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LATE CENOZOIC GEOMORPHIC EVOLUTION OF THE TEXAS PANHANDLE AND NORTHEASTERN NEW MEXICO: CASE STUDIES OF STRUCTURAL CONTROLS OF REGIONAL DRAINAGE DEVELOPMENT

by

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CAUTION

This report describes research carried out by staff members of the Bureau of Economic Geology that addresses the feasibility of the Palo Duro Basin for isolation of high-level nuclear wastes. The report describes the progress and current status of research and tentative conclusions reached. Interpretations and conclusions are based on available data and state-of-the-art concepts, and hence, may be modified by more information and further application of the involved sciences.

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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 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. Following the end of Ogallala in the late Pliocene, surface subsidence had resulted in lacustrine basins along trends of relatively rapid dissolution. Preserved lacustrine sediments contain Blancan faunas, which confirm minimum late Pliocene ages for the basins.

Continued subsidence along trends of relatively rapid dissolution during the late Tertiary and early Quaternary resulted in a series of 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 Pleistocene from a southeasterly drainage through the Portales paleovalley to a southerly drainage through the Pecos Valley. The present-day headwaters of the Canadian River are probably a former tributary of the Pecos-Portales-Brazos system that was diverted to the northeast along a subsidence trend 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 apparent areas of accelerated salt dissolution. These features also lie above 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-day stream valleys formed as early as late Pliocene time. Lacustrine basins probably

formed between late Pliocene and early Quaternary. The basins and stream valleys probably owe most of their form to normal fluvial and eolian erosional processes. Their location, however, is probably the result of dissolution-induced subsidence.

Caprock Escarpment are being extensively dissected, suggesting that much of the drainage on the Rolling Plains in the Texas Panhandle developed during the late Pleistocene and Holocene. That much of the drainage is controlled by dissolution-induced subsidence is indicated by parallelism between major stream segments and dissolution fronts for Permian salt-bearing units. 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 subsidence basins that parallel fracture trends and, in turn, the alignment of drainage as 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 contain bedded Permian salts of sufficient thickness and depth to be considered as potential sites for long-term storage and isolation of high-level radioactive nuclear waste (fig. 1) (Johnson, 1976). Salt (primarily halite) is a desirable host rock because of its low permeability, low moisture content, and high gamma-ray-shielding properties.

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 (Johnson, 1981; Gustavson and others, 1980a; Presley 1980a, b). The coincidence of these zones of dissolution, Southern High Plains 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. In addition, evidence of wide spread dissolution beneath the Southern High Plains has been recognized (McGookey and others, in press; Gustavson and Budnik, in press). To determine whether the continued development of drainage systems in the Texas Panhandle and eastern New Mexico could adversely affect future waste isolation sites, the geologic characteristics and processes that affect drainage development must be understood. This report describes certain structural and topographic controls of both ancient and modern drainage development in the Texas Panhandle and in eastern New Mexico.

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) attributed the morphology of the Canadian River in eastern New Mexico to the river's adjustment to mid-Pleistocene normal faults. Fay (1959) suggested that the present-day 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 to form a series of three large loops. The loops overlie a series of synclines attributed in part to solution and collapse of the Blaine and Cimarron Anhydrites. Gustavson and Finley (1982a, b) have suggested that the path of the Canadian River in eastern New Mexico and the Texas Panhandle was strongly influenced by dissolution of Permian salt and subsidence.

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; Thomas, 1972; Kelley, 1972; Gustavson and Finley, 1982a, b). 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 followed, 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 System were then beheaded by the Canadian River. Dolliver (1984) has synthesised much of the literature pertaining to the development of the Canadian River Basin.

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 and White Water Draws. Reeves, on the other hand, suggested that the fractures are related to the "regmatic shear pattern" of basement rocks. Recently, Woodruff and others (1979) related the development of draws to ponding in playas and the overtopping of playa divides to discharge 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 relationship of dissolution of Permian salt and the present drainage system of eastern New Mexico and the Texas Panhandle is a synthesis of previous work; in particular Gustavson and others (1981) discussion of dissolution zones and collapse features, Gustavson and others (1982) discussion of the relation of dissolution-induced collapse features to fractures and Gustvason and Budnik's (in press) discussion of the relation of Tierra Blanca Creek to dissolution-induced subsidence and fracture systems. In addition, significant new data describing the relation between drainage developent and dissolution is presented.

GEOLOGIC SETTING OF THE PALO DURO BASIN

Structural Development

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

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

Gustavson (1979) and Gustavson and others (1980a) suggested that substantial parts of the Texas and Oklahoma Panhandles and central-eastern New Mexico have undergone nontectonic vertical displacements of as much as 180 m (600 ft). These adjustments were due to dissolution of bedded Permian salts within approximately 400 m (1,300 ft) of the surface. They have also suggested that regional dissolution and resulting subsidence have occurred mostly since the Late Cretaceous. Collapse owing to salt dissolution is currently active along the western, northern, and eastern m gins of the Southern High Plains (Simpkins and others, 1981; Gustavson and others, 1982a, ɔ). For example, numerous sinkholes, small-displacement faults or open fractures, and ɔlines have formed since 1950 in Hall County in the Texas Panhandle. Other instances of re ɜnt collapse resulting from dissolution of Permian salt have been reported in Curry County, Jew Mexico (Judson, 1950), and in Winkler County, Texas (Baumgardner and others, 1982).

Sedimentation

During th early Paleozoic, periods of erosion alternated with episodes of shallow marine-shelf depositio in the Texas Panhandle. During Mississippian time, marine-shelf carbonates were deposited ıcross the area. Major tectonic activity began in the Late Mississippian and continued throı ;h the Pennsylvanian to form the bounding elements of the Anadarko, Dalhart, and Palo Duro ›asins. Deposition of terrigenous clastic sediments, informally called granite wash, was pre\ lent during the Pennsylvanian and Early Permian. Granite wash was derived from and conce ıtrated near the principal uplifts (Handford and Dutton, 1980). Sedimentation during the Late Pennsylvanian was dominated by shelf carbonates, the deeper parts of the basin being filled by ine-grained clastic sediments. Salt, anhydrite, dolomite, limestone, and red beds compose ! ·rmian strata in the Anadarko, Dalhart, and Palo Duro Basins (Presley, 1979a, 1979b; 1980a, b These rock types were probably deposited in a range of subtidal to supratidal environments. ithofacies include halite, anhydrite, dolomite, and limestone. Red beds consist of mudstones aı l fine-grained sandstones that intertongue with evaporites and dolomite.

The Tria: .c Dockum Group consists of fluvial, deltaic, and lacustrine sandstones and mudstones thaı accumulated in a large fluvial-lacustrine basin south of the Amarillo Uplift (McGowen and thers, 1979). Dockum Group strata are overlain unconformably by the Upper Jurassic Exete Sandstone in certain areas and by Lower Cretaceous Kiamichi Formation (Fredericksburg Group), Dakota Group sandstones and conglomerates, and Kiowa Shale in other areas. After a period of extensive erosion, the Miocene-Pliocene Ogallala Formation was deposited in northwestern Texas, western Oklahoma, and eastern New Mexico. Lower Ogallala sediments are primarily fluvial deposits which were deposited in a wet, alluvial fan environment (Seni, 1980). Upper Ogallala sediments are largely eolian. Ogallala surface sediments were extensively calichified to form the Caprock caliche.

The end of Ogallala deposition has not been precisely dated, but it is probable that deposition 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 from whole rock samples (Stormer, 1972) by potassium-argon isotopes to be $3.5 \pm 0.2 \times 10^6$ years old. The Clayton basalt, which is similar in composition to the Raton basalt, occupies paleostream valleys incised into the Ogallala surface and exhibits potassium-argon ages of $2.5 \pm 0.8 \times 10^6$ and $2.2 \pm 0.3 \times 10^6$ years old. These dates indicate that Ogallala fluvial sedimentation in the northeast New Mexico area 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 unconformably overlie the Ogallala Formation. He points out that Boellstorff (1976) obtained a fission track date for the Blanco Ash, which overlies the fossil-bearing beds of the Blanco Formation, of 2.8 ± 0.3 mya. Lindsey and others (1975) determined that the entire Blanco Formation section exposed at Mount Blanco was reversely magnetized. 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 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 also recognized that the Cita Canyon Local Fauna, which is normally correlated with the Blanco Local Fauna, occurs in a normally polarized zone. They consider these strata to be in the Gauss Epoch and to be older than the Blanco fauna. Regardless of the dating inconsistencies, the Blanco Formation unconformably overlies the Ogallala Formation and is probably at least 2.4 to 2.8 m.y. old that took considerable time to form following the end of Ogallala deposition. This suggests that the age of Ogallala Formation in the area of Mount Blanco and Cita Canyon is consistent with the age of the Ogallala Formation in northeastern New Mexico, or about 3.5 m.y. old.

Pleistocene cover sands and the Blackwater Draw Formation form an eolian mantle on most of the Southern High Plains (Barnes, 1974). Late Tertiary to early Pleistocene fluvial and lacustrine deposits occur locally between the Ogallala Formation and the Pleistocene eolian sediments.

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, the Great Plains are known as the Southern High Plains, or the Llano Estacado. The Southern High Plains are truncated to the east and west at the Caprock Escarpment, erosional scarps where relief locally exceeds 500 m (1,500 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 a series of 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 lie west of the Southern High Plains.

SALT DISSOLUTION AND SURFACE COLLAPSE-MAJOR FACTORS IN THE PHYSIOGRAPHIC DEVELOPMENT OF EASTERN NEW MEXICO AND THE TEXAS PANHANDLE

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. There are seven salt-bearing units 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 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 tons of dissolved solids, including 425.3 x 10^3 tons of chloride (U.S. Geological Survey, 1969-1977). Brine springs, salt springs, and salt pans appear along this and other stream valleys (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 may exceed 30,000 ppm chloride, and waters within the alluvium may contain (U.S. Geological Survey, 1969-1977; U.S. Bureau of Reclamation, 1979). The Bureau of Reclamation (1979) estimates that over 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 of parts per million. Morgan (1941) estimated that 266.0 x 10^3 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 valley of the Pecos (Morgan, 1941; Reeves, 1972).

(2) As interpreted from geophysical logs, the abrupt loss of salt sequences between relatively closely spaced oil and gas exploration wells indicates salt dissolution and not facies change has occurred where structural collapse of overlying strata is evident in the wells where salt is missing (figs. 4, 5, 6, and 7)(McGookey and others, in press).

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

(4) Permian outcrops along parts of the Canadian River Valley and east of the High Plains Escarpment display folds, systems of extension fractures, breccia-filled chimneys, breccia beds, and caverns, 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. No. 2 Mansfield in Oldham County and No. 2 Sawyer well in Donley County suggests that dissolution in these areas is active (fig. 3) (Dutton, in press). In the No. 2 Mansfield well dissolution of the Seven Rivers salt is underway at a depth of 811 ft (247 m). In the No. 2 Sawyer well dissolution of the San Andres salt is underway at a depth of 830 ft (252 m). Brines undersaturated with respect to sodium chloride have been pumped from both wells.

Dissolution Along the Margins of the Southern High Plains

The zones of salt dissolution that exist east of and beneath the Caprock Escarpment on the eastern margin of the Southern High Plains also underlie the Canadian River Breaks, the northern edge of the Southern High Plains (Presley, 1979a; Gustavson and others, 1980a), and the valley of the Pecos River to the west. Because this area is peripheral to the Southern High Plains it is called the peripheral salt dissolution zone. The younger or stratigraphically higher salt units have undergone more extensive dissolution than have lower units, and salt dissolution zones in the upper units lie nearer the center of the Palo Duro Basin. The steplike character of salt dissolution zones and their relation to major physiographic features, such as the Canadian River Valley the Caprock Escarpment, and Palo Duro Canyon are illustrated by stratigraphic cross sections (figs. 4, 5, 6, and 7). In these cross sections, Glorietna Formation salts and younger salts are interpreted to be undergoing dissolution.

The 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, in press). Local dip reversals occur, such as those in Quay County, New Mexico, where over 122 m (400 ft) of salt have been removed (fig. 5).

Gustavson and others (1980a, 1981a, b, 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 High Plains. The Pecos River parallels the salt dissolution zone from Guadalupe County to Chaves County.

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 Coun (McGillis and Presley, 1981). Figures 6 and 7 show the salt-bearing units within the Sa do Formation thinning from 50 to 65 m (150 to 200 ft) to no salt. Examination of the net- lt map of the Salado Formation (fig. 8) and of the structure-contour map of the Alibates Fc nation (fig. 9) suggests that as much as 122 m (400 ft) of salt have been lost to dissolution in n thern Hockley County, southern Lamb County, and northwestern Lubbock County. The oincidence of structural lows over salt thins is indicative of dissolution because analyses of ophysical logs show that strata beneath the Salado Formation are not structurally disturbed an that overlying strata have collapsed into the section from which salt was removed.

The thickness of salt lost to dissolution can also be estimated from insol ble residues in core. The most serious problem with procedure is that the cleaner the origin salt, the less evidence exists of its former presence. Estimates of salt loss in the Salado rmation were made from cores from three wells: Stone and Webster Engineering Corp. No. Zeeck, No. 1 Detten, and No. 1 Grabbe (S. D. Hovorka, written communication, 1983). Estim es were based on a comparison of the textures and mineralogies of non-salt residues to t textures and mineralogies of non-salt material in intervals where salt is still present. I each case, a conservative range for the amount of salt lost from the Salado Formation wa made: No. 1 Zeeck, 2 to 15 m (6 to 45 ft); No. 1 Grabbe, 3 to 18 m (10 to 55 ft); No. 1 Dette 8 to 35 m (25 to 107 ft). The estimates from the cores from the Swisher County wells (No. 1 rabbe and No. 1. Zeeck) are low when compared with salt-loss estimates derived from stratig phic sections. However, considering the probability that clean salt with little or no insoluble r sidue is poorly represented by these estimates, the estimates of thickness of salt lost as a resu of dissolution are valid as minimum thicknesses. Furthermore 2 m (6 ft) of core are missing from the No. 1 Zeeck well, and 10 m (31 ft) of core are missing from the Grabbe well; these sections may have contained additional insoluble residues.

Dissolution of Salado Formation salt, and subsidence beneath the Tule lacustrine basin along the Swisher - Briscoe County border can also be inferred from stratigraphic and outcrop structural data (Gustavson, in press). 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 bedding plain and inclined fractures occurs in mudstone of the Triassic Dockum Group agove the area of thin Salado salt and 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 following salt dissolution. The vertical juxtaposition of thin salt, the structural low on the Alibates Formation and extension fractures in the Dockum Group all suggest that dissolution and subsidence have occurred in the vicinity of the Tule basin. A similar conclusion was reached by Evans and Meade (1945) based on 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 as much as 30 m (100 ft (fig. 8). The structure-contour map on the top of the Alibates Formation in this area hows a broadly defined 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. 11). Farther to the southwest a similar relation-ship occurs along the Yellowhouse Draw in Lubbock, Hockley and Lamb Counties. Here structural lows on the structure-contour map of the Alibates Formation overlie sharply defined areas of thin salt of the Salado Formation (figs. 8, 9). A paleodrainage system developed on the middle-Tertiary erosional surface parallels and nearly underlies the northwest trending zone of thin salt. For both of these areas the relationship between thin salt and structural lows in the overlying Alibates Formation suggest that dissolution and subsidence have occurred.

The widespread evidence of dissolution suggests that most of the uppermost salts of the Salado Formation have been subject to dissolution.

Seven Rivers Formation

Extensive dissolution of the salts of the Seven Rivers Formation 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. No. 1 Detten and the No. 1 G. Friemel, indicates that the remaining upper Seven Rivers salt is overlain in each well by insoluble residues. Conservative estimates of the thickness of net salt removed by dissolution from the upper Seven Rivers salt range from 24 m (80 ft), from stratigraphic analysis, to 4 to 25 m (13 to 76 ft) in the No. 1 G. Friemel core and from 1.7 to 9 m (5 to 28 ft) in the No. 1 Detten core based on insoluble residues (S. D. Hovorka, personal communication, 1983) (fig. 3). These estimates which were also based on insoluble residues are minimum thicknesses because 2 m (6 ft) of core are missing from the No. 1 G. Friemel well. As mentioned before, the original thicknesses of clean salt are difficult to estimate because clean salt that has been dissolved leaves little evidence of its former presence. Considering the problems in estimating original salt thicknesses from insoluble residues, the larger salt thicknesses estimated from core are not substantially different from thicknesses estimated from stratigraphic analyses.

The Stone and Webster No. 1 Detten and No. 1 G. Friemel wells occur within the northeast-trending zone of thin Seven Rivers salt in eastern Deaf Smith County (fig. 8). This zone of thin salt has been interpreted to have resulted from accelerated dissolution related to northeast-trending fractures (Gustavson and Budnik, in press). The zone of thin salt is overlain by a series of structural depressions on top of the Alibates Formation and on the base of the middle-Tertiary erosional surface (figs. 8, 10, 11). Figure 12 illustrates the relationship between salt dissolution, subsidising overlying beds and surface topography. Basement structure, variations in thickness of Paleozoic units and fractures all trend to be oriented the northeast in this area. In this case core, stratigraphic and structural data suggest that dissolution and subsidence have occurred preferentially along the northeast trend.

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 regional structural depression is indicated on the structure-contour map of the Alibates Formation (fig. 9) for 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 in press). The vertical juxtaposition of thin or missing salt in the Seven Rivers and Salado Formations, a structural trough in the Alibates Formation and outcrop evidence of extension fracturing and folding ksuggest that dissolutin and subsidence have been active beneath the Palo Duro Canyon supports the interpretation that Seven Rivers salts have undergone dissolution across the Palo Duro Basin whenever these salts are not overlain by Salado Formation salts.

Although all core through the upper parts of the Salado Formation and the Seven Rivers Formation 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 River Breaks and the Pecos Plains is active and is responsible for the high chloride loads in streams draining the area surrounding the Souithen High Plains, and for collapse features that hav formed hisotrically (Gustavson and others, 1980a, 1982). Beneath the Souithern 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, 9, and 10). The combinations of structural lows and salt thins occur in eastern Dead 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), 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. On the basis of 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. In turn, this suggests that the other lacustrine basins containing Blancan faunas in the Texas Panhandle formed after the development of the Caprock Calicne. Schultz (1977) has reviewed radiometric age dates obtained from volcanic ashes associated with the Blancan Local Fauna at Mount Blanco. Using data from Boellstorff (1976) and Izette and others (1972), Schultz indicates that the Blanco Formation is at least 1.4 $\pm$ 0.2 m.y. old and is probably greater than 2.8$\pm$ 0.3 m.y. old. Thus, the basins that contain Blancan-age sediments began to form at least 2.8 million years ago and are late Pliocene in age.

Lake basins at Canyon, TX in Randall County and midway along the Swisher and 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 (Schultz, in press; G. E. Schultz, personal communication, 1982; Frye and Leonard, 1967; Hawley and others, 1976; Evans and Meade, 1945). The relationship between thin salt, structural lows on the Alibates

Formation and lacustrine basins with Pliocene and Pleistocene sediments suggests that these basins probably began to form in the Pliocene and early Pleistocene. Deformation of Pleistocene Tule Formation sediemtns suggest that dissolution induced subsidence was locally active during the Pleistocene.

A series of lake basins exists along a northeasterly trend from Hockley to Lamb to Bailey Counties. These lake basins are also underlain by areas of thin salt and complex structural lows on the Alibates Formation. Complimentary structures on the base of the middle Tertiary erosional surfaces are not obvious. All these basins contain lacustrine sediments, termed the Tahoka Formation by Evans and Meade (1945), which were probably deposited during the late Wisconsinan (Reeves, 1976). Thus, these lake basins formed in pre-Wisconsinan time. However, resolution of the relationship of these basins to salt dissolution will require additional data and analysis.

Formation of these large lake basins in the Texas Panhandle 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 lec dunes on the down-wind sides of many laka and playa-lake basins on the Southern High Plains and thought that deflation was a far more important process in forming these basins than were dissolution and subsidence. They did, however, recognize subsidence induced by dissolution along the narrows of Tule Canyon in Briscoe County. Reeves (1966, 1969) suggested that large pluvial lakes formed along drainage channels crossing Cretaceous highs. Later Reeves (1970) suggested that these large lakes were the result of accelerated erosion at intersections of lineaments related to the Earth's regmatic shear pattern.

Field and subsurface evidence suggest that both subsidence, as a result of dissolution, and deflation were important in the development of the larger lake basins that occur in the Texas Panhandle. As a result of locally accelerated dissolution, subsidence of overlying strata occurred and localized depressions that would later become 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 would be located, 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 to collapse as a result of evaporite dissolution. Bachman (1974) suggested that dissolution has occurred intermittently since the Triassic in the Delaware Basin and in southwestern New Mexico. Pre-Ogallala dissolution and the presence of a north-south pre-Ogallala paleovalley near the modern Pecos River in New Mexico have been suggested (Bretz and Horberg, 1949; Reeves, 1972; Kelley, 1972). This evidence, coupled with current evidence for salt dissolution, makes it reasonable to infer that salt dissolution has been active, at variable rates, in the Permian salt basin since Triassic time 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 High Plains. Figure 11, a structure-contour map of the base of the High Plains aquifer, approximates this surface because in most areas the base of the High Plains aquifer is the base of the Ogallala Formation.

The presence of a system of major valleys developed on the middle Tertiary erosional surface is indicated by aligned groups of V-shaped contour lines, which point upslope (fig. 11). Paleostream segments appear to have flowed to the southeast 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.

Middle Tertiary Erosional Surface (Collapsed Area)

The character of the middle Tertiary erosional surface is markedly different northwest of a line that extends from central Parmer County northeast to central Randall County (fig. 11). A series of closed basins occurs on this surface along a trend from Parmer to Randall County. These features are thought to have resulted from dissolution of Seven Rivers salt (Gustavson and Budnik, in press). A major paleoscarp, marking the northesat limit of the Dockum Group, trends extends from northeastern Armstrong County westward to northeastern Oldham County, approximately 96 km (60 mi). This paleoscarp is partly structural--the slope of the erosional surface is deflected from the regional southeast slope to a northeast slope within the dissolution zone of salts of the San Andres Formation (figs. 3, 11). The change in slope probably results from the dissolution of Permian salts and the collapse of overlying strata. A north-south cross section through Armstrong, Carson and Potter Counties shows that the thickness of salt that has been removed increases northward beneath the paleoescarpment coincidental with the progressively greater collapse of the erosional surface (fig. 7).

East and northeast of the paleoscarp that formed on Permian rocks, the middle Tertiary erosional surfcace cuts Permian strata and is characterized by numerous large closed basins that are thought to have resulted from salt dissolution and collape (Gustavson and others, 1980a). Severl of these basins exceed 75 m (250 ft) in depth. Because of the extensive collapse, no trace of the middle Tertriary paleodrainage system exists in the area where Permian rocks subcrop beneath the Ogallala. Although closed depressions are fewer in the area of Triassic subcrop in northern Parmer County, Castro County and eastern Deaf Smith County, most of paleodrainage here is also missing.

Seni (1980) noted that Ogallala sediments as thick as 160 m (500 ft) completely cover all but a few small Cretaceous outliers in the Southern High Plains. In most of the map area, depositional trends shown by sand-percent values 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 (Late 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. The reconstruction, which is necessary to understand 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. Long axes of pebbles in Ogallala gravels near the eastern Caprock Escarpment are 2 to 4 cm (0.75 to 1.5 inches) (S. J. Seni, personal communication, 1982). Slopes of stream channels on both the Southern High Plains surface and the pre-Ogallala surface range from approximately 2-4 m/km. Gole and Chitale (1966), Boothroyd and Ashley (1975), Nummedal and Boothroyd (1976), and Gustavson (1978) observed that slopes of 1-4 m/km are required to transport 2- to 4-cm-long pebbles. Therefore, slope values of Recent and paleostream channels are sufficient to transport gravel in the 2- to 4-cm size range, indicating that if tilting of the Ogallala surface has occurred since its deposition, it has been minor. It is also assumed that neither post-Ogallala erosion or deposition has significantly altered the regional topography and that projection of contours from stream divides across valleys will provide a reasonable approximation of paleotopography as it existed in this region immediately after deposition of the Ogallala Formation.

Regional topography (fig. 2) indicates that the present-day High Plains surface north of the Canadian River is as much as 60 to 75 m (200 to 250 ft) lower than that of the Southern High Plains south of the river. Gustavson and others (1980a) suggested that this is the result of post-Ogallala subsidence caused by regional salt dissolution.

From these assumptions and by removing the dissolution-induced subsidence north of the Canadian River, a generalized map of post-Ogallala topography was developed. 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 alluvial fan morphology and 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 PALEODRAINAGE

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 can be compared to the present-day drainage system (fig. 11). There are several significant similarities between the two drainage systems, which are separated by approximately 100 m (330 ft) of sediment and several million years. Major segments of both drainage systems are roughly parallel, and modern streams tend to occur near the paleostreams in some areas. Since both the pre-Ogallala and the present-day erosional surface are in part parallel, both the Recent 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 southeasterly 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 a similar 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. The significant observation here is that associated pairs of present-day streams and paleostreams flowed at similar angles 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 Recent 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 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, on the other hand, contain many parallel segments and are aligned parallel to regional and local structural elements.

The Pecos and Canadian Rivers

The headwaters of the Pecos River are in north-central New Mexico in the Sangre de Cristo Range. The Canadian River also has its headwaters in the Sangre de Cristo Range 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. 12). The Pecos River turns southward approximately 70° to parallel the western Caprock Escarpment, or the Mescalero Escarpment, of the Southern High Plains (fig. 2). The Canadian River turns abruptly 90° eastward to flow east-northeastward and to separate the Southern and Northern High Plains (fig. 2).

Casual 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 very 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 constructed since the end of deposition of the Ogallala Formation, between approximately 3.0×10^6 and 2.5×10^6 years ago.

Any discussion of the origin of the Canadian and Pecos River Valleys must account not only for the development of the streams across regional slopes and structures but also for the processes or conditions under which these streams formed. In relatively arid climates and with small drainage basin areas, these streams were able to excavate very large valleys during a geologically short period of time.

During late Pliocene to early Pleistocene time, 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 and White River. The literature describing the geomorphic evolution of the Pecos River system was reviewed by Thomas (1972), Reeves (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 this supposed 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 Seni's (1980) interpretation of the placement of Ogallala distributary channels and fan lobes and recent topography, an approximation of topography present at the end of Ogallala time was developed for eastern New Mexico and for the Texas Panhandle (fig. 13). Clearly, the major drainage systems at the end of Ogallala time flowed to the southeast and east.

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 (fig. 14). To understand 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 diversion of the Canadian River and the southward diversion of the Pecos River to their present drainages most likely resulted from dissolution of Permian salts; a process supported by diverse but compelling evidence.

A lucid description of the formation of the Pecos River Valley is given by Kelley (1972). Parts of Kelley's hypothesis explaining the formation of the Pecos Valley are elaborated on or modified in the following discussion of the origin of both the Pecos and the Canadian River Valleys.

During early to middle Tertiary time, uplift of parts of central and north-central New Mexico provided increased sediment loads to streams draining eastward and southeastward across eastern New Mexico and the Texas Panhandle. Regional aggradation formed the alluvial fans that are now known as the Ogallala Formation.

Lake basins containing Pliocene and Pleistocene faunas and floras lie near Mount Blanco in Crosby County, at Cita Canyon in Randall County, along Tierra Blanca Creek in Deaf Smith County along the Double Mountain Fork of the Brazos River in Lubbock County, along Rita Blanca Creek in southern Hartley County and along Tule Creek in Swisher and Briscoe Counties. All these basins overlie zones where accelerated dissolution has apparently occurred.

The former lake basins, exposed along Tierra Blanca Creek, Tule Creek Cita Canyon and Rita Blanca Creek, are thought to be the remnants of a system of subsidence basins resulting from salt dissolution that developed after Ogallala deposition (Compare figs. 8 and 9). If this hypothesis is correct, the Pliocene and Quaternary faunas and floras of these basins may provide minimum ages for the onset of subsidence, which initiated major alterations in the regional drainage of the High Plains. Other subsidence basins that may have developed have been consumed as the Pecos and Canadian Rivers and the Prairie Dog Town Fork of the Red River incised and widened their valleys.

Pecos River Valley

The Pecos River valley parallels the dissolution limits of Permian salts in eastern New Mexico (fig. 14). 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 dissolution. Their form 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 the 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 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 diminished gradient and 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 was probably many southeasterly flowing streams, including streams that occupied the Portales and Simanola Valleys, by regional subsidence resulting from salt dissolution (figs. 13, 14, 15). This model differs from the origins suggested by Morgan (1941), Kelley (1972), Reeves (1972), 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 system. The advantage of this model is that it is consistent with the processes of dissolution and collapse that are currently active and were undoubtedly active during early Pecos development.

Canadian River Valley

The path of the Canadian River from southeastern San Miguel County, New Mexico, is nearly normal to the regional slope of the Southern High Plains. The valley is also normal to several southeasterly trending paleodistributaries within the Ogallala Formation (compare fig. 12 and fig. 14). The Canadian River, flowing east-northeasterly across the Texas Panhandle, is the only major stream within the Texas Panhandle since pre-Ogallala time that did not flow 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 dissolution of salt in the Seven Rivers, San Andres, and Glorieta Formations (fig. 14).

When Ogallala deposition ceased during Pliocene time near the present-day 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 dissolution zone. As subsidence occurred, a series of broad basins formed above the dissolution zone. The late Pliocene Rita Blanca lake beds 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 drainage diversion to the northeast. Because of either flooding or additional subsidence, waters would have overtopped divides between adjacent basins. Overtopping between basins that aligned east-northeast on a surface that slopes to the east-southeast would have resulted in flow to the east-southeast. Eventually divides between basins were eliminated either by overtopping and incision or by further subsidence (fig. 15C). The process described here is one of diversion of preexisting streams rather than one of headward erosion and piracy.

Regional subsidence 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).

Prairie Dog Town Fork of the Red River

The Prairie Dog Town Fork of the Red River from northern Briscoe County to southeastern Randall County, a distance of approximately 65 km (40 mi), parallels the northeastern limit of salts of the Salado and Seven Rivers Formations (fig. 8). Where the river has incised into 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 that approximately 60 m (200 ft) of salt have been lost to dissolution. 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 zo es of salt dissolution and resultng from subvsidence due to salt removal. Veins are mostly filled with fibrous gypsum (satin spar).

The depth of the canyon as well as the location of the canyon is thought to be at least partly due to subsidence along the northeastern margfin 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.

The development of subsidence basins in this area as a result of dissolution during the Late Pliocene may also be suggested by Blancan- aged lacustrine sediments that are preserved in Cita Canyon, a short tributary on the south-west side of Palo Duro Canyon (fig. 16). This lacustrine basin may be a remnant of a system of subsidence basins that developed prior to the incision of the Palo duro Canyon.

Drainage on the Rolling Plains

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 streams. In contrast to the Canadian and Pecos River systems, which formed their valleys primarily by incision, the streams east of the Caprock Escarpment are increasing their areas of influence by headward erosion. Gustavson and others (1981b) have suggested scarp retreat rates in the order of 11 to 18 cy/yr (4.3-7 in/yr). 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. 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 SLAR (side-looking airborne radar) 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 Corps 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 recognized from Landsat imagery of the Rolling Plains of the Texas Panhandle. The lineaments include linear streams, topographic elements, and tonal anomalies. 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 available literature indicates that there is 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 do not agree on the origin of the fracture systems.

Subsidence Basins, Sinkholes, and Fractures

Two surface features genetically related to regional fracture trends that result from salt dissolution and collapse are subsidence, basins or dolines and open surface fractures. These processes and the resulting surface phenomena provide major structural controls for the development of aligned drainage segments in the Rolling Plains of the Texas Panhandle.

To understand better the relation between the processes of dissolution and subsidence or collapse and the karst topography that is developing in the Rolling Plains, a large study area encompassing all of Hall County, Texas, was selected for examination (Gustavson and others, 1982b). In addition to numerous sinkholes, over 200 internally drained, closed depressions (dolines) were recognized (fig. 16). These are broad, shallow, typically oblong depressions that range up to 3.5 km (2 mi) long and 10 to 15 m (30 to 45 ft) deep. Many of these elongate depressions show preferential alignments northwesterly, northerly, and northeasterly (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 f Hall County is characteristic of much of the rest of the Rolling Plains in the Texas Pa andle. Two major physiographic units are distinguished: dissected areas of low to modera e relief and areas underlain by Quaternary fluvial and eolian deposits that are of low relief ar that are relatively undissected. Land forms resulting from dissolution and collapse are recogni ed primarily in the undissected areas underlain by Quaternary deposits. Linear stream segments re recognized primarily in dissected areas.

The shapes of the depressions depicted in figure 16 clearly illustrate preferred orientations of NW.-SE., N.-S. and NE.-SW. (fig. 17). These orientations correspond closely to the orientations of fracture within Triassic and Permian Systems exposed to the west along the western margin of the F lling Plains and along the Caprock Escarpment (Finley and Gustavson, 1981). In areas of expo ed Permian bedrock, in Caprock Canyons State Park, a few kilometers west of the area cover l by the Hall County Study Collins (1983) described the relationship between joints and sync nal depressions. He concluded that dissolution and collapse developed preferentially along joi : paths. It is thought that the depressions or dolines observed on Quaternary surfaces are underlain by synclines similar to those observed by Collins. Furthermore, analysis of a Schl nberger, Inc., Fracture Identification Log from the DOE-Gruy Federal No. 1 Rex White well (f . 20) indicates that the preferred orientation for fractures in the well is 290^{o} to 330^{o}. A seco l concentration of fractures appears between 10^{o} and 30^{o}. These two groupings of fractures re similar to the orientations of closed depressions on the Rolling Plains.

Open fractures at ne surface are difficult to observe over a large region because they are either covered by natur processes or infilled by landowners in agricultural areas such as the Rolling Plains. Howeve evidence of six surface fractures was observed along Highway 2639 in Hall County (fig. 16). vo of the six surface fractures observed in Hall County were open intermittently between n 1979 and 1984 to widths of 30 cm (12 inches) where they crossed cultivated fields. The emnants of four previously open tension fractures were preserved as diagonal patches across lighway 2639; the open parts of these fractures in adjacent fields had been filled by the landowners. Fractures that cross 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 of 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 nearly every county within the Pecos Plains, Canadian River Breaks, and Rolling Plains reported that sinkholes had formed in their county (fig. 19). Highway maintenance supervisors from nine of the same counties reported that sinkholes or fractures had formed in the highway right-of-ways 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.

The absence of sinkholes and fractures indicates that recent catastrophic subsidence or collapse as reflected by the formation of sinkholes and open surface fractures is restricted to lands overlying areas of relatively rapid salt dissolution. Gustavson and others (1981a) previously thought that the lack of development of sinkholes and fractures on the Southern High Plains indicated that salt dissolution was not active there. However, after additional core analyses, the lack of sinkhole development seems only to suggest 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 imagery (Finley and Gustavson, 1982; Gustavson and others, 1982b). Linear stream segments in Hall County were identified from black and white aerial photgraphs (fig. 16). Linear stream segments appear primarily in dissected areas. Undissected areas or slightly dissected areas have few linear stream segments but contain most of the closed depressions.

Linear stream segments have preferred orientations that are NW.-SE., N.-S., and NE.-SW. and are generally comparable to the preferred orientations of closed depressions (fig. 16). 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 surfaces beneath the Rolling Plains. The approximate limits of Permian bedded salts that are undergoing dissolution beneath the Rolling Plains have been identified (Presley, 1979a, b; Gustavson and others, 1980a). The 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 non-salt-bearing well to the east. Even with this potential source of error, a strong relation still 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 fracture systems, 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 posssibly the location of surface streams.

A conceptual model of a salt dissolution surface can be developed on the basis of an understanding of the following: (1) the landforms that are developing as a result of dissolution and collapse, (2) the spatial distribution of salt dissolution fronts, and (3) the variability of salt dissolution rates that apply to the Rolling Plains. Sinkholes and closed subsidence basins exist in areas where salt removal has been locally accelerated and where caverns formed. Closed depressions tend to be oriented parallel to the orientations of known fracture trends, which suggests that dissolution is accelerated along fracture traces. Field observations imply that fractures exposed along the Caprock Escarpment are not randomly distributed but exist in groups with similar preferred orientations (Collins, 1983). If the fractures beneath the Rolling Plains also occur in groups with preferred orientations, then this supports the inference that dissolution has been accelerated along fracture trends beneath elongated and aligned closed depressions.

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 successively higher salt-bearing unit has undergone progressively 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 High Plains. This pattern suggests that dissolution of different salt-bearing units occurs at similar rates across the eastern part of the dissolution zone. Although this may be true on a long-term (geologic) basis, it is certainly 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 4 orders of magnitude (vertical, 0.062×10^{-3} to 94.14×10^{-3} cm/yr; horizontal, 0.3 to 81.71 cm/yr; 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 periods of time 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, suggests that the internally variable rates of dissolution may average out over geologically significant lengths of 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 open at the surface that are also parallel to regional fracture trends or to the trend of the dissolution zone (Goldstein, 1982). Closed subsidence depressions and open surface fractures are similar to regional fracture trends and, in turn, have influences 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. Little interconnecting drainage exists between these lake basins, known by various names including, small lake basins, playas, and buffalo wallows except following periods of very heavy rainfall. The possible origins and ages of these enigmatic features have been described by Gilbert (1895), Evans and Meade (1945), Judson (1950), Gustavson and others (1980a), Price (1958), Reeves (1965, 1966, 1970, 1971b) and Woodruff and others (1979). They 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 report because they only rarely contribute runoff to the regional drainage system.

The second type of drainage on the Southern High Plains is one composed of a series of elongate stream valleys having very narrow drainage basins. These drainage elements 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 drain 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 have their headwaters in eastern New Mexico, where both streams flow to the southeast (fig. 2). In the western part of the Texas Panhandle, both streams flow first eastward then northeastward. These streams probably would not have developed where they are as a simple consequence of adjustment to regional southeast slope.

Furthermore these streams cross the trends of Ogallala distributaries at high angles (fig. 13). The position of this stream system is apparently not related to either regional slope nor is it inherited from Ogallala deposition. Figures 8, 9, and 10 illustrate a zone of thin salt in the Seven Rivers Formation overlain by structural lows on the Alibates Formation beneath the valleys of these streams. The structure-contour map on the base of the Ogallala Formation (High Plains aquifer) (Knowles and others, 1982) shows a series of closed structural depressions, which tend to overlie depressions on the Alibates surface, and a northeast grain to the paleotopography (fig. 11). 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. This evidence leads to the interpretation that Tierra Blanca Creek and Frior Draw 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 dissolutoin and subsidence. Surface erosion by wind and streams has probably played an important role in lowering the High Plains surface along Tierra Blanca Creek (see Gustavson and Budnik, in press, for a detailed discussion of the development of Tierra Blanca Creek).

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

The timing of the formation of these lacustrine basins is problematical because in each case the contained lake sediments provide only a minimum age. However, it seems 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 the case. Therefore, the range of ages of lake sediments, from Pliocene to Pleistocene, suggests that the range in timing of dissolution for parts of the Southern High Plains is also Pliocene to Pleistocene.

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

Insufficient information is available to fully characterize the development of Yellow House, Blackwater, and Running Water Draws. Certain 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 these have been described as the Running Water Draw - White River lineament (Finch and Wright, 1970). On the basis of the recognition of this lineament and of 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 NW.-SE.-trending fault.

Farther south are Blackwater and Yellow House Draws. Like the Running Water Draw - White River drainage element, these streams occupy broad shallow valleys. In these cases, parts of both of these broad shallow valleys have been interpreted as being remnants of a partly filled Portales paleovalley (Reeves, 1972; Price, 1944; Fiedler and Nye, 1933; Baker, 1915.) 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 a contour map of the pre-Ogallala erosional surface (Cronin, 1961; 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 the 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 Couinties overlie areas of thin Salado salt, structural lows on the Alibates Formation and paleotopographic lows on the middle-Tertiary erosional surface (figs. 8, 9, 10, 110. Blanco Formation lacustrine deposits occur above the area of thin salt in the White River area. Suggesting that dissolution and subsidence may have influenced the development of these streams locally.

EVOLUTION OF REGIONAL PHYSIOGRAPHY

Late Tertiary

Regional drainage in late Tertiary time, 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 lobes of the Ogallala bahada.

Interlobe areas were topographically low and may have been collection troughs for the discharge of fan distributaries. The present-day valleys of the Canadian, Brazos, Colorado Rivers, and Prairie Dog Town Fork of the Red, lie along the trends of projections of interlobes in the eastern Texas Panhandle (fig. 13).

The previous discussion has suggested that drainage development in the Texas Panhandle and eastern New Mexico was strongly influenced by structure in the form of surface subsidence induced by dissolution of Permian salts. It is also clear that 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. These are the upturned edges of the basin where Permian strata are closest to the surface (fig. 1). Active dissolution in the form of historical collapse events and high choloride loads in local springs characterize these areas. In the interior of the basin where Permian salts are deeply buried by sediments of the Dockum Group and Ogallalas and Blackwater Draw Formations dissolution is much slower. Here subsidence has occurred without resulting in large-scale collapse breccias in the subsurface or in catastrophic collapse features such as sinkhole at the surface.

Locally dissolution has been influenced by both basement faulting and by fracture systems associated with basement faulting. Accelerated dissolution of the salts of the Seven Rives Formation beneath Tierra Blanca Creek in eastern Deaf "Smith County appears to be related to a northeast trending set of fractures (figs. 8, 19) (Gustavson and Budnik, in press). In the Rolling Plains collapse features consisting of small synclines and dolines are elongated parallel to regional joint trends (figs. 16, 17) suggesting that dissolution has been accelerated along regional joint trends (Gustavson and others, 1982; Collins, 1983, in press).

Southeast trending basement faults that are part of the complex of structure that makes up the Amarillo Uplift parallel and underlie salts undergoing dissolutin along the soutwest side of the Amarillo Uplift. Salt margins as mapped in figure 3 are parallel to these faults and to fracture systems mapped by Colliins (1984). 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.

Because of a reduced source area, 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.

Following Ogallala fluvial deposition a long period of eolian deposition occurred punctuated by periods of soil development. Ogallala deposition culminated with the formation of the Caprock caliche.

Late Pliocene to early 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 from subsidence caused by salt dissolution. If this is true, then the Rita Blanca lacustrine sediments, lying at the northern margin of the Canadian River Valley; the Cita Canyon lacustrine sediments, lying adjacent to the western rim of the Palo Duro 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 Blanco Creek and the White River.

Subsidence basins on the Ogallala surface along the present trend 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-day Canadian River near the Ute Reservoir. No unequivocal evidence of the proto-Canadian southeast of the Ute Reservoir is recognized in New Mexico, but it may have been a tributary of the Pecos-Portales-

Brazos system. By the end of this time period, 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. A Canadian River terrace east of Lake Meredith lies about 125 m (400 ft) below the High Plains surface and contains Pearlette type "O" (Lava Creek B) dash (G. Izette, written communication), 1979.

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 system. Timing of the diversion of the Pecos-Portales-Brazos system is not clearly understood, but some speculations have been offered. Hawley and others (1976, p. 245) thought that any "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 for the upper Pecos from Roswell to Fort Sumner, New Mexico, because this area has also undergone extensive subsidence from dissolution of evaporites. Consequently, an understanding of the timing of Pecos River diversion that is based on relating features like the Portales Valley to Quaternary surfaces will always be subject to question.

Reeves (1972) reviewed the literature describing the Portales Valley and concluded that since the oldest terrace found both above and below the point of diversion is the Diamond-A Mescalero, 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 and is therefore about 610,000 years old. The Mescalero surface is capped by the Mescalero caliche, which ranges in age from 510,000 years 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 ashfall 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 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 system. This is approximately the elevation of the Mescalero Diamond-A Plain when it is 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) suggested 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 late Pleistocene and perhaps as early as late Kansan time. 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 the time of incision of the Diamond-A Mescalero Plain, about 600,000 year ago, the Pecos has incised its valley approximately 65 m (200 ft).

Diversion of more southerly streams probably predated diversion of the Pecos-Portales system; for example, the threshold to the Simanola Valley lies 254 m (800 ft) above the Pecos River and appears to lie largely above the Mescalero surface. This suggests that diversion of this stream occurred during the early Pleistocene.

Late Pleistocene

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 is well established, and local relief along major segments of the streams is approximately 200 m. Drainage to the east during Kansan time near the Texas-Oklahoma border is poorly understood. During Kansan time, the Seymour Gravel was 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 (G. Izette, personal communication, 1981; 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" ash associated with the Seymour gravels, then the Kansan 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 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 (Baumgardner and Cavan, in press; Cavan and Baumgardner, in press a, b). 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 series 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 streams that are 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 a series of paleosols. Soils of the Miles, Springer, Olton Series, and related associations are extensively developed on these the surfaces all suggest that the surfaces were previously much more extensive. Much of the Rolling Plains east of the Southern High Plains was probably covered with an alluvial veneer during late Pleistocene and Holocene time.

Geomorphic evidence based on analysis of remnants of these surfaces provides insight into the evolution of drainage systems in the Rolling Plains during the late Wisconsinan and Holocene. During Wisconsinan time, 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-day 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 surface in Hall County appears to have undergone extensive local subsidence because of evaporite dissolution. Subsidence basins on the Quitaque surface are oriented in a way that is 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 a process 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 perimeter of the Southern High Plains provides a rationale for answering several perplexing 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 column of rock removed from these valleys are accounted for by subsidence of the valley floor. As much as 60 m (200 ft) of salt has 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's depth. Fracturing and minor faulting, attendant with subsidence, has mechanically broken the rocks exposed along the canyon and valley walls and, thus, made them more accessible to erosion. Collectively, the processes of dissolution, subsidence, and mechanical disruption of overlying sediments have had a major role in 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 Brazos, and the Canadian, and Colorado Rivers all lie either in the eastward extensions of interfan areas or in topographic lows on the Ogallala surface. The orientation and location of segments of tributaries of these streams are strongly influenced by regional tectonic jointing and dissolution. Forty percent of the length of major tributaries lies parallel to or within 20 degrees of the orientation of nearby salt dissolution fronts. The preferred orientations of straight segments of minor tributaries are NW.-SE., N.-S., NE.-SW., and these correspond to the preferred orientations of both the regional fracture system and the elongate subsidence basins. In turn this suggests 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, the valleys of Yellow House Draw and Running Water Draw - White River lineament. Yellow House Draw lies in an interfan area, and Running Water Draw - White River lineament seems to occupy a valley that may have originated as a distributary on the Ogallala fan surface. Locally, however, both of these streams may have been influenced by dissolution and subsidence.

Frio Draw is a major tributary of Tierra Blanca Creek; these two stream segments are the only streams on the Southern High Plains surface that drain northeast, normal to the regional slope. 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 accelerated 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 the late Pliocene Ogallala Formation. Lacustrine basins within the dissolution zones that ring the Southern High Plains probably resulted from subsidence. Lacustrine sediments preserved in basins associated with the Canadian River Valley Tierra Blanca Creek and with 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 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 Gravel containing Pearlette type "O" (Lava Creek B) volcanic ash occurs 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-day 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, vertebrate and invertebrate faunas, and archeological materials, all fans are probably 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 segments are probably all Holocene features.

On the surface of the Southern High Plains, the timing of the establishment of many drainage elements is questionable. Those parts of the Yellow House Draw and Running Water-White River lineament having topographically controlled locations on the surface of the Ogallala fan may have begun to develop as early as early Pleistocene or late Pliocene. The development of Frio Draw and Tierra Blanca Creek, on the other hand, is understood relatively well because Tierra Blanca Creek drains the lacustrine basins in which Pliocene and Kansan vertebrate fossils have been observedat Hereford and Canyon, Texas. Therefore, the present-day drainage of Tierra Blanca Creek and Frio Draw is a late Pliocene - Pleistocene feature.

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Figure Captions

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.

Figure 2. Physiography of eastern New Mexico and the Texas and Oklahoma 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 is apparent that the northern side of the valley is approximately 80 m (250 ft) lower in elevation than the south rim of the valley.

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 towards 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 in the vicinity of Hutchinson County. A marginal 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 underlain 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 No. 1 Rex White
2. DOE - Gruy Federal No. 1 Grabbe
3. Stone and Webster Engineerng Corporation No. 1 Sawyer
4. Stone and Webster Engineering Corporation No. 1 Mansfield
5. Stone and Webster Engineering Corporation No. 1 Detten
6. Stone and Webster Engineering Corporation No. 1 G. Friemel
7. Stone and Webster Engineering Corporation No. 1 Zeeck

8. Stone and Webster Engineering Corporation No. 1 J. Friemel

9. Stone and Webster Engineering Corporation No. 1 Harman

10. Stone and Webster Engineering Corporation No. 1 Holtzclaw

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

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

Figure 6. Stratigraphic section illustrating dissolution of Salado Formation salts 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 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 location of section A-A'.

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, 1981.

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 with sparse data show little in the way of structures.

Figure 10. Structure-contour map on the Alibates Formation based on reflection seismic velocity data. See figure 11 for location. Figure from Gustavson and Budnik (in press).

Figure 11. Structure-contour map on the base of the Ogallala Formation (derived from Knowles and others, 1982). Paleo streams are interpreted from contour Vs pointing up-slope. Modern drainage is superimposed to show the relationship between modern drainage and structure and between modern and paleodrainage. Inset in Deaf Smith County gives the location figure 10.

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. Note that units underlying the Seven Rivers Formation thicken in the same area that dissolution has occurred. See figure 8 for the location of Section E-E'.

Figure 13. Regional topography in eastern New Mexico and the Oklahoma and Texas Panhandles at the end of late Pliocene time. 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 Panhandle and the Oklahoma Panhandle, 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 head into interfan areas. Post-Ogallala drainage was probably to the east and southeast on this surface.

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 Draw that are essentially flowing parallel to regional slope.

Figure 15. Stages in the evolution of the drainage of eastern New Mexico and the Texas and Oklahoma Panhandles since the end of Ogallala deposition. The sizes of dissolution induced subsidence basins are speculative because only remnants of these features may be preserved. Rather than a few large basins there may have been numerous small basins.

Figure 16. Location of sinkholes, dolines (closed depressions) 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 colored aerial photography flown in 1979.

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

Figure 18. Fracture orientations from nine surface locations in the Texas Panhandle and eastern New Mexico and from Schlumberger Inc. Fracture Identification Logs from eight test wells in the Texas Panhandle.

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

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 lie within 20 degress of the orientation of the one or more of these salt limits.

See separate file for Figure 1

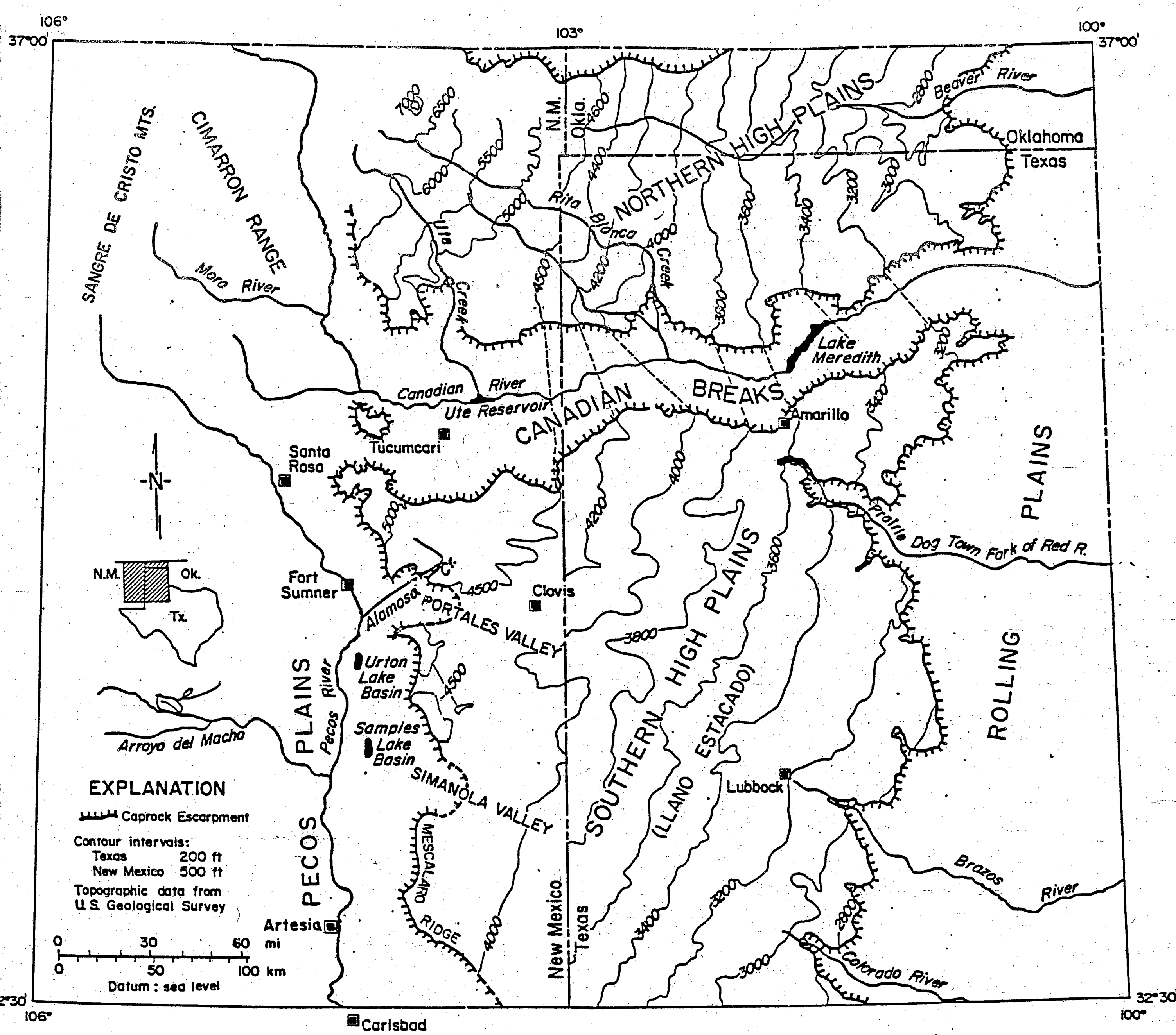


Figure 2. Physiography of eastern New Mexico and the Texas and Oklahoma Panhandles. Dashed lines tie topographic contours across the Canadian Breaks. If the strike of contour lines on the Southern High Plains is projected across the Canadian River Valley, it is apparent that the northern side of the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

See separate file for Figure 3

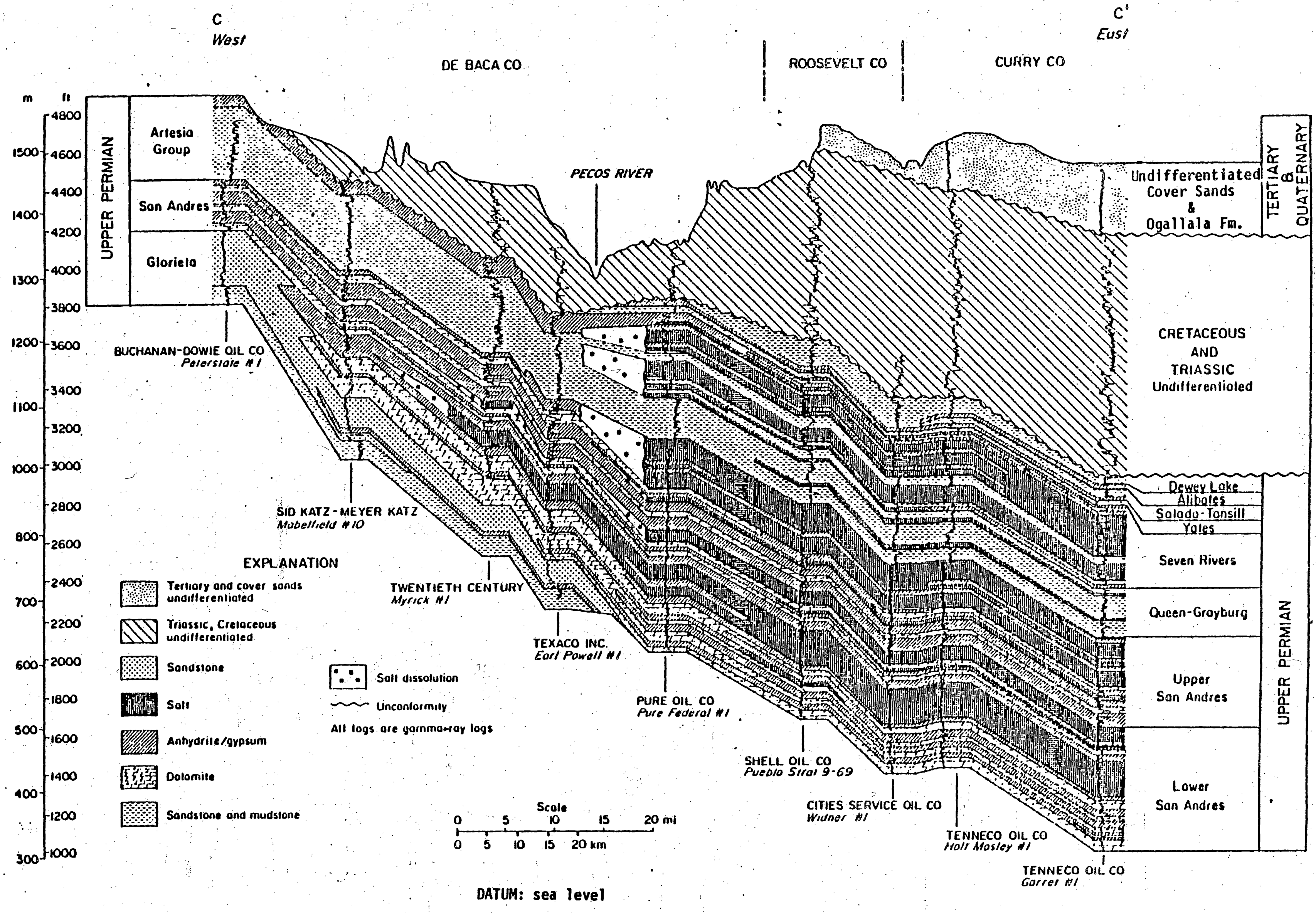


Figure 4. Stratigraphic section illustrating salt dissolution and collapse of strata beneath the Pecos River. See figure 3 for the location of cross section C-C'. From GC 82-7.

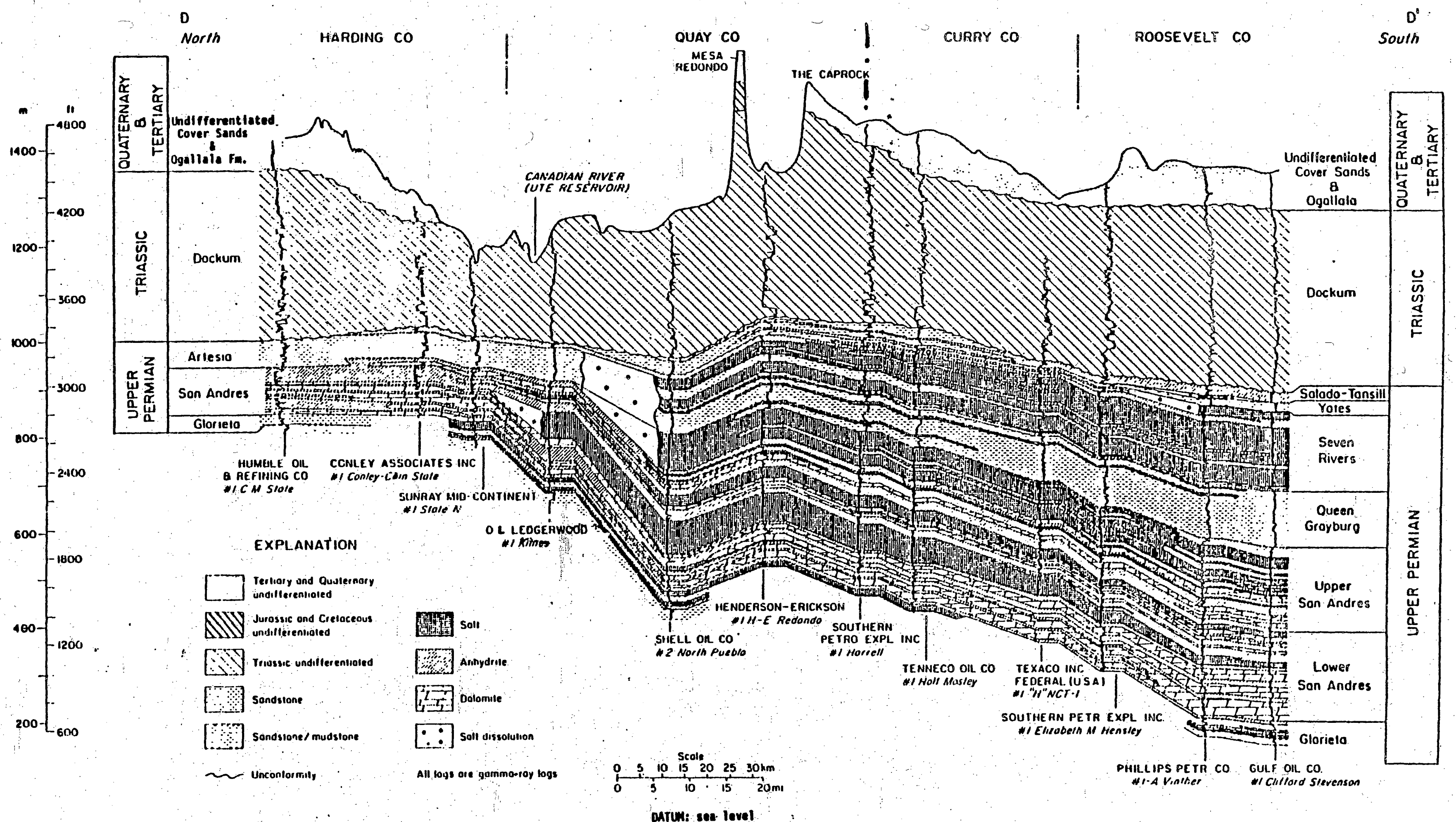


Figure 5. Stratigraphic section illustrating salt dissolution and collapse of strata beneath the Canadian River. See figure 3 for the location of cross section D-D'. From GC 82-7.

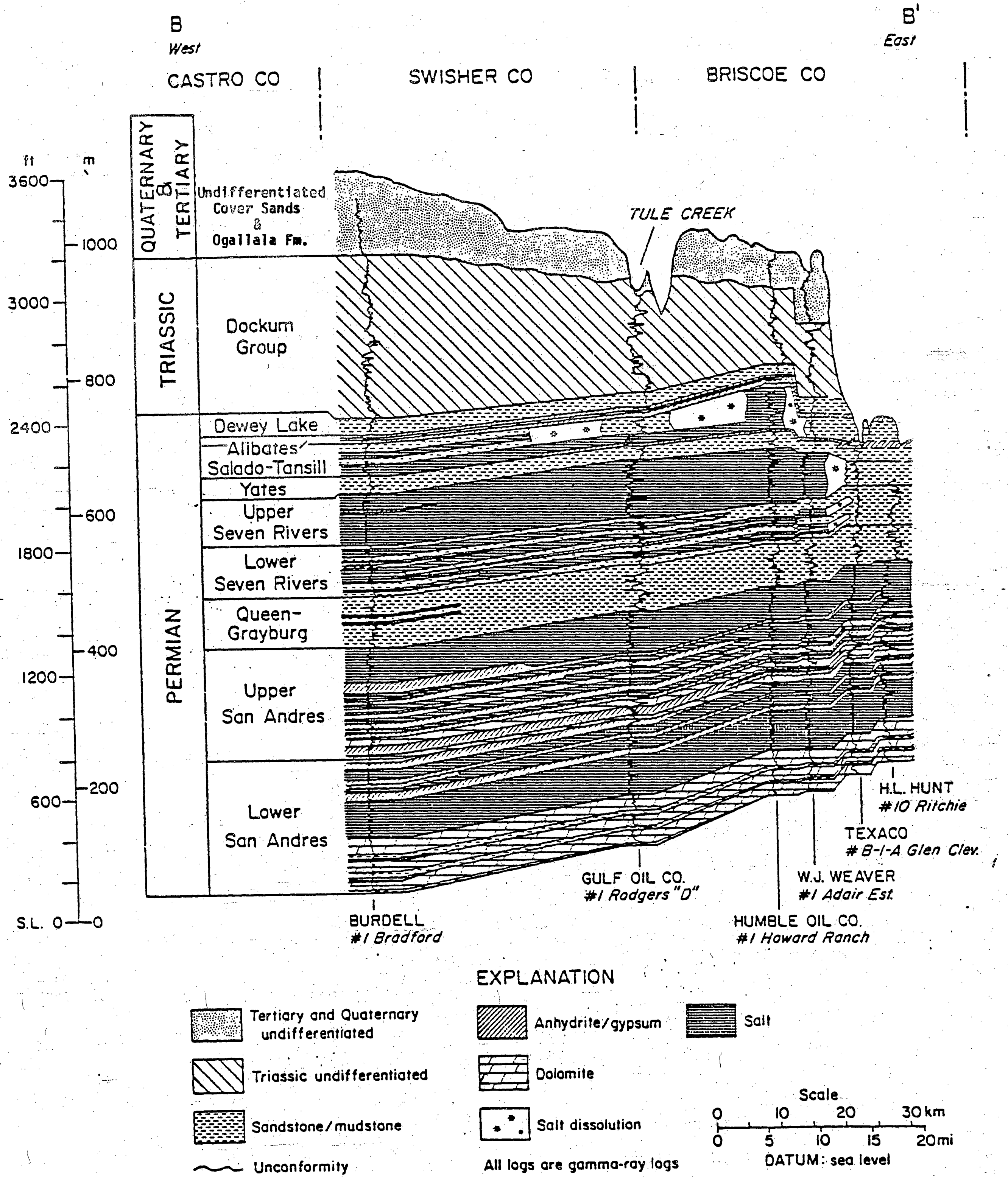


Figure 6. Stratigraphic cross section illustrating dissolution of Salado Formation salts beneath Tule Creek. Tule Formation lacustrine beds, not shown on the cross section crop out along the valley sides of Tule Creek. See figure 3 for the location of section B-B'. From GC 82-7.

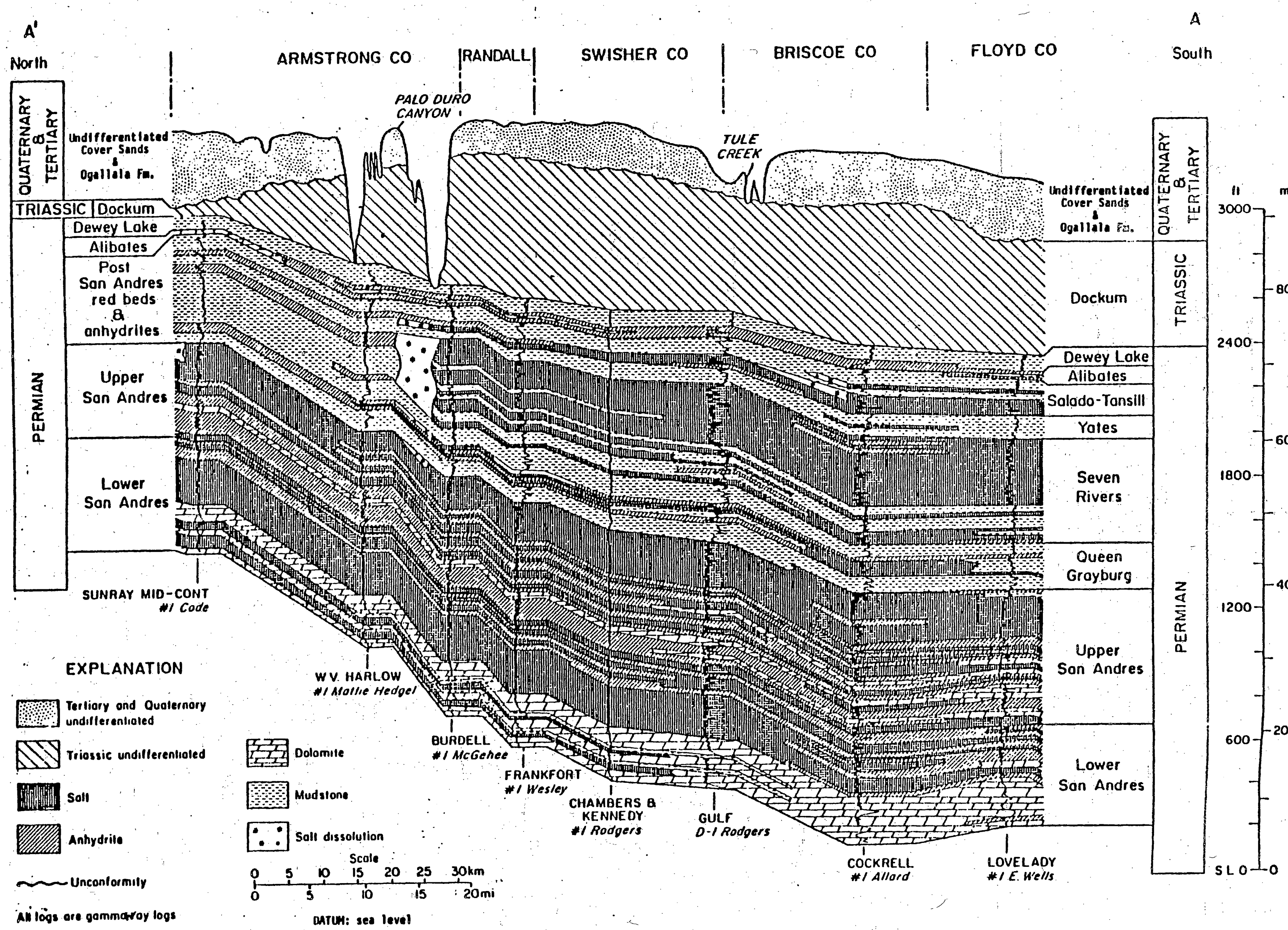


Figure 7. Stratigraphic section illustrating salt dissolution and collapse of overlying strata beneath the Palo Duro Canyon (Prairie Dog Town Fork of the Red River). See figure 3 for location of section A-A'. From GC 82-7.

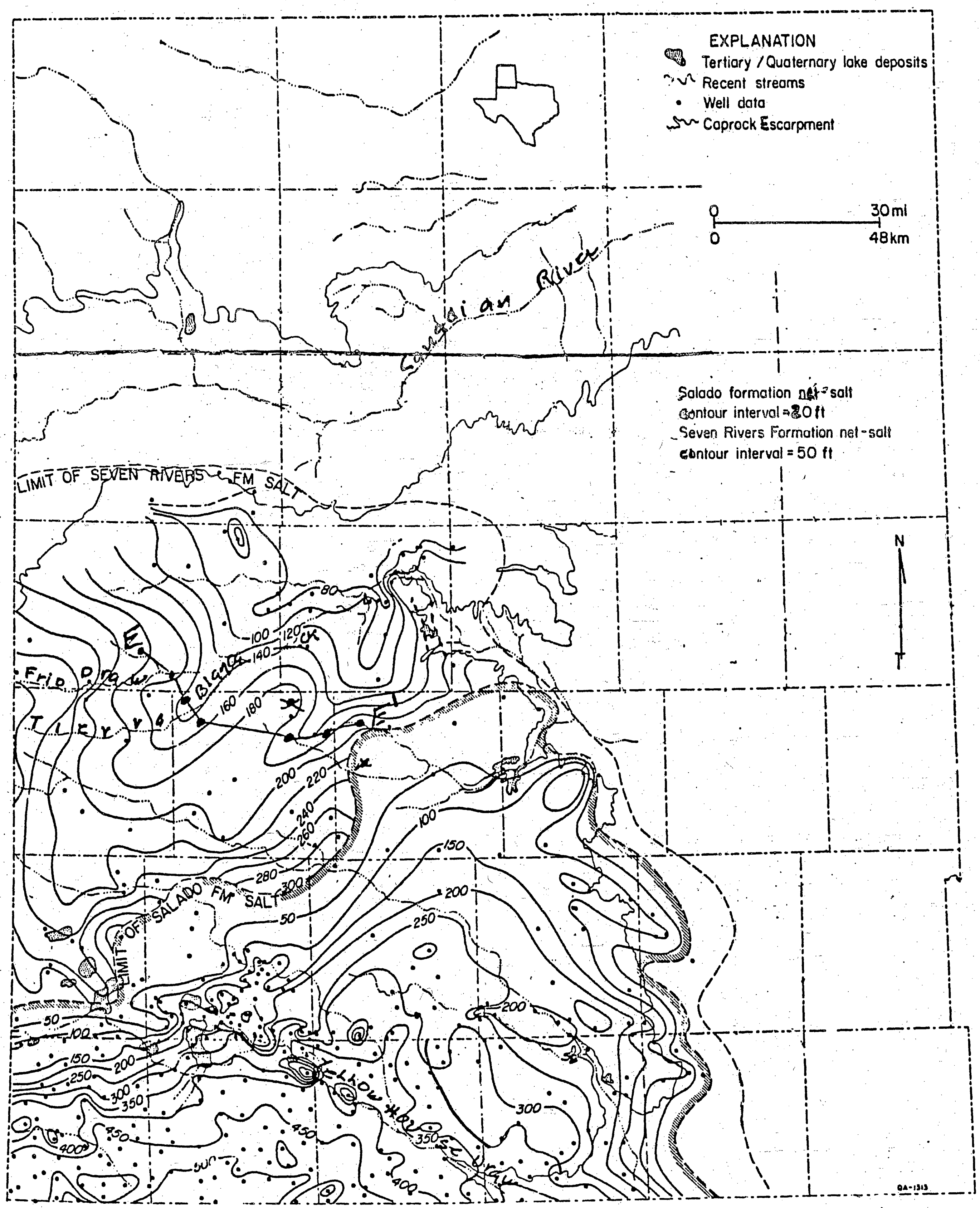


Figure 8. Net-salt map of parts of the Salado and Seven Rivers Formations. Net salt thickness of the Seven Rivers Formation is shown only where Seven Rivers salts are not overlain by salts of the Salado Formation. Adapted in part from Gustavson and others, 1981.

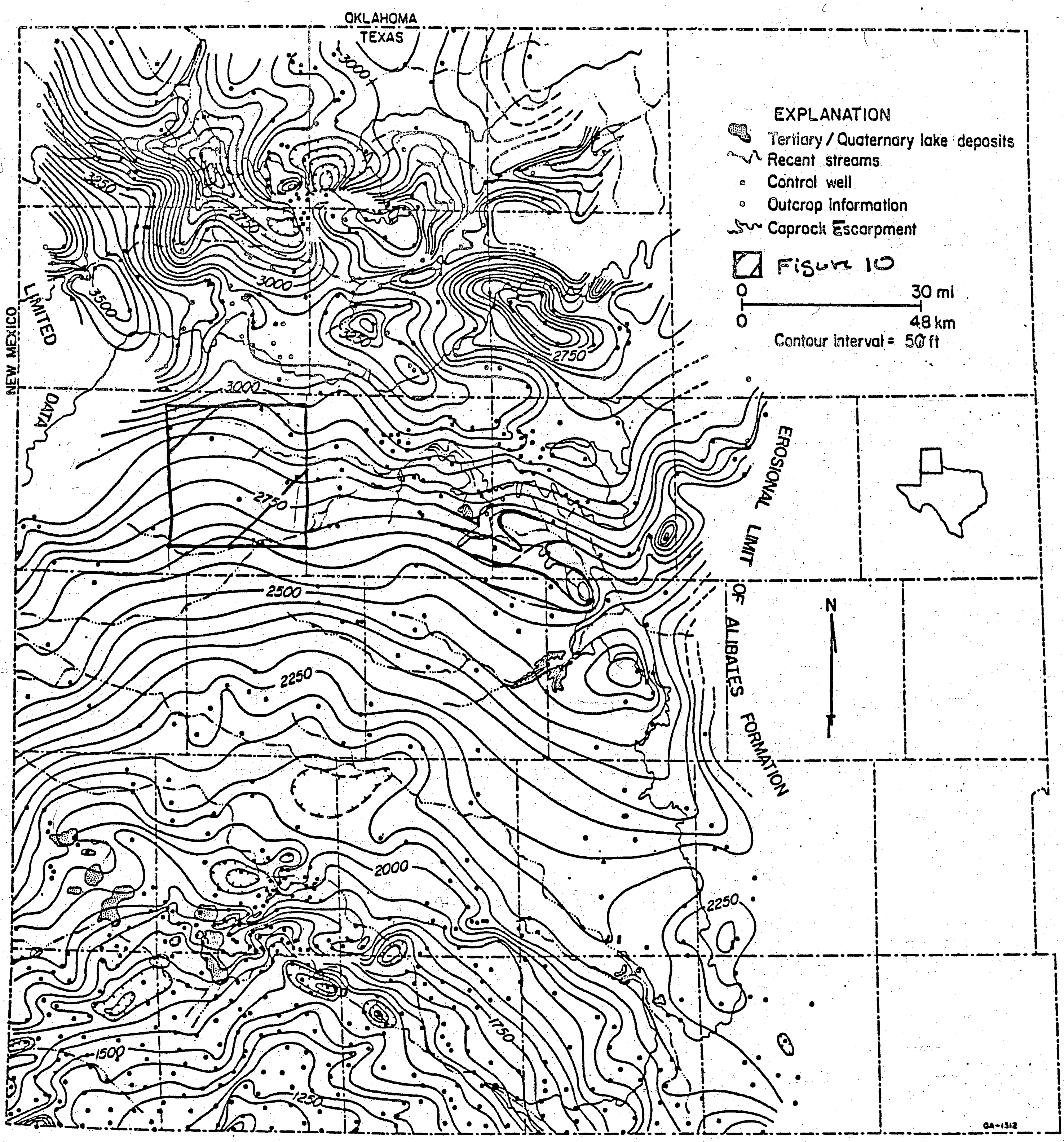
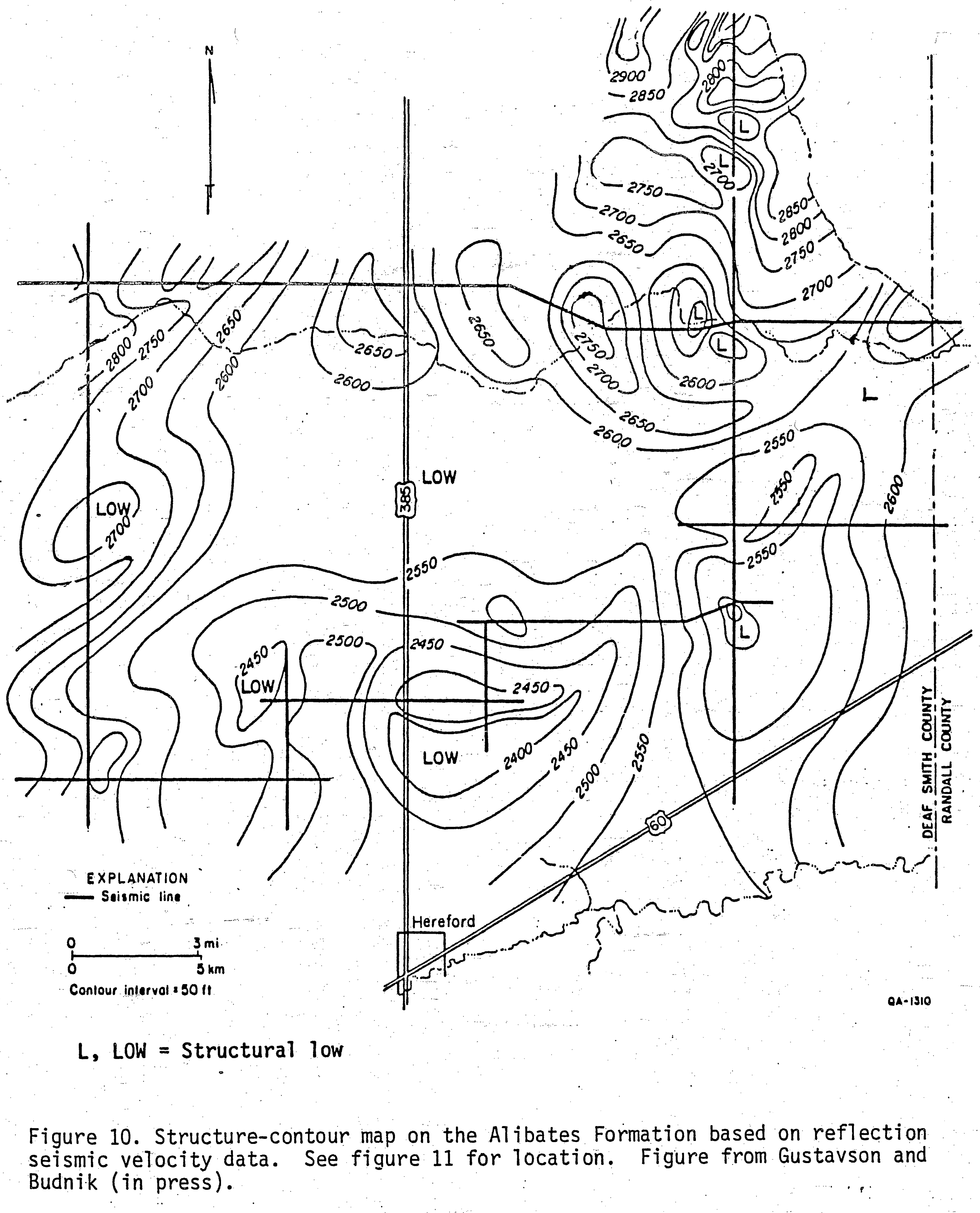


Figure 9. Structure-contour map on the top of the Alibates Formation. Note that structures are complex and well defined in areas of sufficient data, but with sparse data show little in the way of structures.



L, LOW = Structural low

Figure 10. Structure-contour map on the Alibates Formation based on reflection seismic velocity data. See figure 11 for location. Figure from Gustavson and Budnik (in press).

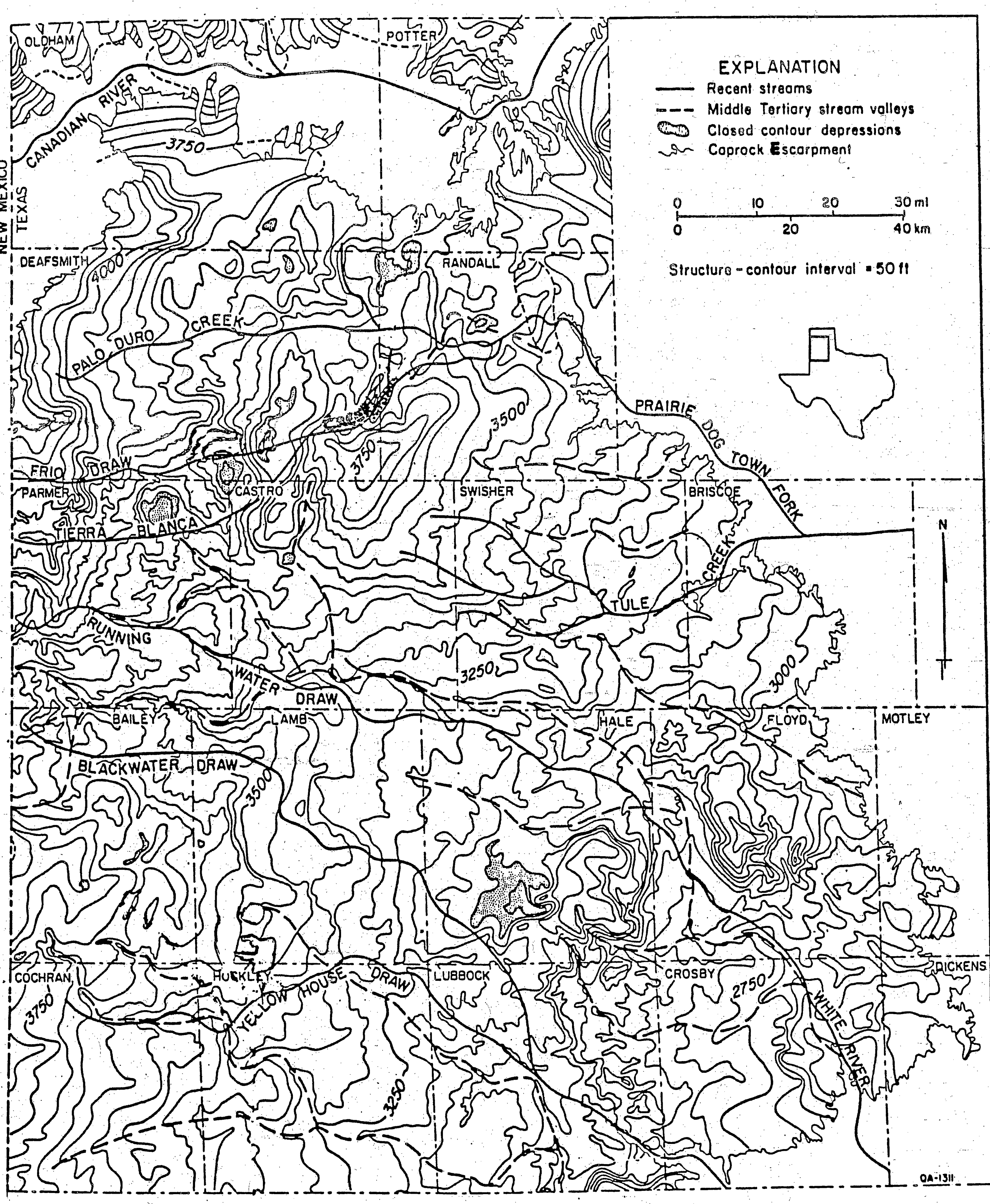


Figure 11. Structure-contour map on the base of the Ogallala Formation (derived from Knowles and others, 1982). Paleo streams are interpreted from contours Vs pointing upslope. Modern drainage is superimposed to show the relationship between modern drainage and structure and between modern and paleodrainage. Inset in Deaf Smith County gives the location figure 10.

See separate file for Figure 12

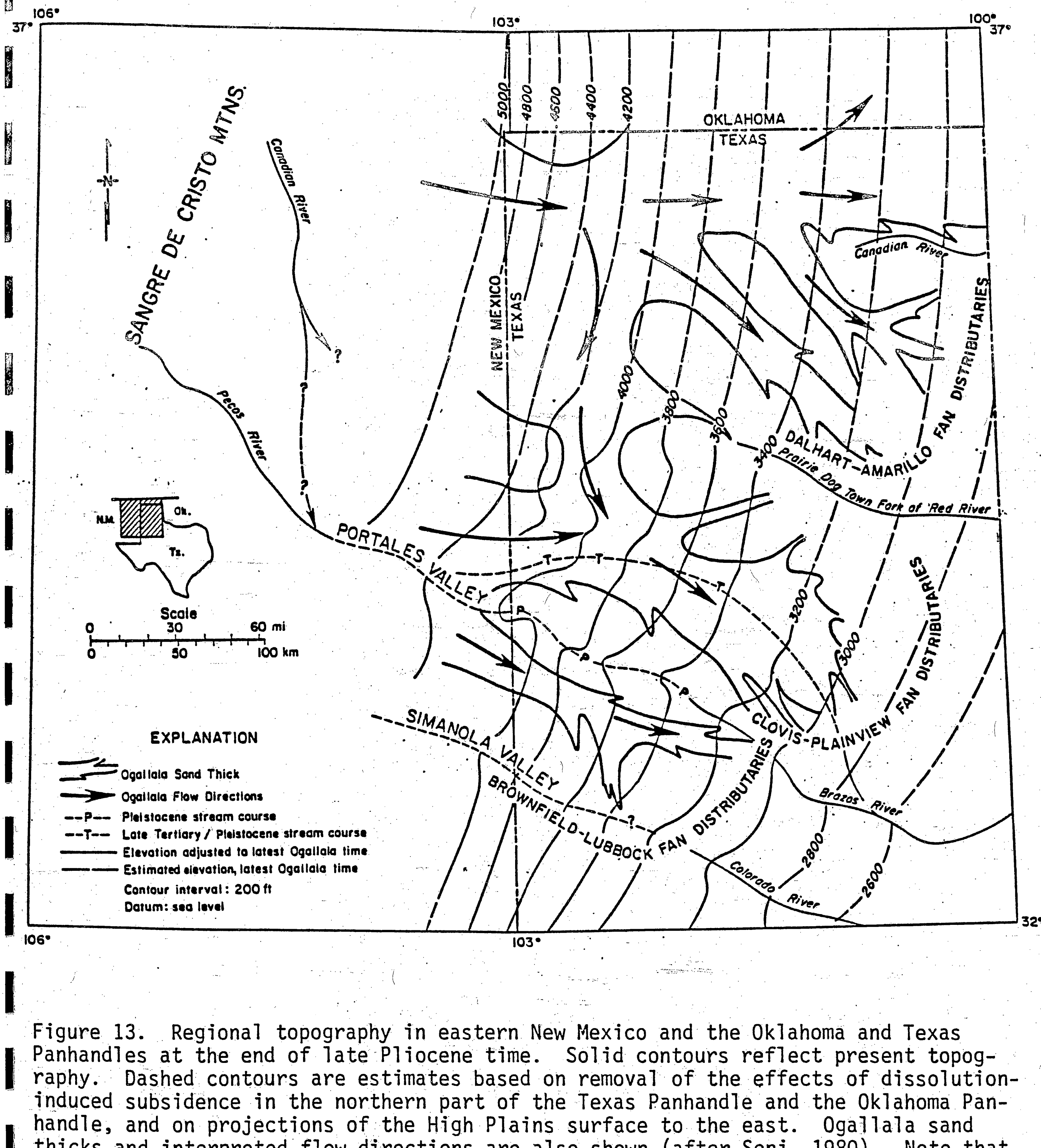


Figure 13. Regional topography in eastern New Mexico and the Oklahoma and Texas Panhandles at the end of late Pliocene time. Solid contours reflect present topography. Dashed contours are estimates based on removal of the effects of dissolution-induced subsidence in the northern part of the Texas Panhandle and the Oklahoma Panhandle, 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 head into interfan areas. Post-Ogallala drainage was probably to the east and southeast on this surface.

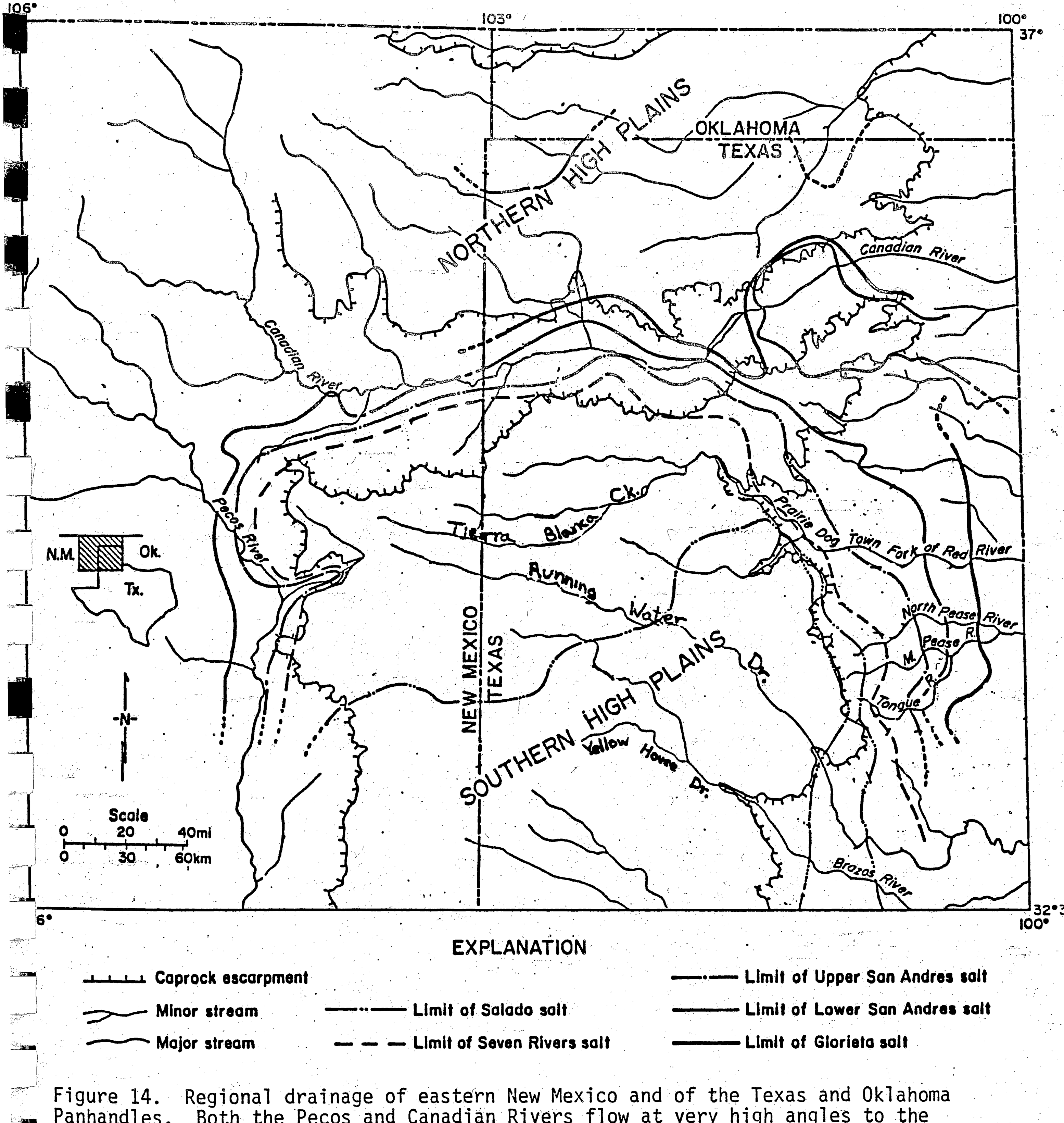


Figure 14. Regional drainage of eastern New Mexico and of the Texas and Oklahoma Panhandles. Both the Pecos and Canadian Rivers flow at very high angles to the regional southeasterly slope and to streams such as Running Water and Yellow House Draw, which are essentially flowing parallel to regional slope.

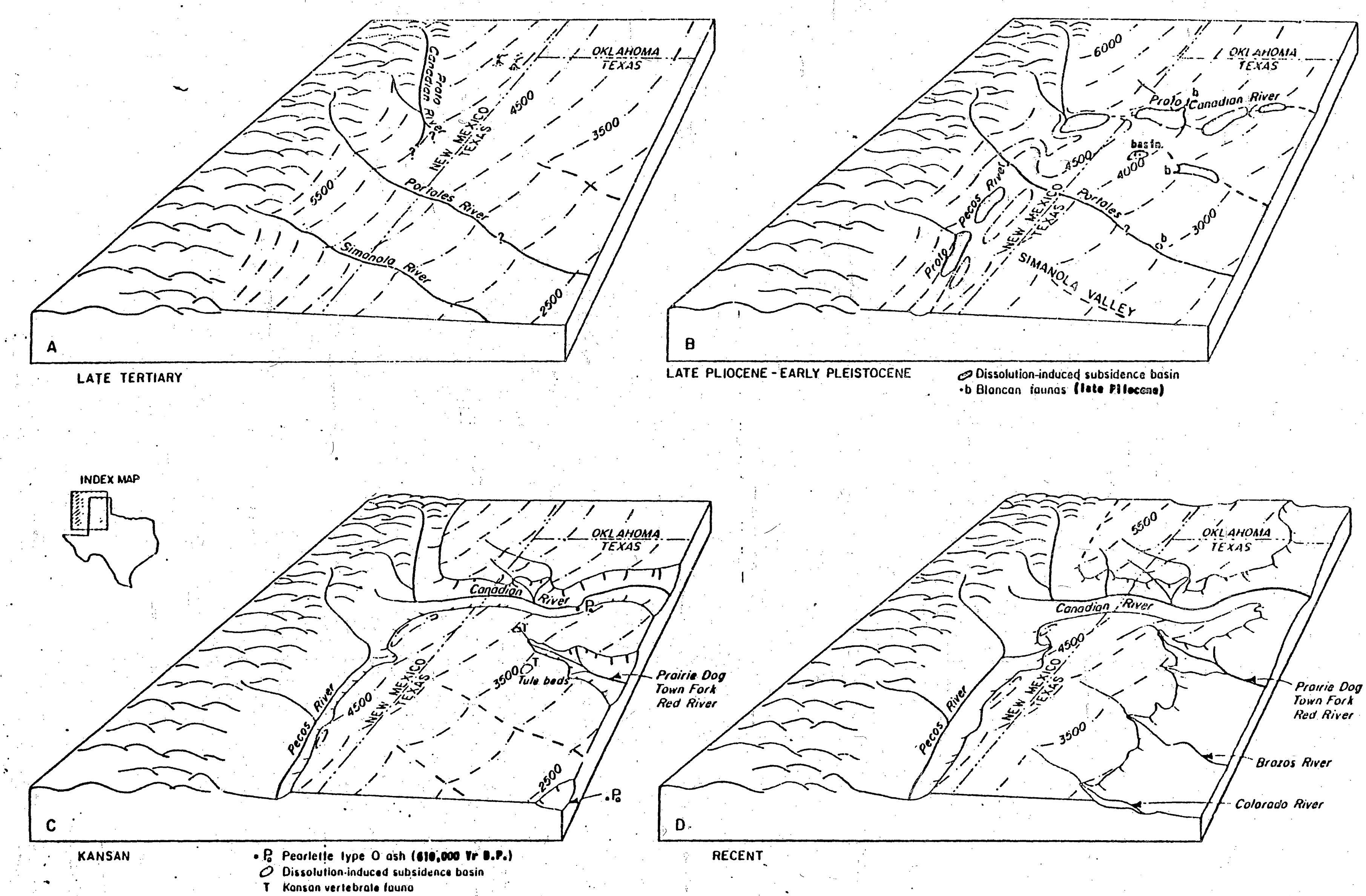


Figure 15. Stages in the evolution of the drainage of eastern New Mexico and the Texas and Oklahoma Panhandles since the end of Ogallala deposition. The sizes of dissolution induced subsidence basins are speculative because only remnants of these features may be preserved. Rather than a few large basins there may have been numerous small basins. From GC 82-7.

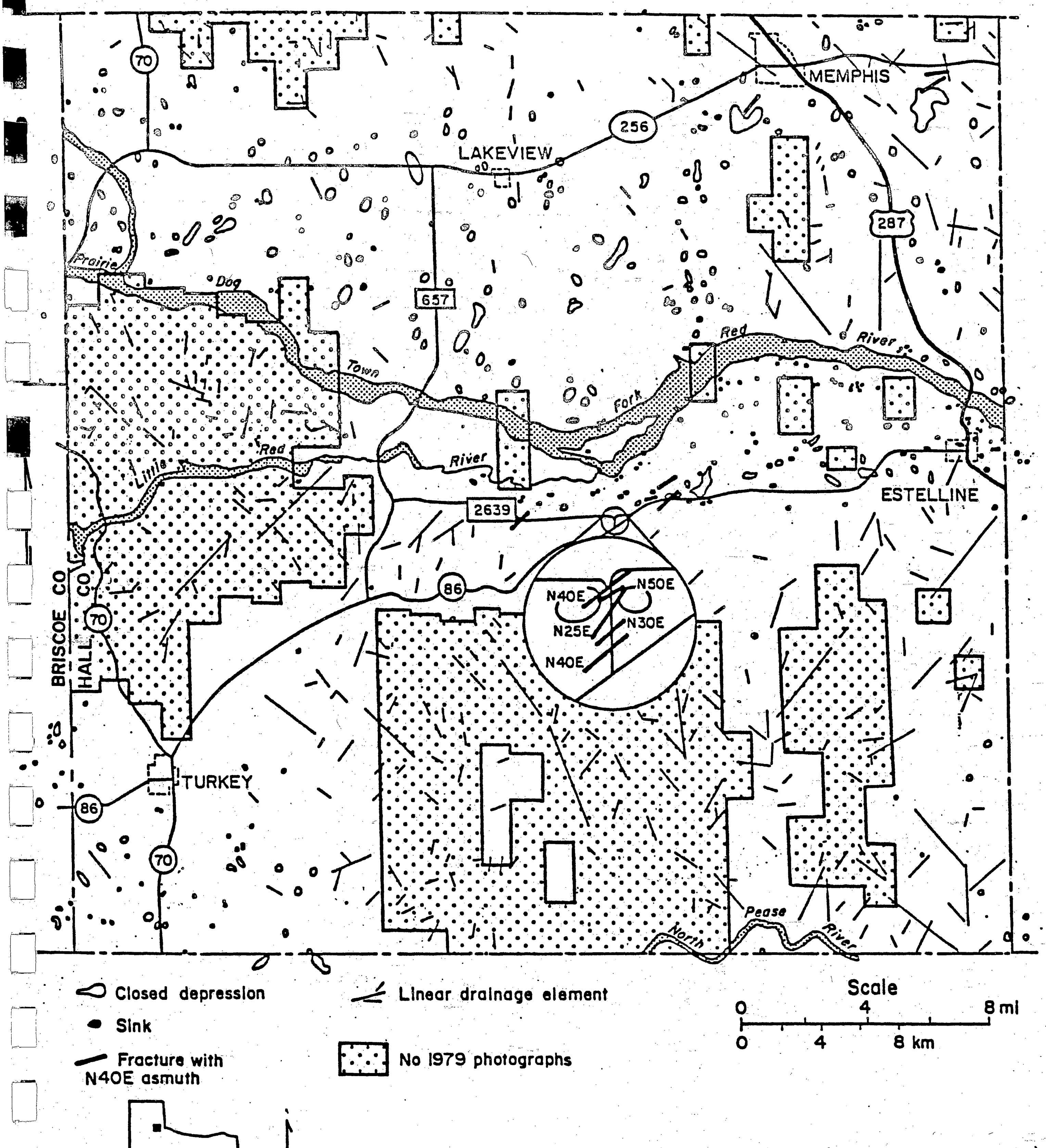
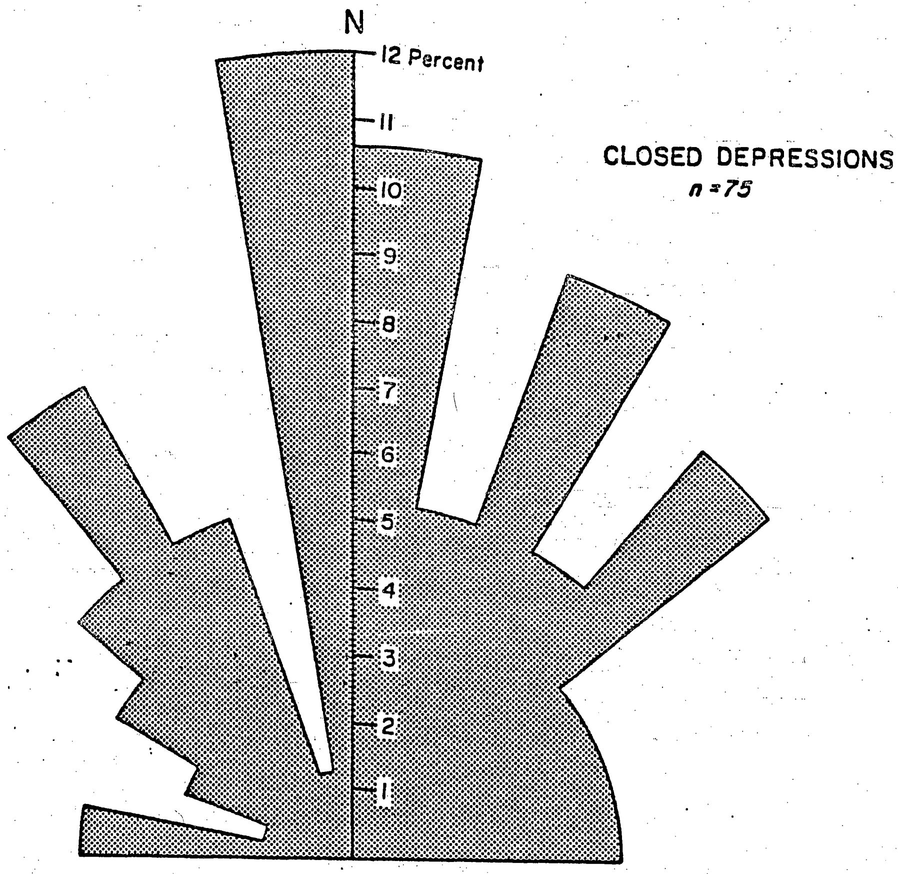


Figure 16. Location of sinkholes, dolines (closed depressions) and fractures in Hall and eastern Briscoe Counties, Texas. Dolines are drawn to scale, sinkholes which are much smaller are not drawn to scale. Dolines and sinkholes were recognized from colored aerial photography flown in 1979.



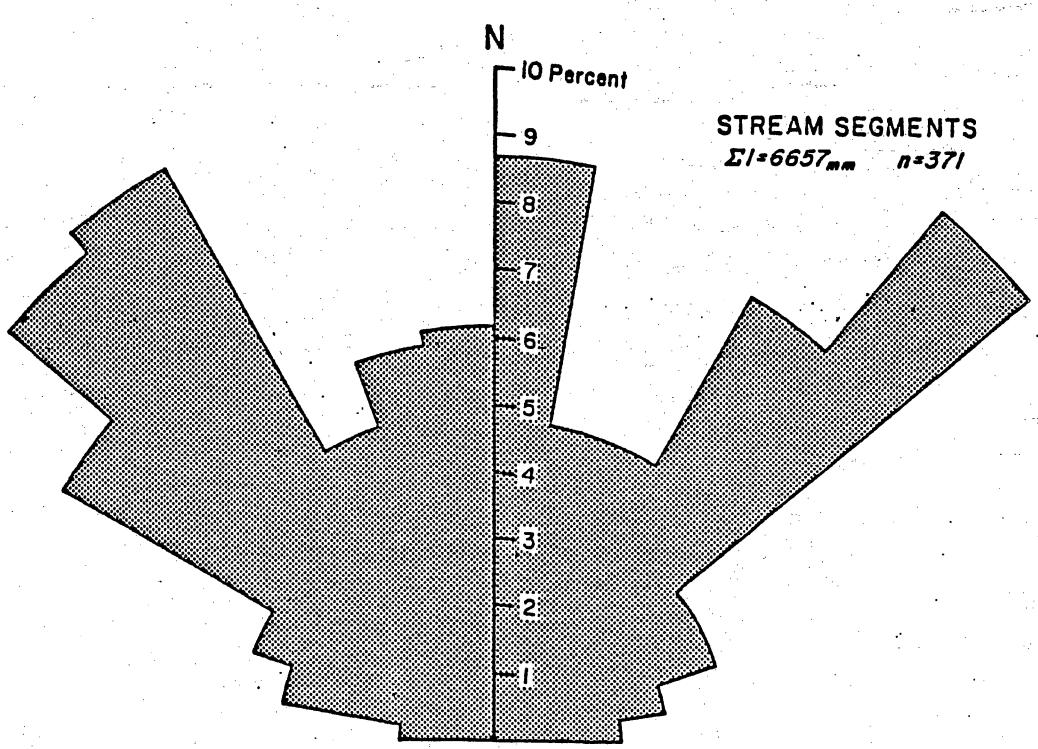


Figure 17. Diagrams indicate orientations of long axes of dolines and linear stream segments in Hall County. For each 10° sector, linear data are plotted as a percentage of total number of closed depressions and as a percentage of total length of linear stream segments.

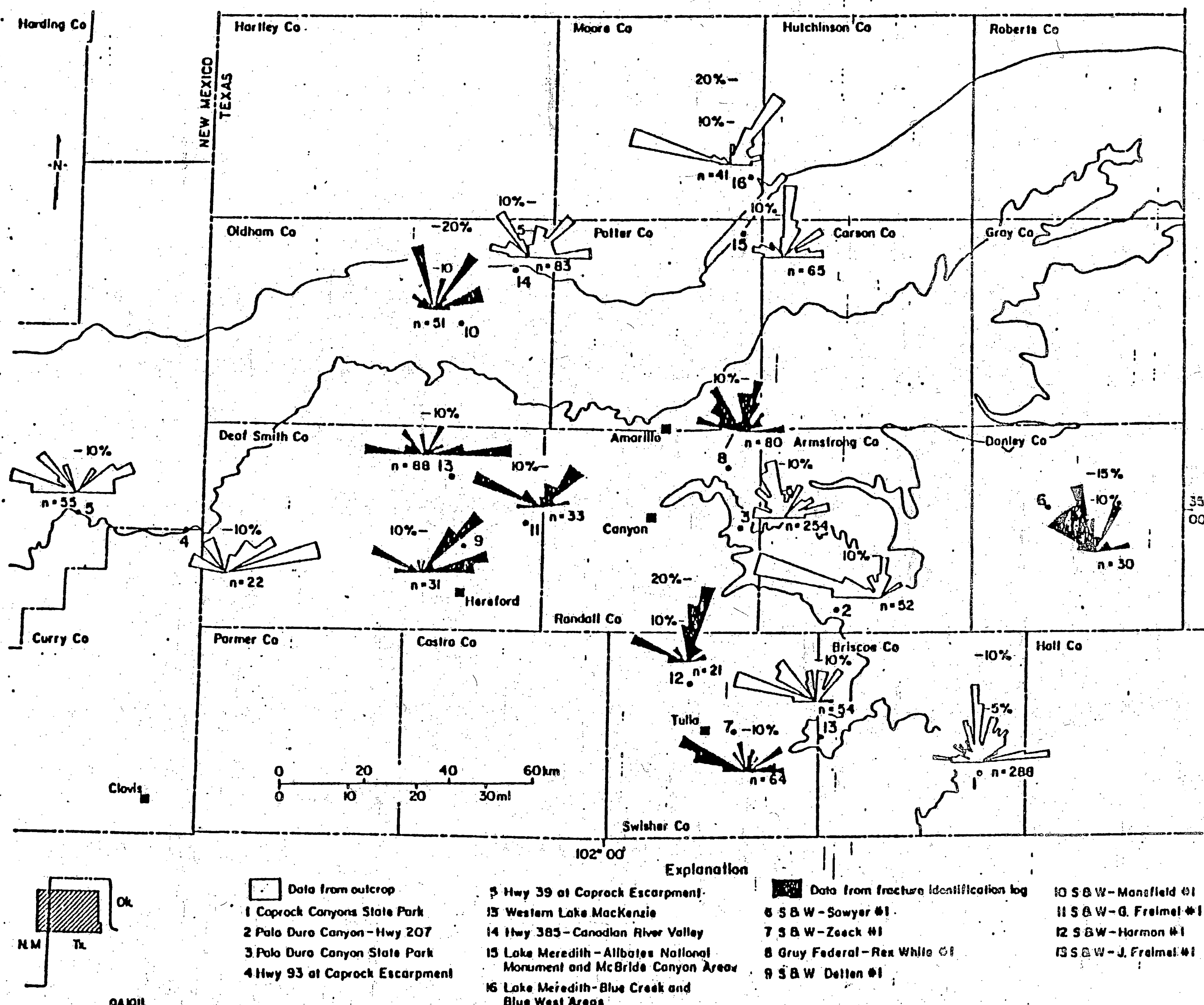
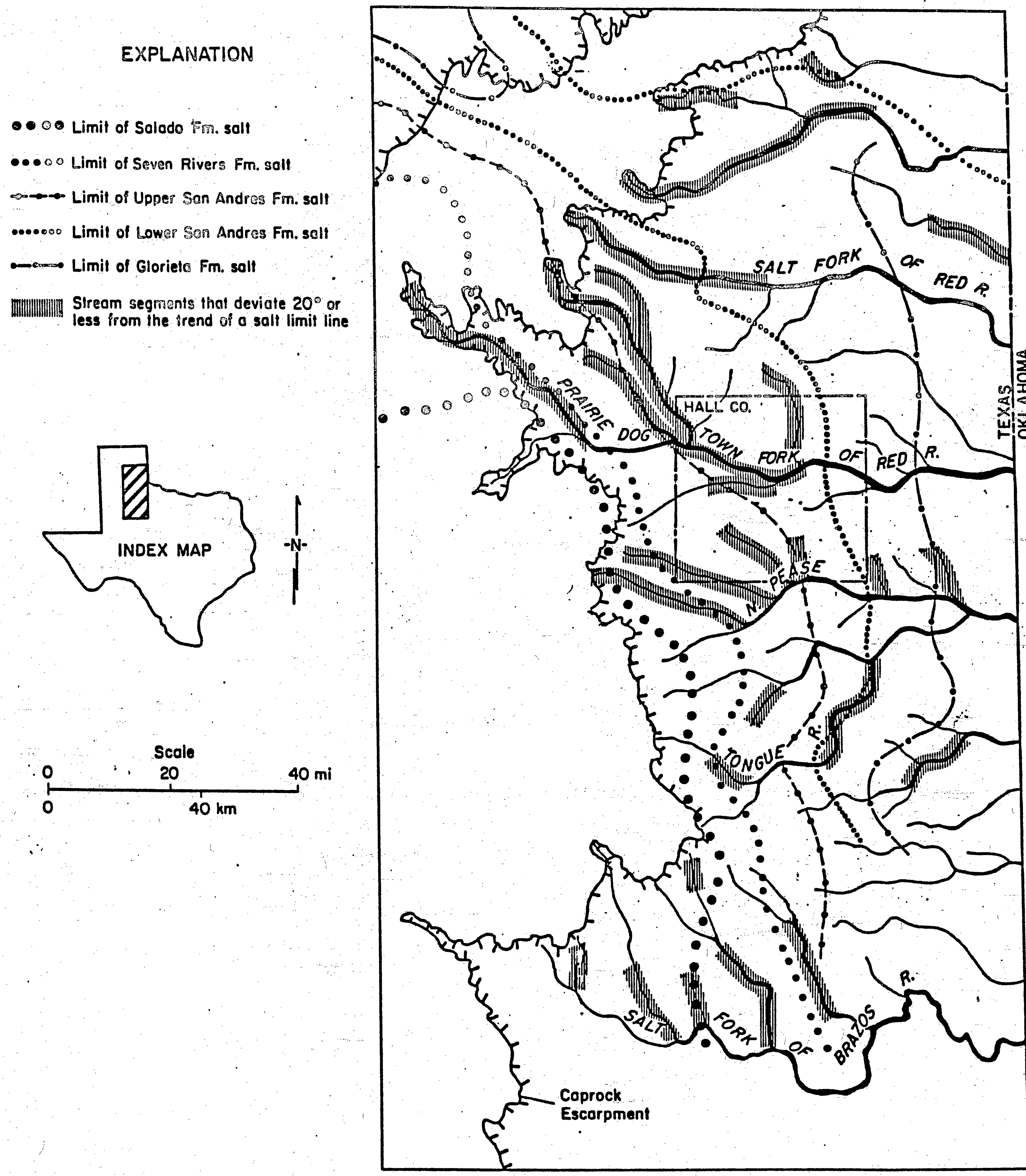


Figure 18. Fracture orientations from nine surface locations in the Texas Panhandle and eastern New Mexico and from Schlumberger Inc. Fracture Identification Logs from eight test wells in the Texas Panhandle.

See separate file for Figure 19



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