalley that is more than 30 m (100 ft) deep (see Gustavson and Budnik, 1985, for a detailed discussion of the development of Tierra Blanca Creek).

The age of onset of subsidence in eastern Deaf Smith and adjacent counties can be determined relatively. The northeast-trending topographic low deforms the Southern High Plains surface, a late Pliocene feature. The trough incorporates ancient lacustrine basins at two locations: outcrops of early to middle Pleistocene lacustrine sediments in Canyon, Texas (Frye and Leonard, 1963), and outcrops of Pliocene lacustrine sediments in Hereford, Texas (Norton, 1954). If the basins that hold the lacustrine sediments resulted from subsidence along the topographic low, then subsidence may have begun as early as late Pliocene, according to these data.

Timing the formation of these lacustrine basins is problematical because in each the contained lake sediments provide only a minimum age. It seems, nevertheless, that if the basins were much older than the contained lake sediments, evidence of older stratigraphic units would have been found, but this is not true. Therefore, the range in ages of lake sediments, from Pliocene to Pleistocene, suggests that the range in timing of dissolution in parts of the Southern High Plains is also Pliocene to Pleistocene.

Yellow House, Blackwater, and Running Water Draw/White River

Insufficient information is available to characterize fully the development of Yellow House, Blackwater, and Running Water Draws. Some information, however, is available on the origin of these streams. Running Water Draw is the major tributary of the White River and, together with other linear drainage elements, has been described as part of the Running Water Draw/White River lineament (Finch and Wright, 1970). Upon recognizing this lineament and a subtle topographic flexure along the track of the lineament, Finch and Wright interpreted the presence of a fault to account for the topographic anomaly. The structure map on the top of the Alibates Formation (fig. 9) shows no evidence of a northwest-southeast-trending fault.

Farther south are Blackwater and Yellow House Draws. As does the Running Water Draw/White River drainage element, these streams occupy broad shallow valleys. Parts of these broad shallow valleys have been interpreted as being remnants of a partly filled Portales paleovalley (Baker, 1915; Fiedler and Nye, 1933; Price, 1944; Reeves, 1972). Interpretations of the path of the Portales Valley across the Southern High Plains have been made on the basis of analyses of topographic data (Baker, 1915; Theis, 1932; Price, 1944) and according to thickness and texture of Ogallala sediments (Reeves, 1972). Neither approach provides unequivocal evidence of the actual path of the Portales River across the Southern High Plains. Thus, although the point of entry of the Portales Valley onto the Southern High Plains in eastern New Mexico is widely recognized, it is not clear whether the Portales leaves the High Plains through Blanco canyon in the present drainage of the White River or near Yellow House Canyon in the present drainage of the Double Mountain Fork of the Brazos River.

The White River in northern Crosby and southern Floyd Counties and Yellow House Draw in Lubbock and Hockley Counties overlie areas of thin Salado salt, structural lows on the Alibates Formation, and paleotopographic lows on the middle Tertiary erosional surface (figs. 8 through 11). Blanco Formation lacustrine deposits occur above the area of thin salt in the White River area, suggesting that dissolution and subsidence may have locally influenced the development of these streams.

Structural Controls on Dissolution

The previous discussion suggests that drainage development in the Texas Panhandle and eastern New Mexico was strongly influenced by surface subsidence induced by dissolution of Permian salts. Basement structure has strongly influenced dissolution. The areas of most rapid dissolution occur along the western, northern, and eastern margins of the Palo Duro Basin in the upturned edges of the basin where Permian strata are closest to the surface (fig. 1). Active dissolution evidenced by historical collapse events or high chloride loads in local springs or both characterize these areas. In the interior of the basin where Permian salts are deeply buried by sediments of the Dockum Group and the Ogallala and Blackwater Draw Formations, dissolution is or was much slower. Here dissolution has not resulted in catastrophic collapse features, such as sinkholes, at the surface.

Locally dissolution has also been influenced by both basement faulting and fracture systems associated with basement faulting. Dissolution of the salts of the Seven Rivers Formation beneath Tierra Blanca Creek in eastern Deaf Smith County appears to be related to a northeast-trending set of fractures (figs. 8 and 18) (Gustavson and Budnik, 1985). In the Rolling Plains, collapse features consisting of small synclines and dolines are elongate parallel to regional joint trends (figs. 16 and 17), suggesting that dissolution has accelerated along regional joint trends (Gustavson and others, 1982; Collins, 1983, 1984).

Southeast-trending basement faults that are part of the structure complex making up the Amarillo Uplift parallel and underlie salts undergoing dissolution along the southwest side of the Amarillo Uplift. Salt margins as mapped in figure 3 are parallel to these faults and to fracture systems mapped by Collins and Luneau (1985). From these data it appears that dissolution is strongly influenced by the regional structure of the basin and locally by fracture systems within the basin.

Gable and Hatton (1983) showed that the Southern High Plains and surrounding region have been uplifted several hundred meters in the last 10 m.y. Uplift (1,000 to 1,500 m [3,000 to 4,500 ft]) since the Cretaceous, when this region was at sea level, has provided the hydraulic head that drives the present ground-water flow system and greatly influences the process of salt dissolution.

EVOLUTION OF REGIONAL PHYSIOGRAPHY

Miocene to Early Pliocene

Regional drainage in the late Tertiary, after the final stages of Ogallala fluvial deposition, was eastward across the northern Texas Panhandle and Oklahoma Panhandle (fig. 15A). Over the rest of the Texas Panhandle, drainage was oriented progressively more to the southeast. Drainage consisted of distributary channels on Ogallala fan lobes. Interlobe areas were topographically low and may have been collection troughs for the discharge of fan distributaries. The eastern reaches of present valleys of the Canadian, Brazos, and Colorado Rivers and of the Prairie Dog Town Fork of the Red River lie along the trends of interlobe projections in the eastern Texas Panhandle (fig. 13).

Because of a reduced source area and because the Pecos and Canadian Rivers diverted or cut off Ogallala distributaries, Ogallala fans during the late Tertiary were no longer being actively constructed. The Pecos-Portales-Brazos, Simanola-Colorado, and proto-Canadian Rivers and probably several other southeast-flowing streams began to incise their valleys. Salt dissolution, which was active during Ogallala deposition, probably continued through the late Tertiary.

After Ogallala fluvial deposition, a long period of eolian deposition punctuated by periods of soil development occurred (Hawley, 1984; Winkler, 1984). Ogallala deposition ended when the Caprock caliche formed.

Late Pliocene to Middle Pleistocene

Salt dissolution and subsidence in wide zones along the east, north, and west sides of the Southern High Plains suggest that lacustrine basins containing Blancan-age sediments resulted in part from subsidence caused by salt dissolution. If this is true, then the Rita Blanca lacustrine sediments that lie at the northern margin of the Canadian River valley, the Cita Canyon lacustrine sediments that are adjacent to the western rim of the Palo Duro Canyon, the unnamed beds near Tierra Blanca Creek, and the Blanco beds in Blanco canyon may provide minimum dates for the onset of subsidence and related processes that marked the initial phases of development of the Canadian River, Prairie Dog Town Fork of the Red River, Tierra Blanca Creek, and the White River.

Subsidence basins on the Ogallala surface along the present trends of the Canadian River as far west as the Ute Reservoir in New Mexico and the Prairie Dog Town Fork of the Red River near the Palo Duro Canyon developed from regional dissolution along the northern flanks of both valleys (fig. 15B). Subsidence along the Canadian River valley intercepted easterly and southeasterly flowing streams, including the headwaters of the present Canadian River near the Ute Reservoir. No unequivocal evidence of the proto-Canadian southeast of the Ute Reservoir is recognized in New Mexico, but the river may have been a tributary of the Pecos-Portales-Brazos river system. By the end of this time, the Canadian had incised its valleys to a depth of 125 m (400 ft), relative to the south flank of the valley, as the result of erosion and subsidence. This measurement is based on a Canadian River terrace east of Lake Meredith that lies about 125 m (400 ft) below the Southern High Plains surface and contains Pearlette type "O" (Lava Creek B) ash (Izett and Wilcox, 1982).

Subsidence basins formed along the trend of the Pecos River valley and began to divert southeasterly flowing streams to the south. The northernmost stream to be diverted was the Pecos-Portales-Brazos river system. Timing of the diversion of the Pecos-Portales-Brazos river system is not clearly understood, but some speculations have been offered. Hawley and others (1976, p. 245) thought that "interpretation of Quaternary history in much of the lower Pecos Valley . . . is complicated by the long history of subsidence resulting from the dissolution of evaporites." Clearly, this is also true of the upper Pecos from Roswell to Fort Sumner, New Mexico, because this area has also undergone extensive subsidence from dissolution of evaporites. Consequently, interpretations of the timing of Pecos River diversion that are based on relating features such as the Portales Valley to Quaternary surfaces will always be subject to question.

Late Pleistocene

Reeves (1972) observed that the oldest terrace found both above and below the diversion point of the Portales to the Pecos River is the Diamond-A Mescalero and concluded that diversion must have happened during Kansan time. Remnants of the Mescalero Plain appear as the flanks of the Portales Valley west of Tolar, New Mexico (Reeves, 1972). The Mescalero Plain is developed across a variety of lithologies and formations, the youngest of which is the Gatuna Formation. The Gatuna Formation consists of a variety of fluvial sediments laid down along the Pecos Valley (Robinson and Lang, 1938; Bachman, 1980). Bachman (1980) reported that the upper part of the Gatuna Formation on the east side of Nash Draw contains Pearlette type "O" (Lava Creek B) ash (Izett and Wilcox, 1982) and is therefore about 610,000 years old. The Mescalero surface is capped by the Mescalero caliche, which ranges from 510,000 years old in the lower part to 410,000 years old in the upper part (Bachman, 1980). Therefore, the age of the Mescalero surface is bracketed between the 610,000-year-old ash fall and the 510,000-year-old caliche.

According to projections of the floor of the Portales Valley (fig. 2), the elevation of the Pecos-Portales-Brazos river system thalweg must have been approximately 1,319 m (4,400 ft) near Fort Sumner, New Mexico, the presumed point of diversion of the Pecos-Portales river system. This is approximately the elevation of the Diamond-A Mescalero Plain projected into the Fort Sumner area. The projections plus the occurrence of younger Pleistocene terraces only downstream of Fort Sumner suggest that the time of capture must have followed development of the Mescalero Plain. Hawley and others (1976) proposed that the 2 to 4 m (6 to 12 ft) of gravel in the floor of the Portales Valley (Theis, 1932) may be equivalent to the Gatuna Formation. Although none of this evidence is unequivocal, it collectively suggests that diversion occurred during the middle to late Pleistocene and perhaps as late as 600,000 years ago. By this time, the floors of the Pecos and Pecos-Portales drainages had been incised by erosion and subsidence approximately 210 m (700 ft) below the projected level of the High Plains near Fort Sumner. Since incision of the Diamond-A Mescalero Plain, about 600,000 years ago, the Pecos has incised its valley approximately 65 m (200 ft).

Major drainage elements were established by the late Pleistocene: the Pecos River in eastern New Mexico and the Canadian River across the Texas Panhandle (fig. 15C). On the west and north, the Caprock Escarpment was well established, and local relief along major segments of the streams was approximately 200 m (600 ft). Drainage to the east during the late Pleistocene near the Texas and Oklahoma border is poorly understood. Approximately 600,000 years ago, Seymour Gravels were deposited along the margin of what was then the High Plains Escarpment. An ash associated with the gravels has been established as equivalent to the Pearlette type "O" (Lava Creek B) ash (Izett and Wilcox, 1982; Simpkins and Baumgardner, 1982). Additional scattered remnants of high gravel terraces exist as far north as Hall and Collingsworth Counties in the eastern part of the Texas Panhandle. On the basis of interpretation of fossil faunas and recognition of a Pearlette ash (type unknown), Frye and Leonard (1963) suggested that these terrace remnants were Kansan in age. If the ash in northeastern Hall County is equivalent to the Pearlette type "O" (Lava Creek B) ash associated with the Seymour Gravels, then the 600,000-year age of the high-level terraces is confirmed. Meinzer and Slaughter (1971) thought that the Seymour Gravels represented a series of alluvial fans that developed adjacent to the eastern High Plains Escarpment; however, Seymour Gravels are present in only a small part of the eastern Texas Panhandle area and are of insufficient quantities to characterize stream development during the late Pleistocene.

Late Pleistocene to Holocene

A series of nearly continuous Holocene alluvial surfaces, here informally called the Quitaque plain, are capped by eolian sands and silts and extend from near the base of the eastern Caprock Escarpment eastward to Childress and Cottle Counties (Caran and others, 1985). These surfaces, extending from Briscoe County on the north to Kent County on the south, grade eastward with diminishing slopes. They seem to be a related group of pediment and alluvial surfaces that are locally interrupted by inselbergs of Permian or Triassic rocks. The Quitaque plain is being rapidly and extensively eroded. Farther east, remnants of the Quitaque plain occur as the uplands between tributaries of the Prairie Dog Town Fork of the Red River.

Exposures of the fluvial and eolian sediments that immediately underlie the Quitaque plain contain fossil molluscan faunas, archeological material, and several paleosols. Soils of the Miles, Springer, and Olton Series and related associations are extensively developed on these surfaces (U.S. Department of Agriculture, 1967). Development of calcretes within these soils ranges from weak to distinct.

Fossil molluscan faunas were identified from exposures of the sediments underlying the surfaces of the Quitaque plain at Lake Theo (Neck, 1978) and near Quitaque and Turkey, Texas (Frye and Leonard, 1963, 1964). Fossil faunas collected from these localities contain no extinct species. Frye and Leonard considered these faunas to be Kansan and post-Kansan and the eolian sediment that blankets these surfaces to be Illinoisian. Organic humates from paleosols and pedogenic calcrete from the exposures that yielded the faunal remains examined by Frye and Leonard (1957) have radiocarbon ages of less than 19,000 years (Caran and others, 1985). Recently, paleosols associated with Paleo-Indian remains, archeological material, and fossil gastropods from the Lake Theo camp and bison-butchering site were analyzed. The paleosols are developed in alluvial material and range in age from 10,000 ± 120 to 8,010 ± 100 years B.P. (Harrison and Killen, 1978; Johnson and Holliday, 1980). The McCormick Local Fauna, which occurs in terraces along the upper reaches of the Palo Duro Canyon, is compositionally similar to the Lake Theo fauna; radiocarbon dating of the mollusks gives an age of 10,800 ± 835 years B.P. (Schultz and Cheatum, 1970). Ages for archeological materials consisting of Folsom and Plainview points from the Lake Theo site are consistent with radiocarbon dates.

Dalquist (1964) identified the Quitaque Local Fauna from a terrace along Quitaque Creek where the creek has incised approximately 18 m (60 ft) into the Quitaque plain. The terrace is a strath terrace incised into sediments underlying the Quitaque plain. Shells of mollusks associated with the vertebrate remains have radiocarbon ages of 31,400 ± 5,600 years and 31,400 ± 3,200 years B.P., whereas the age for the vertebrate remains alone suggests that the fauna is Illinoisian or younger. Organic humates from this same horizon have radiocarbon ages of more than 35,000 years (Caran and Baumgardner, 1985).

The base levels for the Quitaque surface were precursors of the Pease River and its major tributaries, Quitaque Creek, Middle Pease River, and Tongue River. Other similar surfaces appear in drainage basins north and south of the Pease River basin, but no datable material is now available from the sediments underlying these features. The widespread occurrence of the surfaces, their similarity, and the appearance of rapid erosion in progress around their margins all suggest that they were previously much more extensive. Much of the Rolling Plains east of the Southern High Plains was probably covered with an alluvial veneer during the late Pleistocene and Holocene.

Geomorphic evidence based on analysis of remnants of these surfaces provides insight into the evolution of drainage systems in the Rolling Plains during the Wisconsinan and Holocene. During the Wisconsinan, a series of extensive alluvial surfaces was constructed eastward from the eastern escarpment of the Southern High Plains. These alluvial surfaces were graded to the precursors of major present streams, such as the Prairie Dog Town Fork of the Red River, Quitaque Creek, Middle Pease River, Pease River, Tongue River, and the Salt Fork of the Brazos River, which have not changed their positions since the Wisconsinan. These streams have incised vertically, perhaps locally adjusting to structures in the underlying bedrock. The Quitaque plain in Hall County appears to have undergone extensive local subsidence because of evaporite dissolution. Subsidence basins on the Quitaque plain are oriented similar to regional joint orientations and to preferred stream segment orientations in Hall County. Streams appear to have adjusted to the subsidence troughs that formed on the alluvial surface, or they may have adjusted to the structures in the underlying bedrock that are the result of the regional joint pattern or of dissolution-induced subsidence.

CONCLUSIONS

Subsidence induced by the dissolution of Permian bedded salts and the collapse of overlying strata is fundamental to the development of the physiography of the Texas Panhandle and eastern New Mexico. Linking salt dissolution and subsidence to the formation of the three large valleys that define the western, northern, and northeastern perimeters of the Southern High Plains provides a rationale for answering several questions: Why are the valleys of the Pecos River, Canadian River, and Prairie Dog Town Fork of the Red River where they are? How did the valleys of the Pecos and Canadian Rivers form when they now lie nearly normal to the regional slope? How were such large valleys excavated in such a geologically short period of time, especially considering the small drainage basin of streams like the Canadian and upper Prairie Dog Town Fork?

Clearly, subsidence basins along a dissolution zone could divert the flow of the Pecos River to the south and the flow of the Canadian River to the northeast. Several hundred feet of salt have been removed from beneath the Pecos and Canadian River valleys, and significant parts of the rock column removed from these valleys are accounted for by subsidence of the valley floor. As much as 60 m (200 ft) of salt have been removed from beneath parts of the Palo Duro Canyon of the Prairie Dog Town Fork of the Red River, the canyon being 300 m (1,000 ft) deep at that point. Subsidence, therefore, could account for as much as 20 percent of the canyon depth. Fracturing, minor faulting, and attendant subsidence have mechanically broken the rocks exposed along the canyon and valley walls and, thus, made them more easily erodible. Collectively, dissolution, subsidence, and mechanical disruption of overlying sediments have contributed greatly to determining the placement and rates of incision of the major streams draining the periphery of the Southern High Plains.

Drainage in the Rolling Plains has been partly shaped by topography inherited from the Ogallala alluvial-fan system that spread across the Texas and Oklahoma Panhandles and eastern New Mexico. In the eastern Texas Panhandle, the Prairie Dog Town Fork of the Red River and the Canadian, Brazos, and Colorado Rivers all lie either in the eastward extensions of interfan areas or in topographic lows on the Ogallala surface. Regional tectonic jointing and dissolution strongly influence the orientation and location of tributary segments of these streams. Forty percent of the length of major tributaries lies parallel to or within 20° of the orientation of nearby salt dissolution fronts. The preferred orientations of straight segments of minor tributaries are northwest-southeast, north-south, and northeast-southwest; these correspond to the preferred orientations of both the regional fracture system and the elongate subsidence basins. In turn these orientations suggest that dissolution was accelerated along regional fractures and that subsidence basins, developing in response to accelerated dissolution, controlled or influenced the position and shape of stream valleys.

With two exceptions, drainage on the Southern High Plains surface developed primarily as a result of relict Ogallala fan topography and regional southeasterly slope. The ancient Portales River could have flowed in either, or perhaps in both, of the valleys of Yellow House Draw and Running Water Draw/White River. Yellow House Draw lies in an interfan area, and Running Water Draw/White River seems to occupy a valley that may have originated as a distributary on the Ogallala fan surface. Locally, however, both these streams may have been influenced by dissolution and subsidence.

Frio Draw is a major tributary of Tierra Blanca Creek; these two stream segments drain northeast, normal to the regional slope of the Southern High Plains. Frio Draw and Tierra Blanca Creek connect three topographic basins, including basins at Canyon and Hereford, Texas, where lacustrine sediments have been preserved. Both the topographic basins and Frio Draw and Tierra Blanca Creek seem to be related to preferential dissolution of salt in the Seven Rivers Formation. A broad, shallow dissolution trough lies beneath the valley of Frio Draw and Tierra Blanca Creek and parallels both regional preferred fractures and basement faults. Dissolution and subsidence in conjunction with fluvial and eolian erosion can be used to explain both the formation of the topographic basins and the northeasterly drainage of these two stream segments.

Dissolution affecting the Pecos and Canadian Rivers and Prairie Dog Town Fork of the Red River occurred after deposition of fluvial sediments of the Miocene-Pliocene Ogallala Formation. Lacustrine basins within the peripheral dissolution zone that rings the Southern High Plains probably resulted from subsidence. Lacustrine sediments preserved in basins associated with the Canadian River valley, Tierra Blanca Creek, and the Palo Duro Canyon of the Prairie Dog Town Fork of the Red River contain Blancan-age fossil faunas. Therefore, the basins containing these faunas are at least as old as late Pliocene. No evidence is available to suggest a time for the onset of subsidence along the trend of the Pecos River valley. Although the drainage of the Canadian River was completely established by the early Pleistocene, the Pecos was not fully developed until the middle to late Pleistocene, when the headwaters of the Portales River were diverted to the Pecos River.

Drainage elements of the Rolling Plains probably developed almost entirely during the late Pleistocene and Holocene. Seymour Gravels containing Pearlette type "O" (Lava Creek B) volcanic ash occur with similar gravels containing similar, but undated, ashes along the eastern part of the Texas Panhandle. These gravels are topographic highs and are remnants of middle Pleistocene terraces. A series of alluvial surfaces extends eastward from near the eastern Caprock Escarpment. These surfaces are lower than the ash-bearing gravels and are graded to the valleys of the Prairie Dog Town Fork of the Red River, Quitaque Creek, and North Pease River, although the present streams have incised their valleys well below the fan surfaces. The fans have developed the same soils, are at similar elevations, and are graded to about the same elevation in the eastern part of the Panhandle. Although the age of only one fan is known from radiocarbon dates of paleosols, of vertebrate and invertebrate faunas, and of archeological materials, all fans probably range from at least Wisconsinan to Holocene in age. The margins of all the fans are being actively eroded, and the streams to which the fans were graded are actively incising into the fans. Drainage developing on the fan surfaces consists of internally drained subsidence basins and streams that have many segments aligned parallel to subsidence basin alignments. Because most of the minor drainage segments on the Rolling Plains are either developing on Holocene alluvial-fan surfaces or eroding into the margins of these fans, the minor drainage segments of most Rolling Plains streams are probably all Holocene features.

On the surface of the Southern High Plains, the timing of the development of many drainage elements is questionable. Those parts of the Yellow House Draw and Running Water Draw/White River lineament that were controlled by topography on the surface of the Ogallala fan may have begun to develop as early as late Pliocene or early Pleistocene. The development of Frio Draw and Tierra Blanca Creek, however, is understood relatively well because Tierra Blanca Creek drains the lacustrine basins in which Pliocene and middle to late Pleistocene vertebrate fossils have been observed at Hereford and Canyon, Texas. Therefore, the present drainage of Tierra Blanca Creek and Frio Draw is a late Pliocene-Pleistocene feature.

A close spatial relation exists between the surface streams and the areas of dissolution and subsidence in eastern New Mexico and the Texas Panhandle. Furthermore, the peripheral dissolution zone around the west, north, and east margins of the Southern High Plains clearly coincides with the structural margins of the Palo Duro Basin, suggesting that ultimately basin structure has controlled existing patterns of dissolution and in turn has affected drainage development.

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