

STRUCTURAL GEOLOGY AND TECTONIC HISTORY  
OF THE PALO DURO BASIN,  
TEXAS PANHANDLE

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Prepared for the  
U.S. Department of Energy  
Office of Nuclear Waste Isolation  
under contract no. DE-AC97-83WM46651

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1984

# Structural Geology and Tectonic History of the Palo Duro Basin, Texas Panhandle

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## ABSTRACT

The Palo Duro Basin is a broad, structural low that occupies the southern part of the Texas Panhandle. It is separated from the Anadarko Basin to the north by a complex zone of horsts and grabens which includes the Amarillo Uplift. The Matador Arch, an east-west trending series of en echelon fault blocks, defines the southern margin of the Palo Duro Basin. Intrabasinal structures consist of small, isolated basement highs.

The northwest-southeast structural grain of the region originated during the Precambrian or Early Paleozoic. Major deformation of the southern Texas Panhandle and formation of a depositional basin occurred in response to the Ancestral Rocky Mountain orogeny in the Pennsylvanian. Structural relief was reduced during the early Permian, as the entire region subsided to form the Permian Basin. Pennsylvanian and older structures continued to subtly influence deposition during the Permian, Triassic, Cretaceous, and Tertiary.

This report examines the effects of Early Pennsylvanian and older structures on the geometry and depositional patterns of Phanerozoic strata preserved in the basin. The structural and stratigraphic data are then used to document the tectonic history of the basin.

## INTRODUCTION

A thorough understanding of the structural geology and tectonic history of a region is critical in the assessment of potential sites for the disposal of

high-level nuclear waste. Faults and fractures associated with geologic structures could affect engineering and hydrologic characteristics of the host rock in the vicinity of a nuclear waste repository. Knowledge of the long-term stability of a site is important in determining an appropriate design for a repository.

A specific objective of the West Texas Waste Isolation Project has been to assess the structural geology and long-term tectonic stability of the Palo Duro Basin. The relative paucity of structural data, especially relating to the configuration of the basement surface, has dictated the use of an integrated approach in the assessment of the structural geology and tectonic history of the basin. Analysis of depositional patterns in the basin fill, combined with structure contour and isopach maps has allowed the development of a coherent, although incomplete, picture of the evolution of structures in the basin. Individual structures were identified through structural mapping: the history of the development of these structures was interpreted through the use of published and unpublished lithofacies, isopach, and structure contour maps. Many of these structures, although recognized by other workers in the area, have never been formally named. The names used in this report come from published and unpublished sources or are derived from nearby geographic or cultural features.

The Palo Duro Basin is a shallow, intracratonic structural basin located in the southern part of the Texas Panhandle (fig. 1). The present configuration of the basin is the result of episodic subsidence, which began in the Early Paleozoic. The southern Panhandle was the site of a carbonate platform during the Early Ordovician and again in the Mississippian (fig. 2). Rapid subsidence of the area produced a depositional basin which was filled with approximately 5,000 ft (1,500 m) of marine clastics and carbonates during the

Pennsylvanian and Early Permian. Regional subsidence, associated with the larger Permian Basin, began in the Early Permian and continued through the end of the Paleozoic. During this time about 4,000 ft (1,200 m) of evaporites, red beds, and shallow water carbonates were deposited at or very near sea level. Minor subsidence in the Late Triassic and again in the Late Tertiary allowed the accumulation of up to 1,500 ft (450 m) of continental clastics in the Palo Duro Basin area.

The Palo Duro Basin has undergone episodic deformation during the Phanerozoic. Basement uplifts, formed in part along older structural trends, were produced in the Pennsylvanian as a result of the Ancestral Rocky Mountain orogeny. Intermittent rejuvenation of structures since the Pennsylvanian has influenced later deposition. Structural changes produced by the dissolution of Middle and Upper Permian salt beds (Gustavson and others, 1980) have complicated the understanding of the structural development of the Palo Duro Basin. The dissolution, and collapse of overlying strata, has been most extensive at the margins of the basin, but has occurred to some degree throughout the region (fig. 3; Hovorka, in preparation; Gustavson and Budnik, 1984).

#### METHODOLOGY

The primary sources of structural data from the Palo Duro Basin include petroleum exploration wells, seismic reflection surveys, and outcrop studies. However, each source is somewhat limited. The Palo Duro Basin has been only sparsely drilled. In some counties within the basin, well density is less than one well per 80 square miles. The density of wells that reach basement is even lower. Within hydrocarbon fields, which are almost exclusively limited to the margins of the basin, well density ranges from one to 64 wells per square mile.



In the central part of the basin, a total of 625 miles of seismic reflection data were available for study (fig. 4). These data consist primarily of 24-fold, vibroseis, CDP stacked data, acquired during 1982 and 1983. Included were 145 miles of non-proprietary data; the remainder were proprietary.

Cenozoic deposits, which underlie the Southern High Plains, cover the central portion of the basin (fig. 5). Outcrops of Triassic and Upper Permian rocks are confined to the margins of the basin. Structural studies of the outcrops were used to help determine the nature of late stage deformation in the area.

The comparison of the effects of a single structure on several consecutive horizons is sometimes difficult, as the same amount of control is not always available for each horizon. Surface topography is determined using thousands of data points. Control for the map of the base of the Ogallala Formation includes hundreds of data points per county. On the other hand, the structure contour map on the top of the basement is based on only 10 to 20 wells per county. It is not always possible, therefore, to match structures seen on one horizon with those seen on another. Only those structures with sufficient control at a number of different horizons were studied.

The structural and depositional patterns of the Ogallala Formation were studied in order to determine the effects of Cenozoic deformation on the region. The primary sources of information on the Ogallala Formation came from Seni (1980), Knowles and others (1981, 1982a, 1982b). Additional data have been gathered from the study of surface exposures. Structure contour maps on the erosional base of the Ogallala Formation (Knowles, 1981, 1982b) and surface structural mapping of the Ogallala Formation were used to determine the nature of deformation of the unit. Gustavson and others (1980) and Seni (1980) noted that a structure contour map on the base of the Ogallala Formation is primarily a paleotopographic map on the pre-Ogallala surface. Preexisting structures may

have been exhumed during pre-Ogallala erosion, and thus be reflected in the structure contour map of the base of the Ogallala Formation. However, where observed locally, bedding within the Ogallala appears to parallel that in underlying units (fig. 6) suggesting that the Ogallala was deformed in places along with the older strata. Although there is a regional erosional contact between the Ogallala and underlying units, the contact is used in this report as an indicator of local post-Mesozoic deformation.

The evidence for the folding of a horizon is usually unambiguous and based on structure contour maps, seismic data, or surface exposures. Evidence of a horizon being faulted, however, is much more subjective, even at the surface or on seismic. For the purposes of this paper, a fault was interpreted to lie between any two wells if the slope between the wells on the basement surface was greater than 250 ft/1 mi (75 m/1.6 km) or greater than approximately 150 ft/1 mi (45 m/1.6 km) for higher horizons. In the absence of additional data, faults in the sedimentary section were assumed to extend down to the basement surface.

The recognition of faults on seismic data was based on the criteria presented by Sheriff (1982). These include (1) abrupt termination of reflections, especially after migration; (2) diffractions associated with fault terminations; (3) changes in dip in the vicinity of a fault; (4) displacement of correlations across the fault; (5) fault-plane reflections; and (6) misties of an event around a seismic grid.

A structural comparison of horizons below and above the salt-bearing interval was made for each structure studied in order to separate the effects of salt dissolution from changes produced as a result of tectonic deformation. In the absence of dissolution, tectonically-produced structures in the salt-bearing and post-salt horizons should have amplitudes or displacements not

greater than those in the pre-salt units. Preexisting structures may enhance dissolution processes; structures produced as a result of salt dissolution may or may not overlie structures in pre-salt units. The removal of salt may produce structural reversals in overlying units or an upward increase in displacement along faults that extend above the salt-bearing section. In areas where salt has been uniformly removed by dissolution, the parallelism of formation contacts appears to be preserved (fig. 7). Large-scale structures in strata overlying zones of uniform salt dissolution, where similar to structures in underlying pre-salt units, were probably tectonically produced (fig. 8). Collins (in press) was able to distinguish between tectonic and dissolution-related structures in outcrop, on the basis of structural style. Subparallel, cylindrical anticlines and synclines were interpreted to be tectonic in origin; conical depressions, breccia pipes, and sinkholes were formed by dissolution collapse.

#### REGIONAL SETTING

The Palo Duro Basin is a shallow, asymmetric, structural basin that occupies the southern part of the Texas Panhandle (fig. 1). The present configuration of the basin is the result of recurrent subsidence, primarily in the Late Paleozoic and the Triassic. The Palo Duro Basin existed as a distinct depositional basin only during the Late Pennsylvanian and Early Permian, when well-defined, carbonate shelf margins bordered a relatively deep, northwest-southeast trending shale basin (figs. 9 and 10).

The Palo Duro Basin is separated from other basins in the region by a series of basement uplifts (fig. 9). The Amarillo Uplift, one of a series of Ancestral Rocky Mountain uplifts that extends from central Colorado to southern

Oklahoma (ver Wiebe, 1930), is the most prominent of these in the Texas Panhandle. The Amarillo Uplift, together with the Wichita Uplift to the southeast, forms the southern margin of the Anadarko Basin. The Amarillo Uplift includes a number of smaller, en echelon basement uplifts and several small, deep closed basins (fig. 9).

The Palo Duro Basin is bounded on the north by the herein named Oldham-Harmon trend (includes the Oldham-Hall Axis of Soderstrom, 1968). The Oldham-Harmon trend consists of a series of small, en echelon basement uplifts that extend from easternmost New Mexico across the Texas Panhandle to southwestern Oklahoma (fig. 9). Named uplifts along this trend include the Bravo Dome (Gould, 1920; also known as the Oldham Nose, Nicholson, 1960), the Bush and Tuck-Trigg Domes (Gould, 1920), the Armstrong, Donley, and Hall positives (Birsa, 1977; the Hall County anticline of Totten, 1956), the Childress anticline (Totten, 1956), and the Harmon anticline. The Hall positive is also known informally as the Memphis or Plaska structure; the latter name is used in this report. The Childress anticline is also informally called the Hollis anticline by some workers. Uplifts along the Oldham-Harmon trend formed barriers to the movement of clastic sediments eroded from the Amarillo Uplift during the Pennsylvanian and Early Permian (fig. 11).

A discontinuous structural low consisting of the Whittenburg Trough (Soderstrom, 1968) and the Hollis Basin (fig. 9) lies between Oldham-Harmon trend and the Amarillo Uplift. The Dalhart Basin is separated from the Whittenburg Trough by a narrow basement uplift (fig. 9).

To the southeast of the Palo Duro Basin lies the Hardeman Basin, a small, fault-bounded graben (Montgomery, 1984) which is separated from the former by a low structural divide in Cottle County (fig. 12). Although probably continuous with the Palo Duro depositional basin during the Late Pennsylvanian (Dutton,

1980, fig. 33), the Hardeman Basin may be more closely related tectonically to the Whittenburg Trough and Hollis Basin (Soderstrom, 1968).

The Palo Duro Basin is separated from the Midland Basin by the Matador Arch (Matador Archipelago, Totten, 1956), part of an east-west trending structural zone that includes Roosevelt Positive (Krisle, 1959; also known as the Milnesand Dome; Nicholson, 1960) to the west and the Electra-Red River Arch to the east (fig. 9). The Matador Arch consists of a series of isolated, fault-bounded blocks that have up to 4,000 ft (1,200 m) of structural relief across them (fig. 12).

The western margin of the Palo Duro Basin is poorly defined, because of a lack of drilling in the area. A small basement uplift in Curry and Quay Counties, New Mexico (San Jon High; Krisle, 1959) separates the Palo Duro and Tucumcari Basins (fig. 12). The San Jon High appears to be bounded on the west by a normal fault (the Bonita Fault); seismic data indicate that it is bounded on the east by a reverse fault (fig. 12).

The regional structural trend in the area is generally northwest-southeast with a less prominent northeast-southwest trend (fig. 12; Budnik and Smith, 1982; Gustavson and Budnik, 1984). The Matador Arch trends east-west and seems to terminate a northeast-southwest structural trend present in the northwestern shelf of the Midland Basin (fig. 12).

#### STRUCTURES MARGINAL TO THE PALO DURO BASIN

Selected structures that lie at the margins of the Palo Duro Basin, for which there are sufficient available data, have been studied to better understand the tectonic history of the region. These include structures along the Amarillo Uplift, the Oldham-Harmon trend, and the Matador Arch. The Bonita and



Alamosa Creek faults in eastern New Mexico have also been studied, as have surface exposures along the eastern margin of the basin.

### Amarillo Uplift

Extensive drilling in the Panhandle field has delineated a series of west-northwest-trending anticlines on the western Amarillo Uplift that are expressed as domes at the surface (fig. 9; Gould, 1920). These include the Channing Dome (here named for a town in Hartley County), the Indian Creek Dome (here named for a tributary to the Canadian River), the Excell Dome (also spelled X-L; Rogatz, 1939), and the John Ray Dome (Gould, 1920). The Ogallala Formation has been eroded from the axes of the Channing and Indian Creek Domes, where the Triassic Dockum is exposed at the surface (fig. 13). The Permian Quartermaster Formation is exposed over much of the John Ray Dome.

Along the Canadian River in Potter County, the Ogallala Formation, Dockum Group, and Quartermaster Formation dip up to  $10^{\circ}$  off the south and southwestern flanks of the John Ray Dome (fig. 6; Patton, 1923). Locally, bedding within the Ogallala Formation appears to parallel the contact between the Ogallala and underlying units (figs. 6 and 8). Locally, there is an angular unconformity between the Ogallala Formation and older units, as evidenced by the truncation of the Dockum Group by the Ogallala on the flanks of the dome (fig. 14; Barnes, 1969). The southwest flank of the dome is truncated by a surface fault that juxtaposes the Dockum Group against the Quartermaster Formation (fig. 14; Barnes, 1969). The offset is down to the south, but the dip of the fault is unknown.

The Channing Dome in Hartley and Oldham Counties (fig. 9) is expressed at the surface by south dips of the Dockum Group and Ogallala Formation (fig. 15). These are best exposed along U.S. Highway 385, south of Channing.

The Potter County fault (Rogatz, 1939), or fault zone, separates the series of domes from the Whittenburg Trough to the southeast (fig. 12). The surface fault that lies along the southwest side of the John Ray Dome (Barnes, 1969) directly overlies a portion of the Potter County fault (figs. 12 and 13) and juxtaposes the Dockum Group against the Quartermaster Formation. The Ogallala is indicated as overlying the fault (Barnes, 1969); however, field relations suggest that it may be offset along a branch of the fault (fig. 17). The Potter County fault does not appear to be exposed at the surface along the rest of its length, although the area has not been studied in detail. The youngest unit offset along the remainder of the fault is unknown.

The Amarillo Uplift has had a subtle but recognizable influence on depositional patterns since the Early Pennsylvanian. In general, the Pennsylvanian is absent from the Amarillo Uplift (fig. 19a), but may be represented by some of the arkosic clastics in deep, intra-uplift grabens, such as the Carson, Deep Lake and LeFors Basins (fig. 9). The Wolfcamp Series thins over the uplift (fig. 19b), as does the lower part of the evaporite sequence (fig. 19c). The non-salt part of the San Andres thins over the John Ray and Excell Domes (M. Fracasso, personal communication, 1984), indicating that the domes formed slightly positive features in the Middle Permian. The Ogallala formation contains a lower percentage of sand and gravel over the uplift compared with basins to the north and south, suggesting that the Amarillo Uplift was a slight topographic high in the Late Tertiary.

#### Whittenburg Trough

The Whittenburg Trough (fig. 9; Soderstrom, 1968) is a narrow, deep fault-bounded graben that lies along the southern flank of the Amarillo Uplift, and separates the uplift from the Oldham-Harmon trend to the south. The exact

configuration of the basin is not known, as it has been only sparsely drilled, but it appears to consist of two smaller, trapezoid-shaped subbasins.

The northwestern subbasin (herein named the Tascosa Basin from a town site in northeastern Oldham County) contains 13,000 ft (400 m) of Mississippian through Tertiary strata at its deepest known point in northeastern Oldham County. It is approximately 10 mi (16 km) wide and 50 mi (80 km) long (fig. 12). The Tascosa Basin is bounded on the north by the Potter County fault (Rogatz, 1939). Seismic reflection data indicate that the basin is bounded on the south by a reverse fault.

The Tascosa Basin developed as a result of differential subsidence along a series of faults in the Late Mississippian/Early Pennsylvanian. Depocenters appear to have shifted through time within the basin (fig. 19) as indicated by changing isopachous trends. Mississippian strata are preserved beneath the Pennsylvanian in the deepest part of the Tascosa Basin and across an intrabasin fault to the north. The Pennsylvanian is thickest along the Potter County Fault (fig. 19a), but the thickest Wolfcamp and Leonard strata are along the south-bounding fault (figs. 19b and 19c). Dissolution of Middle and Upper Permian salt from the region (fig. 3) has obscured thickness trends in that interval.

The southeasternmost basin of the Whittenburg Trough (the Carson Basin; Rogatz, 1939), is larger and more irregular in shape than the Tascosa Basin (fig. 12). Although basement has not been reached in the deepest part of the Carson Basin, it probably contains in excess of 9,500 ft (3,000 m) of Late Paleozoic strata. The Carson Basin is bounded on the north by the Carson County fault (Rogatz, 1939). A narrow graben, herein called the White Deer graben from a town in east-central Carson County, extends from the Carson Basin eastward into the Amarillo Uplift (fig. 12). The White Deer graben appears to lie along an east-west trending fault zone that also bounds the north side of

the LeFors Basin (Rogatz, 1939) in central Gray County. Proprietary seismic data across the White Deer graben indicate that it is 2.5 mi (4 km) wide and approximately 3,000 ft (0.9 km) deep.

The early history of the Carson Basin is unknown. The oldest rocks penetrated in the basin are middle Pennsylvanian arkosic clastics, which are in excess of 3,200 ft (1,000 m) thick (fig. 19a). Equivalent age strata are absent from the adjoining Amarillo Uplift. Subsidence in the basin appears to have occurred during the Permian and in the Tertiary. Permian evaporite and pre-evaporite intervals thicken into the basin from the adjoining uplifts (figs. 19b, 19c, and 20). Upper Permian salt is absent from the northern part of the county, including the White Deer graben and the Amarillo Uplift (fig. 21), probably as a result of dissolution (fig. 23; Gustavson and others, 1980). The salt appears to have been uniformly removed from the uplift and northern part of the basin without disrupting the continuity of the strata (fig. 22).

A prominent isopachous thick in the Ogallala Formation overlies the northern part of the basin, including the White Deer graben (figs. 20 and 22), suggesting that salt dissolution and/or tectonic deformation coincided with deposition of the Ogallala.

#### Oldham-Harmon Trend

A subsurface study of several of the uplifts along the Oldham-Harmon trend (fig. 9) has been made to determine the timing of its development. These include the Bravo Dome, the Bush Dome, the Donley positive element, and the Plaska structure (fig. 12).

### Bravo Dome

The Bravo Dome lies at the western end of the Oldham-Harmon trend (fig. 9) along the southwest edge of the Dalhart Basin. The Whittenburg Trough separates the Bravo Dome from the Amarillo Uplift. The highest areas of the dome have only been sparsely drilled; the southwest and northwest flanks are essentially undrilled.

The Bravo Dome appears to have influenced deposition in the Late Paleozoic. Pennsylvanian strata onlap basement on the flanks of the Bravo Dome (Panhandle Geological Society, 1958; Frezon and Dixon, 1975); the Wolfcamp Series lies directly on basement on the highest part of the dome (fig. 10). The Glorieta sandstone thins onto the Bravo Dome (fig. 25), suggesting that the dome affected depositional patterns at least as late as mid-Permian.

The Tubb formation (fig. 23), the Alibates formation (fig. 24), and the Ogallala Formation (fig. 58) have been folded over the Bravo Dome; erosion has exposed Triassic and Permian strata on the crest of the structure.

### Bush Dome

The Bush Dome consists of a northwest-trending series of small domes in central Potter County (fig. 12), although Tade (1967) restricts the term to the largest of the domes in the Cliffside Field which overlies the structures. A satellite dome to the northeast, the Tuck-Trigg Dome (fig. 9; Gould, 1920) is occupied by the Pedrosa Field (National Petroleum Bibliography, 1965). The Tubb formation (fig. 23) and Alibates formation (fig. 24) have been folded over the Bush Dome. Patton (1923) indicates about 400 ft (120 m) of relief on the top of the Triassic Dockum Group from the Whittenburg Trough to the Bush Dome. The Ogallala Formation has been eroded from most of the dome. The Bush Dome is



separated from the Whittenburg Trough to the north by a fault or series of faults with a total basement offset of about 3,000 to 4,000 ft (900 to 1,200 m) on the basement (fig. 12).

### Donley Positive

The Donley positive in southern Donley County is one of three uplifts that make up the Hall axis of Birsa (1977; fig. 9), part of the Oldham-Harmon trend. There is about 2,000 ft (600 m) of relief on the top of the basement (fig. 12). The Donley positive exhibits about 200 ft (60 m) of closure on the top of the Wolfcamp Series (fig. 26) and about 100 ft (30 m) on the top of the Tubb formation (fig. 23; Smith, 1983).

Smith (1983) noted that the Ellenburger Group (Ordovician) thins over the positive, probably as a result of pre-Mississippian erosion. Mississippian strata were thinned by erosion during the Late Mississippian or Early Pennsylvanian. The positive acted as a barrier to arkosic clastics eroded from the Amarillo Uplift during the Pennsylvanian and Early Permian (fig. 11; Smith, 1983). The Donley positive appears to have influenced depositional patterns at least as late as the Middle Permian; salt dissolution has obscured relations in the upper part of the section (Smith, 1983).

### Plaska Structure

The Plaska Structure (Hall positive) lies at the southern end of the Hall axis (Birsa, 1977) in northeastern Hall County (fig. 9). There appear to be about 2,000 ft (600 m) of basement relief across it (fig. 12), although there is little well control to the southwest. Proprietary seismic data indicate that the structure is fault-bounded on the east and west and that the faults extend upward to at least the top of the Red Cave formation. Mississippian

strata are absent from the structure due to Late Mississippian to Early Pennsylvanian erosion (Ruppel, 1982). There are about 250 ft (75 m) of closure on the top of the Wolfcamp (fig. 26). At the surface, the Blaine Formation (San Andres equivalent) is exposed along the axis of the structure, surrounded by strata of the younger Whitehorse Group (Barnes, 1968).

### Matador Arch

The Matador Arch is an enigmatic feature separating the Palo Duro and Midland Basins. It is not a single large anticlinal structure, but consists of a narrow, east-west trending series of en echelon, fault-bounded blocks, separated by basement lows (fig. 9). Basement relief across and along the trend of the arch is on the order of 4,000 ft (1,200 m; fig. 12).

The Matador Arch marks a hinge line between the Palo Duro and Midland Basins that has been episodically reactivated. The Ellenburger Group (Ordovician) thins northward from the Midland Basin toward the arch, and then thickens again into the western Palo Duro Basin (fig. 27) possibly as a result of differential pre-Mississippian erosion. Fault blocks along the arch were loci of carbonate development during the Pennsylvanian and Early Permian (fig. 28; Budnik and Smith, 1982; Dutton, 1982). Pre-late Wolfcampian erosion apparently removed older strata from the Anton-Irish Block, as upper Wolfcamp carbonates rest directly on basement (fig. 28).

The influence of the Matador Arch on deposition continued at least until the end of the Paleozoic. The entire Permian section, including the upper, evaporite-bearing interval, thins over individual fault blocks (figs. 29 and 30). Although studies of every formation have not been completed, available data indicate that individual fault blocks must have been topographically higher than the surrounding areas during deposition of at least some of the

units. For example, Ramondetta (1982) noted that the San Andres Formation thins (fig. 31) over the Anton-Irish Block and becomes less anhydritic.

Post-Permian structural changes appear to have affected the Matador Arch. The Alibates formation has been folded over individual fault blocks (as defined on the top of the Wolfcamp Series; fig. 32). Cretaceous strata are absent over the Anton-Irish and Petersburg Blocks but are preserved in the structural low between them (fig. 33). The blocks may have been high standing during deposition of the Cretaceous or uplifted and eroded prior to the deposition of the overlying Ogallala in the Late Tertiary.

#### Faults in East-Central New Mexico

The Alamosa Creek Fault in Roosevelt County and the Bonita Fault in Curry County (fig. 12) are northeast-trending surface faults that affect post-Paleozoic strata in eastern New Mexico. At the surface the Alamosa Creek Fault juxtaposes the Ogallala Formation against Lower Cretaceous strata (fig. 34), although Barnes (1977) does not indicate the presence of Cretaceous in the vicinity of the fault. A cross section across the fault (fig. 40) indicates approximately 200 ft (60 m) of offset on the top of the Alibates formation, based on well projections. Surface offset could be on the order of 100 ft (30 m) based on mapped outcrop patterns (Lovelace, 1972). Deeper structural relationships along the fault (below the Glorieta Formation) are unknown due to a lack of deep well control.

The Bonita Fault (figs. 12 and 35) has normal offset with a dip of 55 to 60 degrees to the west and 500 to 700 ft (150 to 200 m) of displacement at the surface (Stearns, 1972) where it offsets Cretaceous strata against Triassic (fig. 35; Berkstress and Mourant, 1966; Lovelace, 1972; Barnes, 1977). Lovelace (1972) indicates that the Ogallala Formation has been faulted, whereas

Barnes (1977) indicates that it is unfaulted. Both Lovelace (1972) and Barnes (1977) indicate that Quaternary sediments have been faulted along a portion of the fault. Gustavson and others (1980) suggest that surface displacements along the Alamosa Creek and Bonita Faults are the result of salt dissolution and collapse.

A proprietary seismic line across northern Curry County (fig. 4) revealed the presence of a reverse fault approximately 10 mi (16 km) east of the Bonita Fault. There are about 750 ft (225 m) of basement relief, down to the east, across the fault. There is no well control in the area and only one available seismic line, so that the strike of the fault is indeterminate. It is depicted on the basement structure map (fig. 12) with a northeast trend, parallel to the Bonita and Alamosa Creek Faults.

#### STRUCTURES WITHIN THE PALO DURO BASIN

The Palo Duro Basin is a shallow structural basin with gently dipping northern, eastern, and western flanks (fig. 12). The Matador Arch forms a discontinuous southern margin. The deepest part of the basin is just north of the Matador Arch in Floyd and Motley Counties. Subsurface control is great enough in only a few areas within the basin to define local structures. These areas include Castro, eastern and southwestern Deaf Smith, central Randall, and south-central Lamb Counties. Outside of these areas, well control is too widely spaced to enable the recognition of individual structures.

#### Castro County

Subsurface structure of Castro County is dominated by the Castro Trough, a northwest-southeast-trending structural low that extends from Swisher County to Deaf Smith County (fig. 1; Birsa, 1977; Budnik, 1983). The trough is bounded

on the northeast by the Arney Block (Budnik, 1983; the Castro-Swisher positive of Birsa, 1977). The southwest flank of the trough is poorly defined, but includes several smaller highs. Structural relief from the highest part of the Arney Block to the deepest part of the trough is on the order of 1,600 ft (500 m) at the level of the top of the basement (fig. 12). Proprietary seismic reflection data (fig. 4) suggest the presence of an axial horst within the trough with approximately 800 ft (250 m) of relief (fig. 12).

Pre-Pennsylvanian strata are absent on the Arney Block, but are present within the Castro Trough (fig. 36; Budnik, 1983). The Ordovician Ellenburger Group is projected beneath Mississippian strata in the deepest part of the trough, but is absent from the surrounding uplifts (fig. 37). The Mississippian System thins over the uplifts to the southwest and is absent over the Arney Block (figs. 36 and 37) probably as a result of Late Mississippian or Early Pennsylvanian erosion.

The Castro Trough influenced depositional facies in both Pennsylvanian and Permian strata. During the Pennsylvanian and Early Permian, the Castro Trough formed a subbasin to the northwest of the primary Palo Duro Basin (fig. 10). Lower Pennsylvanian strata thicken into the trough from the adjoining highs (fig. 38e). During the late Pennsylvanian a carbonate shelf margin developed on the Arney Block (fig. 28). Influence of the Castro Trough continued into the Middle and Upper Permian, as evidenced by the thickening of the Permian evaporite sequence into the trough from the surrounding uplifts (fig. 30). Individual units within the evaporite sequence also show evidence of structural influence. For example, the Wichita Group is more clastic-rich in the trough than in adjoining areas (fig. 38f). Also, Presley and McGillis (1982, p. 44) showed that in the Glorieta Formation, mudstone and salt accumulation was thicker in the trough than over the Arney Block or the other structures in the southwestern part of the county. Lithofacies in the overlying San Andres



Formation exhibit a similar trend with the thickest salt in the lower part of the unit occurring in the trough (fig. 38d). Clastics in the Upper Permian Salado/Tansill Formations thicken into the Castro Trough, as well (McGillis and Presley, 1981, p. 13).

The influence of the Castro Trough extended into the post-Paleozoic. The Triassic Dockum Group is thickest in the trough and thins over the highs to the northeast and southwest (fig. 38b). Also, the percent sand in the lower Dockum is higher in the trough (fig. 38c), indicating that the Castro Trough was a topographic low during the late Triassic.

It appears that the Castro Trough was a structural and topographic low during the Late Tertiary. There is a thicker accumulation of sand in the overlying Ogallala Formation in the Castro Trough than over the Arney Block (fig. 39a). Seni (1980) interpreted this and other thick areas of sand accumulation (fig. 39a) as representing deposition in major distributary channel systems on alluvial fans (fig. 39b). Areas of thin sand, such as over the Arney Block, were interpreted as interchannel areas by Seni (1980).

#### Eastern Deaf Smith County

The Castro Trough extends into southeastern Deaf Smith County where it bifurcates into east-west and northeast-southwest trending lows (fig. 12). The east-west trending low is broad and, based on limited control, does not appear to be fault-bounded. Proprietary seismic data indicate that the northeast-trending low is bounded by faults. The northeast-trending low is paralleled on the north by a minor basement high with approximately 200-300 ft (60-90 m) of structural relief. Another northeast-trending low extends into northeastern Deaf Smith County.

Mississippian-age strata are preserved within the northwest and northeast extensions of the Castro Trough, but are absent elsewhere in the county (fig. 36). Pennsylvanian strata are thickest in the structural lows and thin over the high in the east-central part of the county.

Gustavson and Budnik (1984) noted that, although the deeper units thicken into the northeast-trending low (fig. 10), salt in the Seven Rivers Formation thins in the same area (fig. 40). A series of closed topographic basins on the base of the Ogallala overlie this area (fig. 41). Gustavson and Budnik (1984) suggest that the salt was dissolved from the Seven Rivers as a result of the movement of ground water along fractures related to the northeast-trending faults.

#### Southwestern Deaf Smith County

Southwestern Deaf Smith County and northeastern Curry County are occupied by the Garcia Lake high (fig. 9), here named for Garcia Lake which lies at the southeastern edge of the structure in Deaf Smith County. Krisle (1959) included this structure in the San Jon high to the west, but proprietary seismic data indicate that the two are separated by a basement low (fig. 12). Well and seismic data suggest that the Garcia Lake high is fault-bounded on the southeast and northwest.

A thinned Pennsylvanian section overlies basement on the Garcia Lake high, whereas Mississippian strata are present in wells immediately to the east (fig. 43). The entire Upper Paleozoic section appears to have been deformed over the high, including the Wolfcamp Series (fig. 42a), the Tubb formation (fig. 23), the San Andres Formation (fig. 42b), and the Alibates formation (fig. 24). The Ogallala Formation may have been folded as well (figs. 42 and 43).

## Central Randall County

The Arney Block extends into the southwestern part of Randall County and separates the northeast-trending basement low in eastern Deaf Smith County from a north to northwest-trending low in southeastern Randall County (fig. 12). The Arney Block is separated from the central Randall high (new name) by the northwest-trending low (fig. 12). Seismic data (figs. 4 and 44) indicate that the central Randall high is bounded by northeast- and northwest-trending faults (fig. 12).

A thinned section of Mississippian is present on the central Randall high (fig. 36). A carbonate buildup developed on the central Randall high during the Late Pennsylvanian and Early Permian (figs. 28 and 44). The mid- to Upper Permian evaporite sequence thins over the structure (fig. 30). Seismic reflection data (fig. 44) indicate that the Alibates has been folded over the central Randall high.

## Palo Duro Canyon

Evidence of post-Permian tectonic deformation in Randall County has been described by Collins (in press) in Palo Duro Canyon, approximately 10 mi (16 km) to the east of the central Randall high (fig. 45). The Cloud Chief Gypsum (Alibates equivalent) and overlying Permian Quartermaster Formation have been folded into a series of low amplitude, northeast- and northwest-trending folds. The Triassic Dockum Group lies conformably on the Permian Quartermaster Formation in the axes of the synclines, but an angular unconformity separates Permian and Triassic strata on the flanks of the anticlines (fig. 46). Synclinal depressions probably caused by dissolution-induced collapse are superimposed upon the tectonic folds (Collins, in press).

### Caprock Canyons, Briscoe County

The style of deformation caused by the dissolution of Permian evaporites, has been described by Goldstein and Collins (1984) in Caprock Canyons State Park, at the edge of the Southern High Plains (fig. 47). The folding is chaotic and primarily consists of closed synclinal depressions. The depressions are up to 1.5 km long and 0.75 km wide. Superimposed on the synclinal depressions are smaller, conical anticlines and synclines that plunge toward the centers of the depressions. The amplitudes of the subsidiary folds is less than 15 m.

### Lamb County

The structural configuration of the southwestern part of the Palo Duro Basin is not well known because of a lack of deep control in the area. In Lamb County, at the Littlefield and Illusion Lake oil fields, the San Andres Formation has been folded into a northeast-southwest trending monocline (fig. 48). The monocline appears to lie en echelon to a similar monoclinal trend to the south which defines the northern shelf of the Midland Basin (Ramondetta, 1982). Ramondetta (1982) noted that the latter trend overlies an older, Wolfcampian, shelf margin.

The configuration of the basement surface below the monocline in central Lamb County is unknown. Elsewhere in the area, for example in the Anton-Irish field in southeastern Lamb County and along the southern edge of the Roosevelt positive in southern Roosevelt County, New Mexico, the structural configuration of the top of the San Andres Formation reflects that of the top of the basement (compare figs. 48 and 12). A similar relationship between basement and San Andres structure probably exists in central Lamb County, with the Littlefield and Illusion Lake fields overlying a northeast-trending basement structure.

The basement structure map (fig. 12) was contoured in Lamb County to reflect this possible relationship.

Structure in central Lamb County influenced depositional patterns during the Permian. The Wolfcampian shelf margin followed the northeast-trending structure through Lamb County. Up to 1,400 ft (425 m) of porous carbonate accumulated along this trend (Dutton, 1982). Ramondetta (1982) demonstrated that structure influenced the thickness and distribution of porosity in the San Andres at Illusion Lake and Littlefield, as well as on the Anton-Irish Block and other structures to the southwest. The San Andres thins over these structures (fig. 31) and porosity decreases updip.

The style of folding in Central Lamb County changes upward in the section from essentially monoclinal at the level of the San Andres Formation to anticlinal at the top of the Alibates (fig. 49). This change is caused by thinning in the Salado/Tansill interval, probably as a result of salt dissolution (Gustavson and others, 1980).

#### SUMMARY OF STRUCTURAL GEOLOGY

The Palo Duro Basin is a broad, shallow structural low that occupies the southern part of the Texas Panhandle. A complex zone of basement horsts and grabens separates the Palo Duro Basin from the Anadarko Basin to the north. This zone includes the Amarillo Uplift, the Whittenburg Trough and Hollis Basin, and the Oldham-Harmon structural trend. The southern margin is defined by the Matador Arch.

Basement structural highs within and adjoining the Palo Duro Basin are generally small, isolated, fault-bounded, and oriented in a northwest-southeast direction. Pennsylvanian strata exhibit the greatest depositional and structural effects of these basement features. Post-Pennsylvanian strata show



subtle influence of the structures. There has been significant post-Permian deformation in the region. The Alibates formation has been folded over many structures within the surrounding Palo Duro Basin. The Ogallala Formation appears to have been folded over structures in the northern part of the area.

Deformation resulting from the dissolution of Permian evaporites has been recognized within the Palo Duro Basin as well as to the east and north of the basin. Large-scale, dissolution-related folding is identified by anomalous thinning of the underlying halite-bearing interval. Small-scale folding produced by dissolution and collapse is chaotic in contrast with the parallel nature of tectonic folds.

## TECTONIC HISTORY

The development of the Palo Duro Basin in the Late Paleozoic was closely related to the formation of two major regional tectonic features: the Pennsylvanian Ancestral Rocky Mountains and the Permian basin (fig. 1). Many of the structures that influenced depositional patterns during the Late Paleozoic appear to have been formed during the Precambrian or Early Paleozoic. The structures continued to influence depositional processes into the Cenozoic.

### Precambrian

The crystalline basement of the southern Texas Panhandle consists largely of virtually undeformed rhyolite of the Panhandle volcanic terrane, surrounded and presumably underlain by the Chaves granitic and granitic gneiss terrane (fig. 50; Flawn, 1956, Muehlberger and others, 1967). These are part of a very large, epizonal, granite-rhyolite terrane that extends from eastern New Mexico to central Wisconsin (Van Schmus and Bickford, 1981). Initial K/Ar isotopic studies indicated that in the Panhandle the rhyolites were approximately 1,100

to 1,200 m.y. old (Muehlberger and others, 1966). However, recent U/Pb dating of zircons from the terrane suggests that the rhyolites may be 1,350 to 1,400 m.y. old (Thomas and others, 1984). Seismic reflection evidence indicates that the rhyolites are in excess of 30,000 ft thick (Budnik, in preparation). The tectonic setting of the region at the time of formation of the granite-rhyolite terrane is unknown, but its linear geometry and position between older rocks to the north and younger rocks to the south suggest that it may have formed at a continental margin (Van Schmus and Bickford, 1981).

The central part of the Palo Duro Basin, the rhyolite, is overlain by a relatively thin sheet of mafic rocks belonging to the Swisher diabasic terrane (fig. 50). This terrane consists of gabbroic and diabasic rocks that are intercalated with calcareous metasediments (Flawn, 1956). The age of the Swisher terrane is in dispute; a K/Ar date of 1,200 m.y. was obtained from a low potassium pyroxene in a diabase (Muehlberger and others, 1966). Roth (1960), however, described the presence of Paleozoic microfossils from metasediments within the Swisher terrane. The tectonic significance of the Swisher diabasic terrane is not known.

There appears to be a coincidence between the geometry of the Palo Duro Basin and the distribution of Precambrian terranes in the underlying basement (fig. 50). In general, the structurally low areas are underlain by volcanics, whereas the high areas are underlain by granitics. Most of the Palo Duro Basin, the Dalhart Basin, and the Whittenburg Trough are underlain by rhyolite. The eastern part of the Palo Duro Basin, the Bravo Dome, and most of the Amarillo Uplift are underlain by granitic rocks. The deepest parts of the Palo Duro Basin in Motley and southern Floyd Counties are interpreted to be underlain by granitic rocks, (fig. 50) by Muehlberger and others (1967). However, Flawn (1956) infers the presence of metasedimentary rocks in the same location.

In several instances (for example, along the northeast side of the Bravo Dome), contacts between the basement terranes coincide with faults located on the basis of structural mapping. Volcanics may have once covered the entire region and been eroded off the high areas prior to the Paleozoic. If this is the case, then the major structural elements of the region formed prior to deposition of the Ellenburger Group in the Ordovician.

### Late Precambrian-Early Paleozoic

Southwestern Oklahoma, northeast of the Palo Duro Basin underwent a major rifting event in the latest Precambrian to Early Cambrian, culminating in the formation of the southern Oklahoma aulacogen 550-600 m.y.a. A large volume of bimodal volcanics now exposed in the present Wichita Mountains of Oklahoma were produced at that time.

Evidence for coeval deformation within the Palo Duro Basin is tenuous. An arkosic sandstone occurs beneath basal Cambrian(?) quartzose sandstone in a few wells within the basin (fig. 51). This arkose is generally considered on sample logs to be weathered basement. However, Roth (1960) described the unit in the Sun Oil Company No. 1 Herring well in Castro County (fig. 51) as consisting of slightly metamorphosed arkosic sandstone and interbedded pyroclastics. This unit, which lies on diabase of the Swisher terrane in the Sun Oil well, is probably preserved in the deepest part of the Castro Trough (fig. 51). The arkose may have been derived from erosion of rhyolite from the Arney Block, and the pyroclastics may be related to the rhyolites of the Wichita Mountains. These pre-Cambrian (?) sediments were preserved in the Castro Trough as a result of pre-Ordovician deformation.

A stable shelf occupied the area of the Palo Duro Basin during the Late Cambrian to Early Ordovician (Ruppel, 1982). Sometime between the mid-Ordovician and the Early Mississippian, a northwest-trending area in the central

Panhandle was uplifted to form the Texas Arch (fig. 27; Adams, 1954). The east side of the arch, in Armstrong, Briscoe, Hall, and Motley Counties, coincides with the boundary between volcanic and plutonic basement terranes (compare figs. 27 and 50), suggesting a reactivation of pre-Ordovician structures. Ellenburger (Ordovician) carbonates and Cambrian (?) clastics were eroded from the crest of the arch, except where preserved in downfaulted blocks, such as the Castro Trough. To the northeast and southwest of the Panhandle, Silurian and Devonian sediments are present on the flanks, but are absent from the crest of the arch due to erosion or nondeposition. Precise timing of uplift and accompanying faulting is unknown. However, on the eastern flank of the arch in the Hollis Basin, units as young as Early Devonian (Hunton group) are truncated below Upper Devonian and Lower Mississippian strata (Tarr and others, 1965), suggesting a mid-Devonian age of deformation (Eddleman, 1961; Ham and Wilson, 1967).

During the Mississippian, the southern Panhandle was the site of a shallow, carbonate platform (Ruppel, 1982) with shallow water dolomite deposited on the Texas Arch and relatively deeper water limestone being deposited on the flanks of the arch (S. C. Ruppel, personal communication). Carbonate deposition was interrupted briefly during the Late Mississippian by an influx of clastics (Totten, 1956; Ruppel, 1982), possibly in response to initial uplift of the Ancestral Rocky Mountains (Budnik and Smith, 1982).

### Pennsylvanian

The formation of a depositional basin in the southern Texas Panhandle began in the Late Mississippian/Early Pennsylvanian when older basement structures were reactivated in response to the interaction of the North and South American plates (Kluth and Coney, 1981). During the Pennsylvanian period the

Palo Duro Basin underwent three pulses of deformation (Ham and Wilson, 1967). Initially, the Mississippian-age carbonate shelf was tilted to the south. Mississippian and older strata were eroded off a wide, east-west-trending band to the north of the present structural basin (fig. 52). Lower Pennsylvanian (Morrowan) sediments were deposited primarily in the southern part of the basin, and in the Hardeman Basin to the east (fig. 53; Budnik and Smith, 1982).

The main period of deformation occurred during the mid-Pennsylvanian (Desmoinesian; Dutton, 1982; Goldstein, 1982). During this time, the Oldham-Harmon trend and the Whittenburg Trough developed. Most of the arkosic debris that was shed off the Amarillo Uplift was trapped in the trough and in the Hollis Basin, although some of the clastics reached the Palo Duro Basin through lows in the Oldham-Harmon trend (fig. 11). Intrabasinal structures, such as the Castro Trough, probably reached their greatest relief at this time. By the end of the Desmoinesian, structural relief had been reduced; a carbonate shelf covered most of the area (fig. 54; Dutton, 1982; Handford and others, 1981).

In the Late Pennsylvanian, the region was differentiated into a well-defined basin and shelf-margin complex (Dutton, 1982) as a result of renewed deformation. Carbonate buildups were localized on structurally high blocks within the basin, such as the central Randall structure, and along the Oldham-Harmon trend and the Matador Arch (fig. 28; Handford and others, 1981; Budnik and Smith, 1982). Episodic movement on basement structures throughout the Late Pennsylvanian and Wolfcampian maintained these high-standing areas. This phase of deformation culminated with the erosion or nondeposition of Upper Pennsylvanian (Cisco Series) from structures in the southwestern part of the basin (Budnik and Smith, 1982) and probable erosion of sediments from the Amarillo Uplift and the Anton-Irish structure, before deposition of the Wolfcamp Series (fig. 28). The pre-Permian isopach map (fig. 10) delineates a strong north-west-southeast trend to the axis of the basin at the end of the Pennsylvanian.

## Permian

Structural trends established in the Pennsylvanian continued into the Early Permian as the basin filled. The normal-marine phase of sedimentation ended following the development of a widespread carbonate shelf (fig. 54) in the late Wolfcampian.

Deposition during the remainder of the Permian, primarily of evaporites and red beds, was controlled by regional subsidence associated with the larger Permian Basin (fig. 1). The distinction between the Palo Duro and surrounding basins was reduced as a result of subsidence of the intervening uplifts (Goldstein, 1984).

Older, Pennsylvanian structures continued to subtly influence depositional patterns in the Middle and Upper Permian. These deposits thicken into structural lows (for example, the Castro Trough) and thin over structural highs in the basin (central Randall high, the Arney Block, and the Illusion Lake structure) and along the Matador Arch and the Oldham-Harmon trend (fig. 30). A correspondence has been noted between basement lows and areas of thick clastics in the Glorieta Formation by Presley and McGillis (1982) and in the Salado/Tansill Formations by McGillis and Presley (1981). Structural influence continued through the end of the Permian, as suggested by the thinning of the Alibates formation over the Arney Block and the Littlefield and Illusion Lake structures (fig. 55).

The relationship between thickness of Permian strata and basement structure is probably the result of recurrent movement on the older structures and not merely the effects of differential compaction. The best evidence of this is the episodic influence of structures on depositional patterns. For example, the lower and upper salt-bearing parts of the San Andres Formation thin over

structural highs, whereas the middle non-salt-bearing part shows no correspondence between structure and thickness (Fracasso and Hovorka, 1984).

Episodes of deformation continued after the end of Permian deposition throughout the region, as indicated by the folding of the Alibates formation over structures within the basin, and to the north and south of the basin (fig. 24). Folding of the Alibates at Palo Duro Canyon took place prior to deposition of the Dockum Group in the Late Triassic (Collins, in press). In some areas (for example, over the John Ray Dome), the Alibates appears to have been folded since deposition of the Dockum Group in the Late Triassic (fig. 14).

### Triassic Period

Depositional patterns in the Late Triassic were influenced by the same basement structures that affected Permian deposition. For example, the Castro Trough appears to have controlled the distribution of sand in the lower Dockum Group (fig. 38). Johns (in preparation) noted that thick accumulations of sand occupy structurally low areas along the Matador Arch. Patton (1923) described the presence of intraformational angular unconformities within the Dockum Group on the north flank of the Bush Dome, suggesting that the dome was being folded during Late Triassic deposition.

Present distribution of the Dockum Group closely corresponds to the location of the Permian Basin, indicating that regional subsidence continued to be a dominant structural influence into the Triassic. Large-scale positive Paleozoic structural elements such as the Amarillo Uplift also continued to exert some influence on deposition during the Late Triassic (McGowen and others, 1979).

## Cretaceous Period

Cretaceous strata are absent from all but the southernmost part of the Palo Duro Basin (fig. 33) as a result of erosion or non-deposition. Lower Cretaceous units are preserved beneath the Ogallala in the axis of the Palo Duro Basin in Hale and Floyd Counties and in the structural low between the Anton-Irish and West Petersburg Blocks on the Matador Arch (fig. 33).

The distribution of Cretaceous strata in the area may be due, in part, to topographic relief at the time of deposition. Regionally, Lower Cretaceous strata onlap older units northwestward from the Gulf Coast toward the Texas Panhandle, suggesting that the Panhandle was topographically higher than areas to the southeast. Locally, in Lamb County, Lower Cretaceous carbonates thin northward (fig. 56) also suggesting a southward topographic slope at that time. The structural highs along the Matador Arch may have been topographic highs during the Early Cretaceous or they may have been uplifted and the Cretaceous strata eroded prior to deposition of the Ogallala Formation.

## Cenozoic Era

Paleozoic structures have had a subtle, but recognizable, effect on Cenozoic strata in the Palo Duro Basin. These effects have been masked, in part, by erosion and by Late Cenozoic salt dissolution, both of which have been most active along the margins and to a lesser extent in the interior of the basin.

Regionally, isopachous and lithofacies trends in the Ogallala Formation follow large-scale basement structures. The unit is thickest in the axes of the Palo Duro and Anadarko Basins and thins over the Amarillo Uplift (fig. 22). The highest percentage of sand in the formation is in the centers of the basins (fig. 39a), indicating that the structures had enough topographic expression in the Neogene to control drainage patterns. Baker (1932) also recognized that



the Ogallala Formation was thickest in the axis of the Anadarko Basin and thinned over the Amarillo Uplift. He attributed this change in thickness to folding during the Neogene.

The influence of smaller structures is also reflected in the depositional trends of the Ogallala. Structural highs within the basin, such as the Arney Block and Garcia Lake high were areas of interchannel deposition, whereas structural lows, like the Castro Trough, were occupied by major channel systems (fig. 57).

Deformation of the region continued after deposition of the Ogallala Formation. Structures along the western Amarillo Uplift, including the John Ray Dome, were reactivated. The Ogallala and underlying units were folded in the Late Tertiary or Quaternary (figs. 13, 14, and 15). Historic seismicity appears to be concentrated along the Amarillo Uplift (fig. 57), suggesting that some faults in that area may still be active.

Elsewhere in the region, evidence from the structural configuration of the base of the Ogallala suggests that the unit has been folded over the Bravo Dome and the Garcia Lake high, and possibly the Bush Dome and Arney Block (fig. 58).

The extent of Cenozoic faulting in the region is not well documented, except to the west of the Palo Duro Basin in New Mexico. Barnes (1977) indicates that the Alamosa Fault in Roosevelt County, New Mexico, displaces the Ogallala Formation. Lovelace (1972) and Barnes (1983) indicate that the Bonita Fault in Quay County, New Mexico, offsets Quaternary deposits. Finch and Wright (1970) suggest post-Ogallala deformation in the southwestern part of the basin, based on the offset of topographic contours in the area.

Gable and Hatton (1983) projected 300 to 3,000 ft (100 to 1,000 m) of epeirogenic uplift of the western Great Plains, including the Texas Panhandle over the past 10 million years. The effect of this regional uplift on local structures is unknown.

## SUMMARY OF TECTONIC HISTORY

The Palo Duro Basin and surrounding region have had a long history of tectonic deformation, beginning in the Late Proterozoic. The Palo Duro Basin was the site of a tremendous outpouring of rhyolite flows from unknown volcanic centers. The area was deformed in the Latest Proterozoic/Earliest Paleozoic during the rifting of the southern Oklahoma aulacogen. Arkosic sandstone and interbedded tuff may have been deposited in the Palo Duro Basin that time.

The Ellenburger Group was deposited on a carbonate shelf in the Early Ordovician. Uplift of the Texas Arch, probably in the Devonian, occurred along preexisting faults. A carbonate shelf was reestablished in the Mississippian with shallow water carbonates deposited along the axis of the Texas Arch and deeper water sediments formed along the flanks.

The area underwent major deformation in the Late Paleozoic, beginning with a southward tilting of the carbonate shelf in the Late Mississippian/Early Pennsylvanian. Recurrent deformation in the Pennsylvanian and Early Permian maintained high-standing basement blocks. Subsidence, related to the development of the larger Permian basin, and subtle deformation continued episodically to the end of the Paleozoic. Older structures, reactivated during the Triassic and Cenozoic, influenced depositional patterns in the Dockum Group and Ogallala Formation, respectively. Tectonic deformation continued into the Late Cenozoic.

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## FIGURES

Figure 1. Tectonic elements of West Texas and adjacent states. Outline of Permian Basin (heavy dashed line) based on the present distribution of halite-bearing rocks in Permian System (McKee and Oriel, 1967). Original distribution of halite was probably somewhat greater. Pennsylvanian basins (vertical ruling) and uplifts (horizontal ruling) based on isopach of the Pennsylvanian System (McKee, Crosby, and others, 1975; Dutton, 1980). The Amarillo-Wichita, Sierra Grande, Pedernal, Diablo, and Central Basin uplifts were elements of the Ancestral Rocky Mountains.

Figure 2. Stratigraphic column and general lithologies in the Palo Duro Basin (Budnik and Smith, 1982).

Figure 3. Salt dissolution zones marginal to the Palo Duro Basin (Gustavson and others, in preparation). The location of each dissolution zone is defined primarily on the present distribution of salt; salt dissolution is inferred in areas where the salt is absent (Gustavson and others, 1980). Location of cross section in figure 7 is indicated.

Figure 4. Location of seismic lines in the Palo Duro Basin.

Figure 5. Surface geology of the Texas Panhandle and surrounding region (Oetting and others; 1967; Renfro and others, 1973). Cenozoic deposits cover most of the Palo Duro Basin. Triassic and Permian deposits are exposed along the eastern margin of the basin, and to the north (along the Canadian River), and west of the basin. Cenozoic = C, Mesozoic = M, Permian = Pm.

Figure 6. Photograph of outcrop of Ogallala Formation (Tertiary), Dockum Group (Triassic), and Alibates formation (Permian) dipping southward off the John Ray Dome. Exposure is along the west side of Bonita Creek, near its confluence with the Canadian River, in Potter County.

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Figure 8. Northwest-southeast cross section of the southern flank of the John Ray Dome. The base of the Ogallala Formation is dipping southward, as are all of the underlying units. The similarity of structure on the pre-salt strata (Red Cave formation) and post-salt strata (Alibates and Ogallala formations) suggest a tectonic origin to the folding. The position of the photograph in figure 6 is indicated.

Figure 9. Structural elements of the Texas Panhandle. The present structural basins (vertical ruling) and uplifts (horizontal ruling) are the result of episodic deformation throughout the Phanerozoic. The Palo Duro Basin existed as a distinct depositional basin only during the Late Pennsylvanian and Early Permian when well-defined carbonate shelf margins bordered a relatively deep shale basin. The axis of Pennsylvanian deposition is derived from an isopach of Pennsylvanian strata (Dutton, 1980). The present axis of the basin is based on the structure contour map on top of crystalline basement (fig. 12).

The Palo Duro Basin is separated from the Anadarko Basin to the north by a complex structural zone which includes the Oldham-Harmon trend, the Whittenburg Trough and Hollis Basin, and the Amarillo Uplift. The Amarillo Uplift is made up of a number of smaller structures including (1) Channing; (2) Indian Creek; (3) Excell; (4) John Ray; (5) Pantex; (6) 6666; (7) Taylor; (8) LeFors; and (9) Lela Domes, and the (10) Deahl; (11) Deep Lake; (12) and LeFors Basins. The Tuck-Trigg Dome (13) is a subsidiary structure to the Bush Dome.

Figure 10. Pre-Permian isopach map of the Palo Duro Basin. Depicts the configuration of basement structure prior to Permian subsidence. The pre-Permian structural axis coincides with the position of the Pennsylvanian depositional basin.

Figure 11. Isolith map of Pennsylvanian and Wolfcamp arkosic clastics. From Dutton (1982). The clastics were derived primarily from the Amarillo Uplift and trapped in the Whittenburg Trough and other deep basins bordering the uplift. Some of the clastics reached the Palo Duro Basin through lows along the Oldham-Harmon trend.

Figure 12. Structure contour map on the top of crystalline basement. Based on indicated well control and on seismic lines shown in figure 4.

Figure 13. Structure contour map on the base of the Ogallala Formation, western Amarillo Uplift (Knowles and others, 1982a). Contours dashed where projected across areas from which the unit has been eroded. Surface geology from Barnes (1969 and 1983). Outcrop area of Permian Quartermaster Formation indicated by Pq. Outcrop area of Triassic Dockum Group indicated by Trd. Fault separates Permian and Triassic strata at the surface. Locations of figures 14, 15, and 18 are indicated.

Figure 14. South-north cross section B-B' across northern Potter County. Location shown in figure 13. Triassic Dockum Group = Trd; Tertiary Ogallala Formation = Tog.

Figure 15. South-north cross section A-A' across Channing Dome. Location shown in figure 13. Triassic Dockum Group = Trd; Tertiary Ogallala Formation = Tog.

Figure 16. Structure contour map on the top of the Wolfcamp Series, western Amarillo Uplift. From Pierce and others (1964). The Potter County fault is here depicted as a series of en echelon faults.

Figure 17. Structure contour map on the top of the Tubb formation, western Amarillo Uplift.

Figure 18. West-east cross section across the south flank of the John Ray Dome. Field relations suggest that the Ogallala Formation is offset along a fault to the west of the Potter County fault. Location shown in figure 13.

Figure 19. Isopach maps showing the Whittenburg Trough and the western Amarillo Uplift. 19a) Pennsylvanian System; 19b) Wolfcamp Series; 19c) Leonard Series.

Figure 20. South-north cross section and structure contour map on the base of the Ogallala Formation in Carson County. The Alibates formation and Dockum Group (Trd) are absent beneath the Ogallala Formation on the Amarillo Uplift, but are preserved in the White Deer graben and to the south of the uplift. The Ogallala Formation thickens into the graben; faults that bound the graben may offset the base of the Ogallala.

Figure 21. Isopach map of the Middle and Upper Permian, southern Carson County. Interval from top of Tubb formation to top of Alibates formation. Salt is absent from San Andres and younger formations outside indicated area.

Figure 22. Isopach map of the Ogallala Formation, Texas Panhandle. From Seni (1980).

Figure 23. Structure contour map on the top of the Tubb formation, Palo Duro Basin.

Figure 24. Structure contour map on the top of the Alibates formation, Palo Duro Basin.

Figure 25. Net sandstone in the Glorieta Formation (Presley and McGillis, 1982). The sandstone thins against the Bravo Dome, suggesting that the dome was a topographic high during the late Leonardian.

Figure 26. Structure contour map on the top of the Wolfcamp Series, Hall and Donley Counties. Seismic data indicate that the Wolfcamp Series is offset along faults (not shown) that bound the Plaska structure.

Figure 27. Isopach map of Ellenburger Group, Palo Duro Basin (modified from Ruppel, 1982).

Figure 28. Percent carbonate in the Upper Pennsylvanian, Palo Duro Basin (after Dutton, 1980).

Figure 29. Isopach of the Permian System, Palo Duro Basin. Interval mapped is from the top of the Pennsylvanian System to the top of the Alibates formation.

Figure 30. Isopach of the mid- and Upper Permian, Palo Duro Basin. Interval mapped is from the top of the Tubb formation to the top of the Alibates formation.

Figure 31. Isopach maps of the San Andres Formation, Lamb and Hockley Counties (Ramondetta, 1982). a) upper part of San Andres; b) lower part of San Andres. The San Andres Formation thins over the Anton-Irish and other structural highs along the western Matador Arch.

Figure 32. Structure contour maps of the western Matador Arch: a) on the top of the Wolfcamp Series; b) top of the Alibates formation. Structures in the deeper horizons are reflected in the shallower horizons.

Figure 33. Subcrop map of the Ogallala Formation (Knowles and others, 1982b). Location of oil fields along the Matador Arch are indicated: 1) Anton-Irish; 2) Petersburg; 3) Arick; 4) Floydada; 5) Roaring Springs. The Cretaceous is preserved in the structurally low areas in Hale and Floyd Counties.



Figure 34. Alamosa Creek fault, Roosevelt County, New Mexico. a) Surface geology in vicinity of Alamosa Creek fault, Roosevelt County, New Mexico (Love- lace, 1972). Tr = Triassic (diagonally ruled), Tog = Tertiary Ogallala Forma- tion (vertically ruled), K = Cretaceous (+++), Q = Quaternary (unpatterned); b) west to east cross section of the Alamosa Creek fault. The Cretaceous strata are preserved in a graben along the fault.

Figure 35. Bonita fault, Quay County, New Mexico. a) Surface geology in the vicinity of the Bonita Fault, Quay County, New Mexico (Lovelace, 1972). Tr = Triassic (black), K+J = Cretaceous and Jurassic (patterned), T+Q = Tertiary and Quaternary (unpatterned). b) West-east cross section of the Bonita Fault. Modified from unpublished section by E. Collins. Based on surface and subsur- face geology.

Figure 36. Isopach map of the Mississippian System, Palo Duro Basin (modified from Ruppel, 1982).

Figure 37. Cross sections, Castro Trough, Castro County. a) Fence diagram of northeastern Castro County. b) Restored southwest-northeast cross section of the Castro Trough, datum: top of the Wolfcamp Series (Budnik, 1983).

Figure 38. Subsurface maps, Castro Trough, Castro County. Paleozoic, Mesozoic and Cenozoic strata exhibit influence of the Castro Trough: a) net sand map of the Tertiary Ogallala Formation (Knowles and others, 1982b); b) isopach map of the Triassic Dockum Group; c) percent sand map of the Dockum Group (from unpublished data of J. McGowen); d) net salt map of the cycle 4, lower San Andres Formation; e) isopach map of the lower Pennsylvanian System; f) litho- facies map of the Wichita Group (from unpublished data of M. Herron).

Figure 39. Depositional facies within the Tertiary Ogallala Formation in the Texas Panhandle: a) distribution of sand and gravel (Seni, 1980); b) deposi- tional patterns (modified from Seni, 1980).

Figure 40. Net salt, Seven Rivers Formation, Deaf Smith and adjoining counties (Gustavson and Budnik, 1984).

Figure 41. Structure contour map on the base of the Ogallala Formation, Deaf Smith and adjoining counties (Gustavson and Budnik, 1984).

Figure 42. Structure contour maps, Garcia Lake high, Deaf Smith County: a) top of Wolfcamp Series; b) top of San Andres Formation; c) base of Ogallala Formation (Knowles and others, 1981).

Figure 43. West-east cross section of the Garcia Lake high showing thinning of stratigraphic section onto structure.

Figure 44. Seismic reflection profile J, central Randall high. Location also shown in figure 28.

Figure 45. Map of surface structures in Palo Duro Canyon State Park, Randall County (Collins, in press). Location of photograph in figure 46 is indicated. Closed collapse depressions produced by the dissolution of underlying salt are superimposed on northwest and northeast-trending tectonic folds. Compare with the style of folding shown in figure 47.

Figure 46. Photograph of slight angular unconformity between the Permian and Triassic at Capital Peak, Palo Duro Canyon State Park, Randall County. Photograph taken by E. Collins. Unconformity is indicated between arrows. Location shown in figure 45.

Figure 47. Map of surface structures in Caprock Canyons State Park, Briscoe County (Goldstein and Collins, 1984). Closed structures were produced by the dissolution of Permian salt and collapse of overlying strata. Compare with the style of folding shown in figure 45.

Figure 48. Structure contour map on the top of the San Andres Formation, northwest shelf of the Midland Basin (Ramondetta, 1982).

Figure 49. West-east cross section across structural low in southern Lamb County. Dissolution of salt in the Salado Formation west of the Illusion Lake field has produced a structural low (at well #78) on the top of the Alibates formation (fig. 32a).

Figure 50. Basement lithologic provinces in the Texas Panhandle (modified from Goldstein, 1982b).

Figure 51. Distribution of basal clastics, Texas Panhandle. Quartzose: horizontally ruled (Ruppel, in preparation). Arkosic clastics overlying basement in vertically ruled areas. In the Sun Oil #1 Herring well, the arkosic clastics overlies diabase of the Swisher terrane, and, in turn, are overlain by Cambrian (?) quartzose sandstone (Roth, 1960).

Figure 52. Pennsylvanian subcrop map, Texas Panhandle. From Nicholson (1960). Lower Paleozoic strata present in vertically ruled area. Pennsylvanian strata lie on crystalline basement elsewhere. Pennsylvanian strata absent in diagonally ruled area.

Figure 53. Isopach map of the Morrow (lowest Pennsylvanian), Texas Panhandle (McKee, Crosby, and others, 1975).

Figure 54. Block diagrams of paleogeographic evolution of Palo Duro Basin during Pennsylvanian and Wolfcampian time (Handford and Dutton, 1982).

Figure 55. Isopach map of the Alibates formation, Texas Panhandle (McGillis and Presley, 1981).

Figure 56. West-east cross section of Cretaceous strata, Lamb County. All logs are gamma ray.

Figure 57. Present seismicity, Texas Panhandle (Reagor and others, 1982).

Figure 58. Structure contour map on the base of the Ogallala Formation, Texas Panhandle (Seni, 1980).

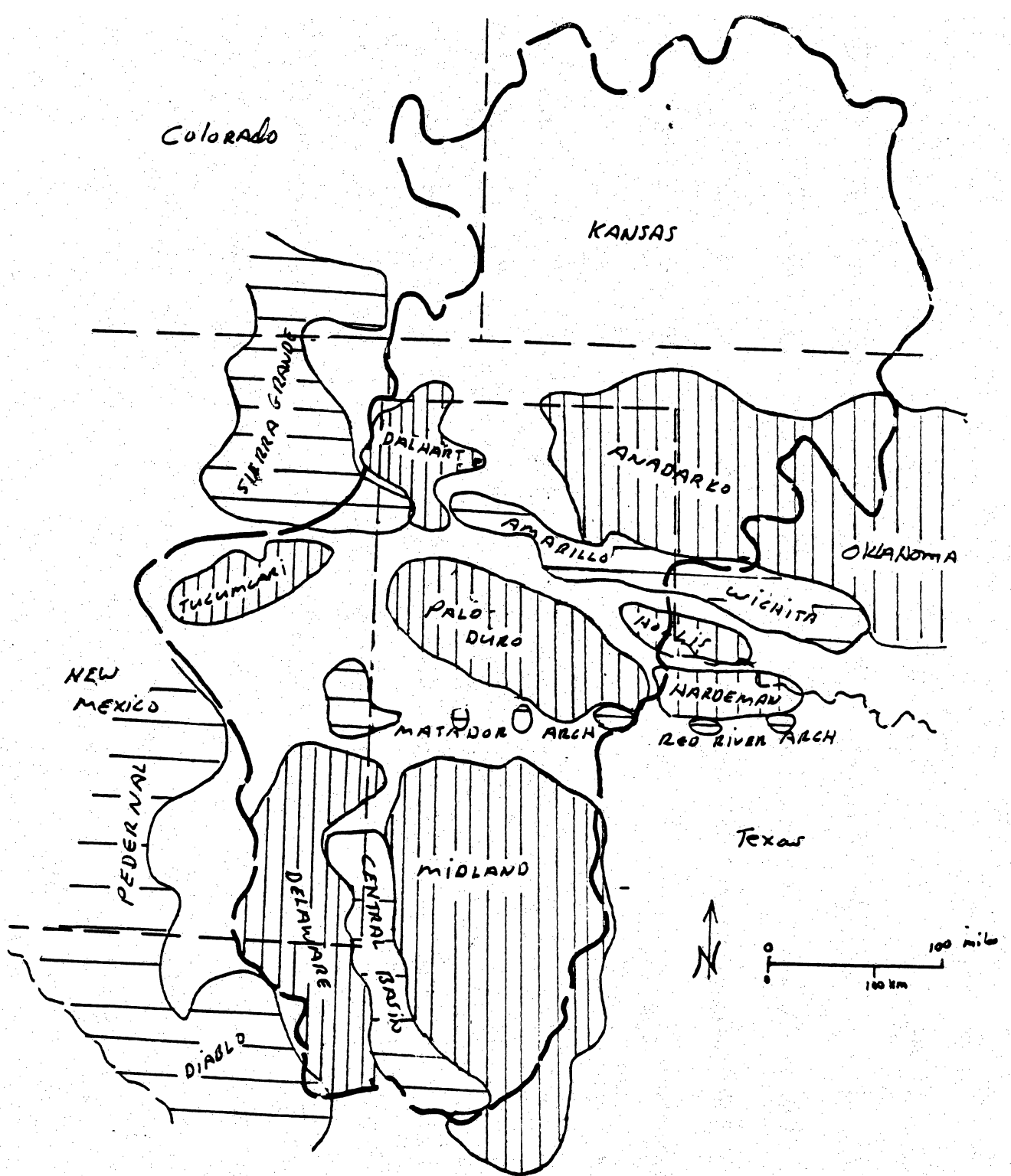


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SYSTEM	SERIES	GROUP	Palo Duro Basin	General Lithology and depositional setting
			FORMATION	
QUATERNARY	HOLOCENE		alluvium, dune sand Playa	
	PLEISTOCENE		Tanoka "cover sands" Tule / "Playa" Blanco	Lacustrine clastics and windblown deposits
TERTIARY	NEOGENE		Ogallala	Fluvial and lacustrine clastics
CRETACEOUS			undifferentiated	Marine shales and limestone
TRIASSIC		DOCKUM		Fluvial-deltaic and lacustrine clastics
PERMIAN	OCHOA		Dewey Lake	Sabkha salt, anhydrite, red beds, and peritidal dolomite
			Alibates	
	GUADALUPE	ARTESIA	Salado/Tansill	
			Yates	
			Seven Rivers	
			Queen/Grayburg	
			San Andres	
	LEONARD	CLEAR FORK	Glorieta	
			Upper Clear Fork	
			Tubb	
			Lower Clear Fork	
			Red Cave	
		WICHITA		
	WOLFCAMP		<i>Brown Dolomite</i>	
PENNSYLVANIAN			?	Shelf and shelf-margin carbonate, basinal shale, and deltaic sandstone
	VIRGIL	CISCO		
	MISSOURI	CANYON		
	DES MOINES	STRAWN		
	ATOKA	BEND		
	MORROW			
MISSISSIP- PIAN	CHESTER			Shelf carbonate and chert
	MERAMEC			
	OSAGE			
ORDOVICIAN		ELLEN- BURGER		Shelf dolomite
CAMBRIAN ?				Shallow marine(?) sandstone
PRECAMBRIAN				Igneous and metamorphic

Figure 2. Stratigraphic column and general lithologies in the Palo Duro Basin (Budnik and Smith, 1982).

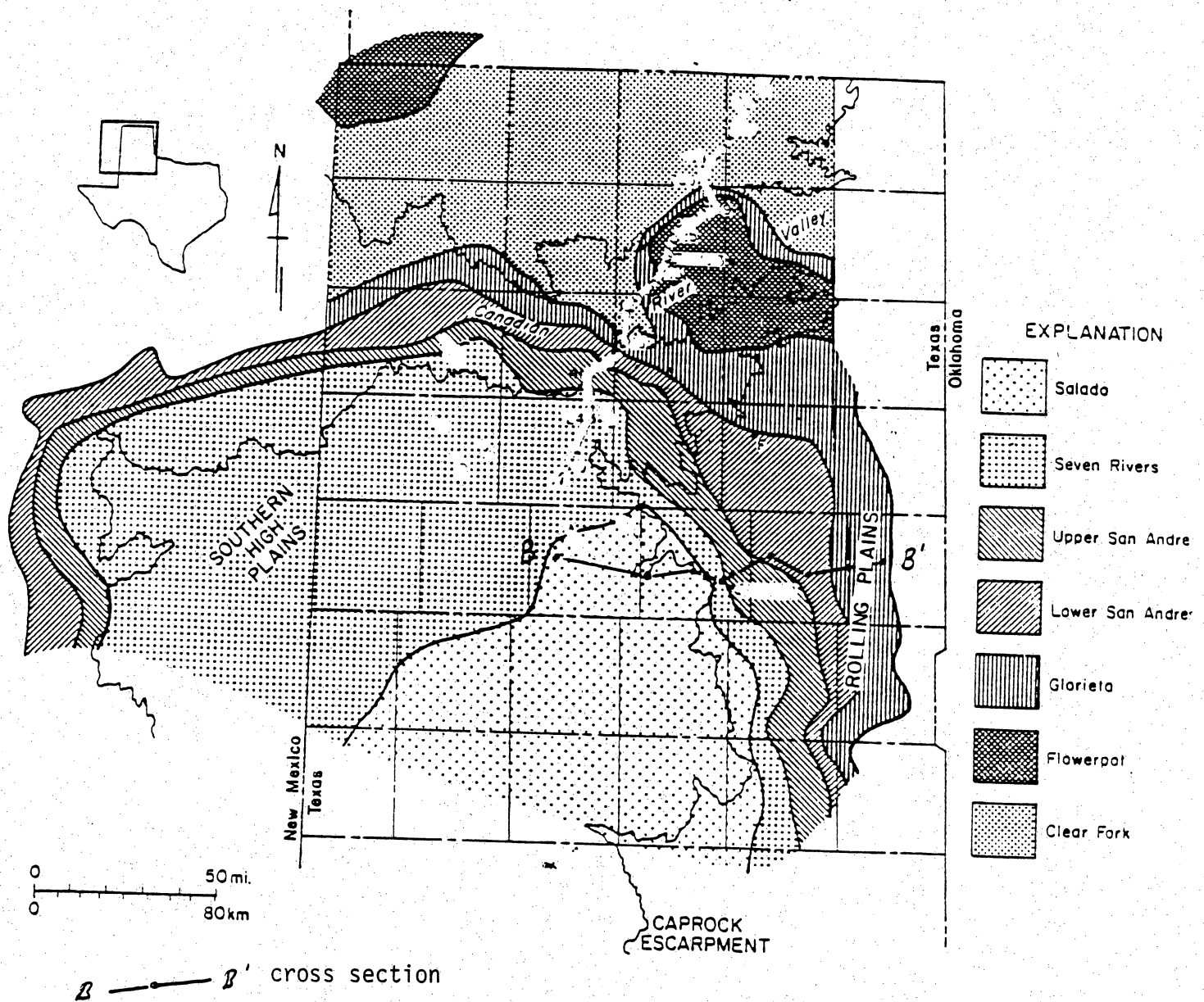


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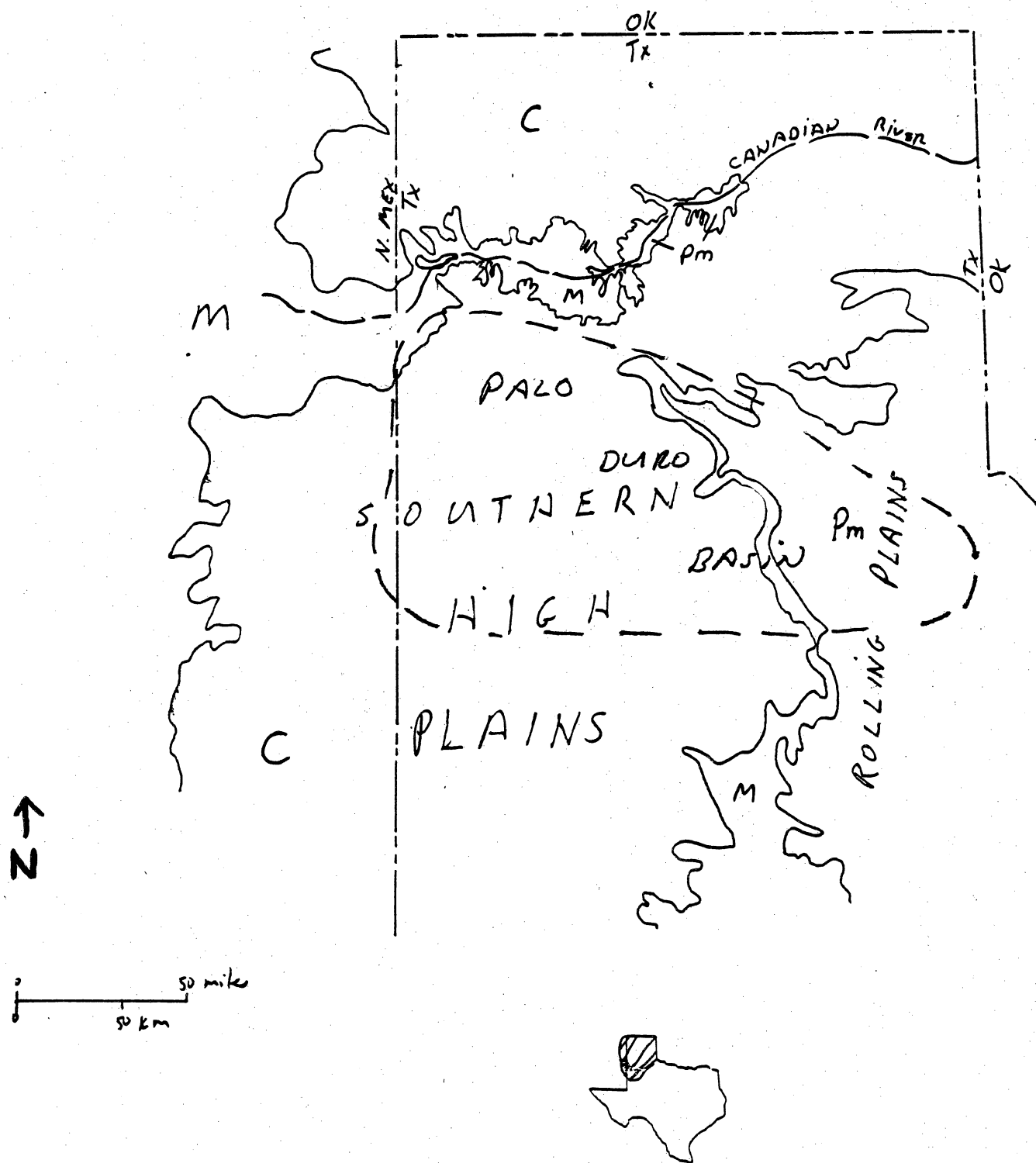


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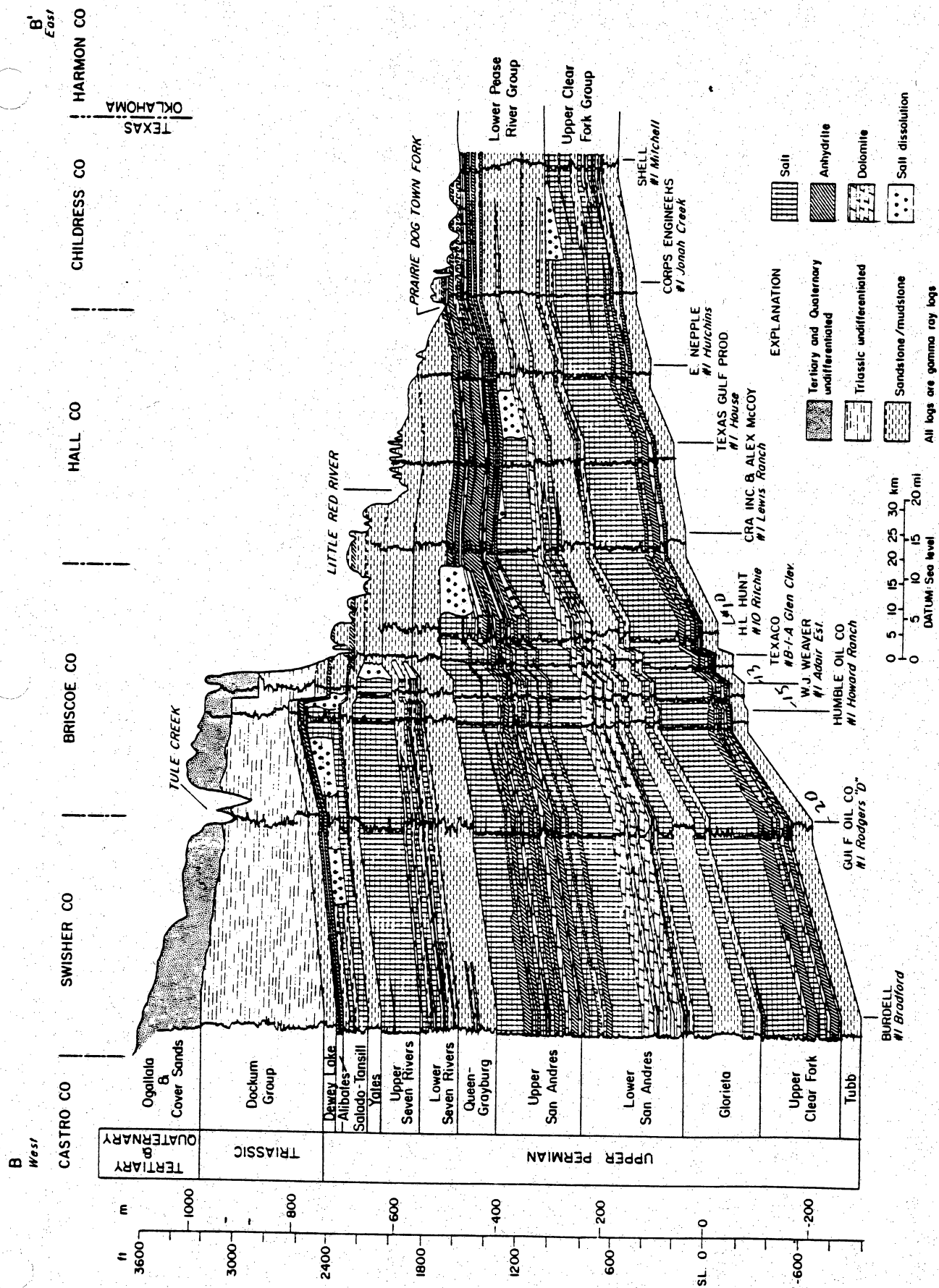


Figure 7. East-west cross section through dissolution zone in Rolling Plains (Gustavson and others, 1980). Parallelism of formation contacts is maintained after salt has been dissolved. Zones of salt dissolution interpreted from gamma-ray logs. Location shown in figure 3.



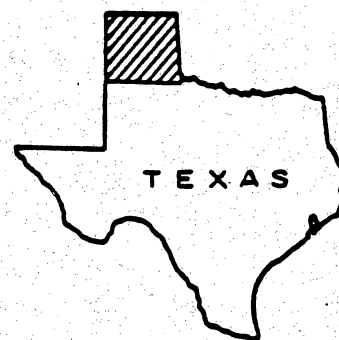
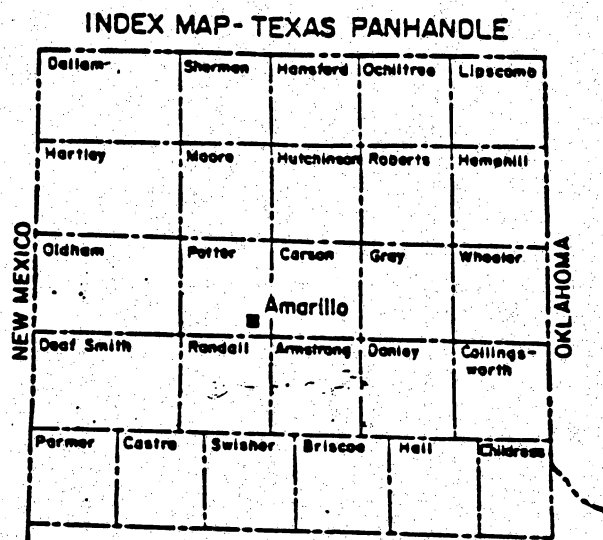
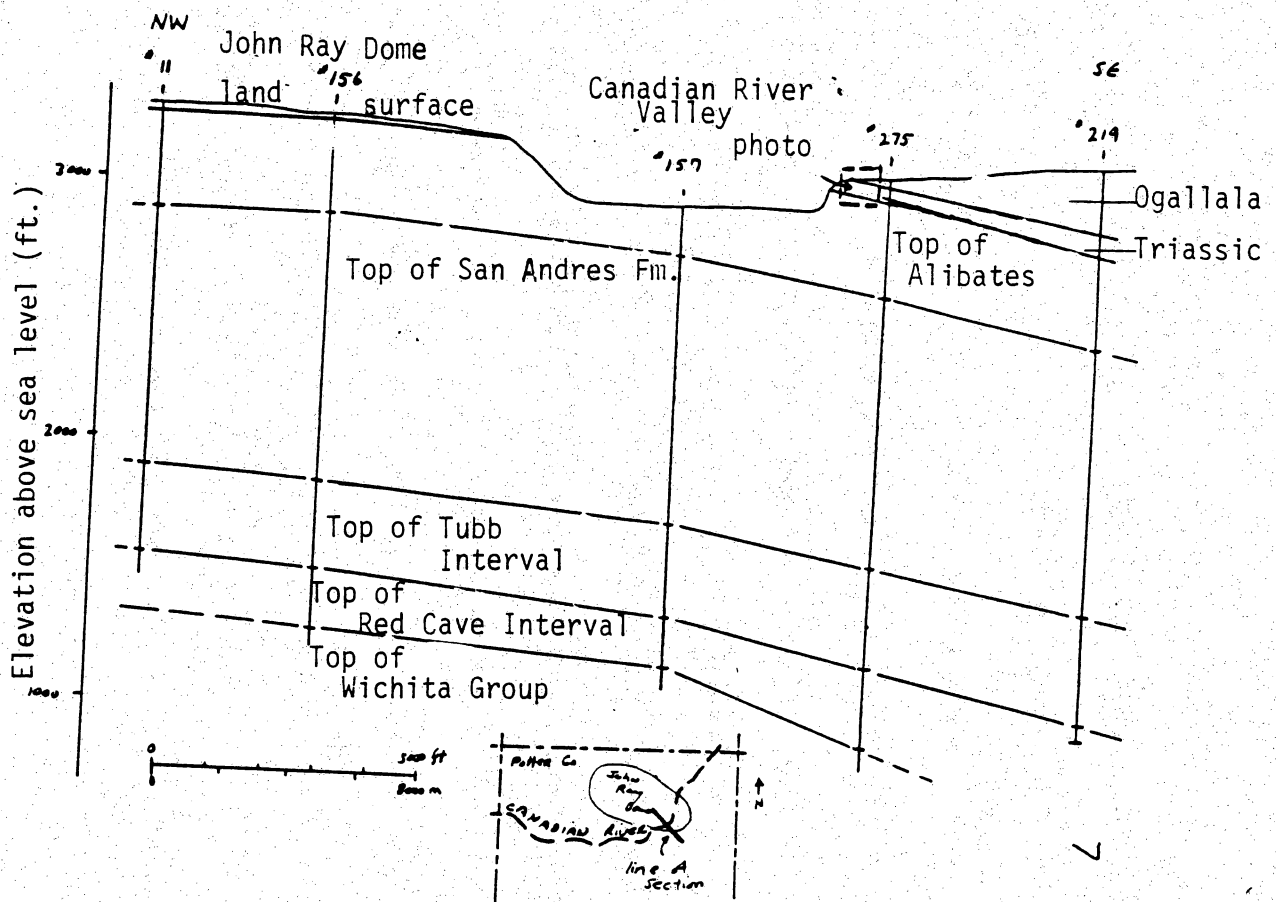


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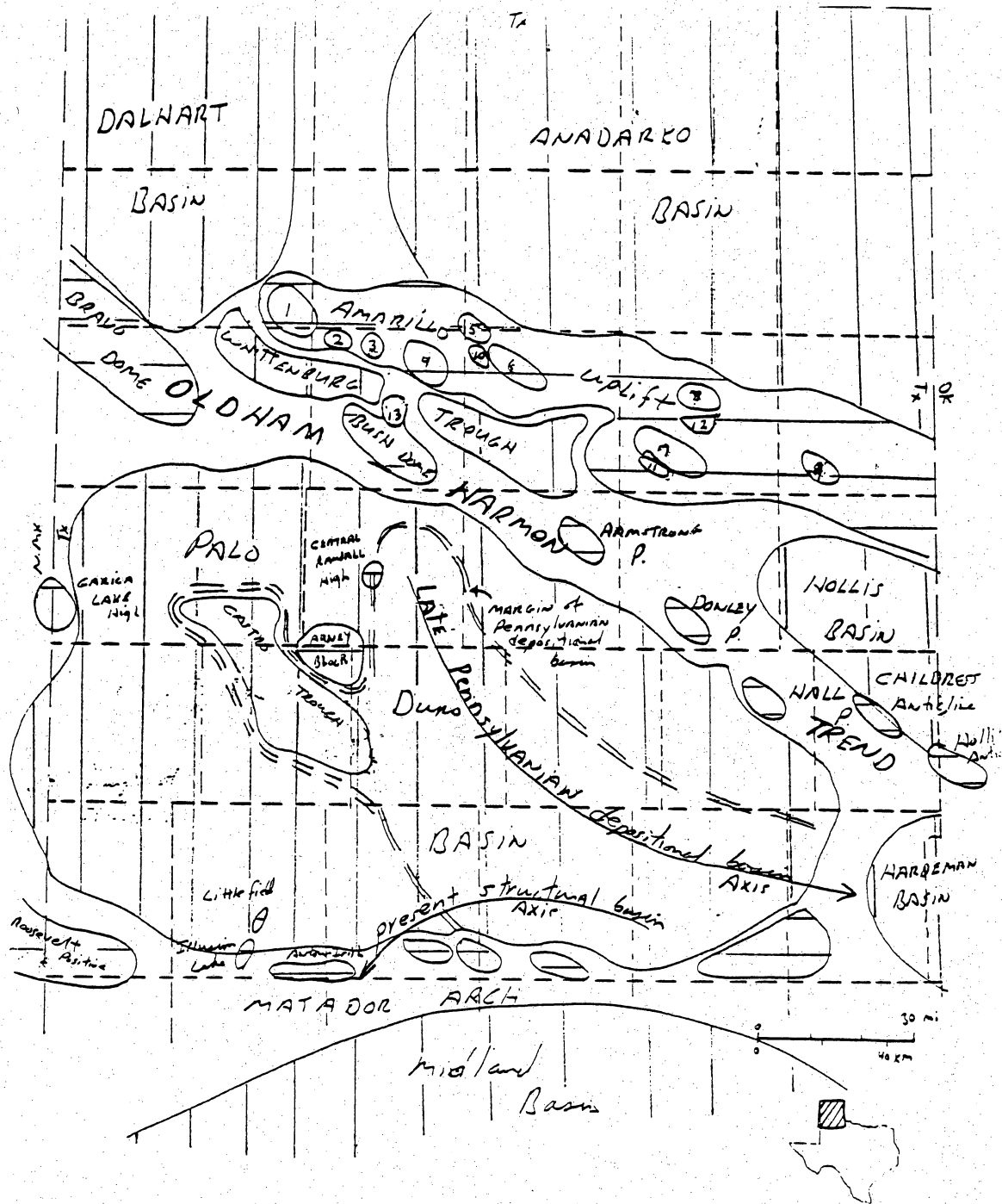


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Figure 10  
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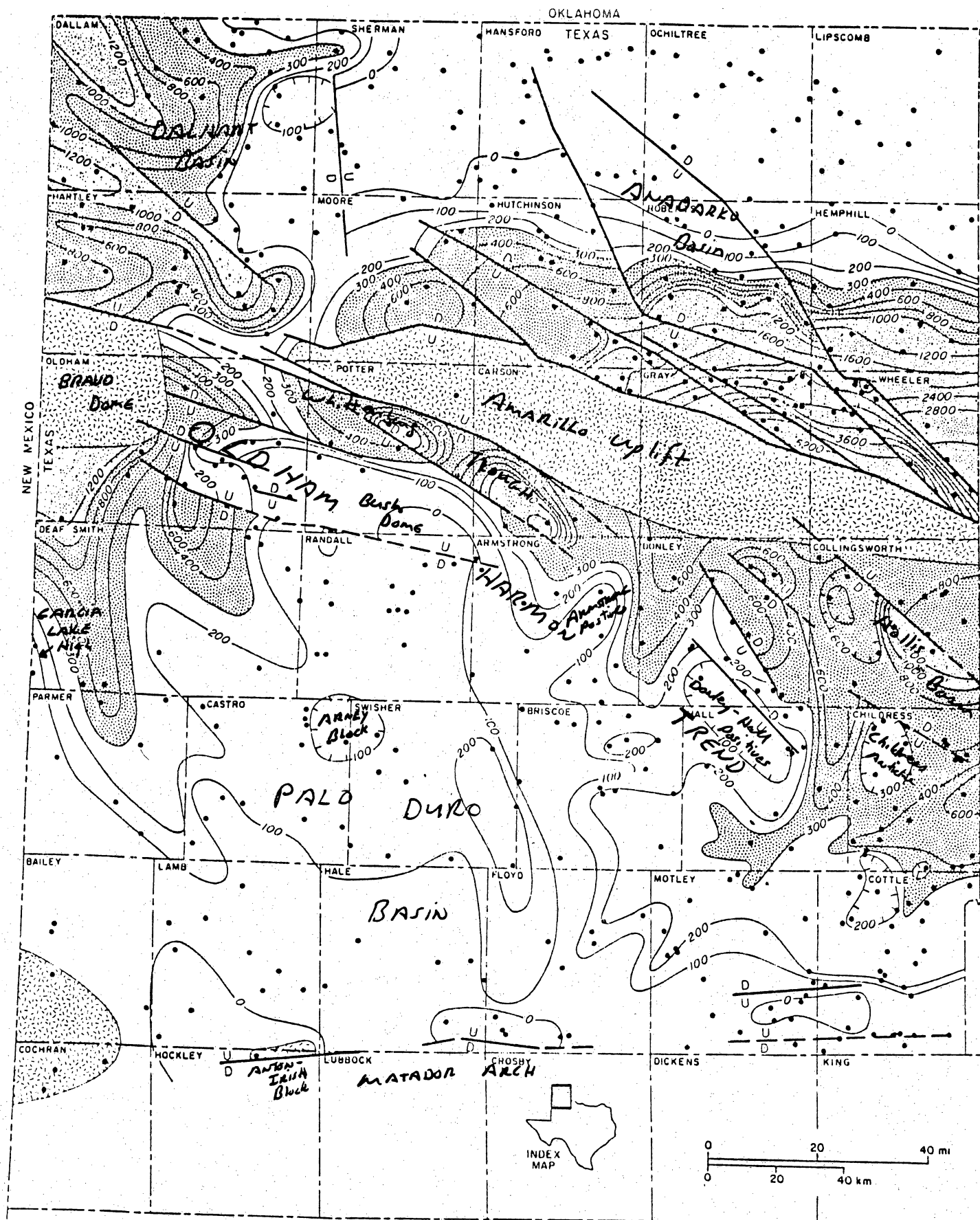


Figure 11. Isolith map of Pennsylvanian and Wolfcamp arkosic clastics (from Dutton, 1982). The clastics were derived primarily from the Amarillo Uplift and trapped in the Whittenburg Trough and other deep basins bordering the uplift. Some of the clastics reached the Palo Duro Basin through lows along the Oldham-Harmon trend.

Figure 12  
See oversized plate for this figure





South

B

North

John Ray Dome, Potter, Moore Co.

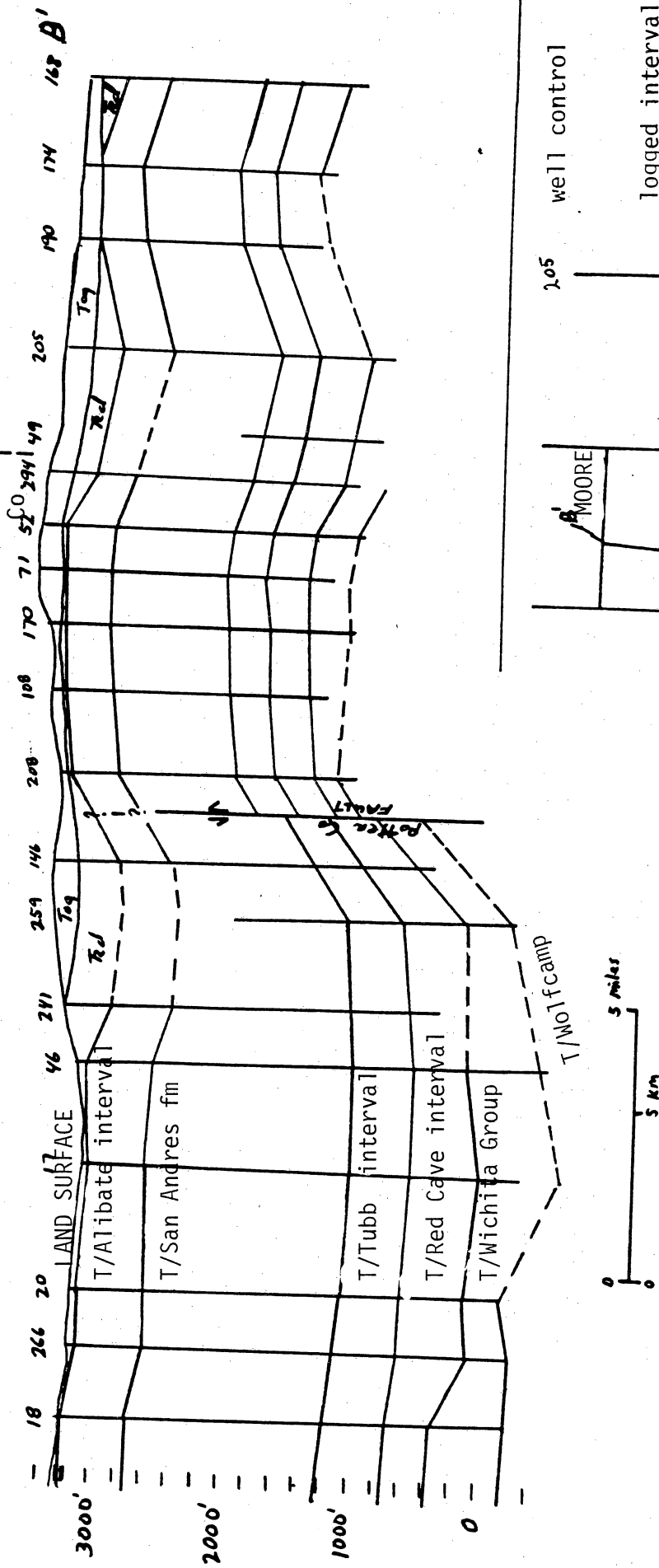


Figure 14. South-north cross section B-B' across northern Potter County. Location shown in figure 13. Triassic Dockum Group=Trd; Tertiary Ogallala Formation=Tog.

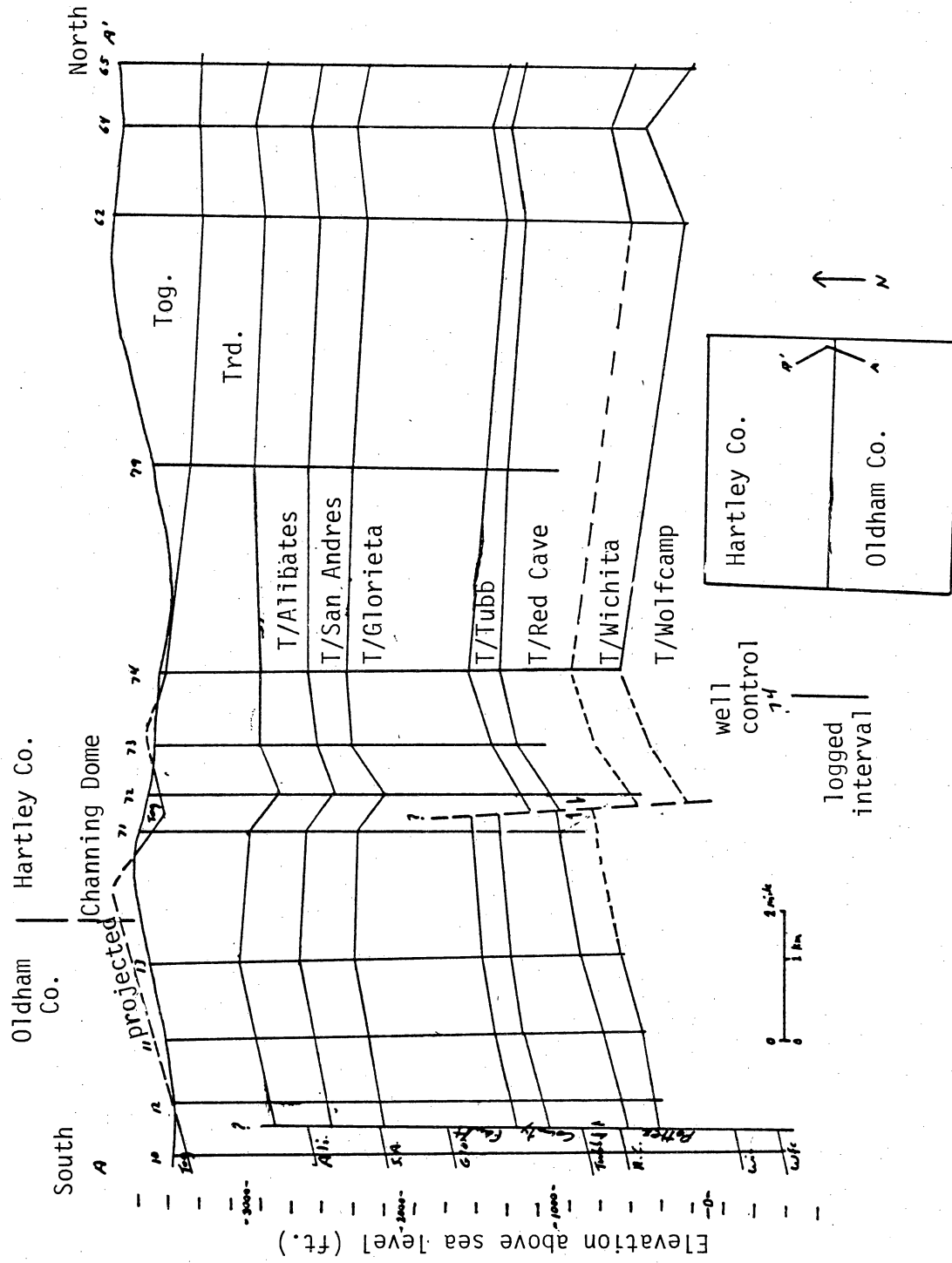


Figure 15. South-north cross section A-A' across Channing Dome. Location shown in figure 13. Triassic Dockum Group=Trd; Tertiary Ogallala Formation=Tog.

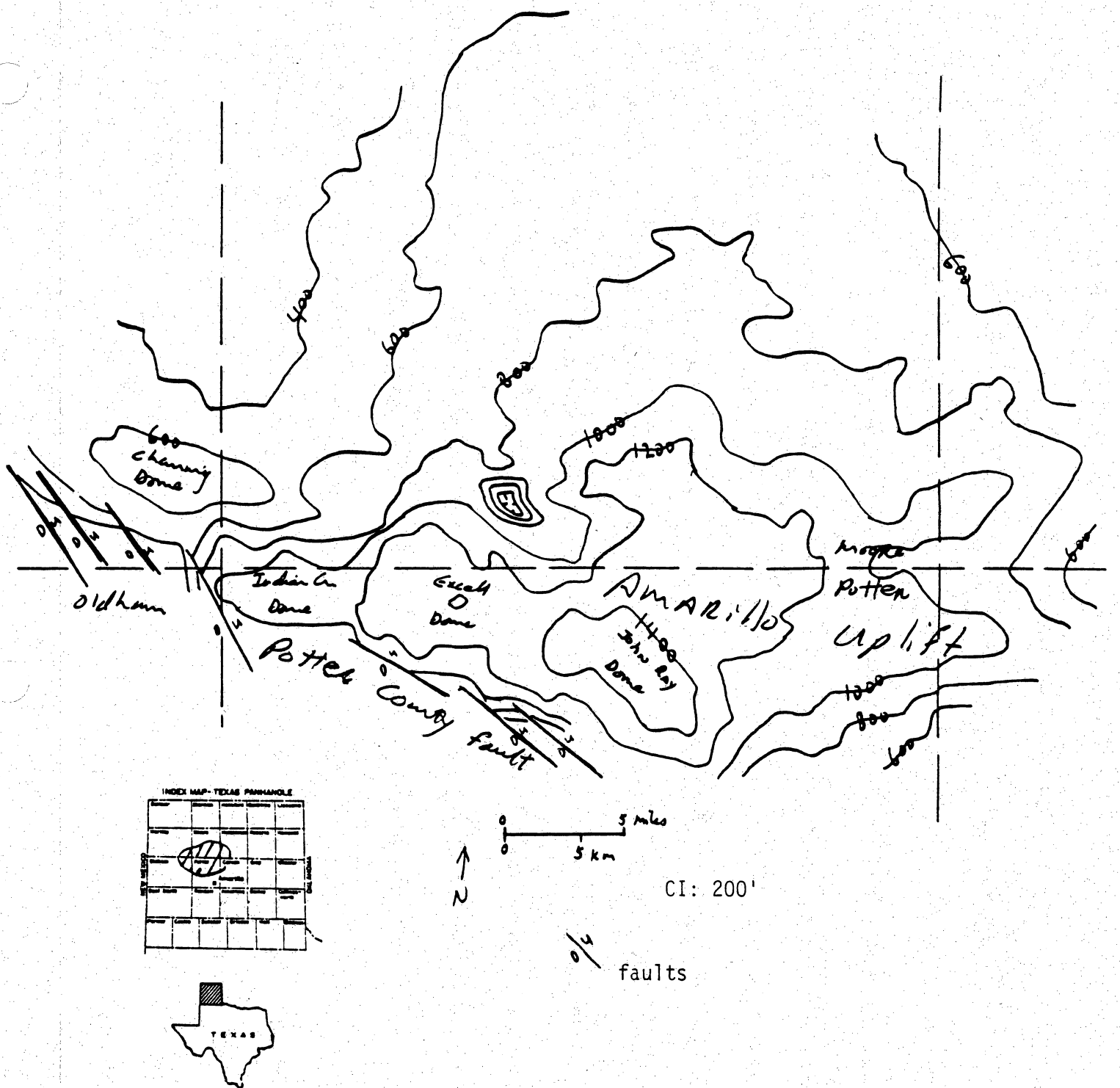


Figure 16. Structure contour map on the top of the Wolfcamp Series, western Amarillo Uplift (from Pierce and others, 1964). The Potter County fault is here depicted as a series of en echelon faults.

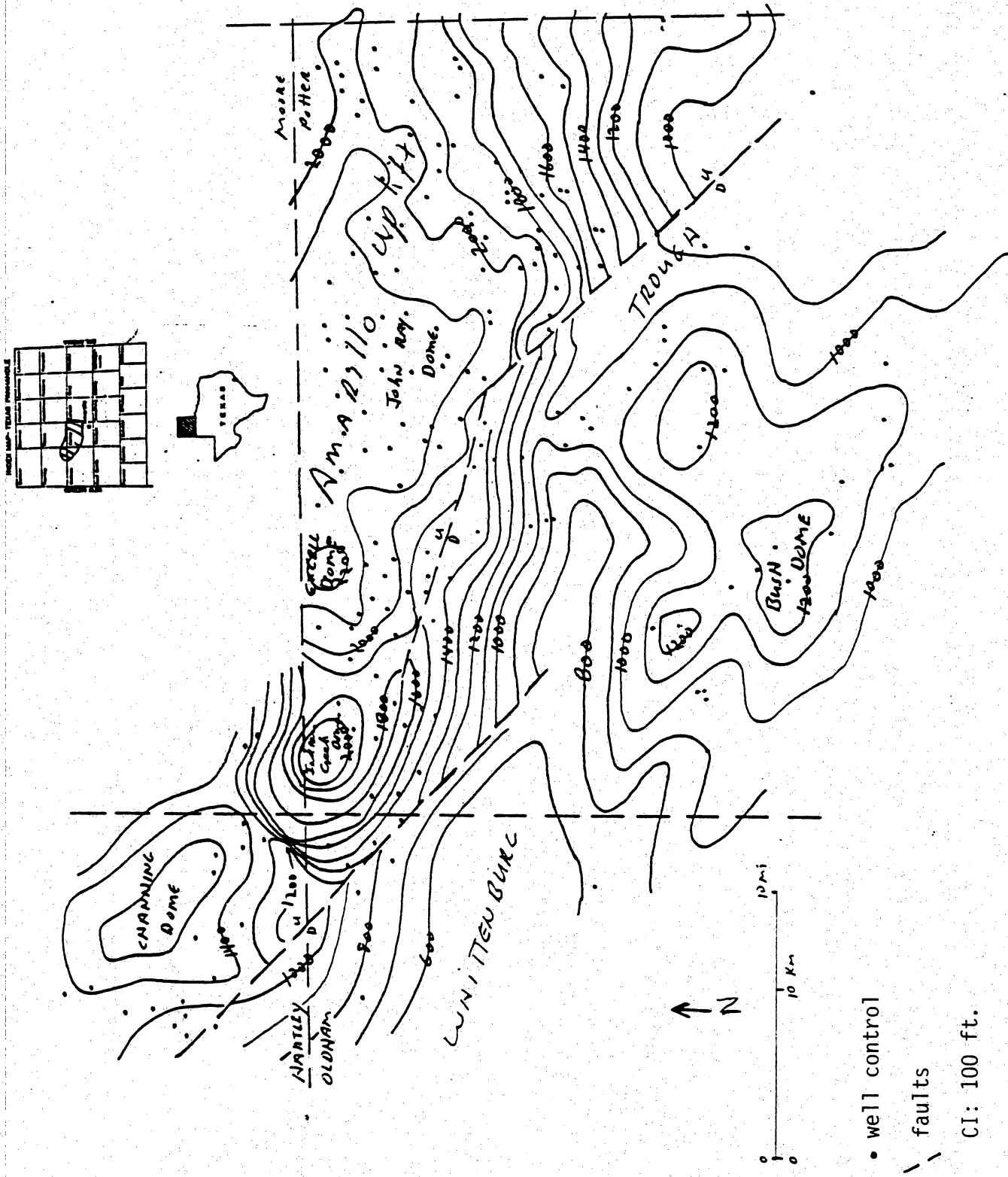


Figure 17. Structure contour map on the top of the Tubb Formation, western Amarillo Uplift.

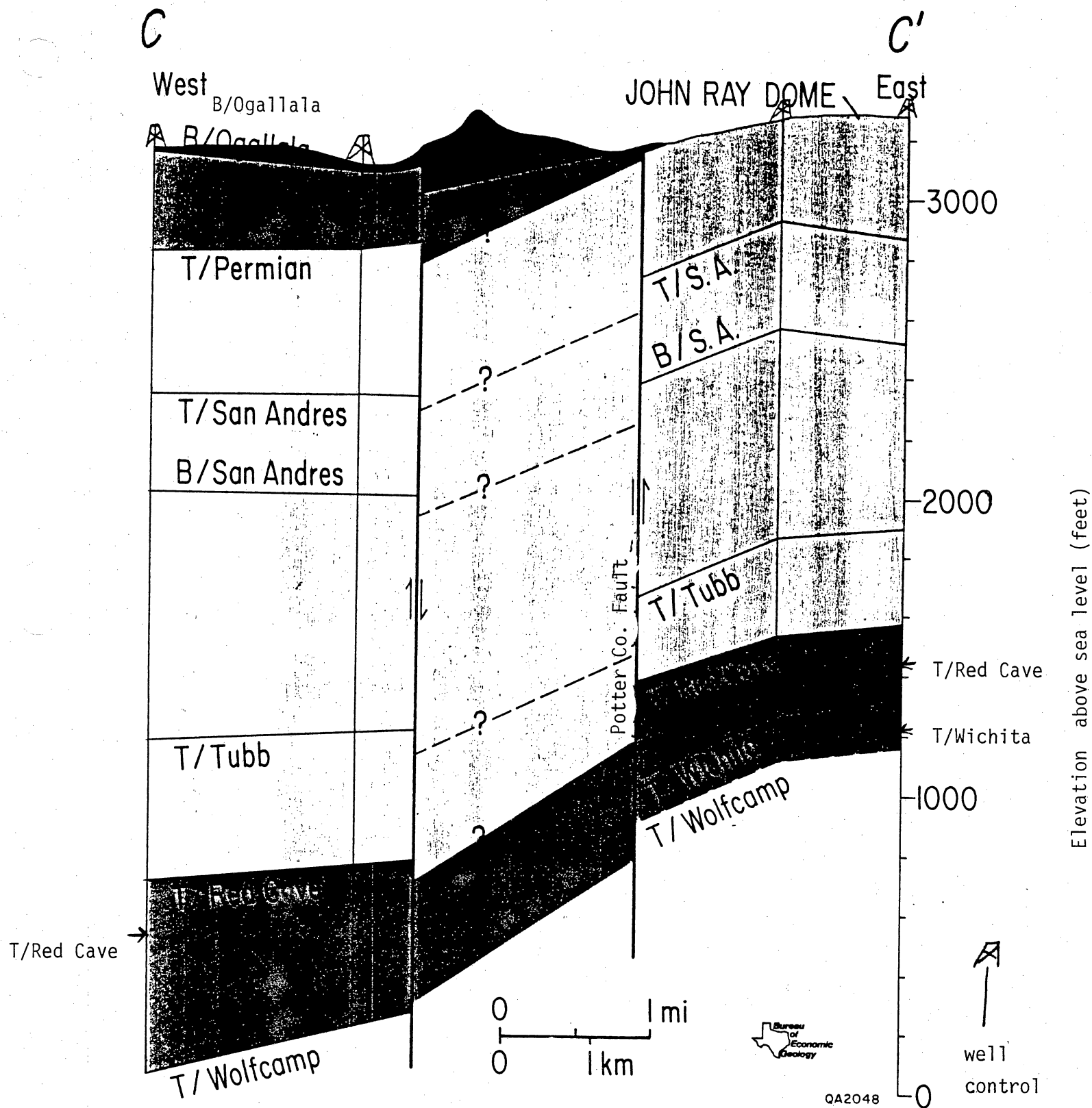


Figure 18. West-east cross section across the south flank of the John Ray Dome. Field relations suggest that the Ogallala is offset along a fault to the west of the Potter County fault. Location shown in figure 13.

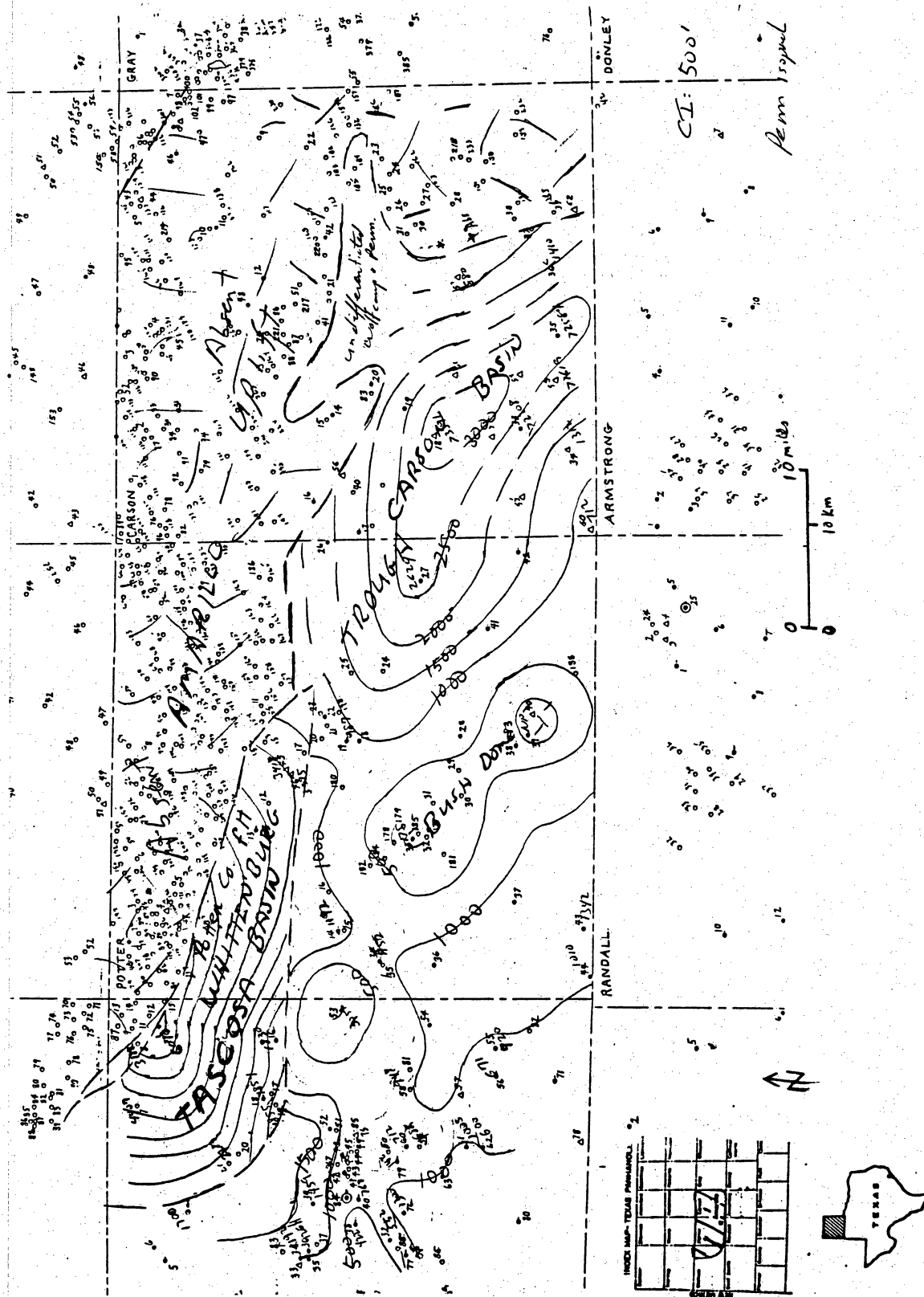


Figure 19a. Isopach maps showing the Whittenburg Trough and the western Amarillo Uplift. Pennsylvanian System.

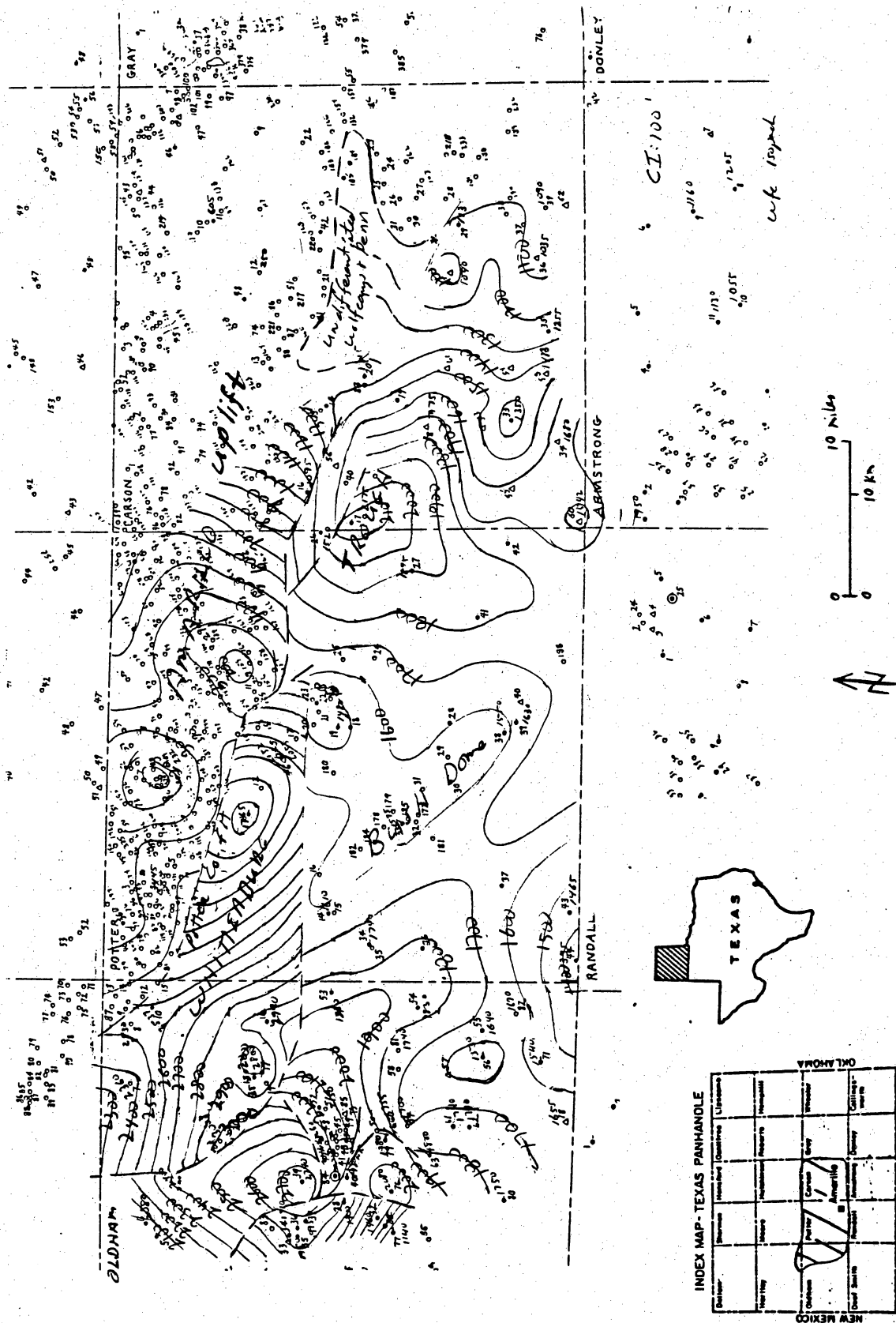


Figure 19b. Isopach map showing the Whittenburg Trough and the western Amarillo Uplift. Wolfcamp Series.

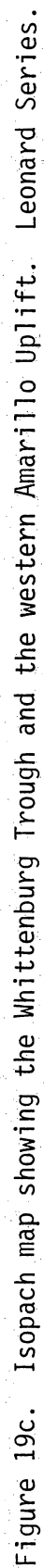


Figure 19c. Isopach map showing the Whittenburg Trough and the western Amarillo Uplift. Leonard Series.



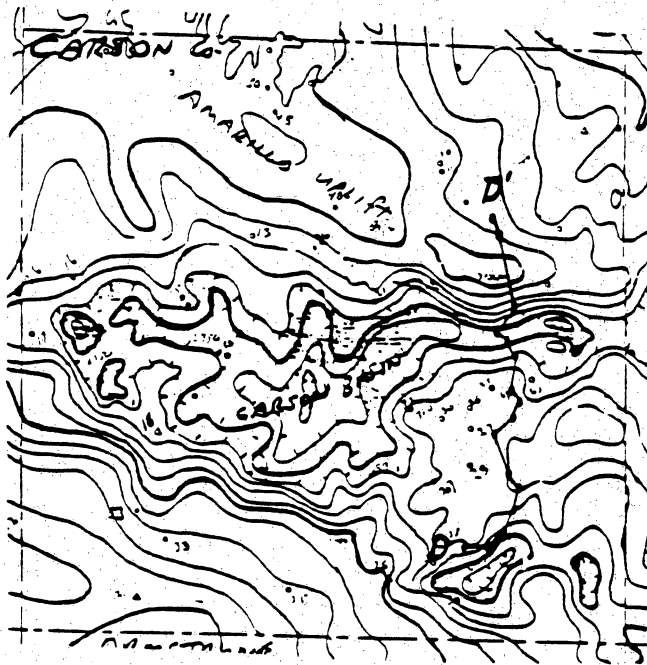
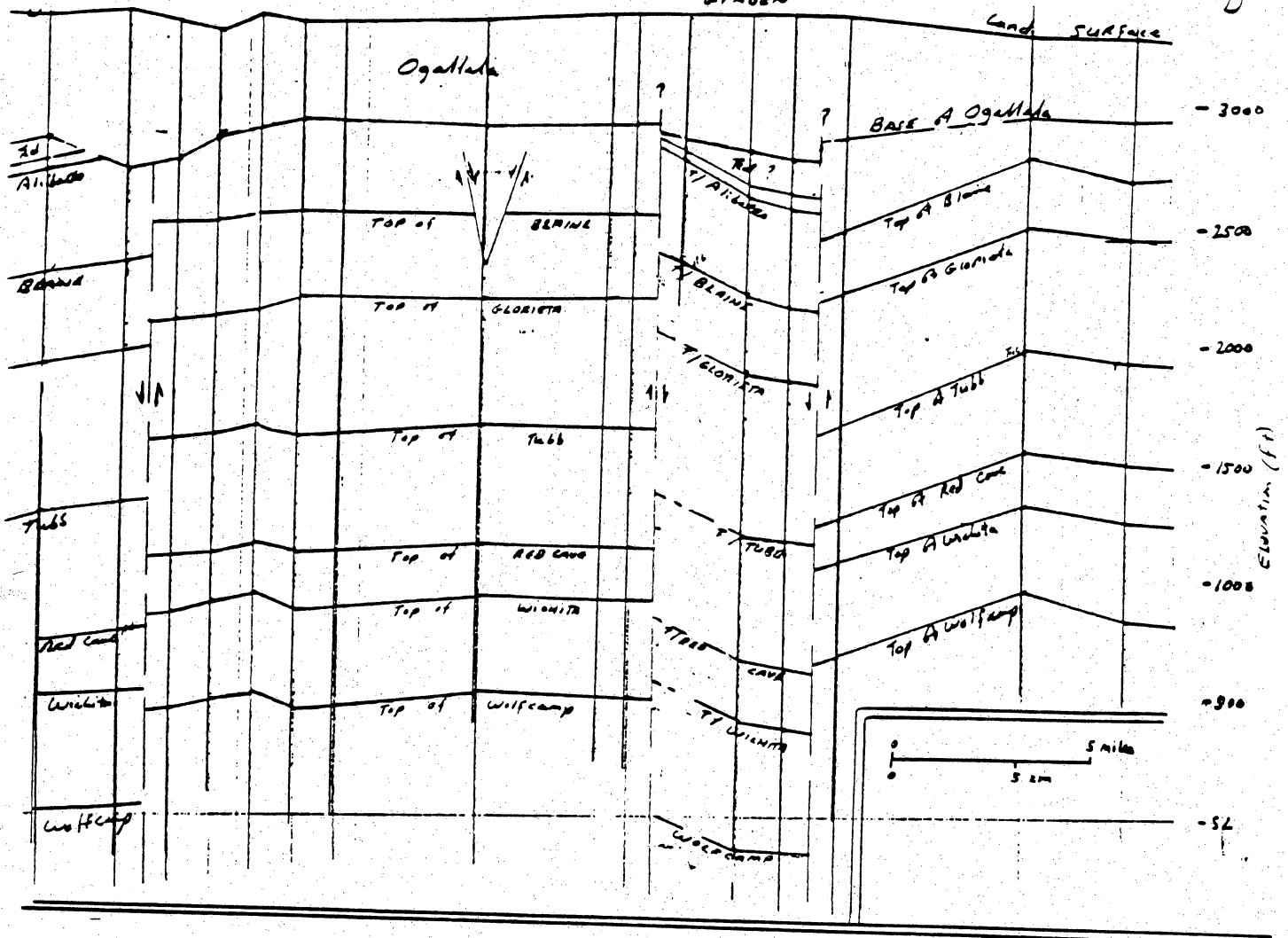
South

D

WHITE  
DEER  
GRABEN

N

D'



Structure on base of Ogallala Formation (after Knowles and others, 1982a)

N

0 10 mi  
10 km

D D' Cross section  
CI = 50 ft

Figure 20. South-north cross section and structure contour map on the base of the Ogallala Formation in Carson County. The Alibates formation and Dockum Group (Trd) are absent beneath the Ogallala Formation on the Amarillo Uplift, but are preserved in the White Deer graben and to the south of the uplift. The Ogallala Formation thickens into the graben; faults that bound the graben may offset the base of the Ogallala.

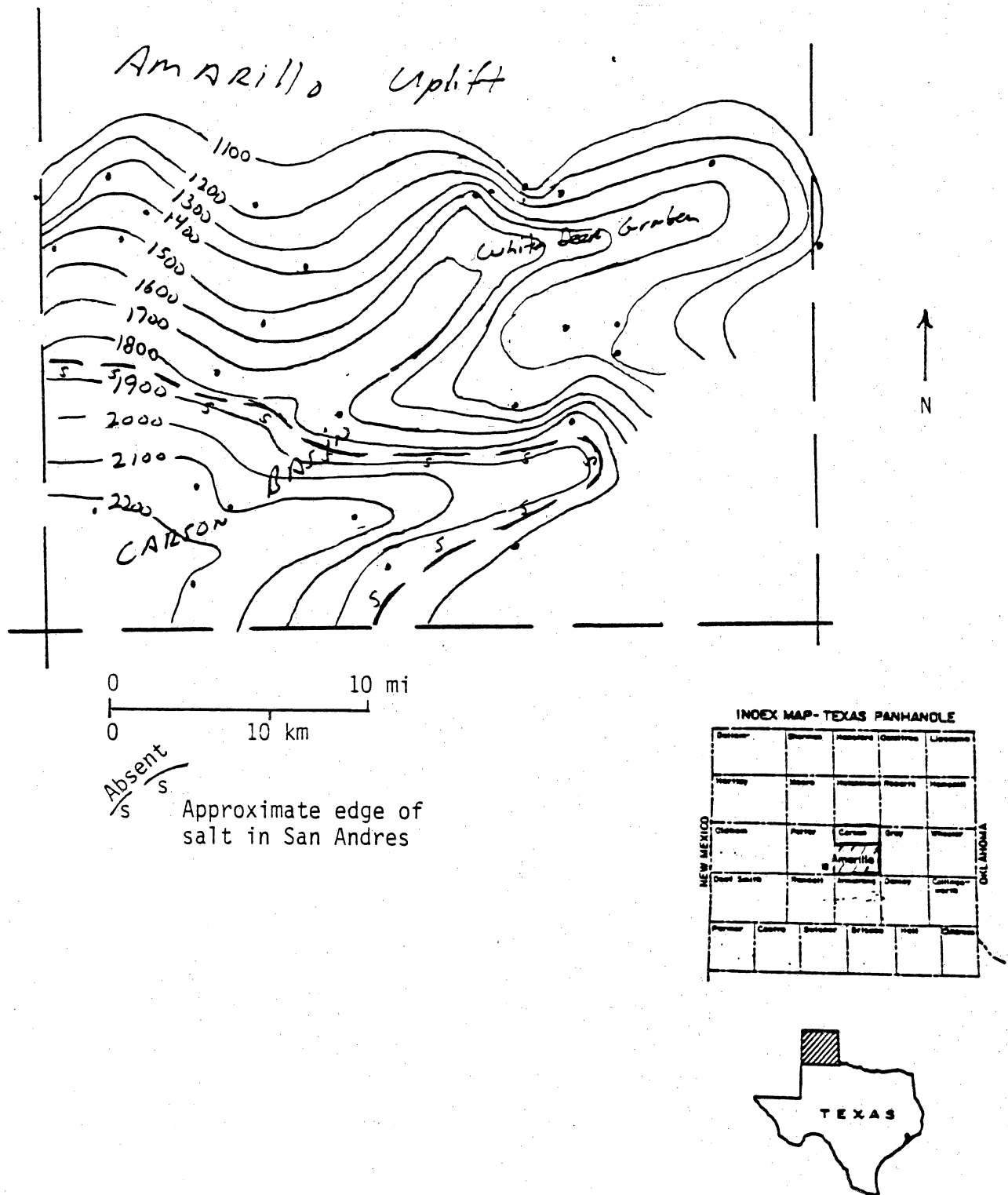


Figure 21. Isopach map of the Middle and Upper Permian, southern Carson County. Interval from top of Tubb Formation to top of Alibates Formation. Salt is absent from San Andres and younger formations outside indicated area.

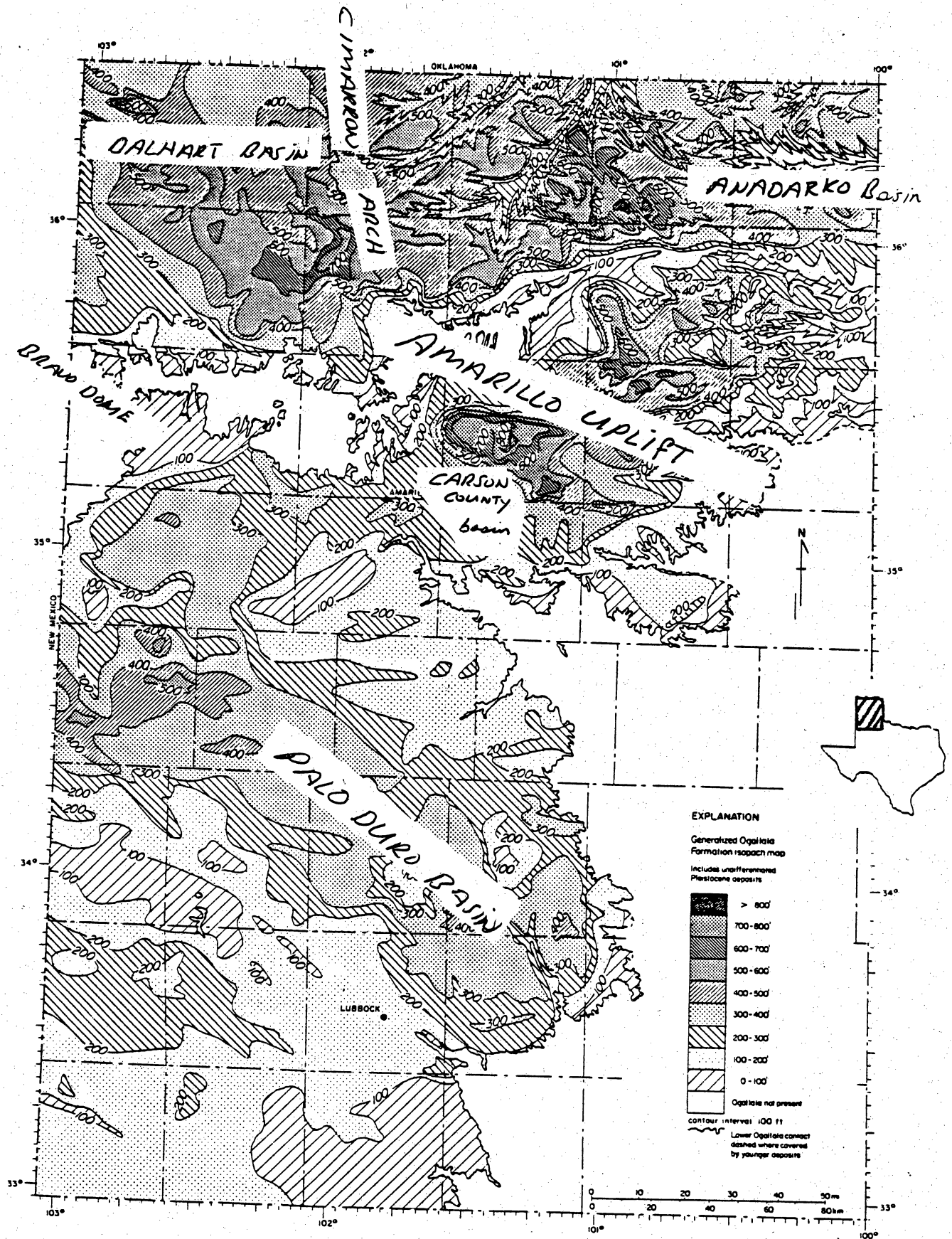


Figure 22. Isopach map of the Ogallala Formation, Texas Panhandle (from Seni, 1980).

Figure 23  
See oversized plate for this figure

Figure 24  
See oversized plate for this figure

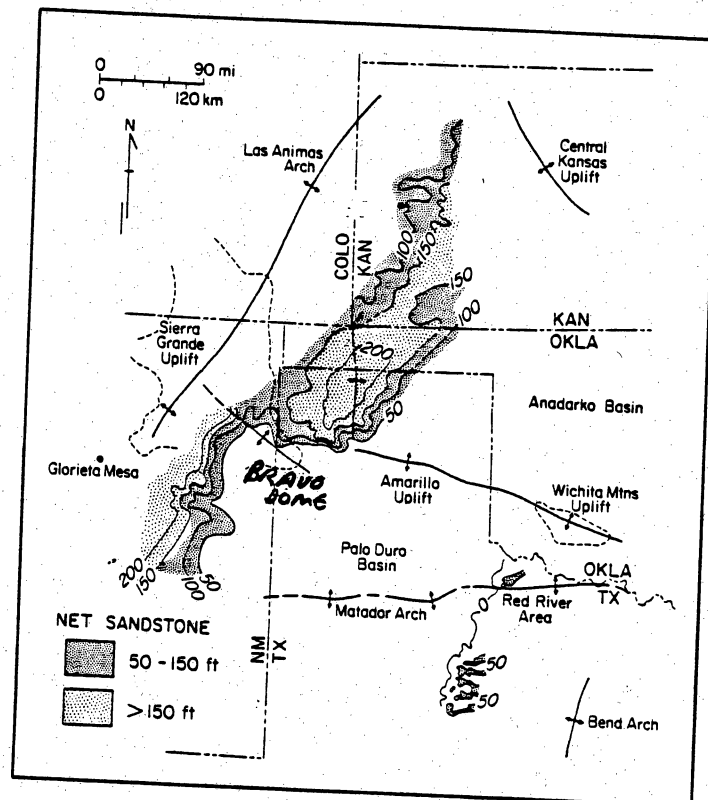
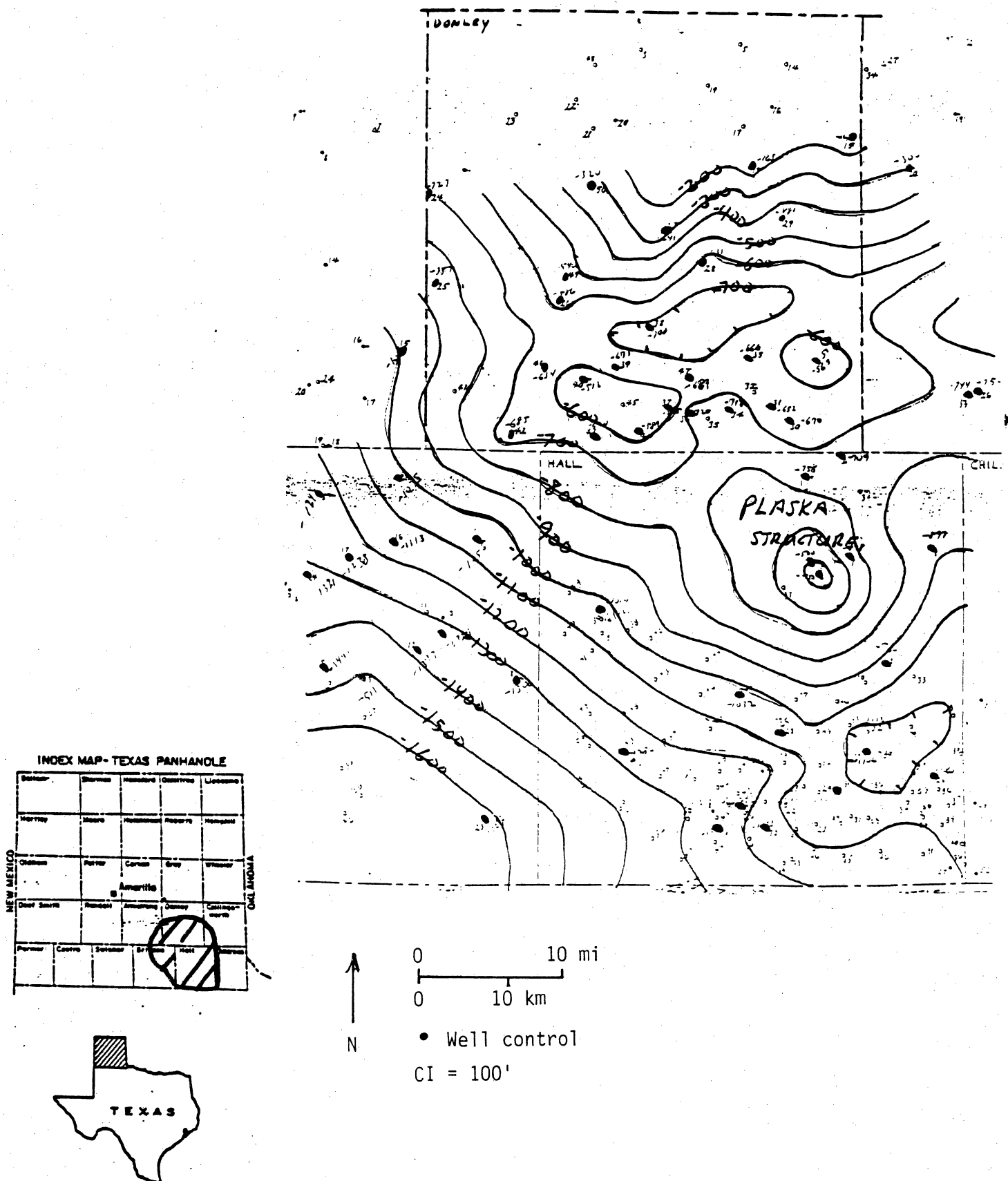


Figure 25. Net sandstone in the Glorieta Formation (Presley and McGillis, 1982). The sandstone thins against the Bravo Dome, suggesting that the dome was a topographic high during the late Leonardian.



Figures 26. Structure contour map on the top of the Wolfcamp Series, Hall and Donley Counties. Seismic data indicate that the Wolfcamp Series is offset along faults (not shown) that bound the Plaska structure.

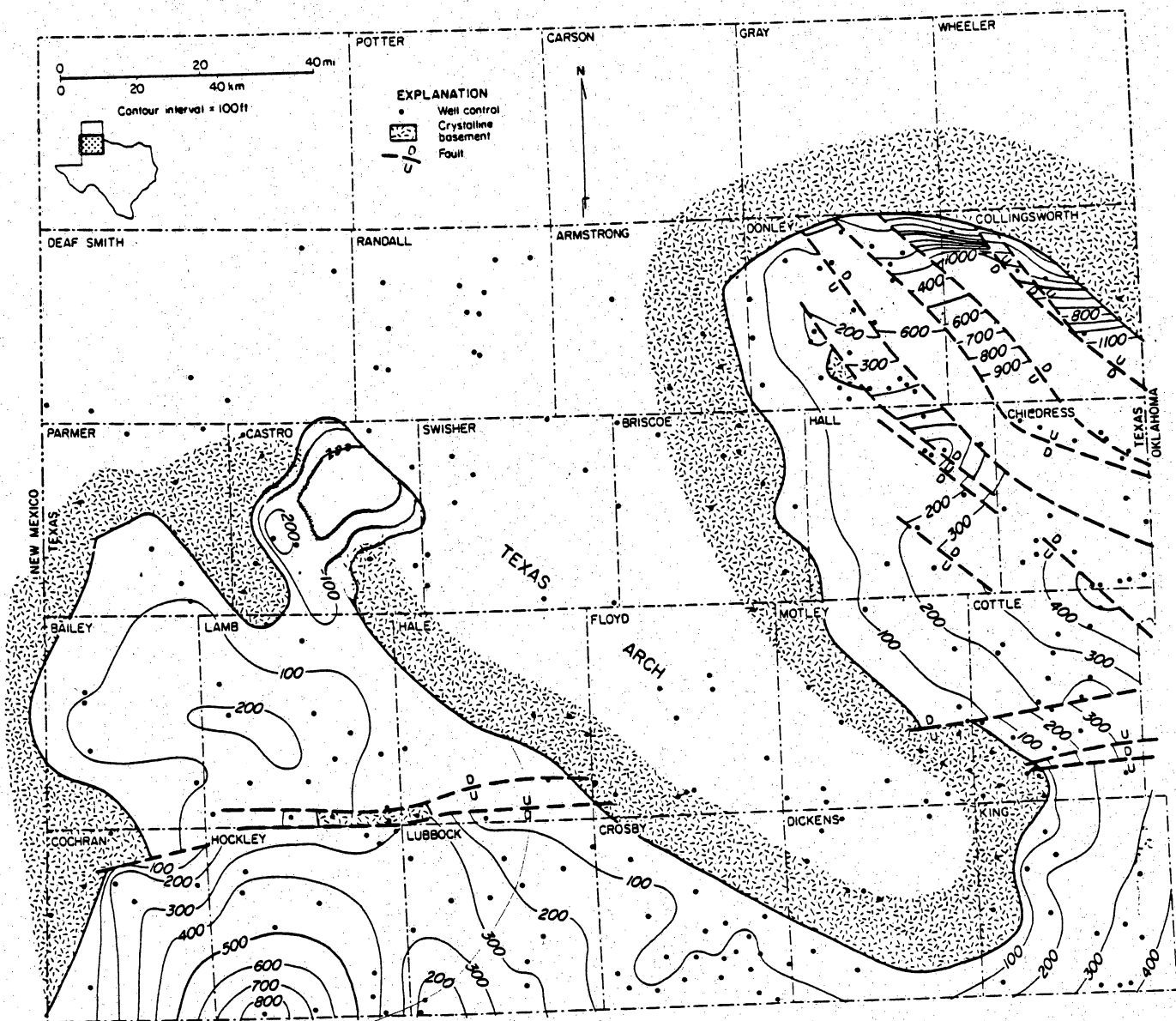


Figure 27. Isopach map of Ellenburger Group, Palo Duro Basin (modified from Ruppel, 1982).



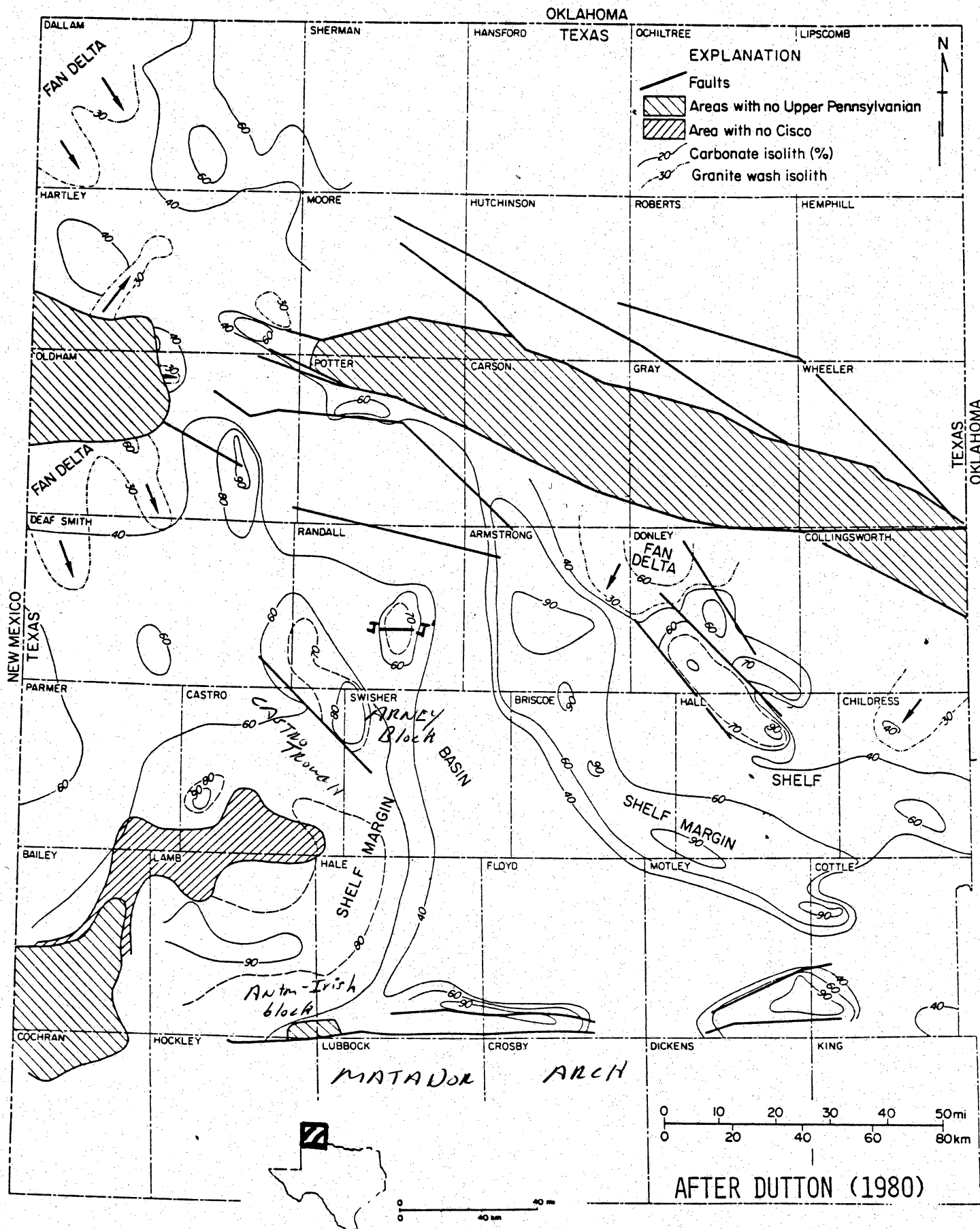
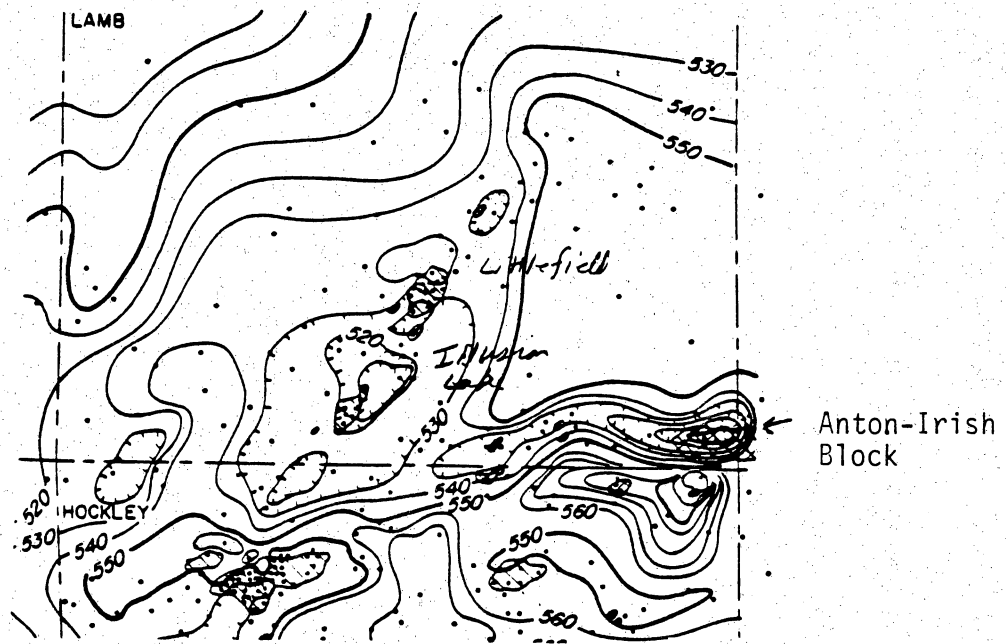


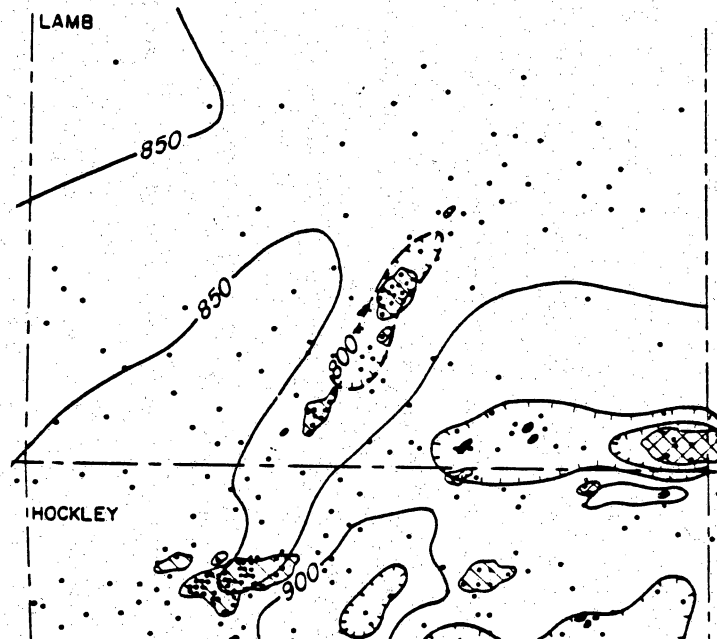
Figure 28. Percent carbonate in the Upper Pennsylvanian, Palo Duro Basin (after Dutton, 1980).

Figure 29  
See oversized plate for this figure

Figure 30  
See oversized plate for this figure



CI = 10 ft



0 10 mi  
0 10 km

CI = 50 ft



Oil Fields

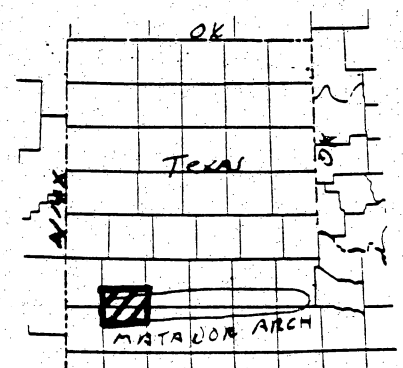


Figure 31. Isopach maps of the San Andres Formation, Lamb and Hockley Counties (Ramondetta, 1982). a) Upper part of San Andres; b) lower part of San Andres. The San Andres Formation thins over the Anton-Irish and other structural highs along the western Matador Arch.

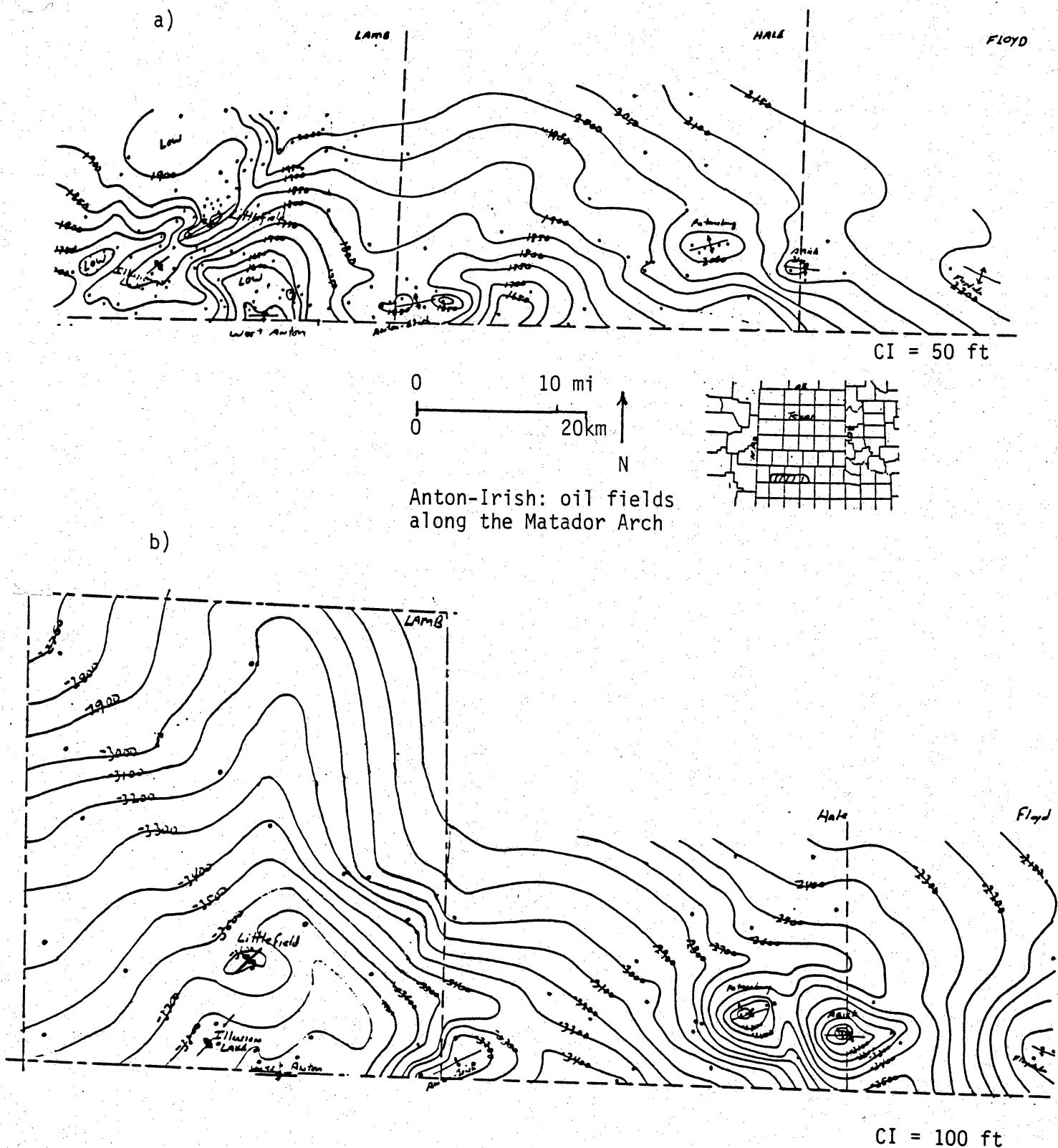
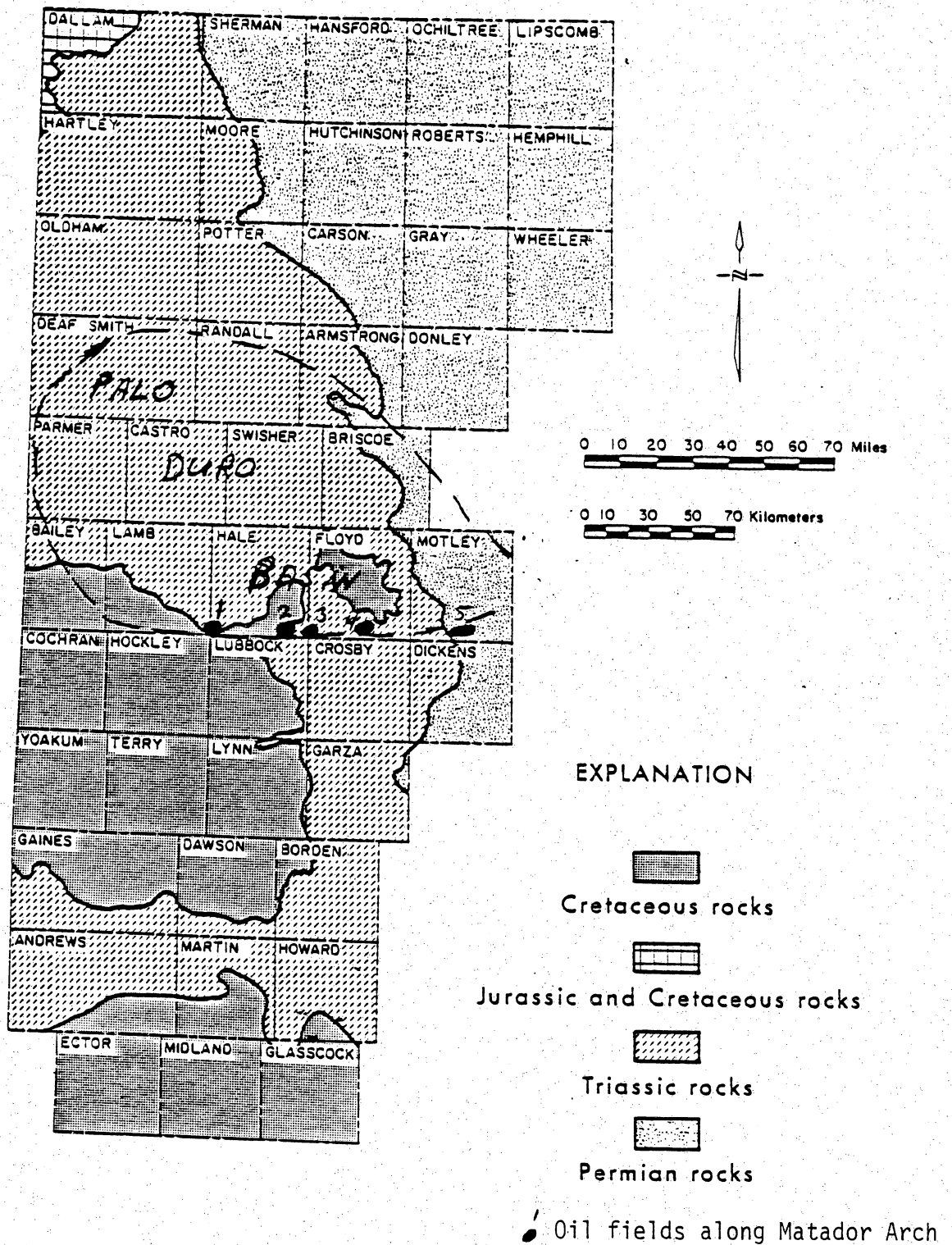


Figure 32. Structure contour maps of the western Matador Arch: a) on the top of the Wolfcamp Series; b) top of the Alibates formation. Structures in the deeper horizons are reflected in the shallower horizons.



Geologic Units Underlying the Ogallala Formation

Figure 33. Subcrop map of the Ogallala Formation (Knowles and others, 1982b). Oil field locations along the Matador Arch are indicated: 1) Anton-Irish; 2) Petersburg; 3) Arick; 4) Floydada; 5) Roaring Springs. The Cretaceous is preserved in the structurally low areas in Hale and Floyd Counties.

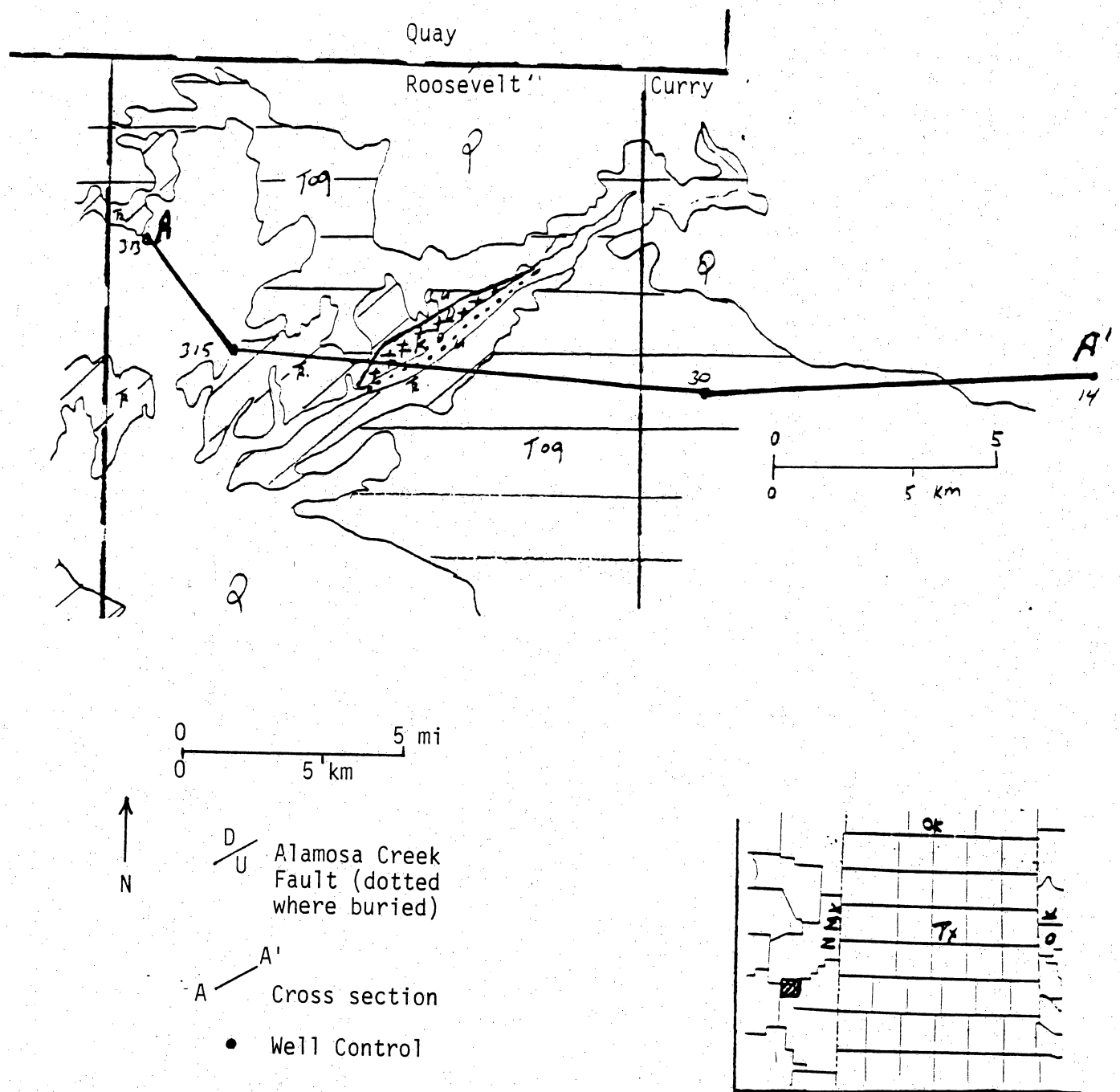


Figure 34a. Alamosa Creek fault, Roosevelt County, New Mexico. Surface geology in the vicinity of Alamosa Creek fault, Roosevelt County, New Mexico (Lovelace, 1972). Tr = Triassic (diagonally ruled); Tog = Tertiary Ogallala Formation (vertically ruled); K = Cretaceous (+++); Q = Quaternary (unpatterned).

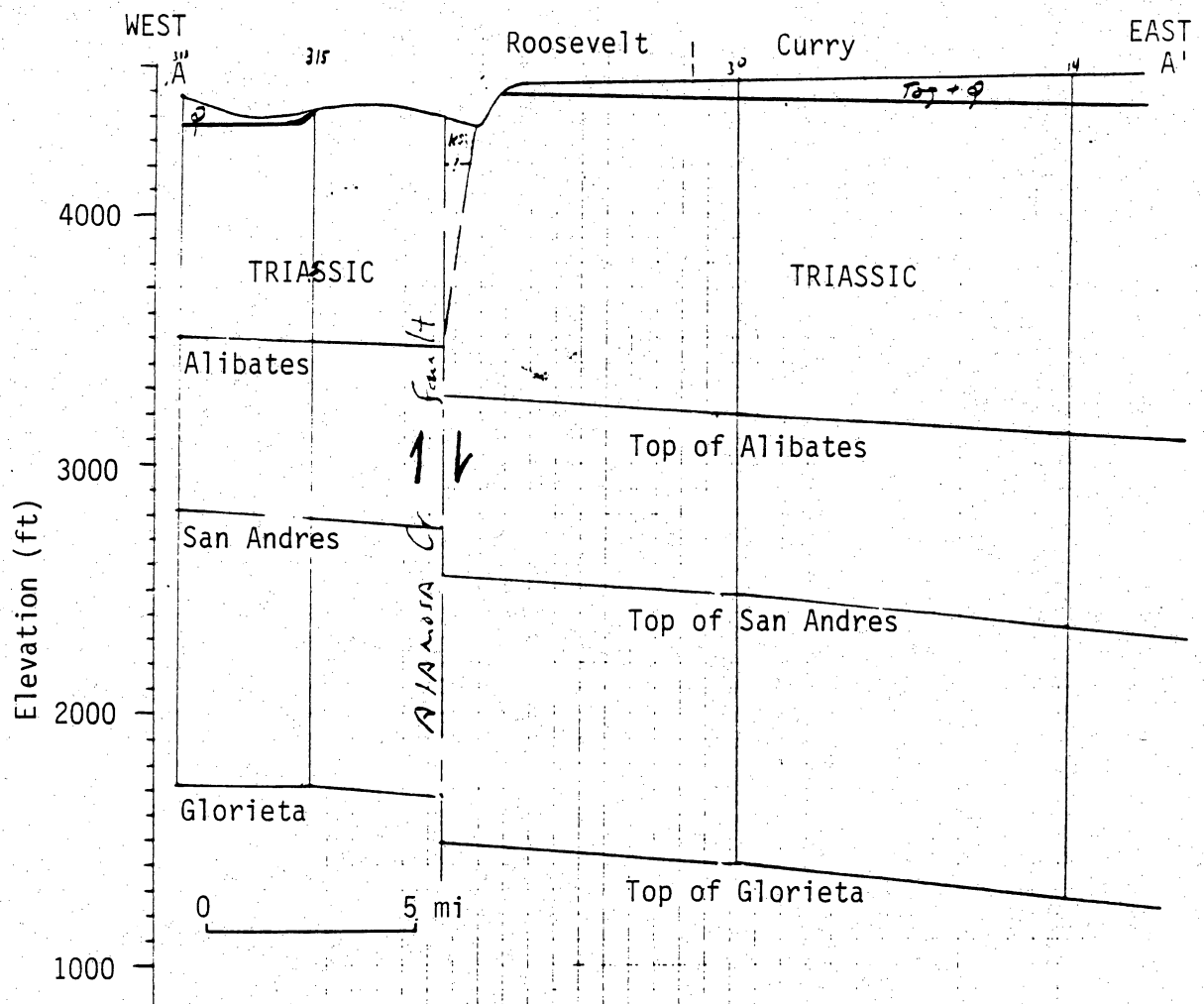


Figure 34b. Alamosa Creek Fault, Roosevelt County, New Mexico. West to east cross section of the Alamosa Creek Fault. The Cretaceous strata are preserved in a graben along the fault.



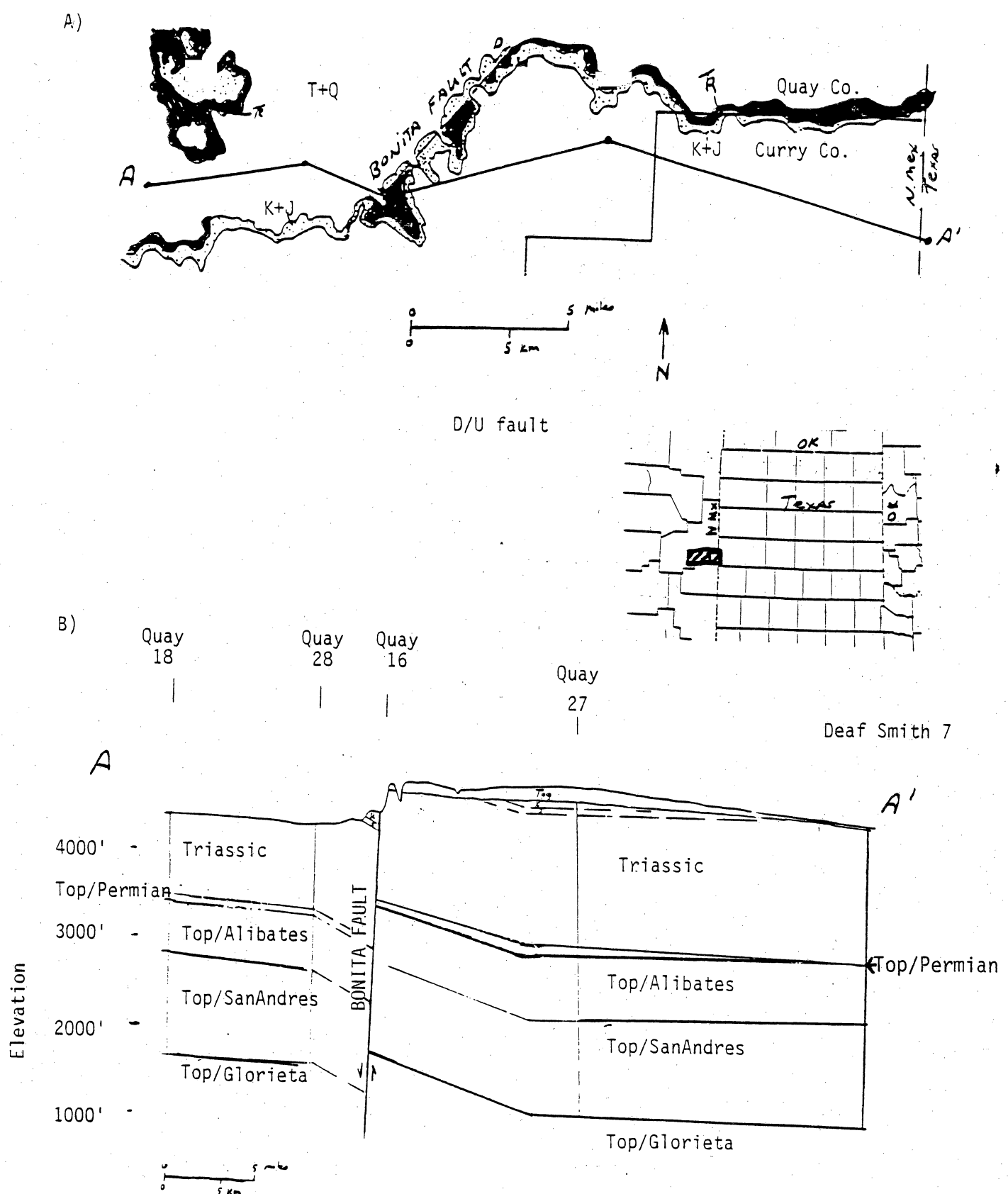


Figure 35. Bonita fault, Quay County, New Mexico. a) Surface geology in the vicinity of the Bonita Fault, Quay County, New Mexico (Lovelace, 1972). Tr= Triassic (black), K+J= Cretaceous and Jurassic (patterned), T+Q= Tertiary and Quaternary (unpatterned). b) West-east cross section of the Bonita Fault. Modified from unpublished section by E. Collins. Based on surface and sub-surface geology.

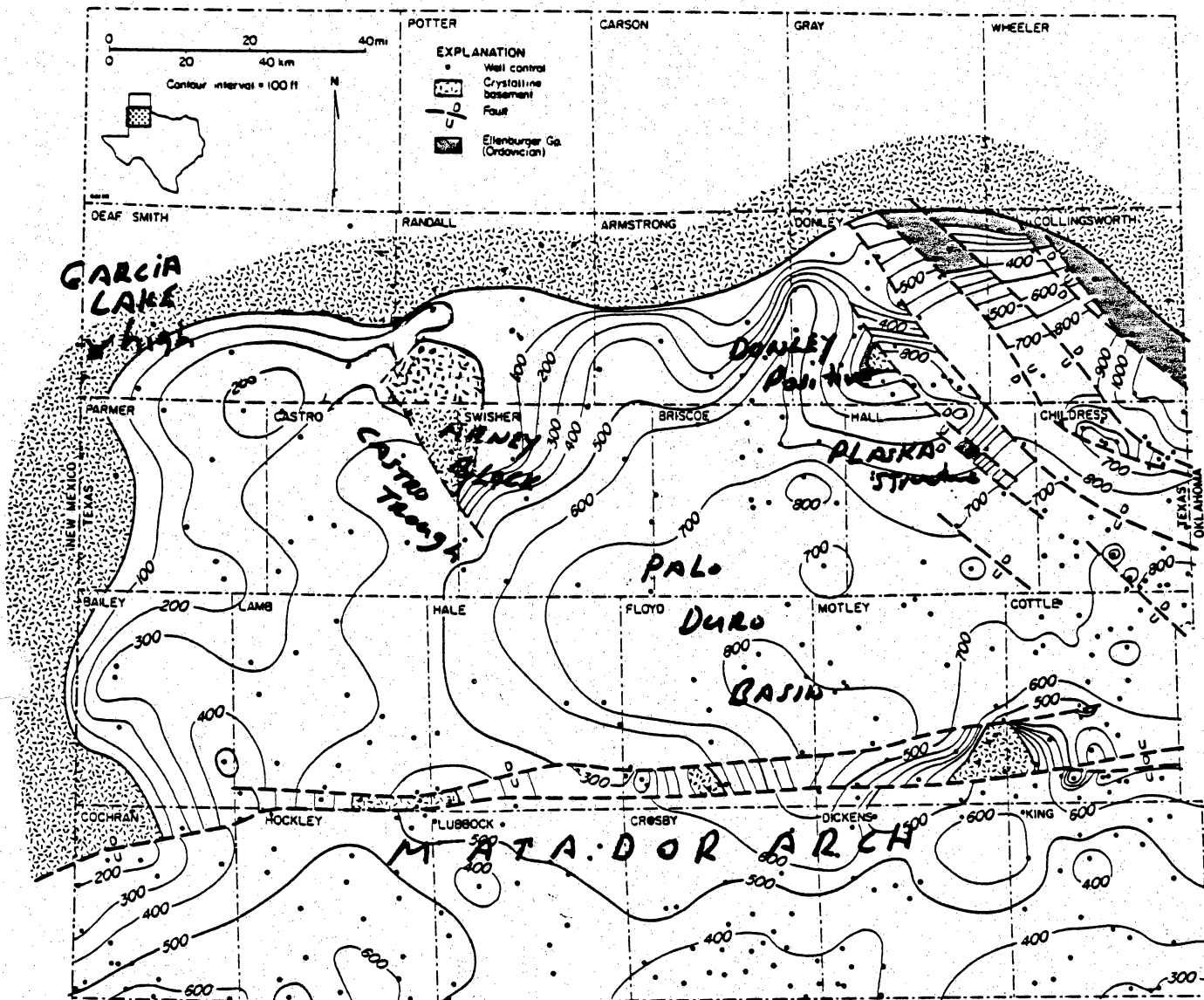


Figure 36. Isopach map of the Mississippian System, Palo Duro Basin (Modified from Ruppel, 1982).

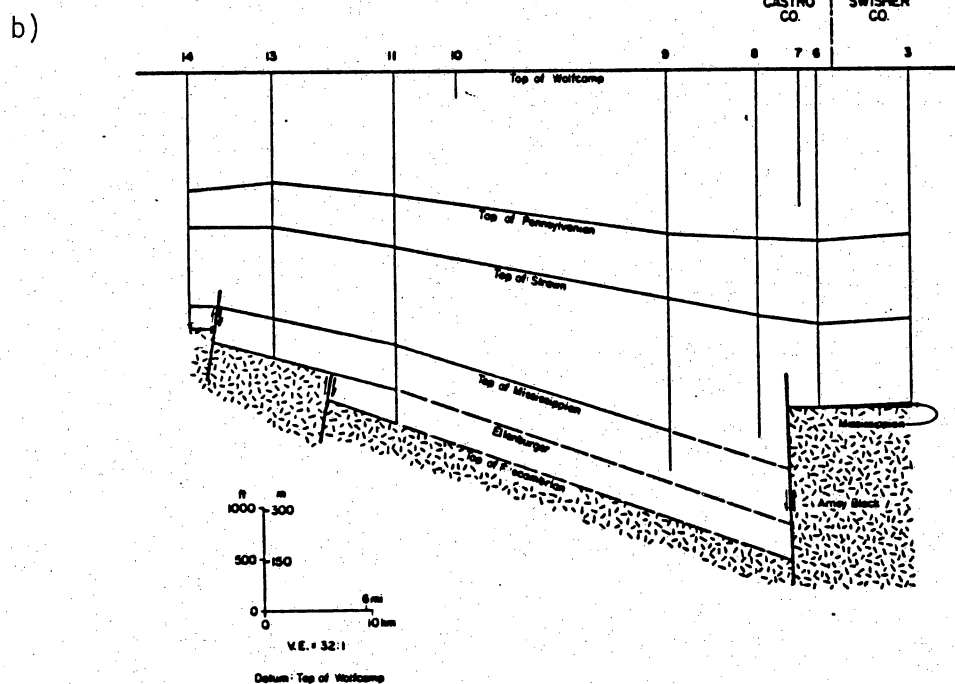
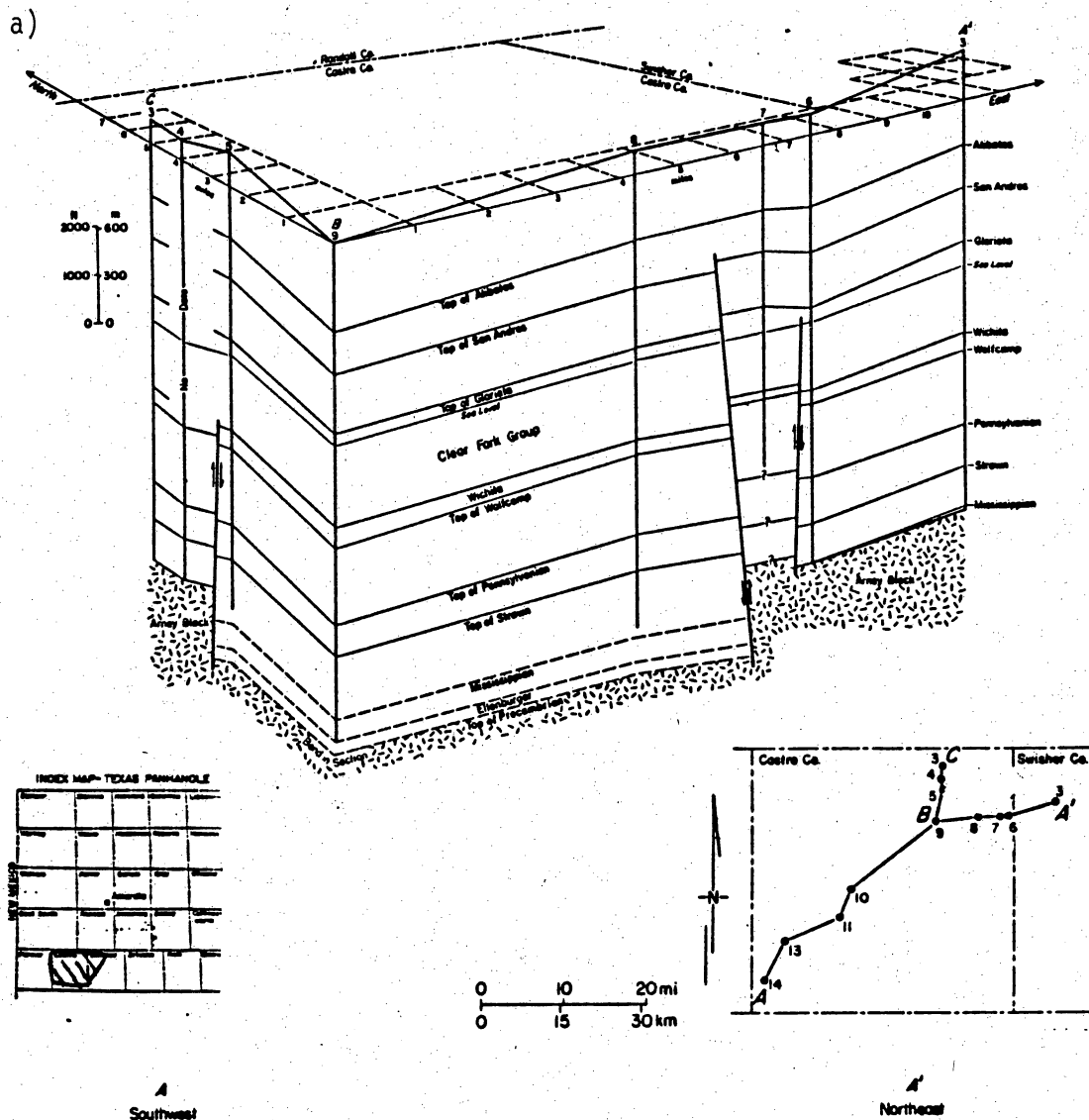
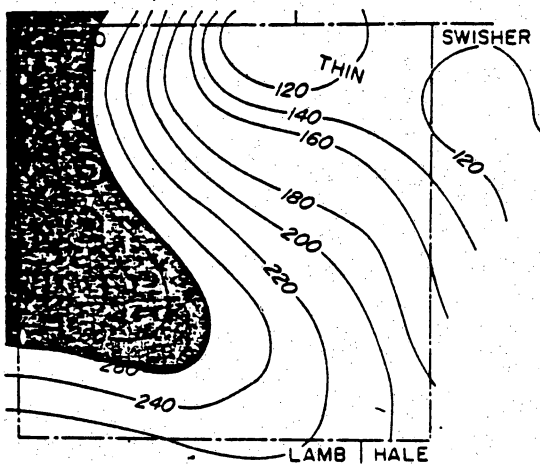


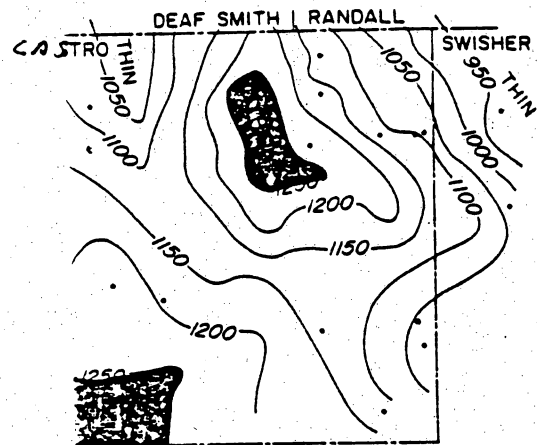
Figure 37. Cross section, Castro Trough, Castro County: a) Fence diagram of northeastern Castro County; b) Restored southwest-northeast cross section of the Castro Trough. Datum: top of the Wolfcamp Series (Budnik, 1983).

a)



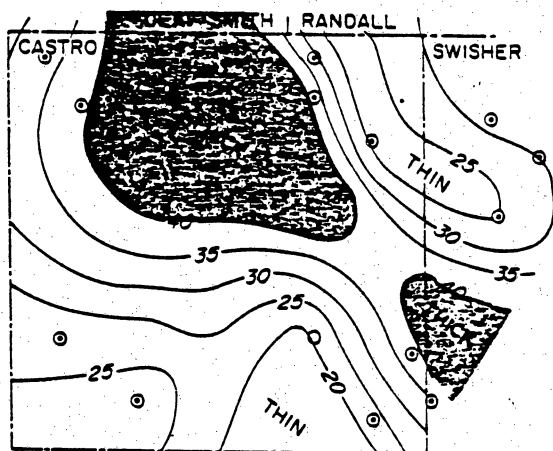
Net sand - Tertiary Ogallala Formation, CI = 20 ft

b)



Isopach - Dockum Group and Dewey Lake Formation  
CI = 80 ft

c)



Percent sand - Triassic lower Dockum Group  
CI = 5%

• Well control

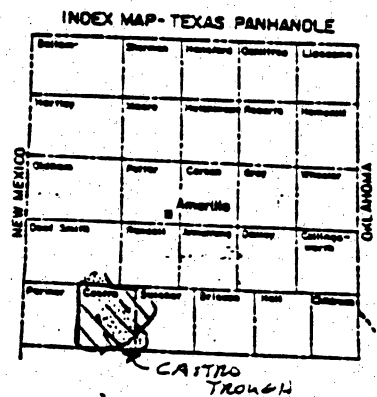
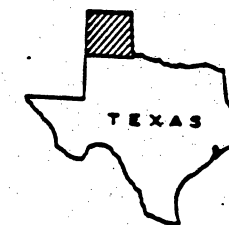
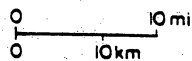
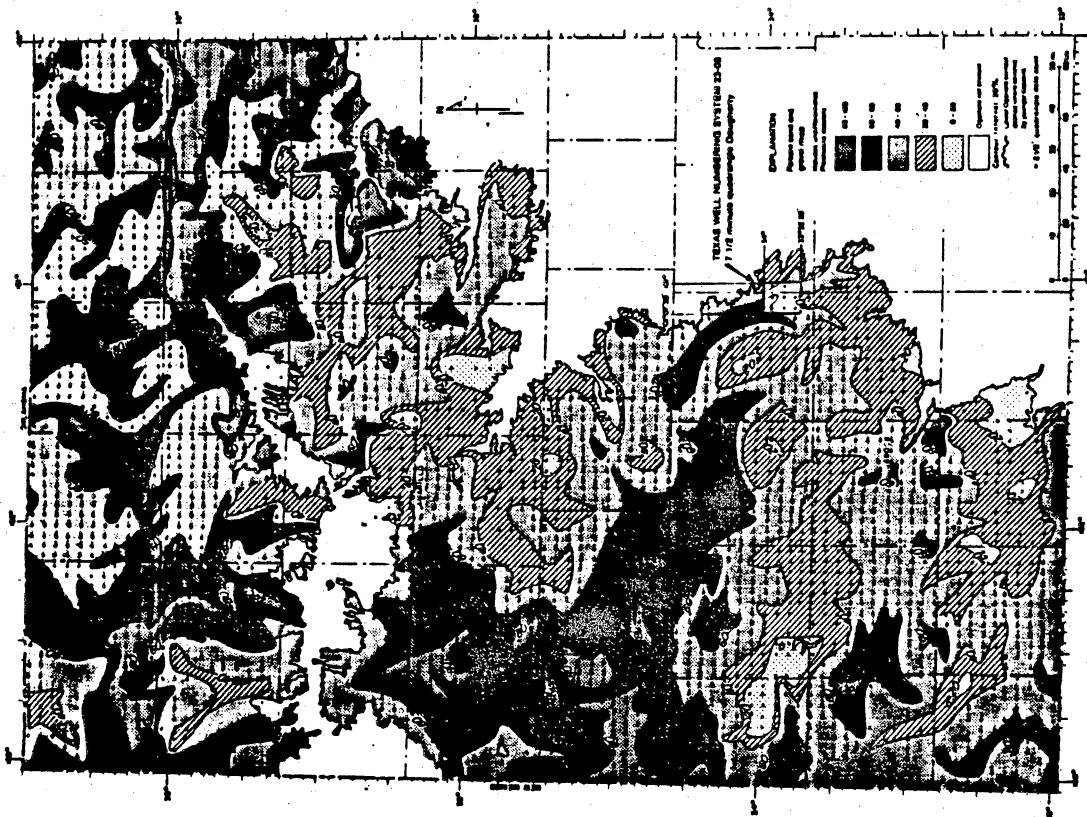
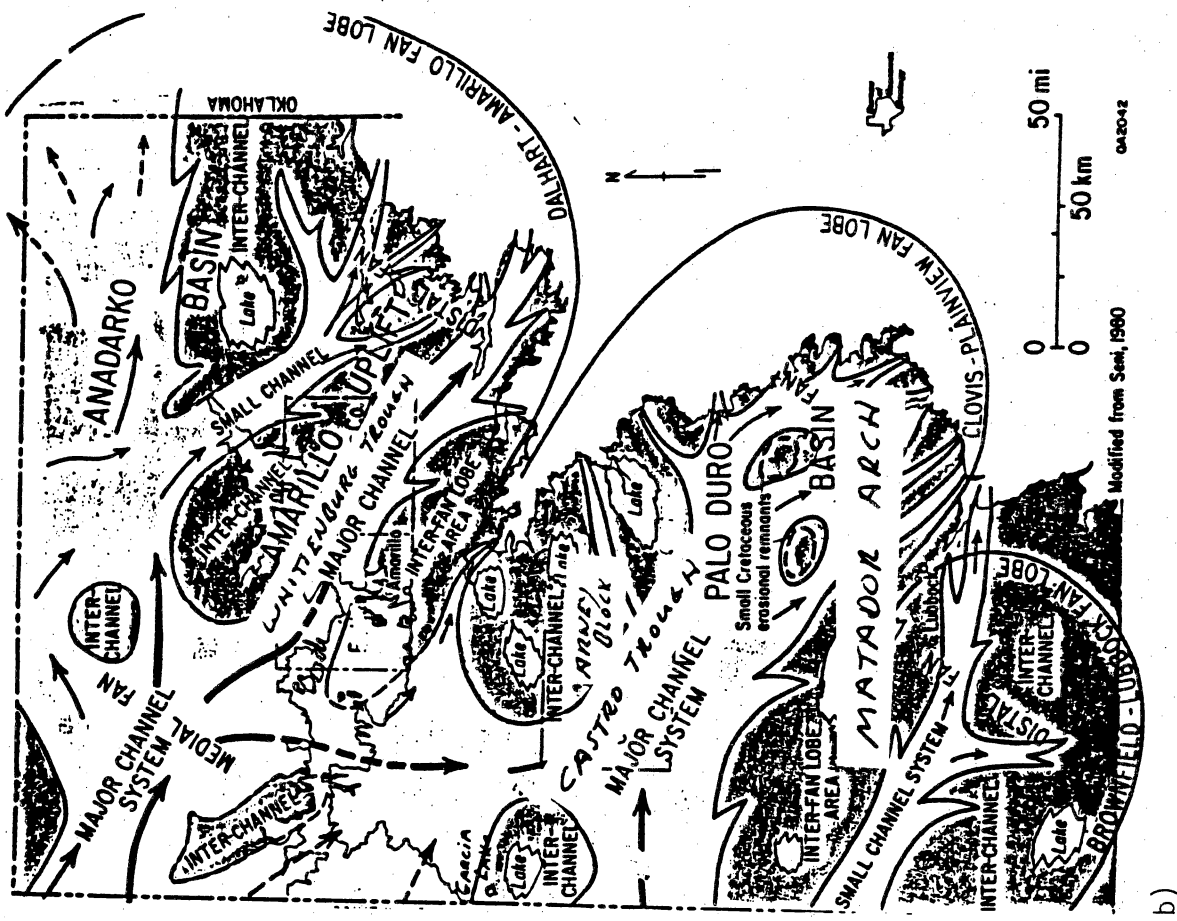


Figure 38. Subsurface maps, Castro Trough, Castro County. Paleozoic, Mesozoic and Cenozoic strata exhibit influence of the Castro Trough: a) net sand map of the Tertiary Ogallala Formation (Knowles and others, 1982b); b) isopach map of the Dockum Group; and c) percent sand map of the Triassic Dockum Group (from unpublished data of J. McGowen).





a)



b)

Figure 39. Depositional facies within the Tertiary Ogallala Formation in the Texas Panhandle: a) distribution of sand and gravel (Seni, 1980); b) depositional patterns (Modified from Seni, 1980).

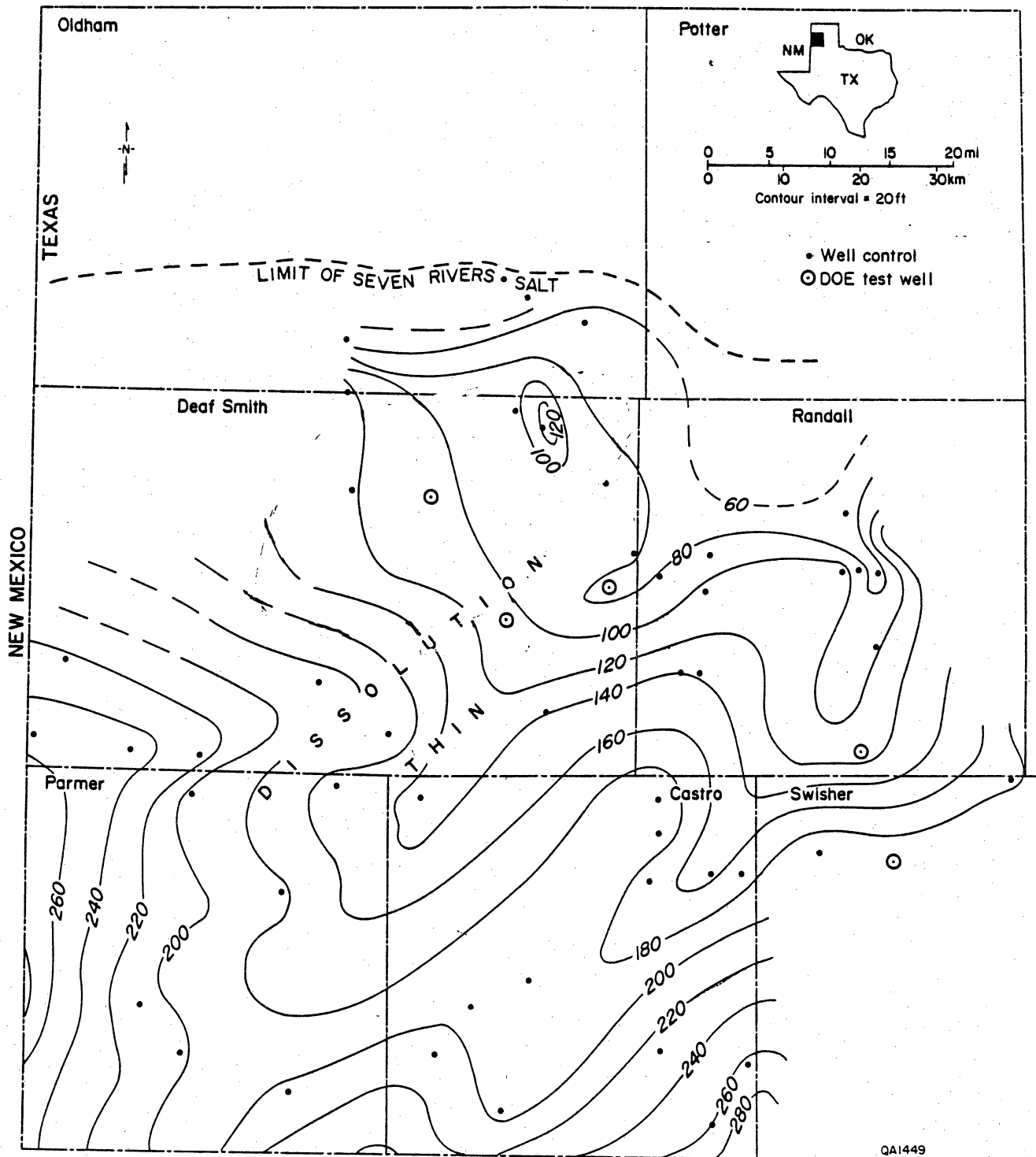


Figure 40. Net salt, Seven Rivers Formation, Deaf Smith and adjoining counties (Gustavson and Budnik, 1984).

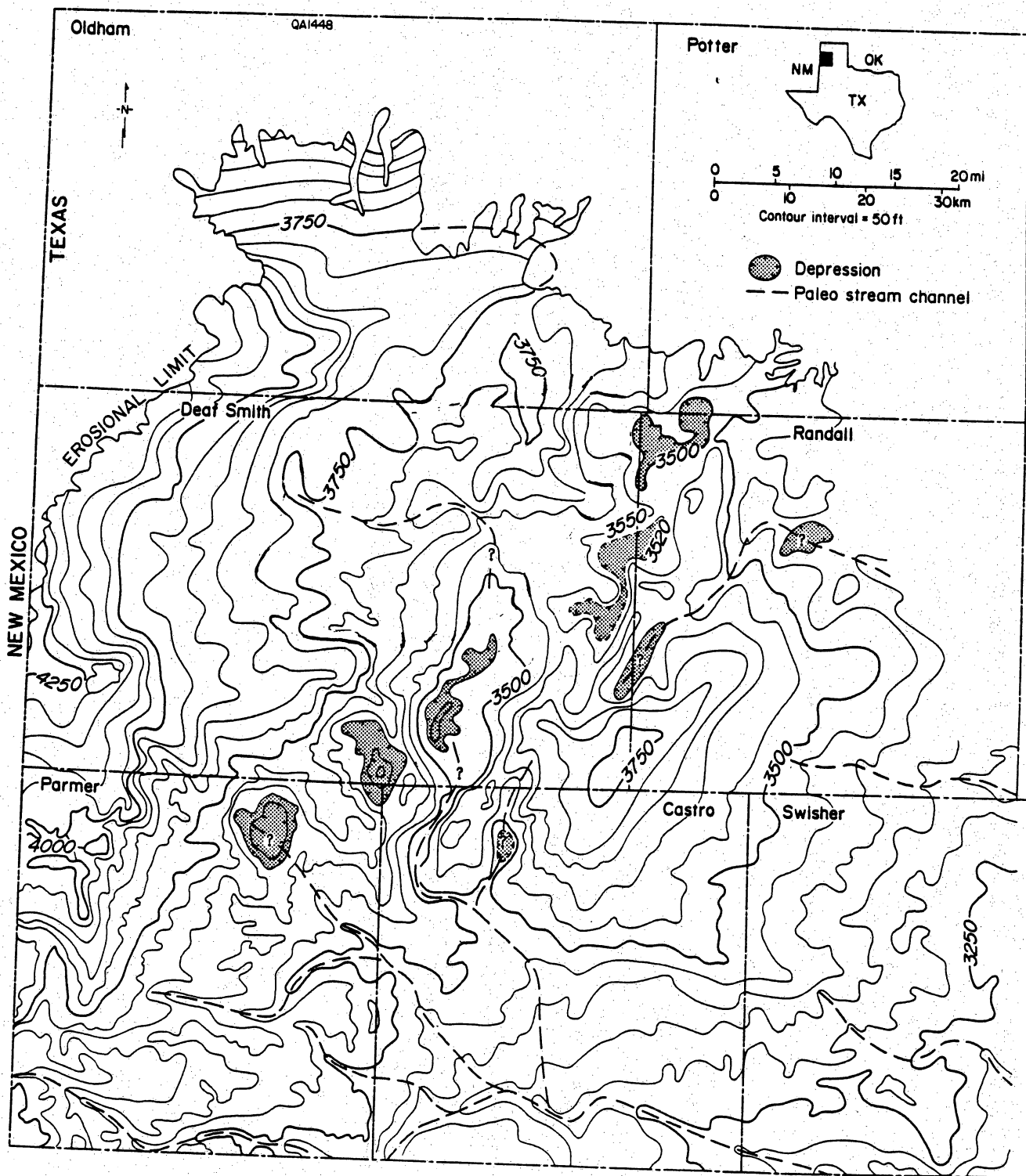


Figure 41. Structure contour map on the base of the Ogallala Formation, Deaf Smith and adjoining counties (Gustavson and Budnik, 1984).



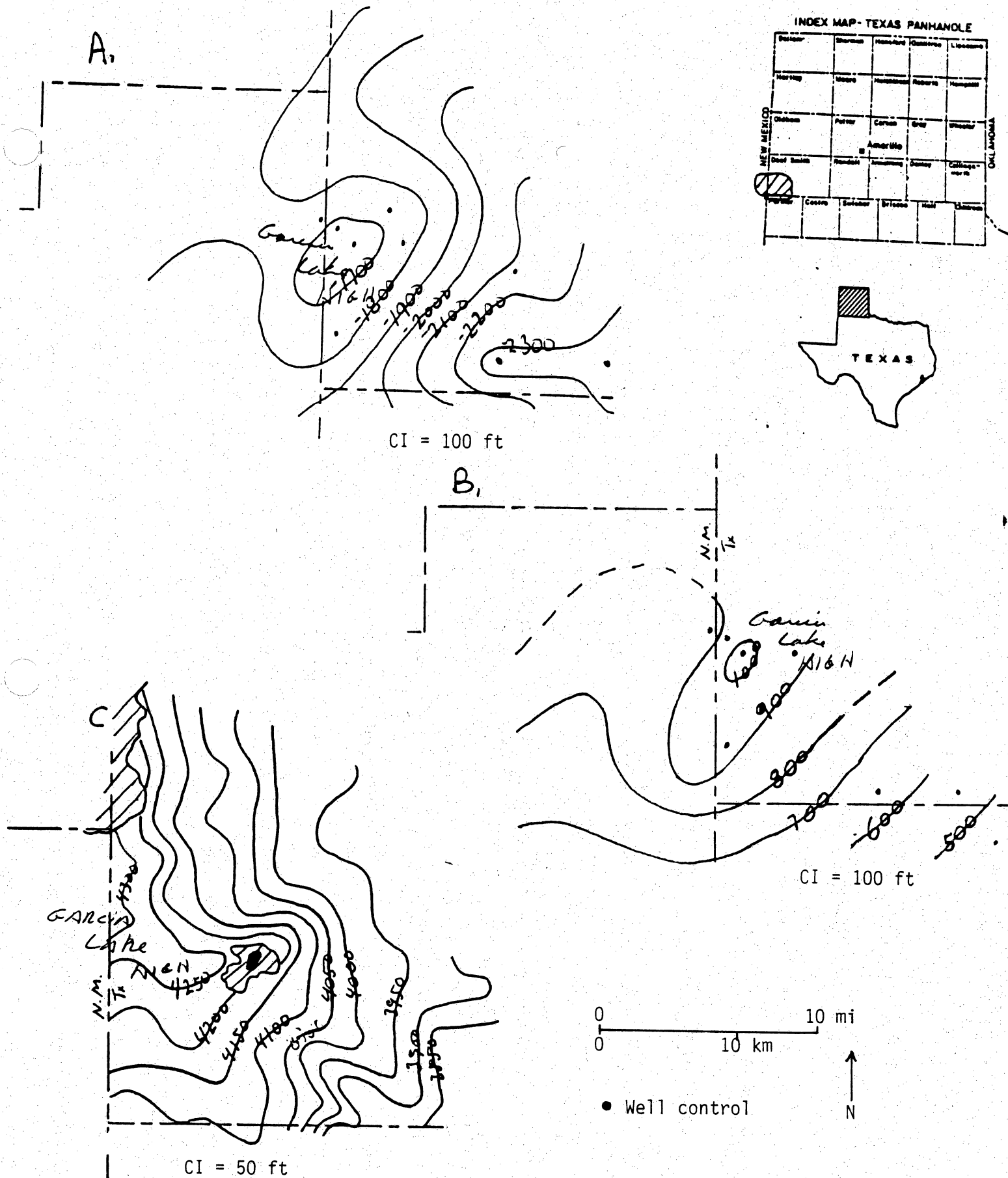


Figure 42. Structure contour maps, Garcia Lake high, Deaf Smith County: a) top of Wolfcamp Series; b) top of San Andres Formation; c) base of Ogallala Formation (Knowles and others, 1981).

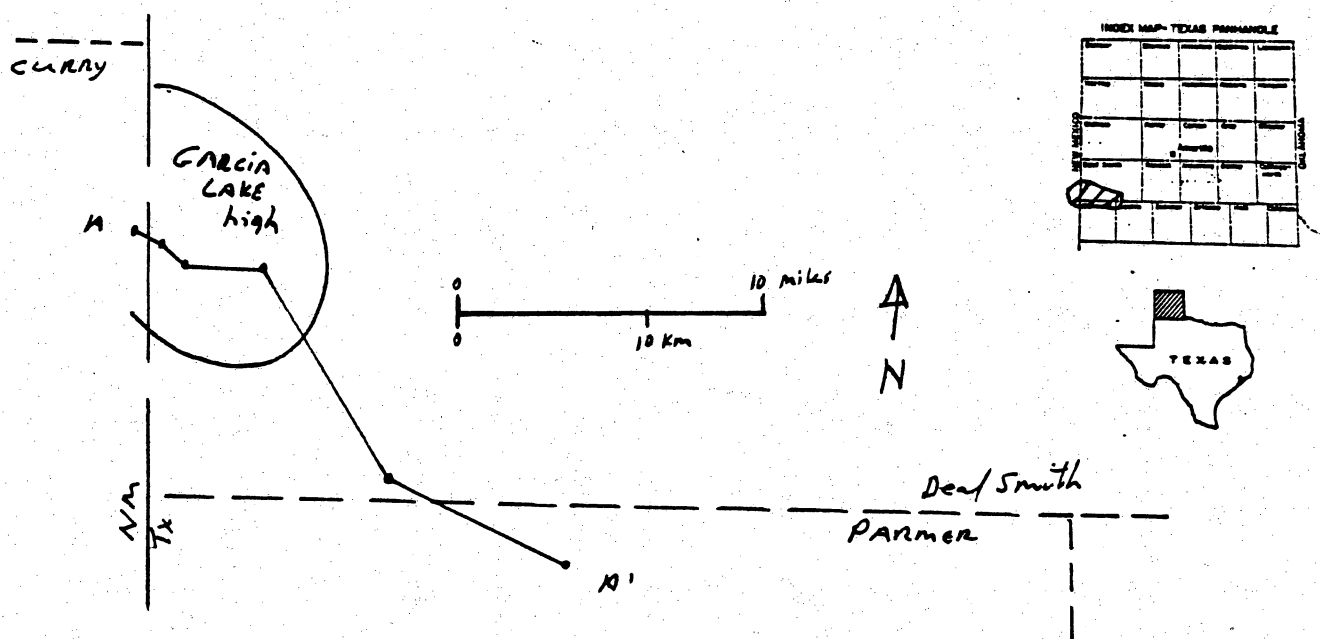
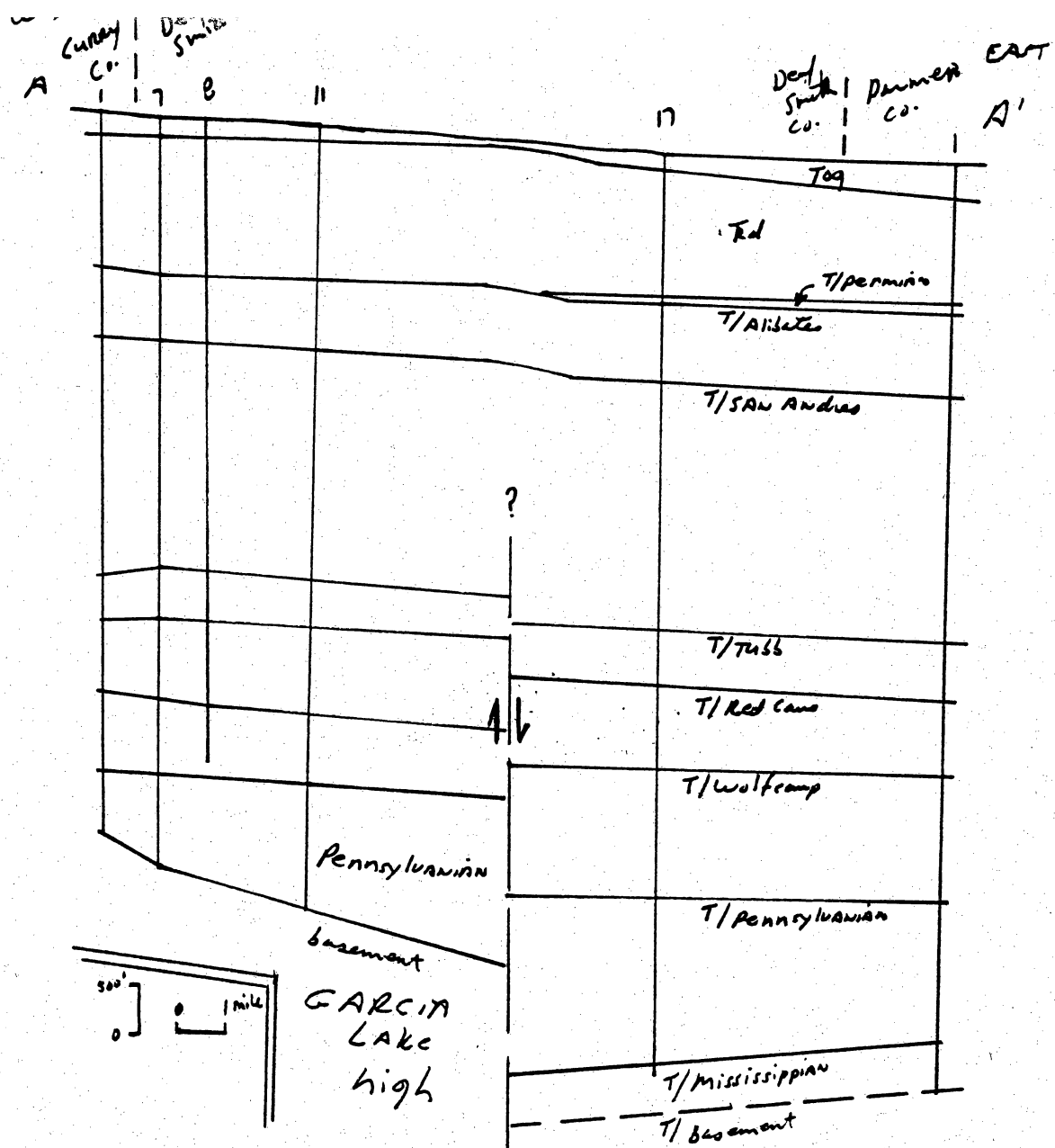
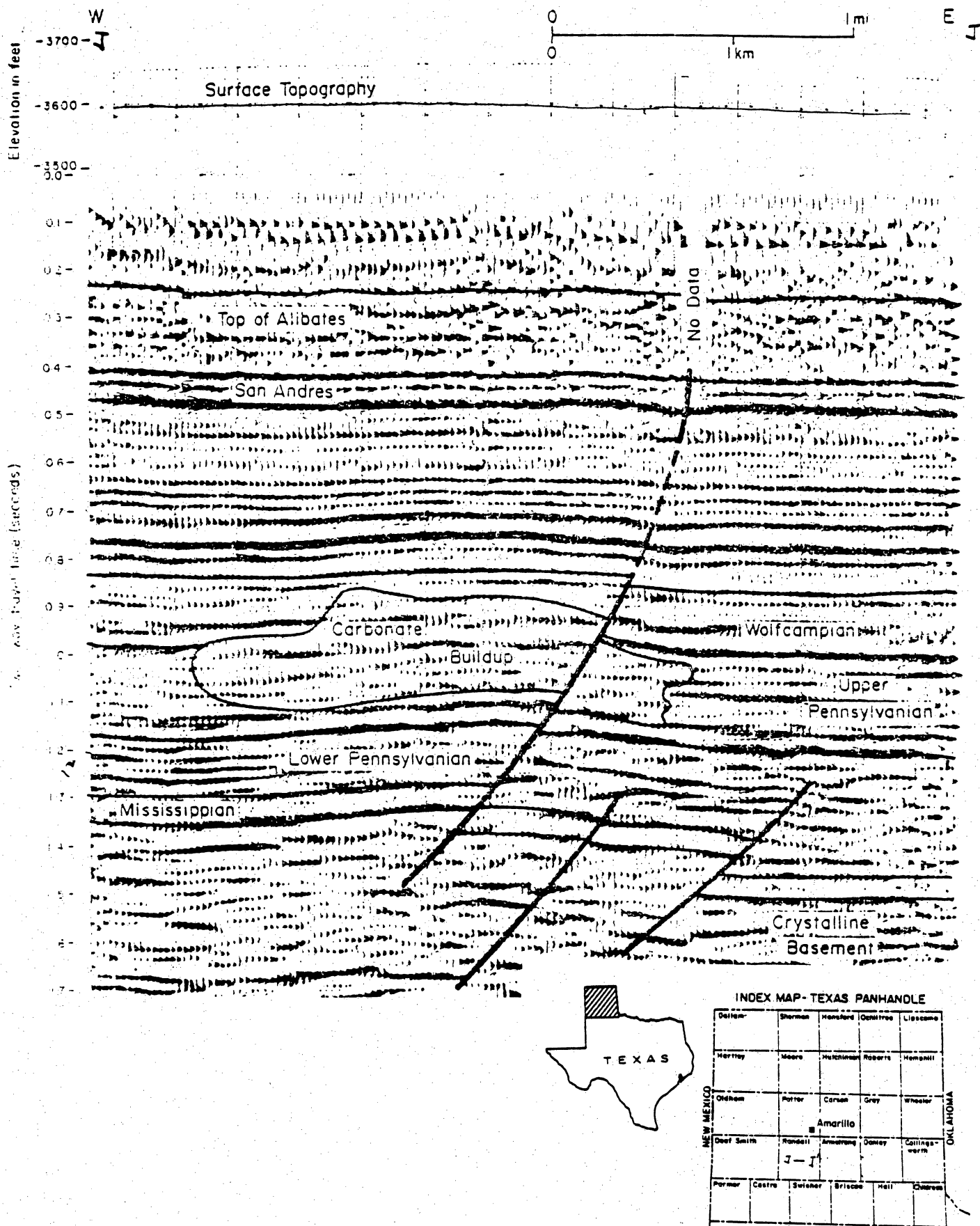


Figure 43. West-east cross section of the Garcia Lake high showing thinning of stratigraphic section onto structure.



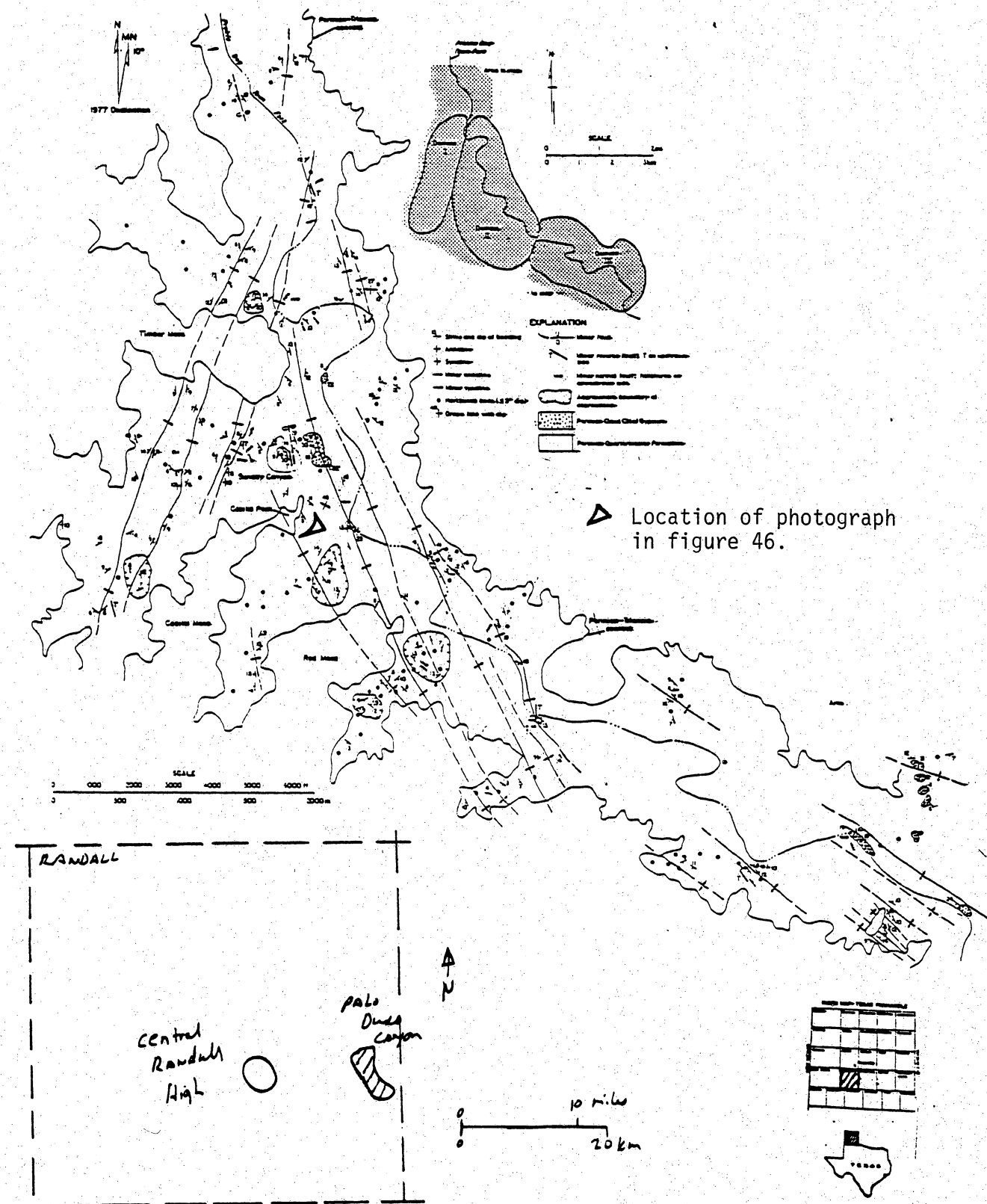


Figure 45. Map of surface structures in Palo Duro Canyon State Park, Randall County (Collins, in press). Location of photograph in figure 46 is indicated. Closed collapse depressions produced by the dissolution of underlying salt are superimposed on northwest and northeast-trending tectonic folds. Compare with the style of folding shown in figure 47.

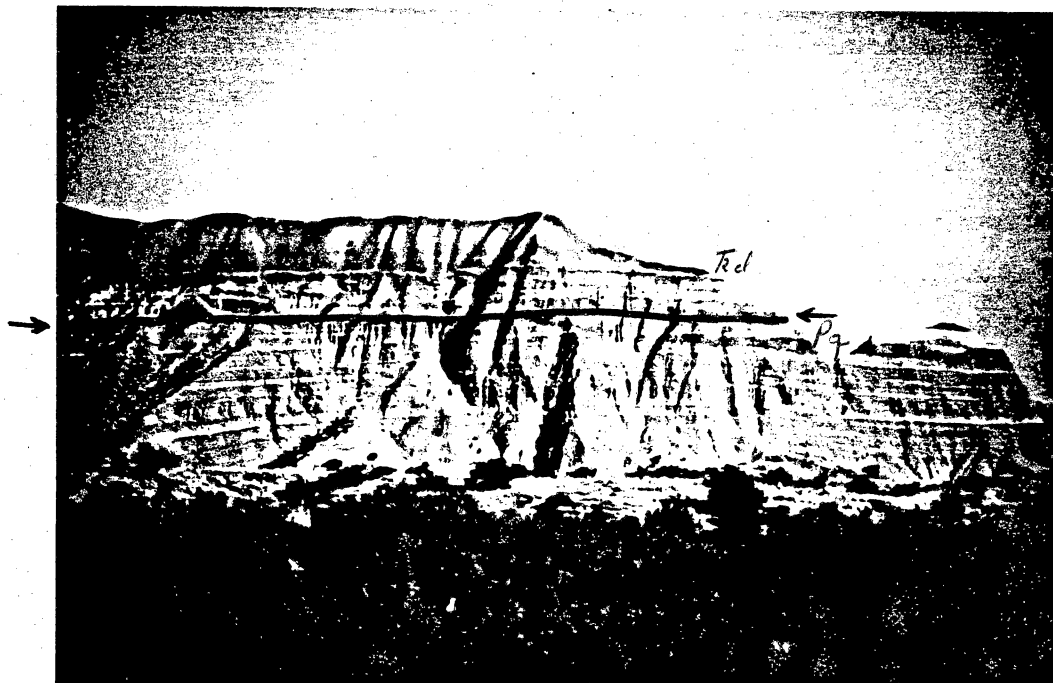


Figure 46. Photograph of slight angular unconformity between the Permian and Triassic at Capital Peak, Palo Duro Canyon State Park, Randall County. Photograph taken by E. Collins. Unconformity is indicated between arrows. Location shown in figure 45.

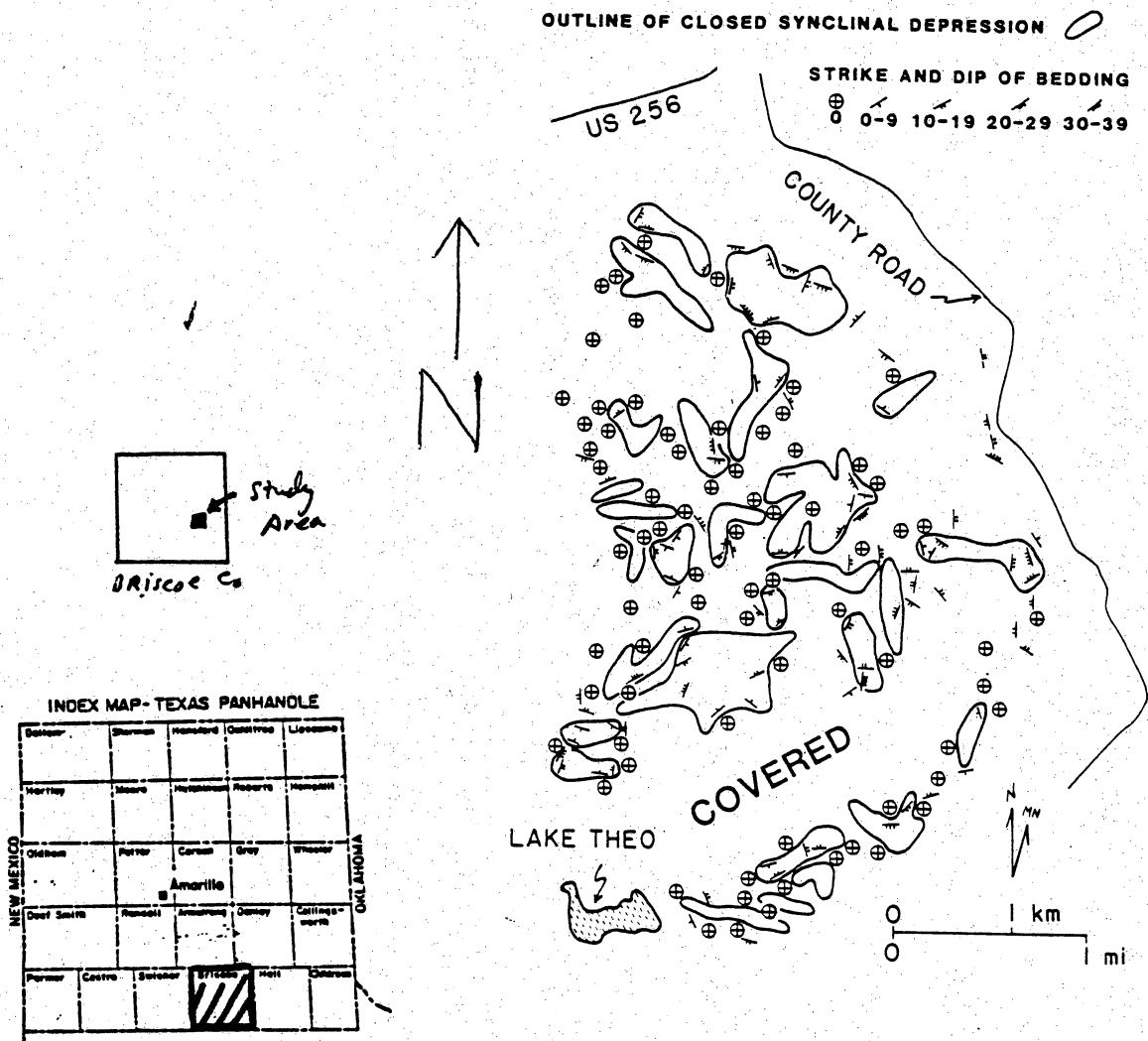


Figure 47. Map of surface structures in Caprock Canyons State Park, Briscoe County (Goldstein and Collins, 1984). Closed structures were produced by the dissolution of Permian salt and collapse of overlying strata. Compare with the style of folding shown in figure 45.

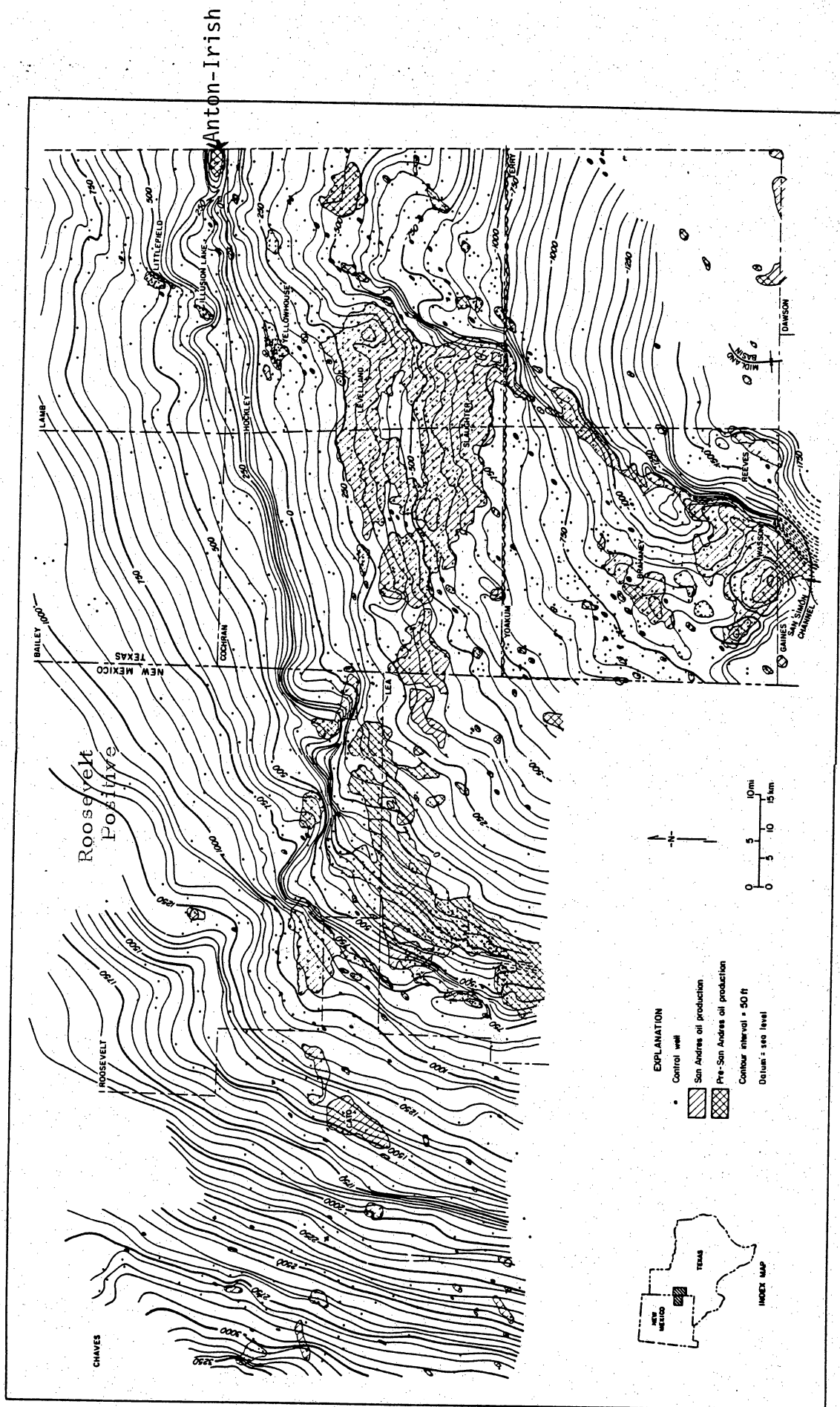


Figure 48. Structure contour map on the top of the San Andres Formation, northwest shelf of the Midland Basin (Ramondetta, 1982).

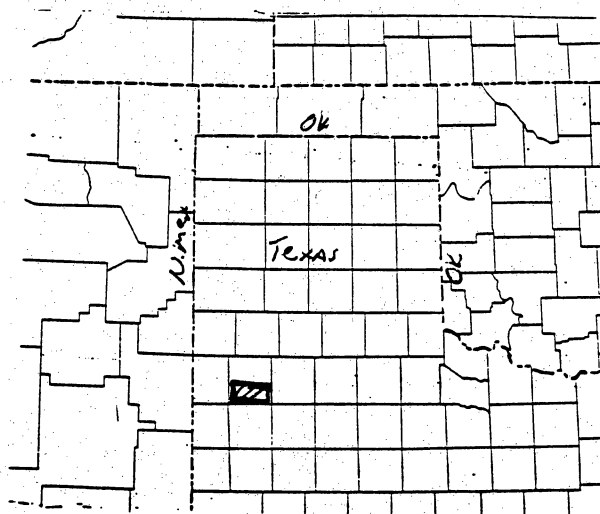
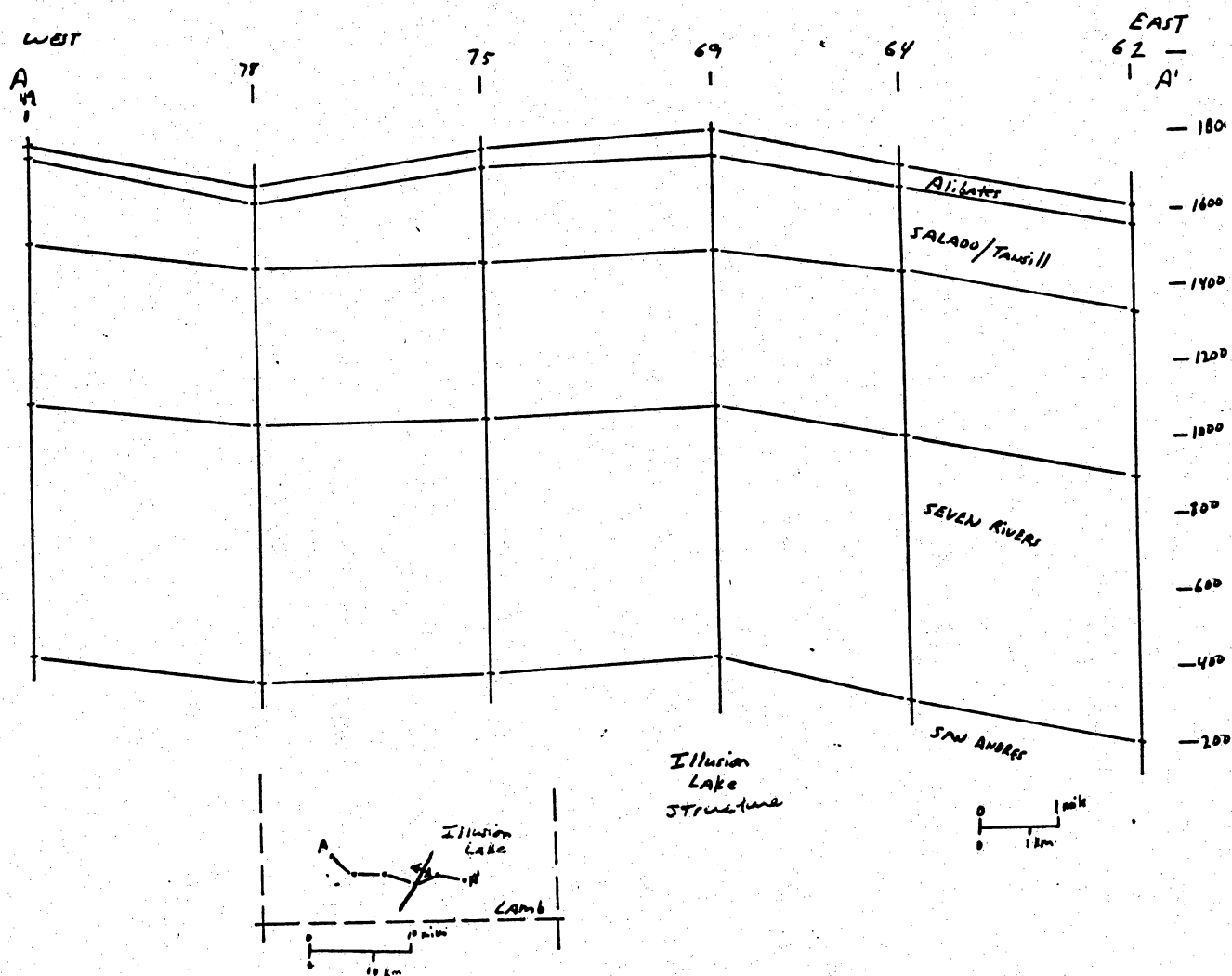


Figure 49. West-east cross section across structural low in southern Lamb County. Dissolution of salt in the Salado Formation west of the Illusion Lake field has produced a structural low (at well #78) on the top of the Alibates formation (figure 32a).



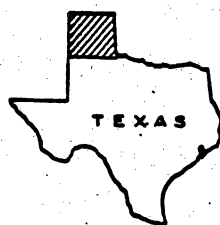
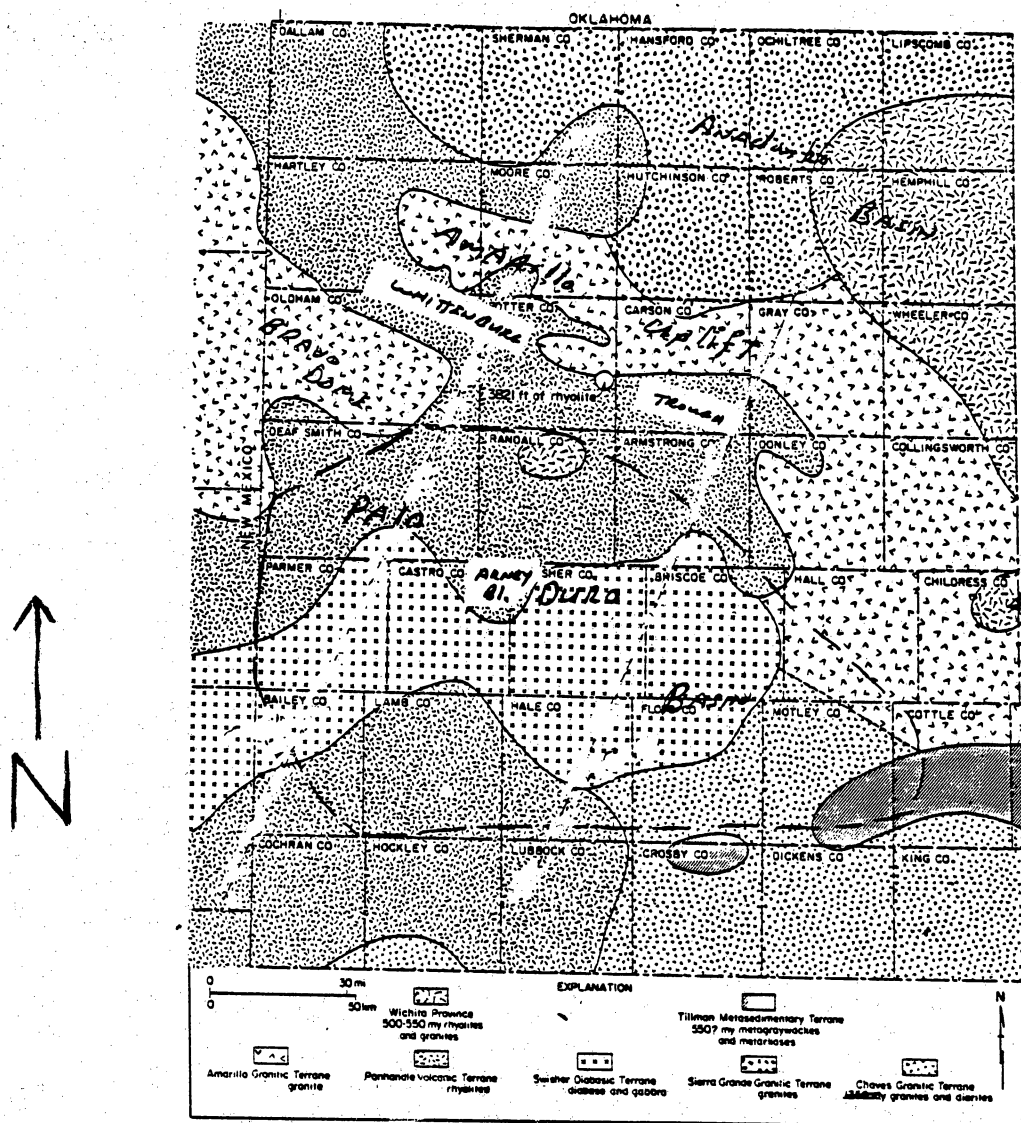
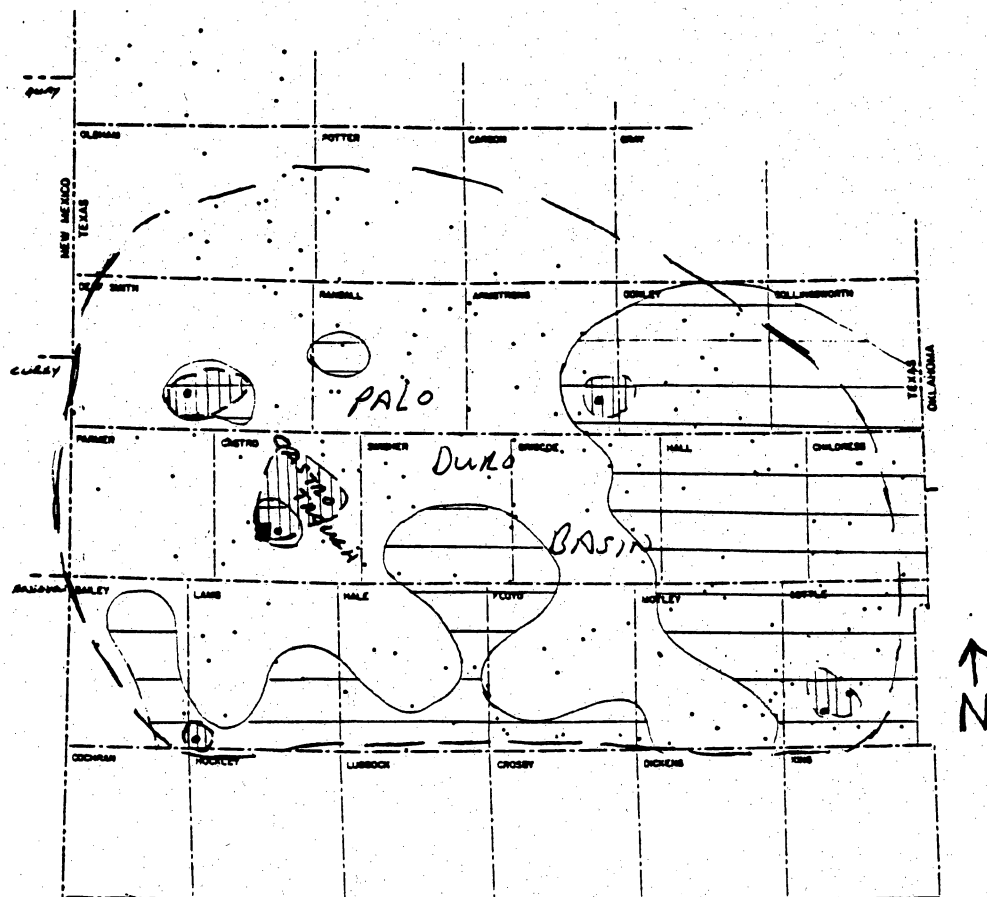


Figure 50. Basement lithologic provinces in the Texas Panhandle (Modified from Goldstein, 1982b).



■ Sun Oil Co.  
#1 Herring

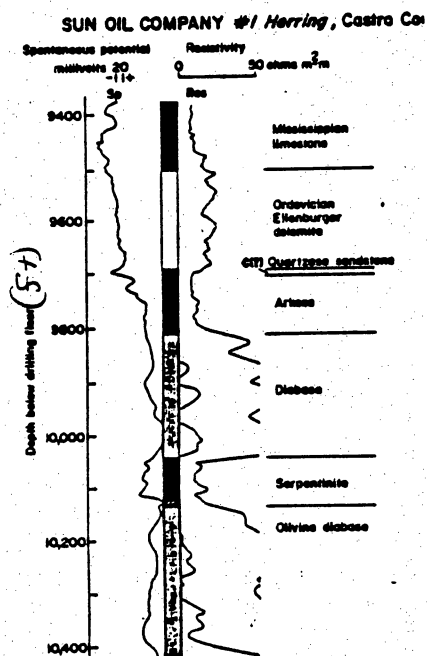


Figure 51. Distribution of basal clastics, Texas Panhandle. Quartzose: horizontally-ruled (Ruppel, in preparation). Arkosic clastics overlying basement in vertically-ruled areas. In the Sun Oil #1 Herring well, the arkosic clastics overlie diabase of the Swisher terrane, and, in turn, are overlain by Cambrian (?) quartzose sandstone (Roth, 1960).

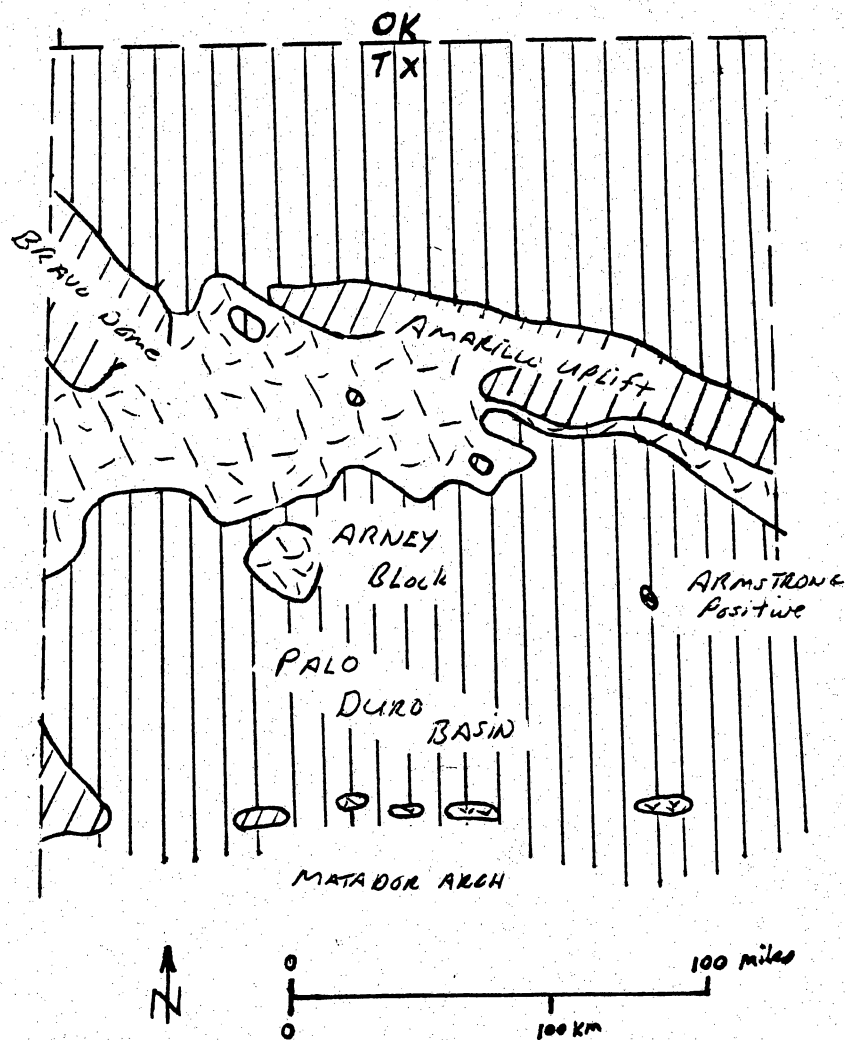


Figure 52. Pennsylvanian subcrop map, Texas Panhandle (from Nicholson, 1960). Lower Paleozoic strata present in vertically-ruled area. Pennsylvanian strata lie on crystalline basement elsewhere. Pennsylvanian strata absent in diagonally-ruled area.

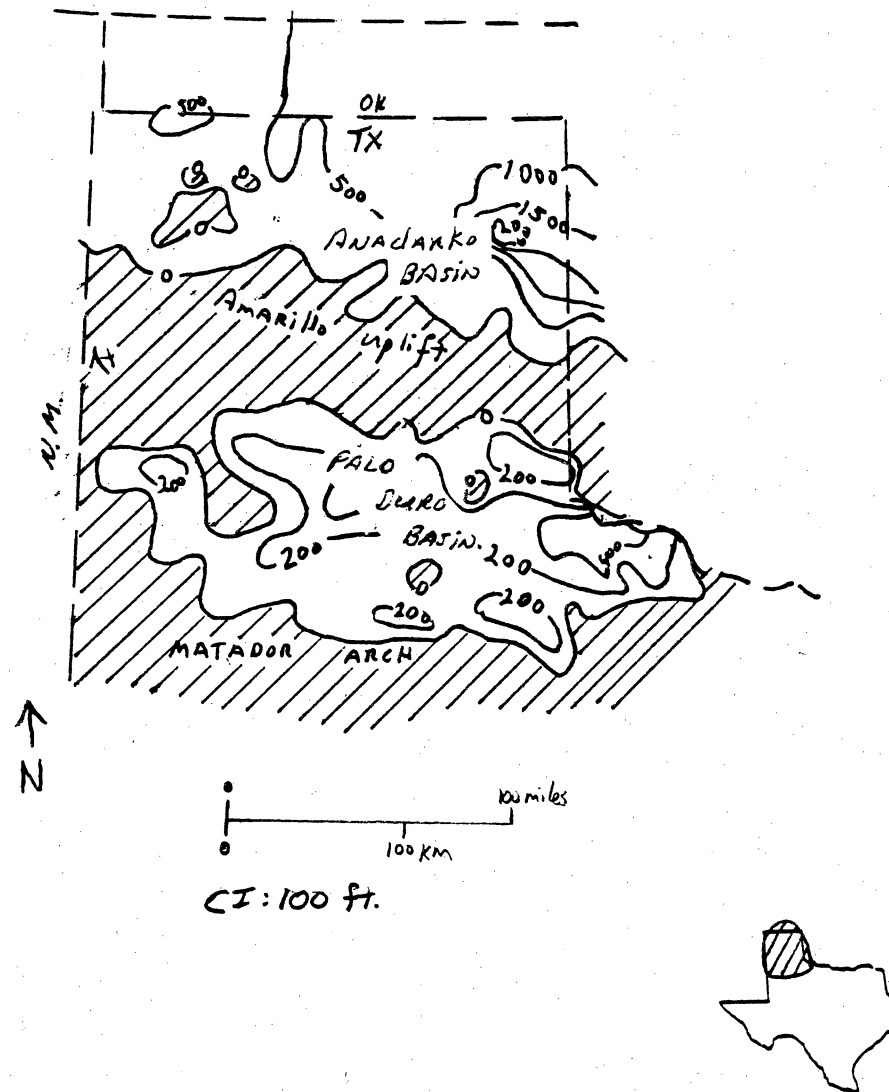


Figure 53. Isopach map of the Morrow (lowest Pennsylvanian), Texas Panhandle (McKee, Crosby, and others, 1975).

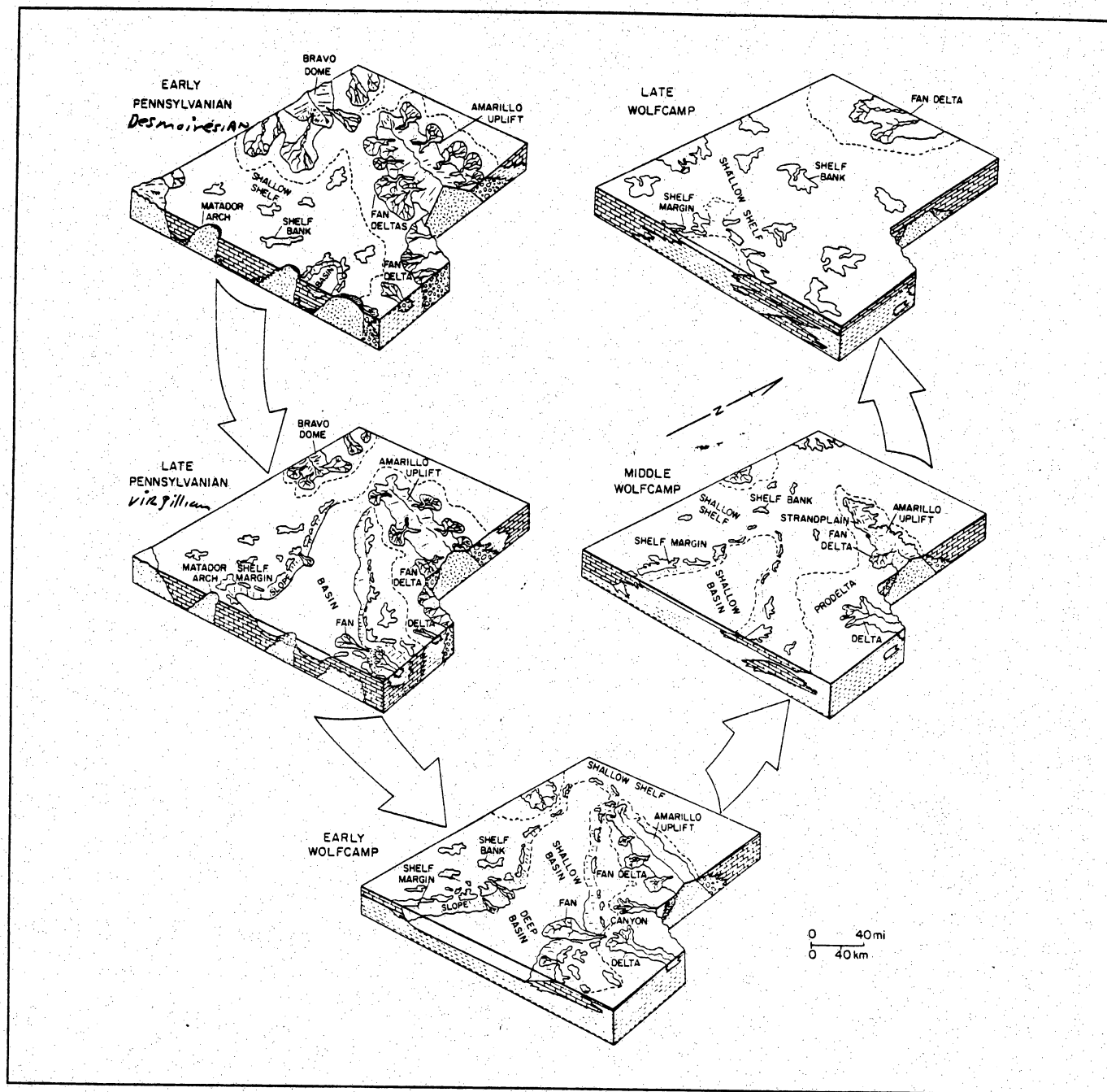


Figure 54. Block diagram of paleogeographic evolution of Palo Duro Basin during Pennsylvanian and Wolfcampian time (Handford and Dutton, 1982).

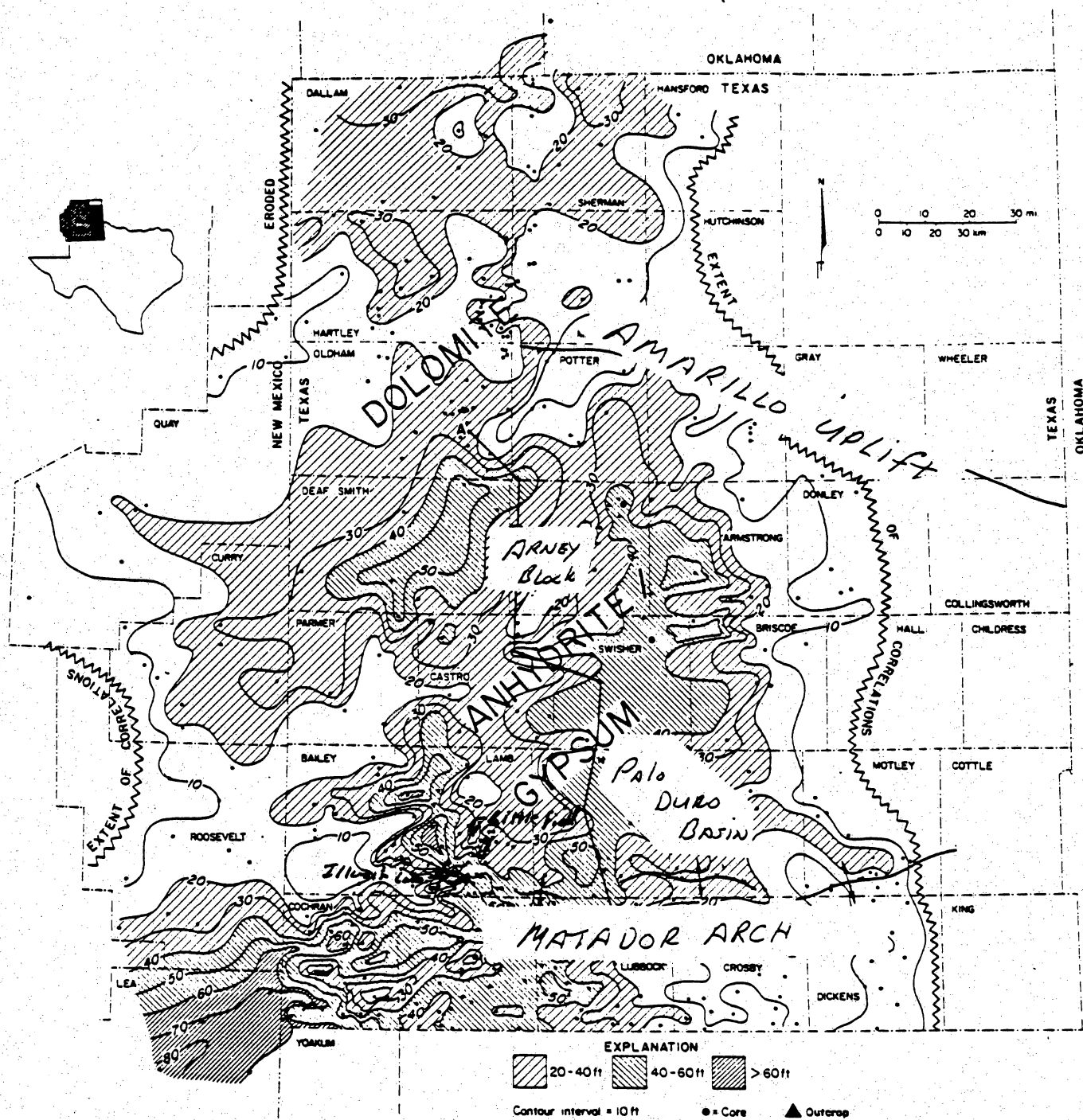


Figure 55. Isopach map of the Alibates formation, Texas Panhandle (McGillis and Presley, 1981).

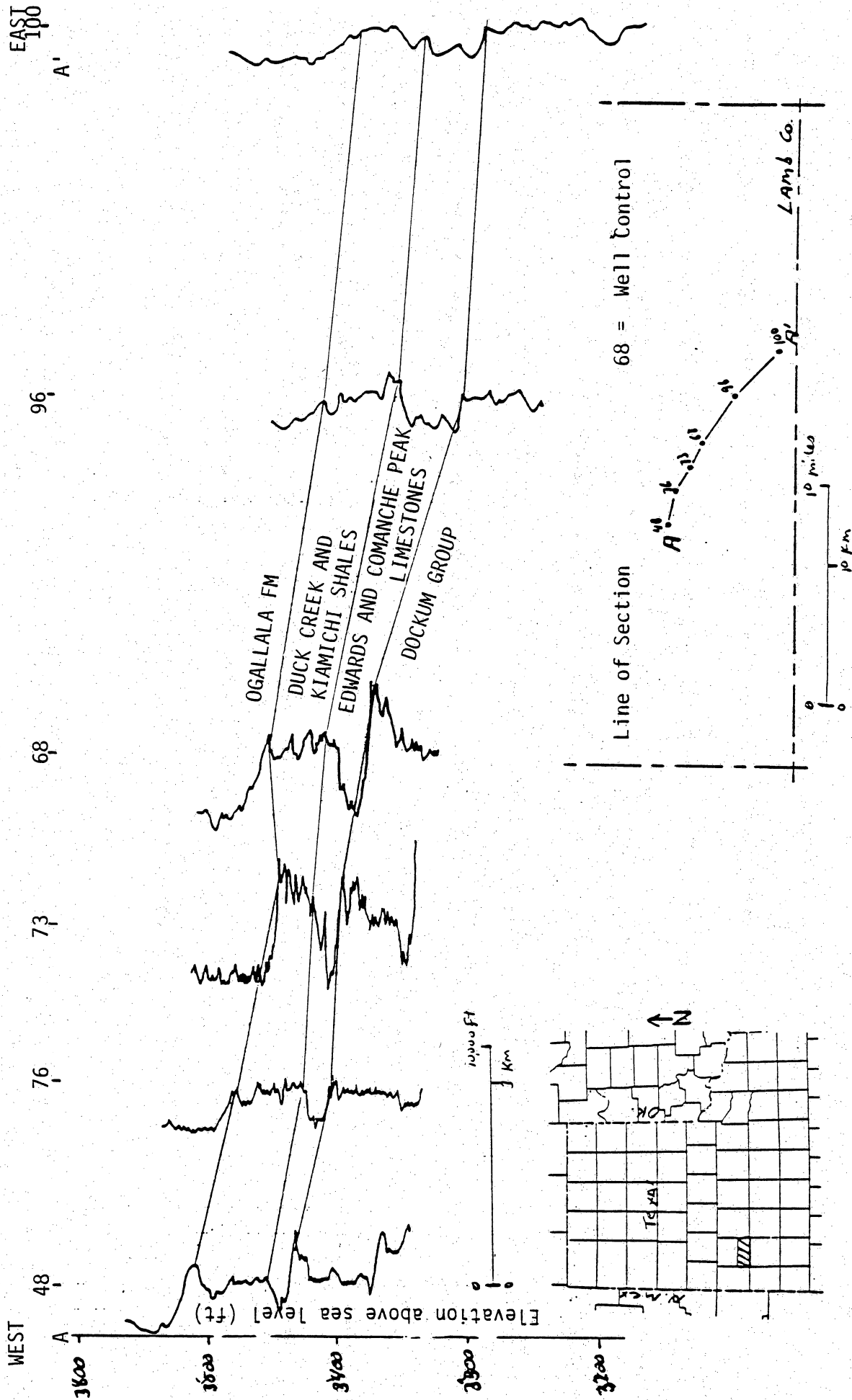


Figure 56. West-east cross section of Cretaceous strata, Lamb County. All logs are gamma ray.

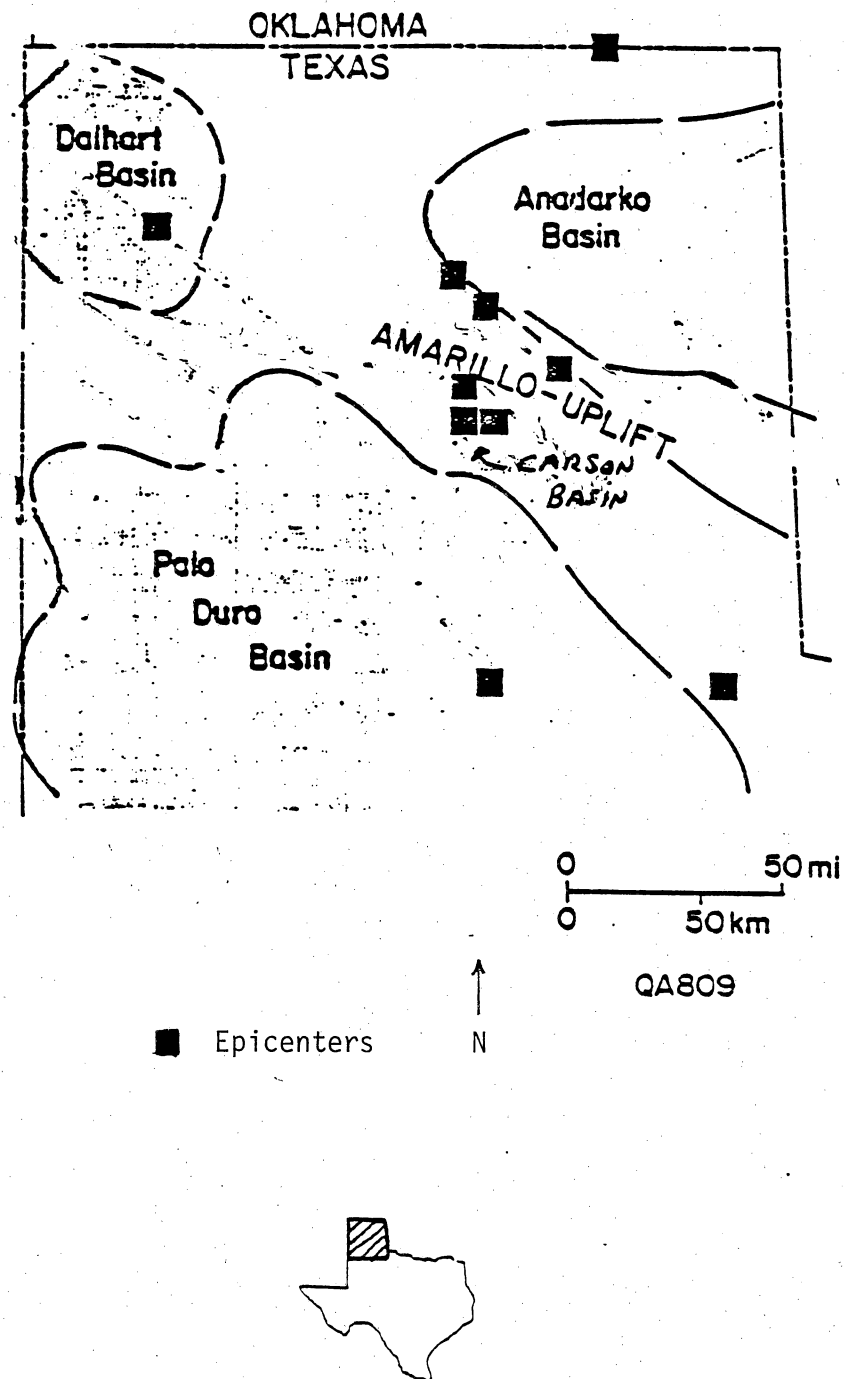


Figure 57. Present seismicity, Texas Panhandle (Reagor and others, 1982).



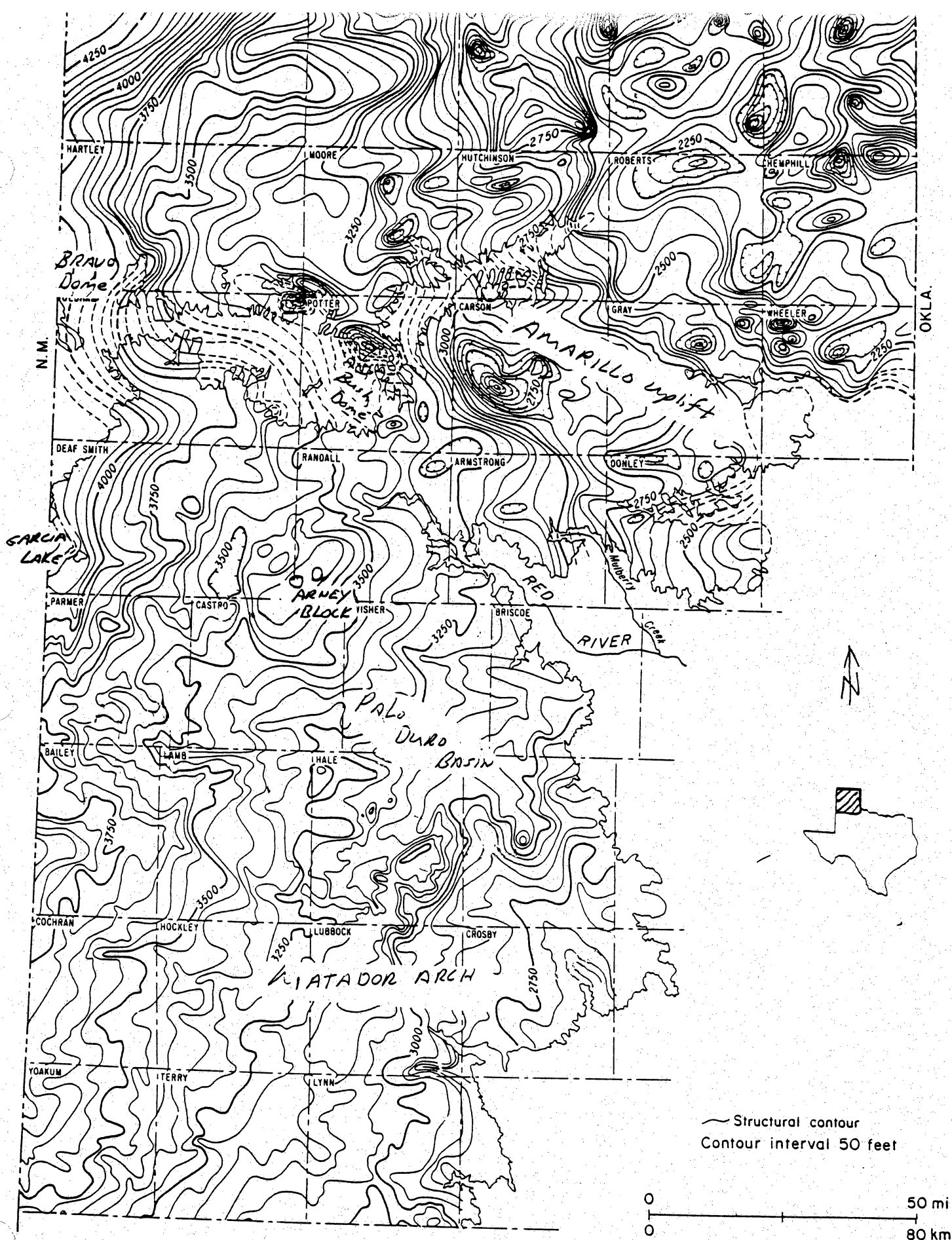


Figure 58. Structure contour map on the base of the Ogallala Formation, Texas Panhandle (Seni, 1980).