September 1, 1977 - September 30, 1978

GEOLOGIC AND GEOHYDROLOGIC STUDIES IN THE PALO DURO BASIN, TEXAS--PROGRESS REPORT

by

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PALO DURO BASIN STUDIES

Executive Summary

No field study areas have been confirmed for the exploration of sites of potential isolation and management of nuclear waste in bedded salts of the Palo Duro Basin.

Purpose.--Integrated, detailed, and comprehensive study of the physical stratigraphy, tectonic history, hydrogeology, physiography, and resource potential of the Palo Duro and Dalhart Basin, Texas Panhandle, provides a necessary prerequisite for a national evaluation of ancient salt basins as potential sites for isolation and management of nuclear wastes.

Scope of FY 78 subsurface studies.--A regional study has outlined the stratigraphy, composition, and extent of salt-bearing Permian strata, has provided a three-dimensional description of lithofacies properties required for hydrologic studies, and has formed the basis for basin resource assessment. The data base was obtained from commercial log supply services. All available subsurface logs from the central portion of the Palo Duro and Dalhart Basins were used. The stratigraphic sequence of the Palo Duro Basin was divided into six genetically related units, each of which records a major event in the history of the basin.

Results of FY 78 subsurface studies.--Pre-Pennsylvanian sediments in the Texas Panhandle were deposited in shallow, stable (cratonic) marine shelf environments and consist of a basal sandstone (Cambrian) and Lower Ordovician and Mississipian carbonates. During the Pennsylvanian Period the Palo Duro Basin deepened and developed a well-defined, mud-filled basin facies surrounded by carbonate shelf-margin buildups. Terrigenous clastic deposits were derived from and concentrated near the principal uplifts. Progradational carbonate shelf margin and slope deposits rapidly filled the Palo Duro Basin during Early Permian time, transforming it into an extensive, evaporitic sabkha rimmed by an alluvial fan plain. Four major genetic subdivisions of Upper Permian evaporite/red bed strata are recognized in the Palo Duro and Dalhart Basins. The overall aspect of the stratigraphy indicates a general southerly facies shift through time. Evaporite facies exhibit many of the features observed in modern coastal sabkhas.

Seven salt-bearing units are of interest as potential hosts for nuclear waste isolation in the Palo Duro and Dalhart Basins. Salt in each unit was deposited in upper sabkha (subaerial) environments. Salt lithofacies interfinger basinward with lower sabkha and shelf lithofacies and towards the margins of the basin with red beds. No economically recoverable deposits of petroleum, copper, uranium, or potash salts have been discovered in the Palo Duro Basin despite the fact that there are numerous favorable host and reservoir rocks throughout the basin.

Two deep core holes (4000 feet) were drilled in Randall County about 17 miles southwest of Amarillo and in Swisher County 9 miles northeast of Tulia. Utilizing modern and innovative drilling methods, the cores provide sample rock material for detailed analytical studies in FY 79.

Scope of surficial studies.--A methodology was developed to provide an integrated program of geomorphic and shallow stratigraphic studies to determine rates of surface erosion, stream incision and development, rates and direction of movement of salt dissolution fronts, fracture analysis, land resources and paleoclimatology.

Results of surficial studies.--Precipitation in the Southern High Plains is primarily from thunderstorms, resulting in brief, localized, and intense rainfall events which produce runoff within restricted areas and result in effective erosional processes. Limited discharge records on the Prairie Dog Town Fork of the Red River illustrate exceptional flood return frequency trends and peak discharges, such as occurred during the flood of May 27, 1978.

Geomorphic mapping of the Llano Estacado and adjacent areas provides a means to extrapolate modern geomorphic process and rate data from process study sites to other areas of the High Plains--an example of the role that playas play in development of High Plains drainage. Landsat imagery of the Texas Panhandle has been used to define linear physiographic elements, or lineaments; the Amarillo-Plainview area exhibits lineaments typical of High Plains and Rolling Plains physiographic regions. Dissolution of Permian bedded salt is an active process that has resulted in major post-Permian structures and is the source of high dissolved loads in streams draining the Llano Estacado and Rolling Plains.

Research goals in FY 79.--The continued goal of nuclear waste management studies ni the Texas Panhandle is a comprehensive, detailed, integrated, and balanced program that is designed to foresee and address all problems that might conceivably affect safe isolation of nuclear materials. Emphasis for the next fiscal year includes (1) interpretations of the hydrologic system of the basin, (2) detailed analyses of the geologic, hydrologic, and engineering properties of the cores, and (3) chemical analyses of ditch and core samples for indicators of potential mineral or petroleum deposits.

LOCATING FIELD CONFIRMATION STUDY AREAS FOR ISOLATION OF NUCLEAR WASTE IN THE TEXAS PANHANDLE

Annual Report

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PURPOSE AND SCOPE

Integrated, detailed, and comprehensive study of the physical stratigraphy, tectonic history, hydrogeology, physiography, and resource potential of the Palo Duro and Dalhart Basins, Texas Panhandle, provides a necessary prerequisite for a national evaluation of ancient salt basins as potential sites for isolation and management of nuclear wastes.

Early in 1977 the Bureau of Economic Geology was invited to assemble and evaluate geologic data on several salt-bearing basins within the State as a contribution to the national nuclear repository program. In response to this request, the Bureau, acting as a technical research unit of The University of Texas at Austin and the State of Texas, initiated a long-term program to assemble and interpret all geologic and hydrologic information necessary for delineation, description and evaluation of salt-bearing strata and their environs in the Panhandle area.

The technical effort has, to date, been divided between two research groups. A basin analysis group has assembled the regional stratigraphic and structural framework of the total basin fill, initiated evaluation of natural resources, and selected stratigraphic core sites for sampling the salt and associated beds. Two drilling sites have provided nearly 8,000 feet of core material for analysis and testing of the various lithologies overlying and interbedded with salt units. Concurrently, a surface studies group has collected ground and remotely-sensed data toward describing surficial processes, including carbonate and evaporate solution, geomorphic evolution, and fracture system development. A newly-formed basin geohydrology group will evaluate both shallow and deep circulation of fluids within the basins.

This paper is a summary report of progress to date. It reviews principal conclusions and illustrates methodologies utilized and the types of data and displays generated. Several topical reports will be forthcoming as various phases of the study are completed and will discuss in detail various geological aspects of the Palo Duro and Dalhart Basins.

BASIC OBJECTIVES OF BASIN ANALYSIS--GENETIC DESCRIPTION OF THE SALT-BEARING INTERVAL AND ASSOCIATED STRATA

A regional study has outlined the stratigraphy, composition, and extent of salt-bearing Permian strata, has provided a three-dimensional description of lithofacies properties required for hydrologic studies, and has formed the basis for basin resource assessment.

Salt beds of the Permian section in the Texas Panhandle have been penetrated by numerous petroleum test wells, but the salt section has not been adequately described because exploration objectives lay primarily in older, deeper rocks. The principal objective of the initial phase of an examination of the Palo Duro and Dalhart Basins (fig. 1) to determine potential suitability for isolation of nuclear wastes was the description of major salt sequences--their distribution, thickness, composition, and lateral and vertical facies associations. At the same time, the subsurface data base also was used to carry out genetic stratigraphic studies of all major underlying older Paleozoic and overlying Triassic, and Pliocene strata (fig. 2). Stratigraphic units provide potential hosts or reservoirs for various deposits, including petroleum, uranium, metals, potash salts, and most importantly, fresh water. Consequently, assessment of resource potential, or resource fairways within the basins, constitutes the second principal objective of the program.

Initial subsurface analysis provided the basis for selection of several alternative sites for stratigraphic core tests. Core tests were designed to provide sample and geophysical logs of all major salt-bearing intervals in the basins. Salt samples obtained from cores will be described and analyzed using a variety of techniques. Geophysical or well logs will enable geologists to calibrate responses of various down-hole measurements (natural gamma radiation, formation density, interval travel time, electrical properties) with actual rock types encountered during the coring operations. Calibrated logs can then be used to improve interpretations of rock composition and thickness that previously have been made using logs from numerous petroleum test wells.

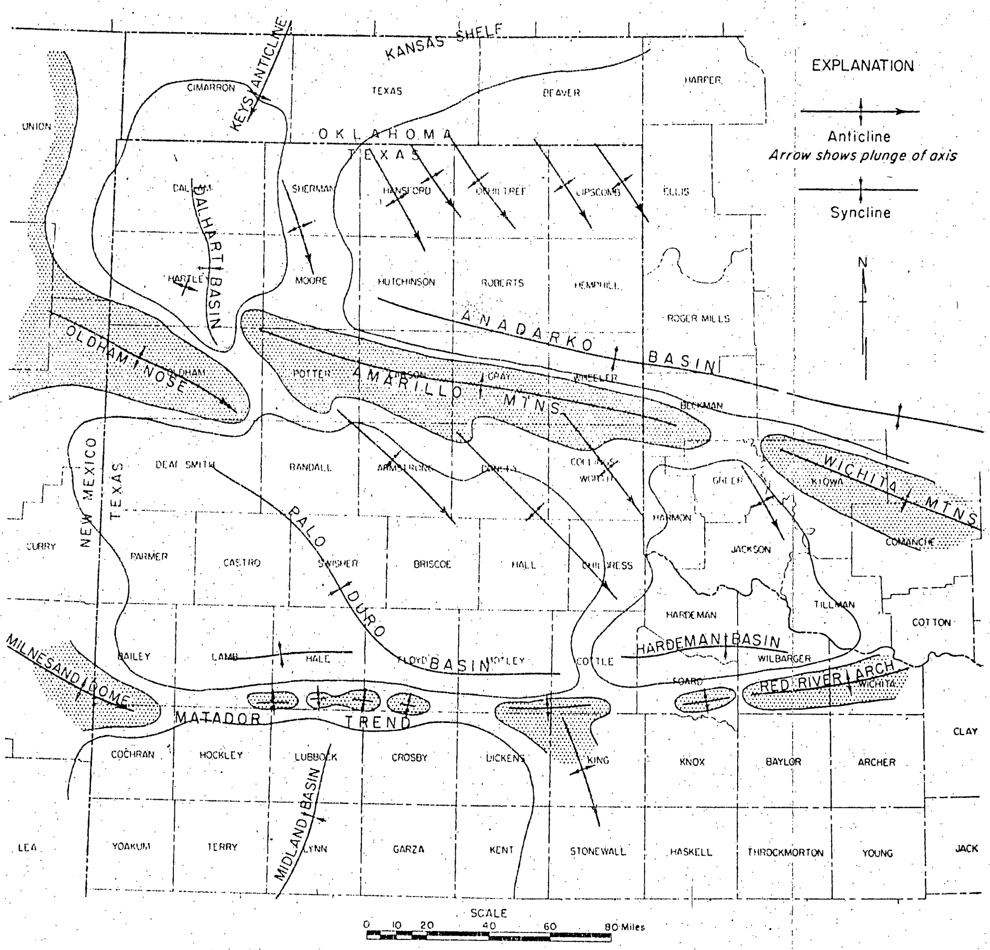

Figure 1. Structural elements and general index map of the Texas Panhandle (from Nicholson, 1960).

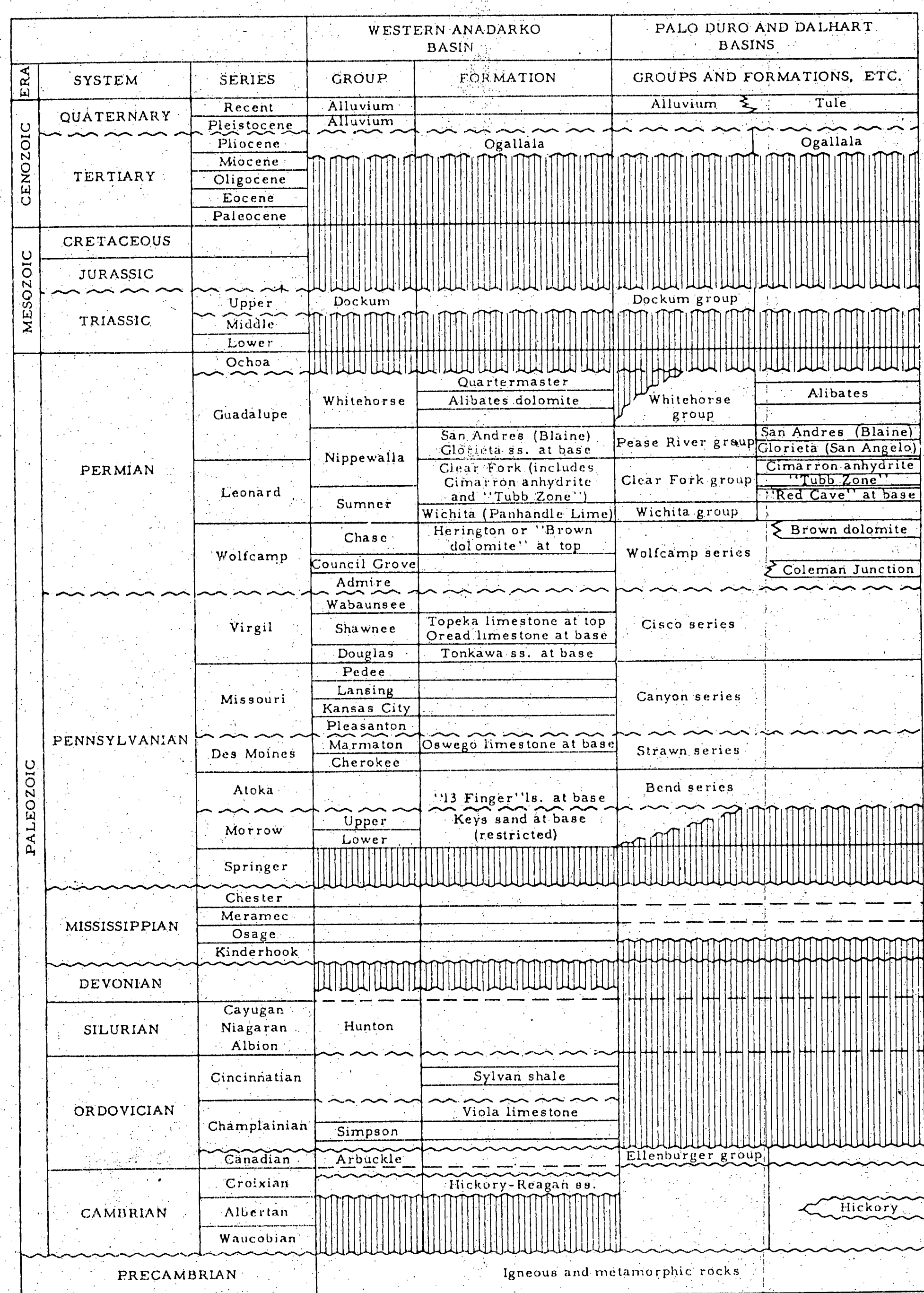

Figure 2. Stratigraphic names applied to the Palo Duro and Western Anadarko Basins, Texas (from Nicholson, 1960).

DATA

The data base was obtained from commercial well log supply services. All available subsurface logs from the central portion of the Palo Duro and Dalhart Basins were used.

The data base shown in figure 3 includes logs from down-hole geophysical probes (well logs) and described well cuttings (sample logs). Each of the 2280 data points (fig. 3) represents 1 or more log types, for a total of 4500 well logs and 888 sample logs.

The data base was chosen (fig. 3) to include all available logs in the counties in the central parts of the Palo Duro and Dalhart Basins. Most wells in this area are represented by both sample and well logs. In Texas counties along the margins of these basins, a second data base was chosen to include wildcats and selected field wells. Outside of this area, a third open grid data base of wells was selected.

Standard log interpretation techniques were used for lithostratigraphic mapping and cross sections. Criteria for defining salt are illustrated in figure 4. The cross section is composed of cyclic units which include salt, anhydrite, and dolomite in the lower portion of the Permian San Andres Formation. The salt beds are defined by: (1) low radioactivity (values to the left) on gamma ray logs (GR), (2) intervals of enlarged borehole diameter (values to the right) on caliper logs (CAL), owing to solution of salt beds during drilling, (3) intervals defined by a sonic transit time (ΔT) of approximately 67 microseconds on sonic logs (SON), and (4) mappable intervals on other log types, including the neutron porosity log (NPOR) in figure 4, in which there are anomalous or missing values owing to the enlarged borehole.

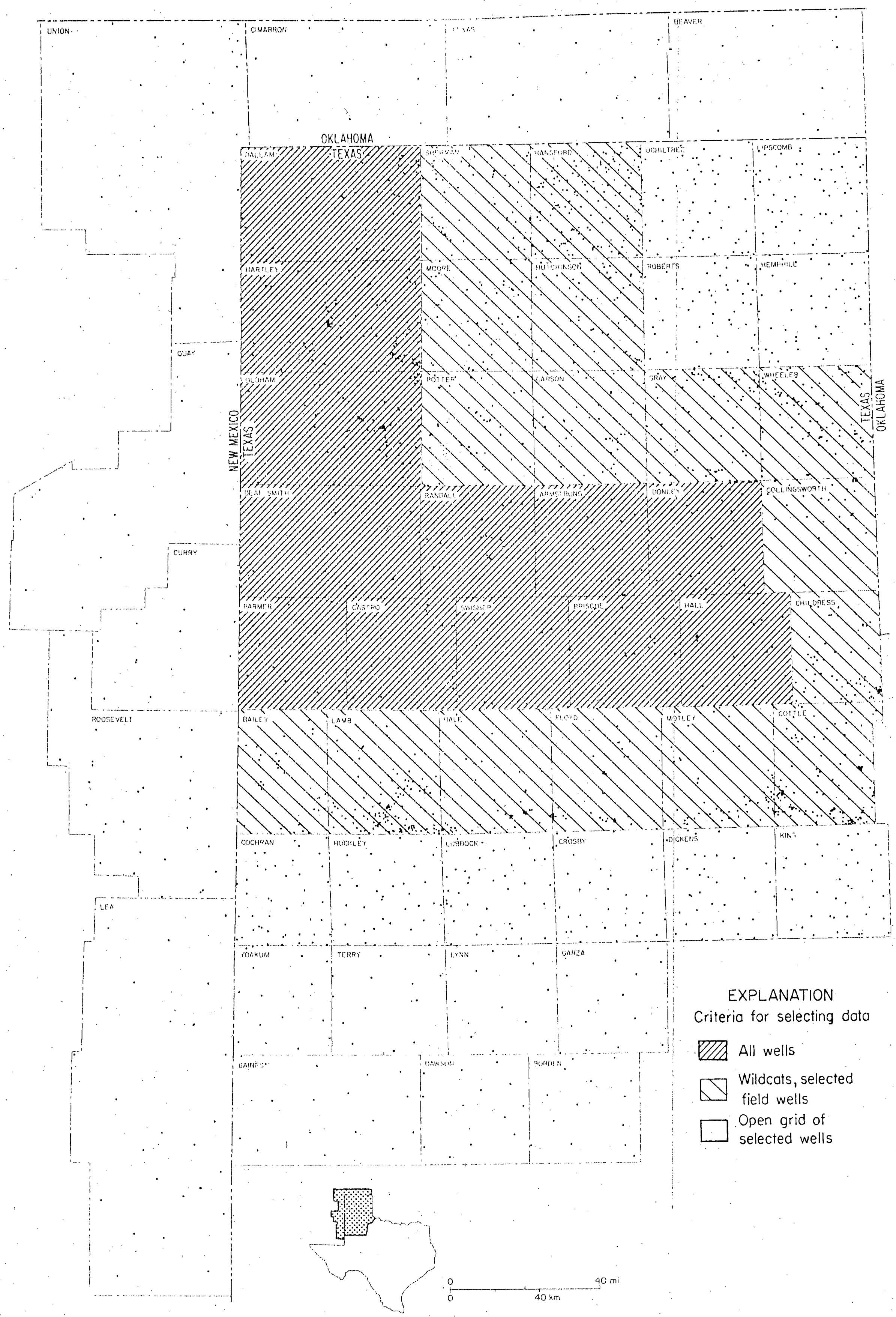

Figure 3. Data base with criteria for selecting data points.

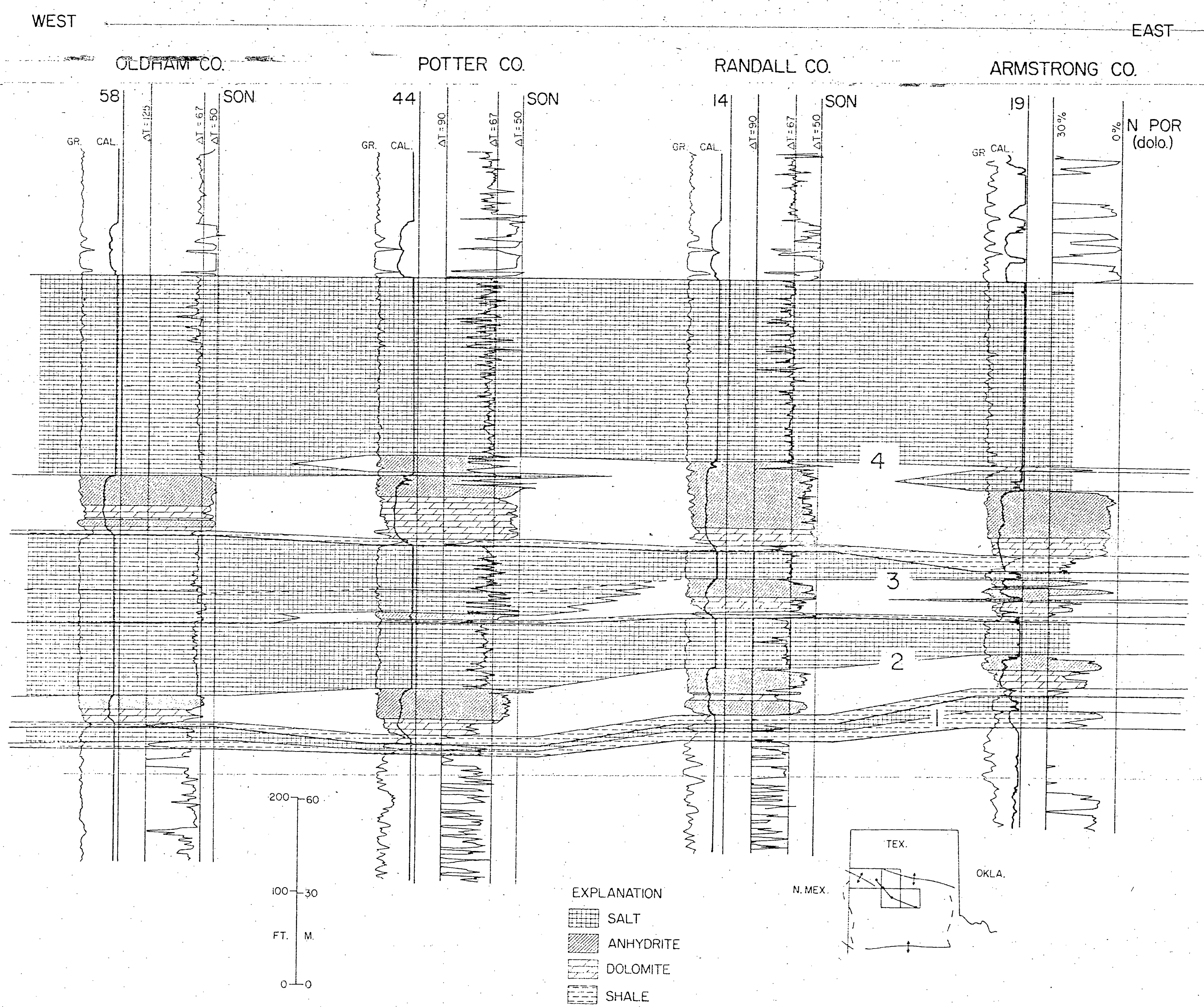

Figure 4. East-west cross section, lower San Andres cyclic units, northern Palo Duro Basin--an example of log-lithology interpretations in the salt-bearing sequence. Log types include gamma ray (GR), caliper (CAL), sonic (SON), and neutron porosity (NPOR).

BASIN STRUCTURAL AND STRATIGRAPHIC FRAMEWORK

The stratigraphic sequence of the Palo Duro Basin was divided into six genetically related units, each of which records a major event in the history of the basin.

The Palo Duro Basin is a shallow, continental-interior basin. Precambrian basement is at most only 10,000 feet below the surface. The basin is asymmetrical, with the deepest part immediately north of the Matador Arch, the basin's southern boundary (fig. 5). The basin axis trends east-west in the eastern half and northwest-southeast in the west. Several northwest-southeast striking faults occur just south of the Amarillo Uplift, but the rest of the basin lacks evidence of faulting.

The stratigraphic section in the Palo Duro Basin contains rocks from Precambrian to Plio-Pleistocene in age (figs. 6 and 7). The sequence can be subdivided into six genetically related units: (1) Pre-Pennsylvanian, (2) Pennsylvanian, (3) Lower Permian, (4) Upper Permian, (5) Triassic, and (6) Plio-Pleistocene. Each unit exhibits distinctive facies tracts and depositional style, geohydrology, and resource potential.

(1) A Pre-Pennsylvanian section consists of a thin basal sandstone and shallow shelf carbonates. These were deposited in the region before the younger Palo Duro and Dalhart Basins developed. Only erosional remnants of these older rocks remain, and the older rocks are separated from overlying Pennsylvanian strata by major unconformity.

(2) A Pennsylvanian mixed carbonate-clastic section records the initial definition and development of the structural and sedimentary basins. Intense tectonic activity strongly influenced sedimentation patterns. Marine transgression occurred throughout this period as the basin subsided.

(3) A Lower Permian carbonate-clastic-evaporite section marks the transition from maximum transgression to basin filling. This regression of marine conditions is reflected in the upward and landward change from open marine carbonate to evaporite deposits.

(4) An Upper Permian evaporite-red bed clastic sequence records the final filling of the basin. Deposition occurred in restricted, back-shelf/sabkha environments.

(5) Triassic strata consist of continental clastics deposited in a major lacustrine basin as fluvial deposits and deltas (deltas and fan deltas).

(6) A Plio-Pleistocene section contains continental clastics deposited by fluvial and eolian processes. Calichefication of the top of this section produced the "caprock" of the Panhandle High Plains.

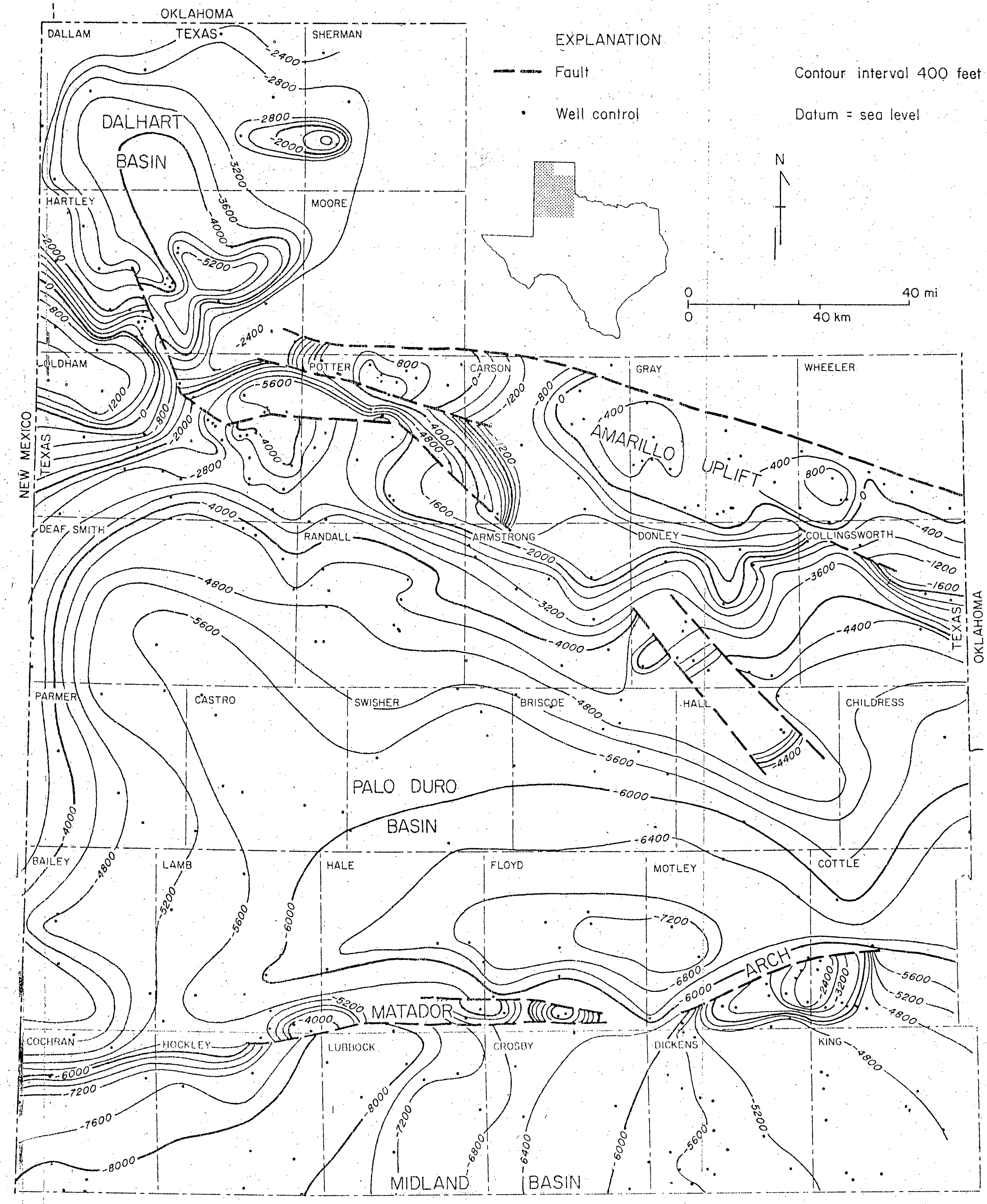

Figure 5. Structure contour map on the top of Precambrian basement, illustrating basement structure in the Palo Duro and Dalhart Basins.

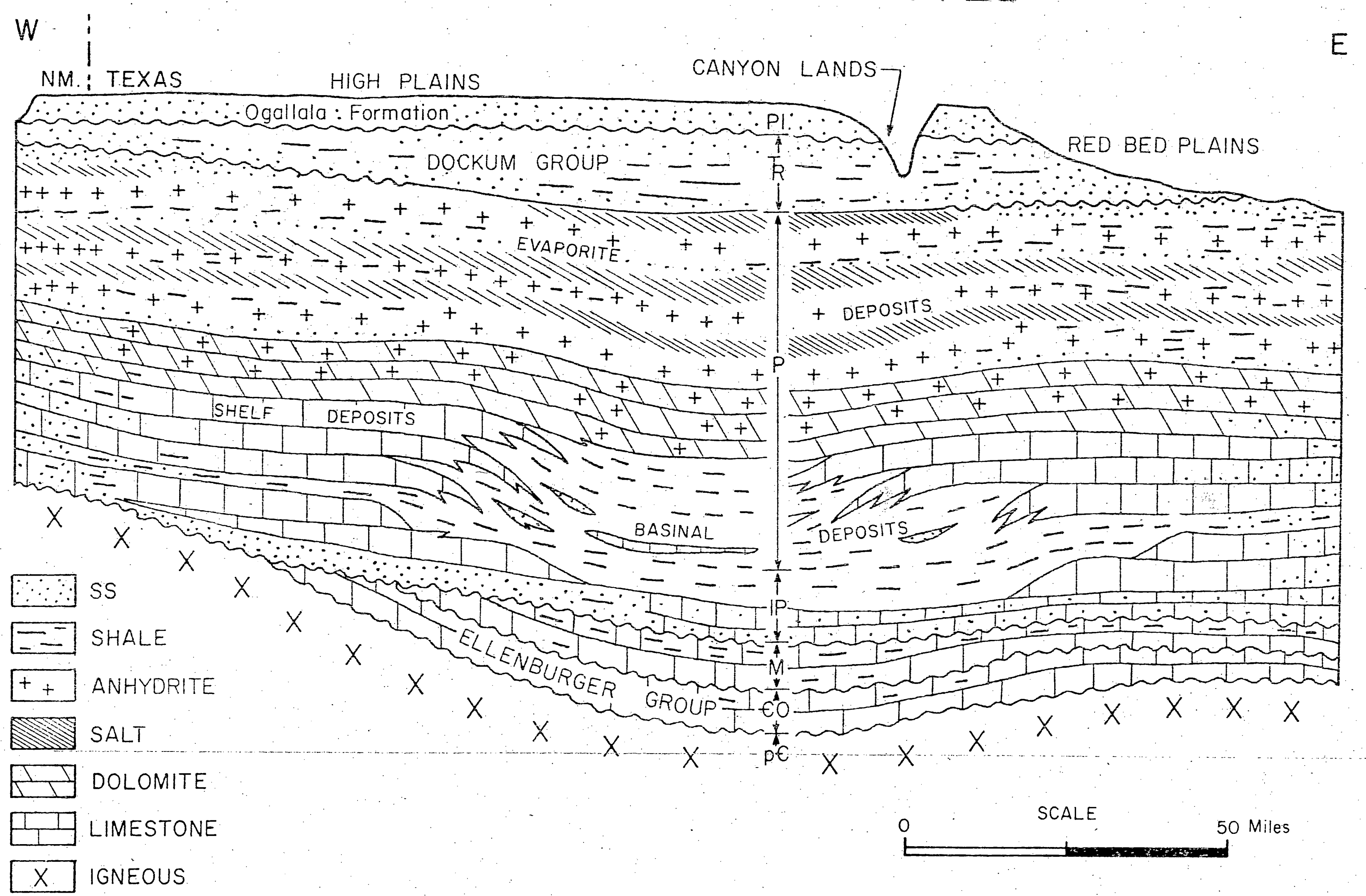

Figure 6. Schematic east-west section across Palo Duro Basin, Texas Panhandle.

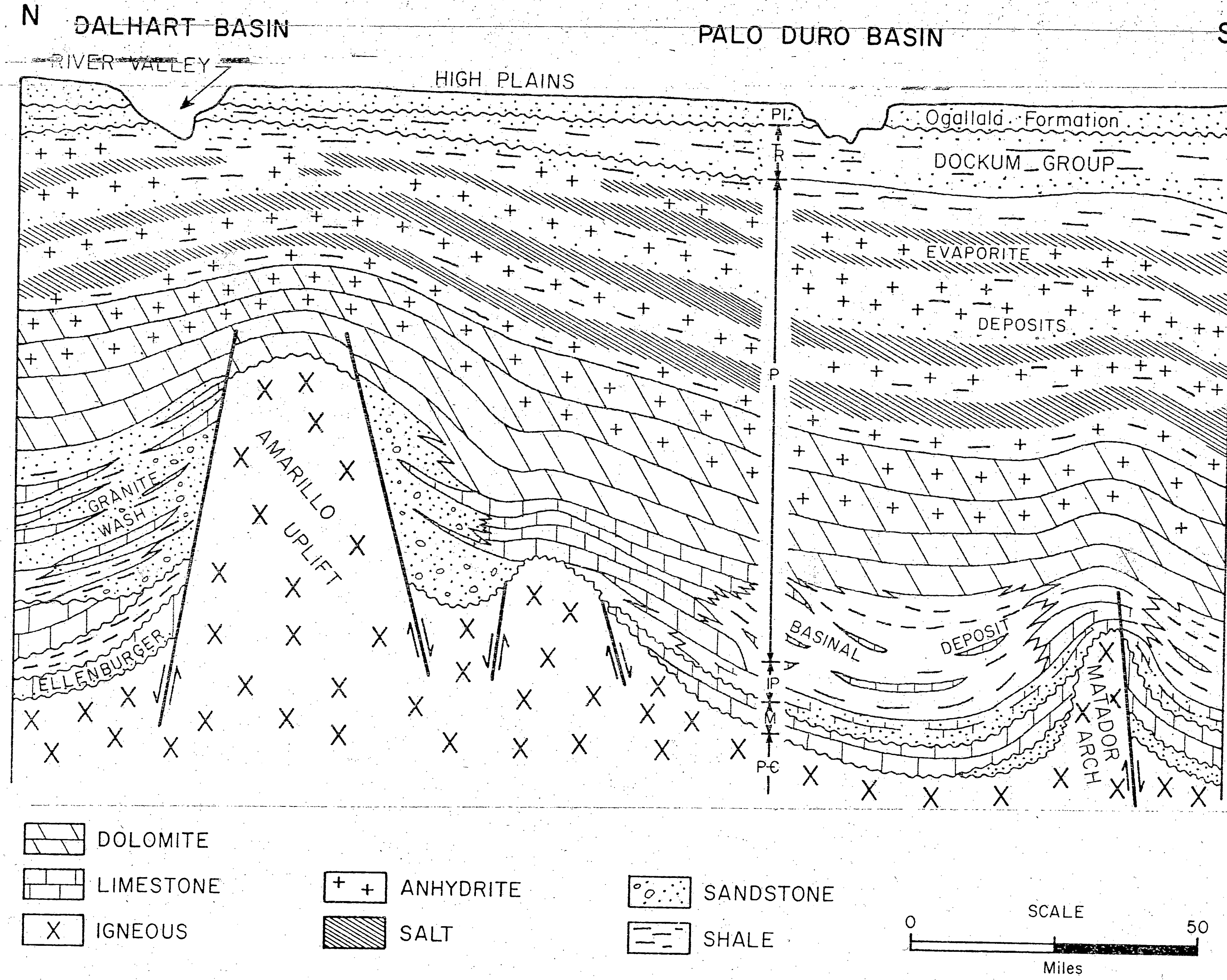

Figure 7. Schematic north-south section across Dalhart Basin, Amarillo Uplift, Palo Duro Basin, and Matador Structural Trend, Texas Panhandle.

PRE-PENNSYLVANIAN EROSION AND SHALLOW SHELF DEPOSITION

Pre-Pennsylvanian sediments in the Texas Panhandle were deposited in shallow, stable (cratonic) marine shelf environments and consist of a basal sandstone (Cambrian) and Lower Ordovician and Mississippian carbonates.

The Early Paleozoic was tectonically quiet, and erosional episodes alternated with shallow marine-shelf deposition. The Paleozoic began with a long period of erosion following the formation of Precambrian basement rocks. Earliest sediments were probably deposited in the Late Cambrian (Birsa, 1977). These are arkosic and glauconitic sandstones which were derived from the underlying basement and deposited locally by nearshore marine processes. Distribution of sandstones is limited to two areas in the eastern and southern parts of Palo Duro Basin.

By Ordovician time the area had been inundated, and shallow shelf carbonates were deposited. These rocks of the Lower Ordovician Ellenburger Group are coarsely crystalline dolomites which display intercrystalline and vuggy porosity. Rocks of the Ellenburger Group occur in the eastern and southwestern portions of the Palo Duro Basin and in the Dalhart Basin (fig. 8).

Upper Ordovician, Silurian, and Devonian strata are absent in the Palo Duro Basin, either because of non-deposition or subsequent erosion. A broad northwest-southeast trending arch ("the Texas Peninsula") was uplifted sometime after deposition of the Ellenburger Group. Rocks on the arch were eroded down to basement. This extensive erosion left the present distribution of isolated remnants of basal sandstone and Ellenburger dolomite along the east and west flanks of the former arch (fig. 8).

The Texas Peninsula was no longer a positive element by Mississippian time, and marine shelf carbonates were deposited across the entire Palo Duro and Dalhart Basins. A maximum thickness of 1100 feet of Mississippian rocks occur in Childress County (fig. 9). Like the Ellenburger, Mississippian deposits formed in a shallow marine shelf environment. Diagenesis has caused dolomitization of much of the lower Mississippian limestone, mainly in the western and northern parts of the Palo Duro Basin.

Little tectonic activity occurred in the Panhandle during most of Pre-Pennsylvanian time, but major deformation began in Late Mississippian and continued through the Pennsylvanian Period. Principal positive features that surround and define the Palo Duro Basin--the Amarillo-Wichita Mountains, Matador Arch, Bravo Dome (Oldham Nose), and Milnesand Dome (fig. 1) were uplifted in Early Pennsylvanian. The newly defined Palo Duro Basin began to subside at that time, initiating a new style of sedimentation that lasted until the end of the Permian Period. Uplifted Mississippian strata exposed in the highland areas were eroded but were preserved within the basin (fig. 9).

Ten cross-sections of the Pre-Pennsylvanian section in the Palo Duro and Dalhart Basins have been prepared. Isopach, porosity, and structure contour maps of each of the Pre-Pennsylvanian units were constructed.

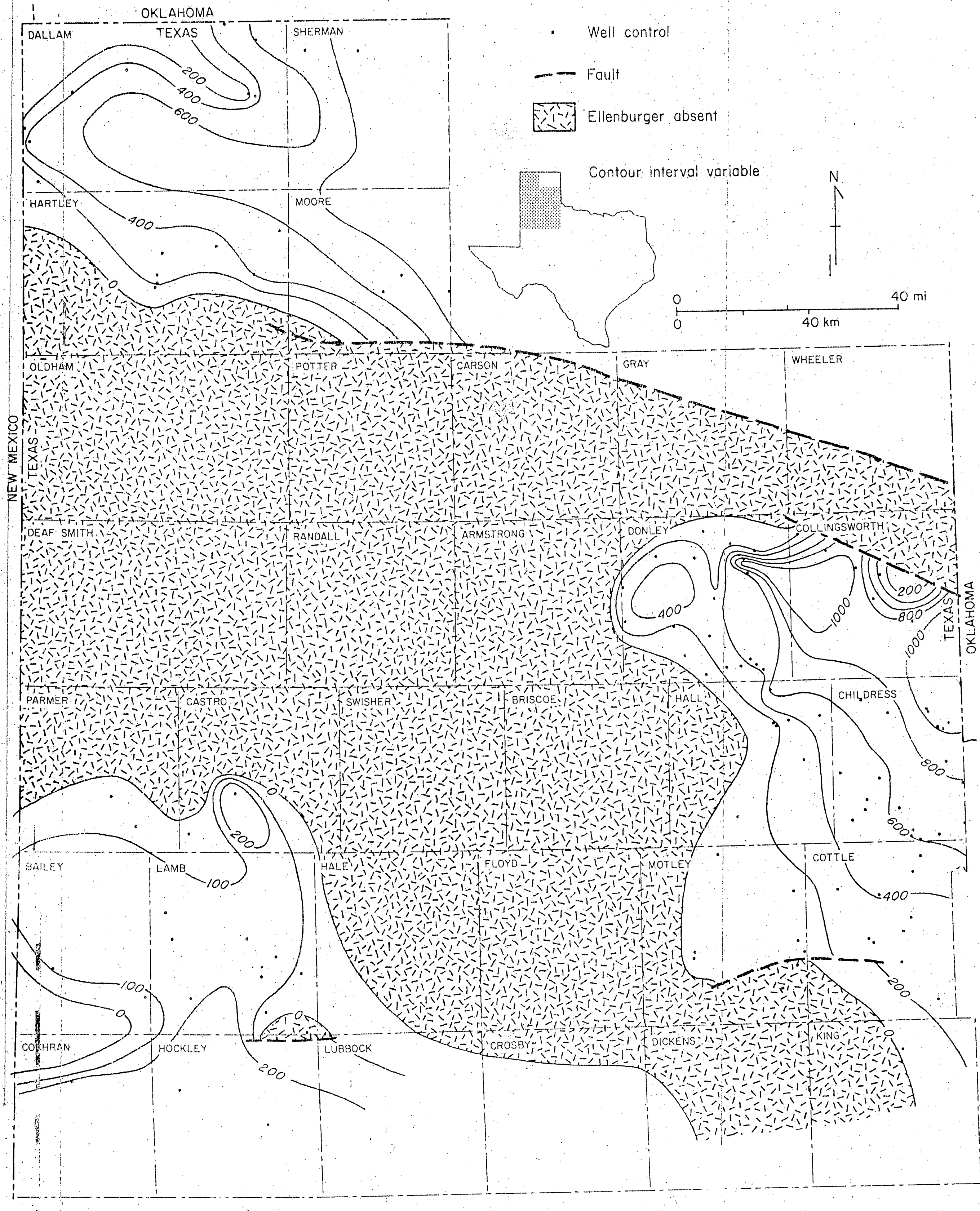

Figure 8. Isopach map of Ellenburger Group.

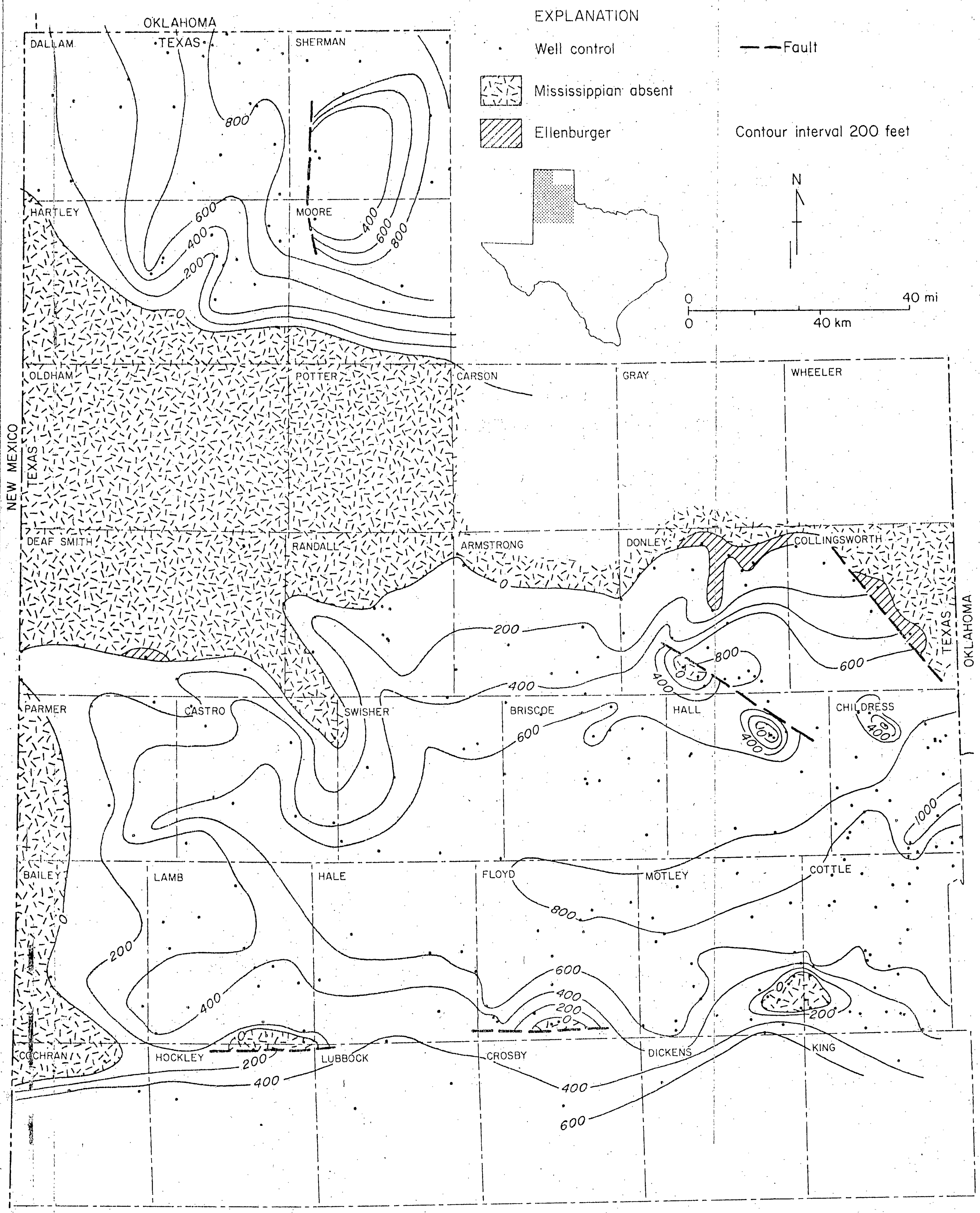

Figure 9. Isopach map of Mississippian section. Mississippian sediments are preserved in the Palo Duro and Dalhart Basins but have been eroded off of adjacent structural uplifts.

PENNSYLVANIAN DEVELOPMENT OF THE BASIN

During the Pennsylvanian Period the Palo Duro Basin deepened and developed a well-defined, mud-filled basin facies surrounded by carbonate shelf-margin buildups. Terrigenous clastic deposits were derived from and concentrated near the principal uplifts.

Pennsylvanian sedimentation was strongly affected by tectonic activity. Uplift of bounding highlands and basin subsidence controlled both the facies patterns that developed and the total thickness of sediments. Marine transgression continued throughout the Pennsylvanian, and subaerially exposed areas were progressively inundated. Sedimentation was continuous in most areas, and there are no widespread unconformities in the section. However, there is a noticeable change in depositional style evidenced by differences in Lower and Upper Pennsylvanian strata. Early Pennsylvanian deposition was dominated by terrigenous clastics, but in Late Pennsylvanian, carbonate buildups dominated sedimentation, and clastic influence was greatly reduced (fig. 10).

Twenty-one Pennsylvanian cross sections were constructed for this study (fig. 11), as well as nine isolith, seven lithologic percent, five porosity maps, a total Pennsylvanian isopach and a top of Pennsylvanian structure contour map.

Early Pennsylvanian--Sediments were deposited in three principal environments: alluvial fan and fan delta, shallow marine shelf, and deep basin. Erosion of Precambrian basement exposed in the Amarillo and Sierra Grande Uplifts supplied coarse arkosic sand and gravel ("granite wash") to alluvial fans and fan deltas located along the northern margin of the basin (fig. 12). Downdip, distal fan sands were interbedded with mud and thin carbonates. Carbonate and clastic sedimentation alternated, and each cycle helped control the distribution of the next. This process is called "reciprocal sedimentation" (Becker, 1977).

Most of the Palo Duro area was a shallow shelf, similar to the Pre-Pennsylvanian structural setting. The southern part of the region was sufficiently removed from the peripheral mountains that few sands reached it, and sedimentation was dominated by shallow marine carbonates and mud. Basinal shales were deposited only in a small area immediately north of the Matador Arch.

Late Pennsylvanian--The major change in deposition from Early to Late Pennsylvanian was development of a large, well-defined, mud-filled basin environment. Carbonate shelf-margin buildups rimmed the basin and stood several hundred feet above the basin floor (fig. 10). Along the eastern and southwestern basin margins the shelf-edge position was stationary, and over a thousand feet of carbonate accreted. In the northwest, however, two shelf margins are recognized, indicating that the younger shelf-edge retreated as much as 18 miles (fig. 13). An increase in clastic deposition combined with continued subsidence may have caused the shelf-margin retreat.

Basin filling occurred in Late Pennsylvanian when sediment entered the basin through breaches and low areas in the shelf-margin carbonates. The main clastic feeder channels that supplied the basin environments occur at the northern and eastern ends of the basin (fig. 14). Basin-fill is mostly shale, but sand was also deposited, especially at the eastern end of the basin. The areal cross-sectional geometry of some sandstone units suggests that they were deposited as bar finger sands in a high-constructive elongate delta.

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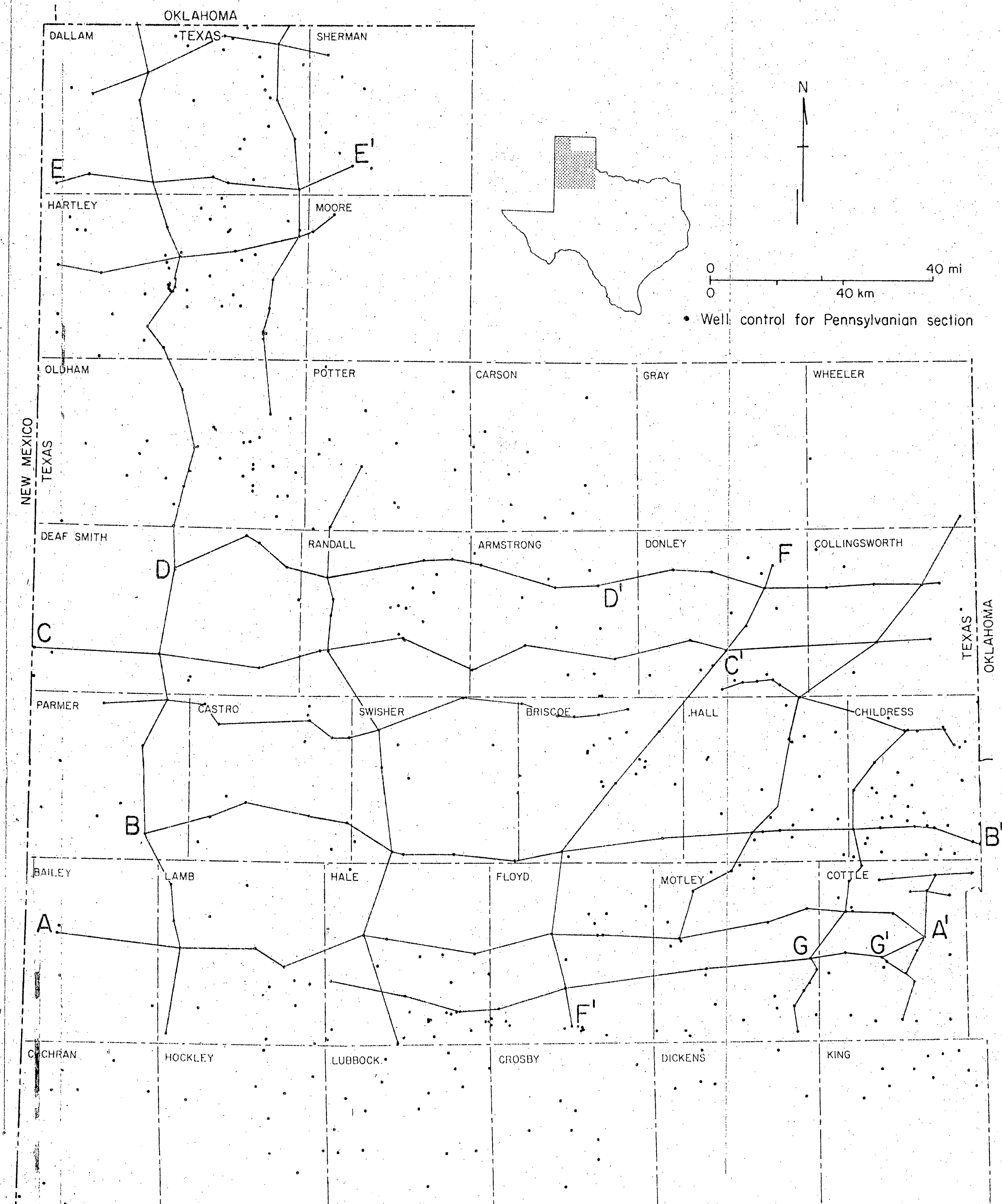

Figure 11. Index map of study area showing Pennsylvanian well control and locations of cross-sections.

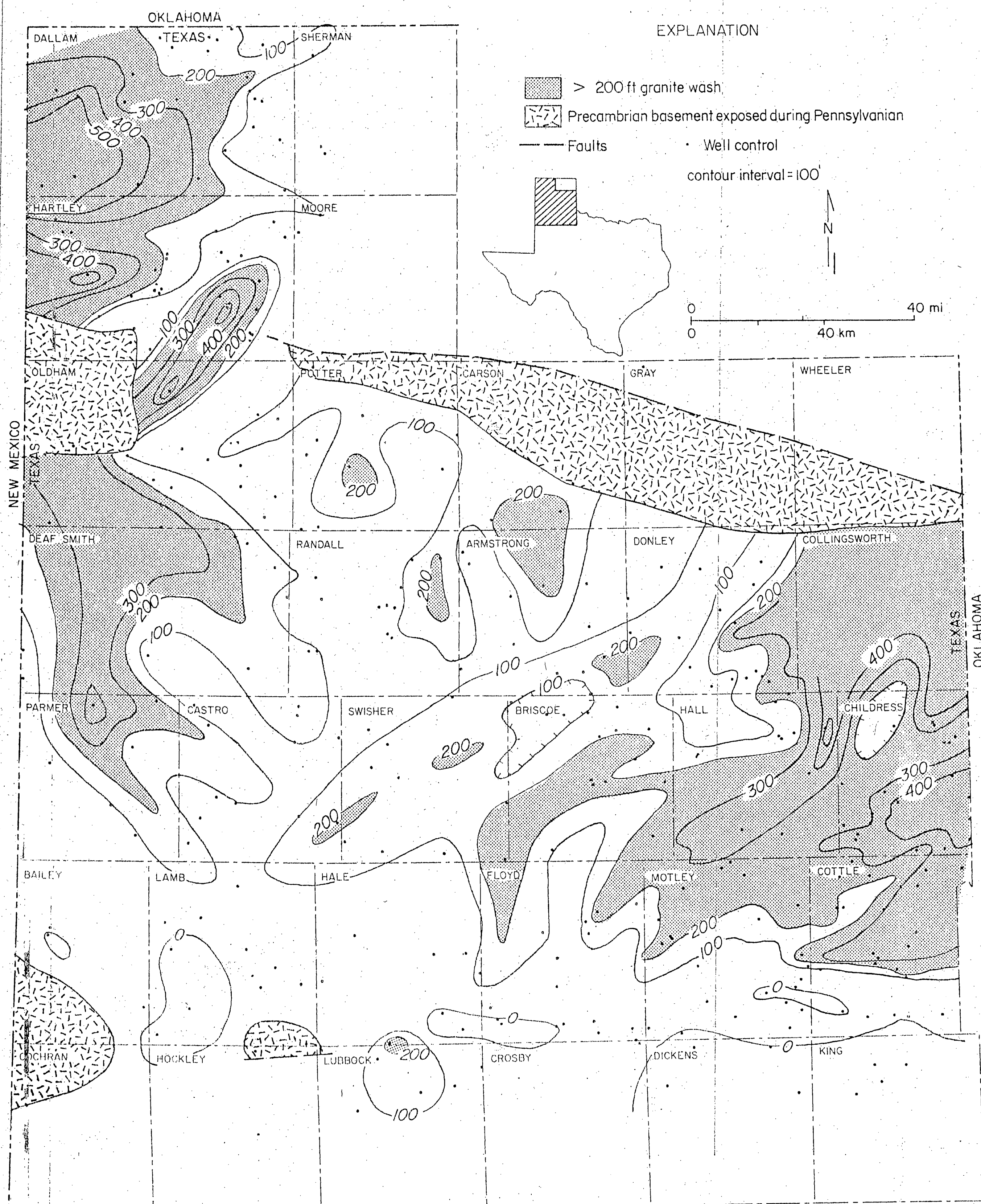

Figure 12. Net granite wash map of lower Pennsylvanian section.

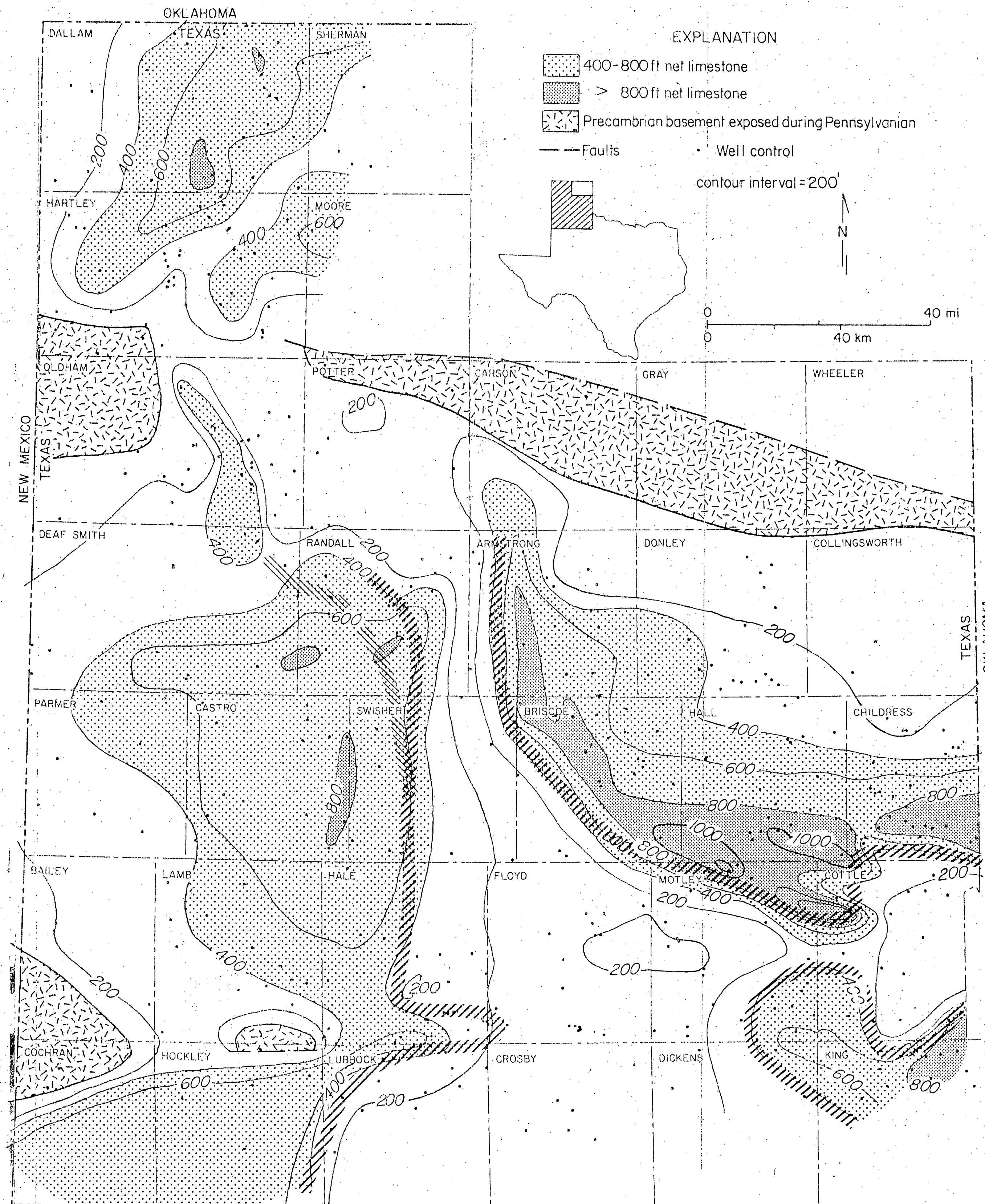

Figure 13. Net limestone map of upper Pennsylvanian section. Position of the shelf margin is shown by dark hachured line. The retreated shelf-edge position is shown by the lighter hachures.

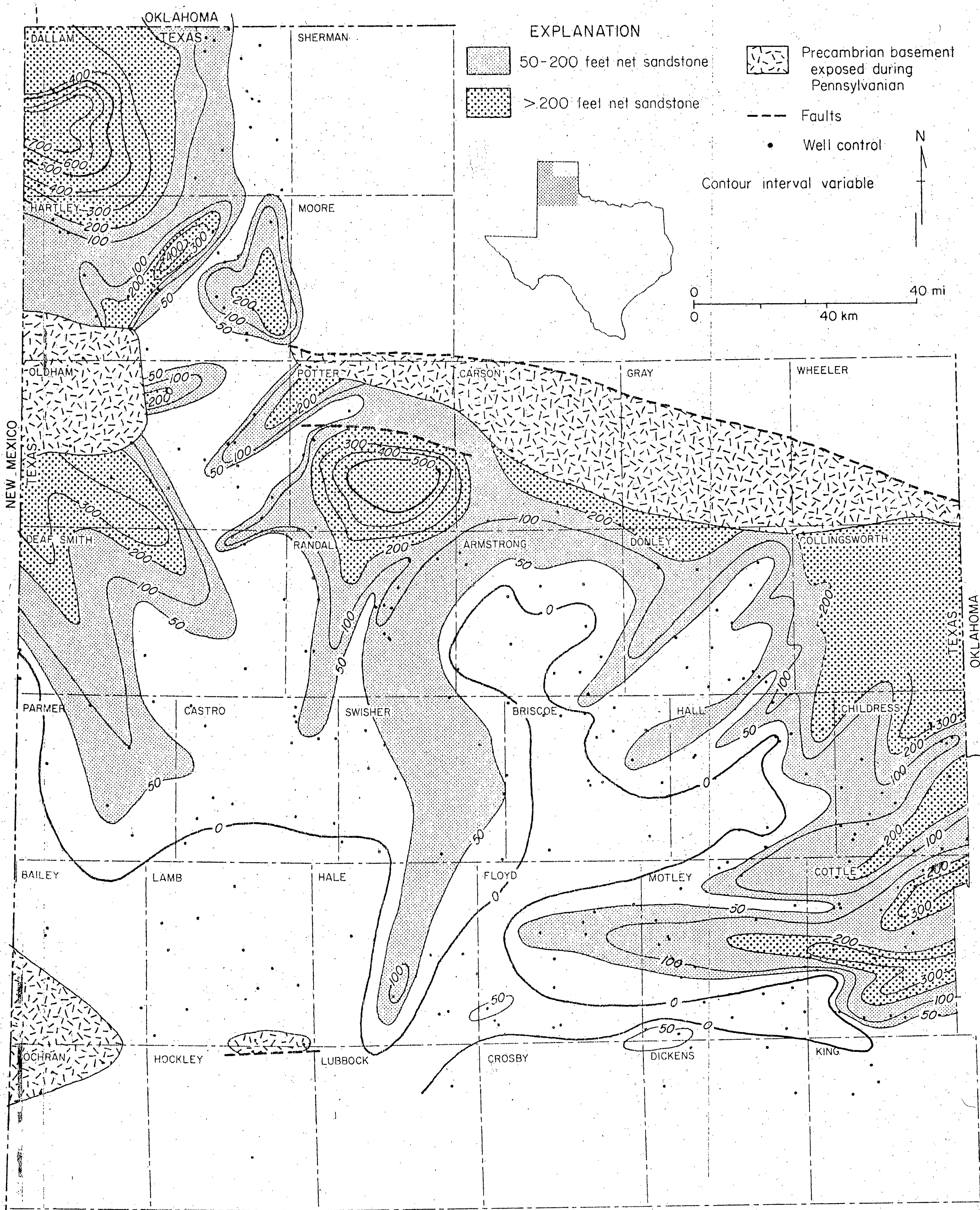

Figure 14. Net sandstone map of upper Pennsylvanian interval.

LOWER PERMIAN DEPOSITIONAL SYSTEMS

Progradational carbonate shelf margin and slope deposits rapidly filled the Palo Duro Basin during Early Permian time, transforming it into an extensive, evaporitic sabkha rimmed by an alluvial fan plain.

Early Permian time in the Palo Duro Basin was one of changing depositional styles. Consequently, a variety of facies and depositional systems are recorded. Wolfcampian strata were deposited in deep basin to slope, shelf margin and deltaic systems. Younger sediments of Leonardian age were deposited principally within sabkha and alluvial fan plain systems.

Representative cross-sections illustrate the stratigraphic framework (figs. 15, 16, 20, and 21). Lithologic data were interpreted from electric logs and used to construct facies maps (figs. 17, 18, 22, and 23). Paleogeographic maps for several stratigraphic intervals were made by combining various facies maps and schematically illustrating interpreted depositional topography and environments (figs. 19 and 24).

Deltaic systems--Lower Permian sandstones are distributed in a band around the periphery of the basin and display isolith patterns indicative of deposition within fan delta and high constructive delta systems. Thick, coarse-grained arkosic sands, or granite wash, were deposited in fan deltas which prograded into the basin from adjacent highlands of the Amarillo Uplift. In the southeastern part of the Palo Duro Basin, high constructive, elongate deltas prograded westward across a marine shelf and deposited quartzose sands in delta front environments. Both fan delta and high constructive delta sandstones interfinger basinward with prodelta clays and shallow marine carbonates.

Carbonate shelf margin system--Seaward of the delta systems was an arcuate, carbonate shelf margin complex, 400-1800 feet thick that separated the deeper basin from shallow shelf environments. Initially the shelf margins were widely separated, but they rapidly closed during Wolfcampian time. Progradational shelf margin sequences range from 200-400 feet thick, implying that each shelf margin bank stood 200-400 feet above the adjacent basin floor.

Slope and basinal system--Dark shales and micritic limestones comprise the bulk of sediments deposited within basin and slope environments. Terrigenous sediments were introduced by deltas that prograded to the shelf margin and were transported downslope by suspension settling, turbidity currents, and debris flows or slumping. Thick slope wedges were thus formed, providing foundations for subsequent shelf margin development and a mechanism for filling and closing the deeper part of the basin.

Sabkha system--Strata belonging to the Wichita Group and Lower Clear Fork Formation were deposited principally within a coastal sabkha environment bordered on the south by the deep Midland Basin and elsewhere by an alluvial fan plain. The sabkha extended northeastward through the Texas and Oklahoma pandhandles into southern Kansas. The Wichita sabkha was comprised of an irregular belt of dolomite and anhydrite deposition; bedded salt was deposited in Oklahoma and Kansas. A southward shift of the facies belts resulted in accumulation of 300 feet of upper sabkha, bedded salt during deposition of the Lower Clear Fork Formation. Two evaporite cycles were identified in the Lower Clear Fork, each generally consisting of a basal clastic sequence overlain by anhydrite and bedded salt. In the northern part of the Palo Duro Basin, salt strata thin sharply and pass into red bed facies.

Alluvial fan plain system--Three distinctive, basinward thinning, clastic lobes of the Red Cave Formation occur between the Wichita Group and Lower Clear Fork Formation. Isolith map patterns indicate that these red beds were deposited along the distal edges of coalescing alluvial fans and on landward fringes of sabkha mudflats. Clastics were transported from the northwest and east across an alluvial fan plain by ephemeral braided streams or wadis.

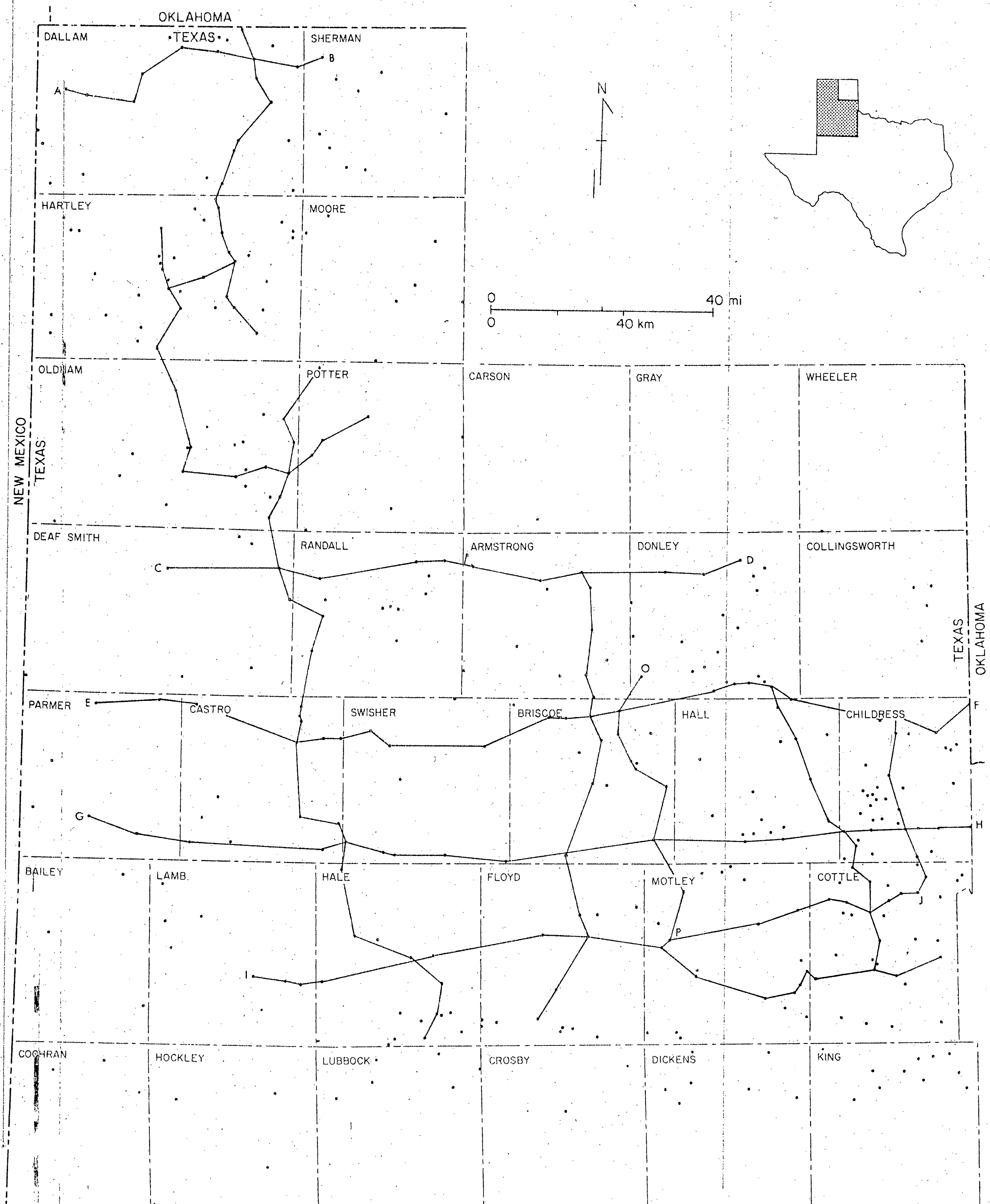

Figure 15. Index map of study area showing locations of Wolfcampian cross-sections. Section G-H is published in this report.

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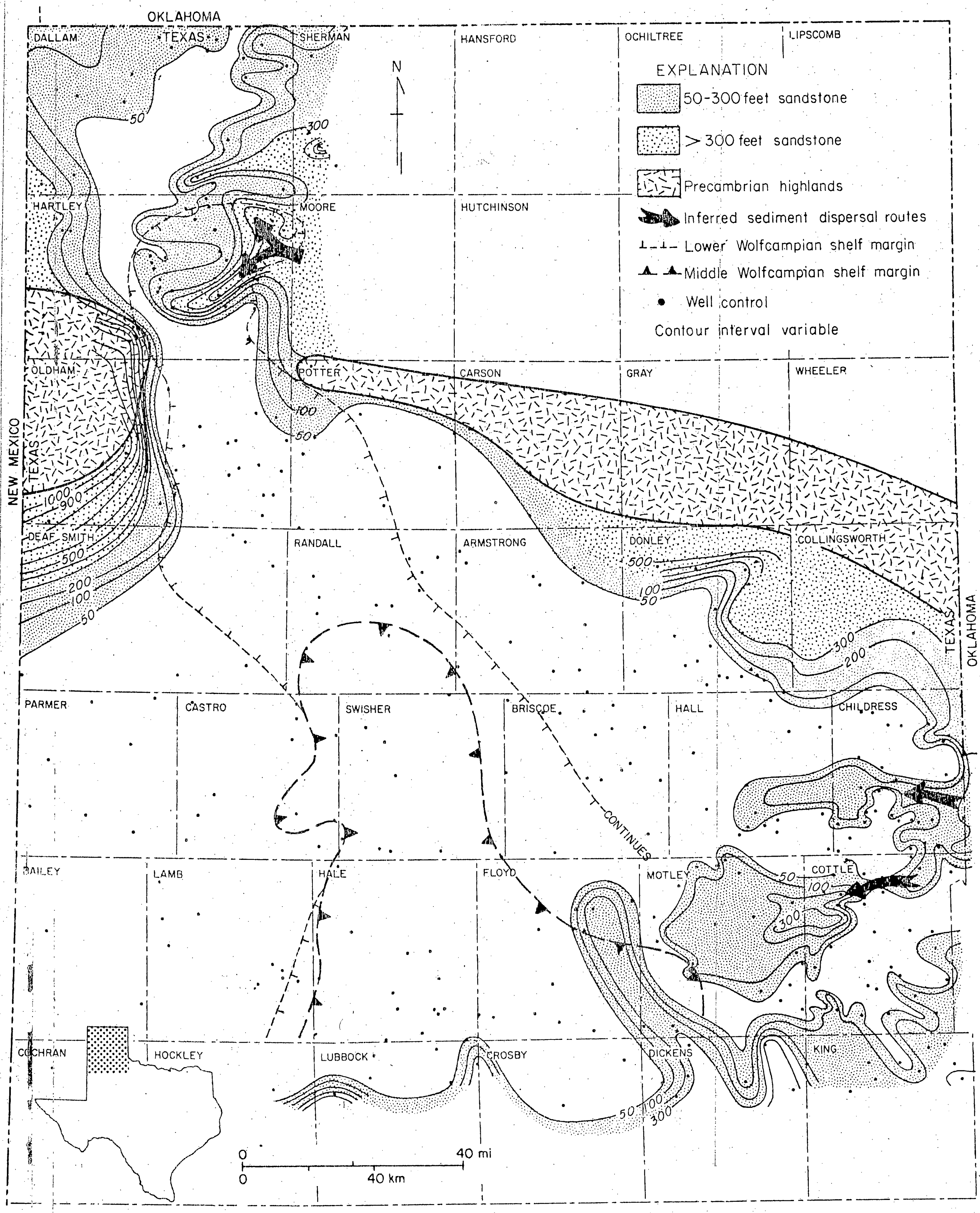

Figure 17. Net sandstone map of Wolfcampian Series.

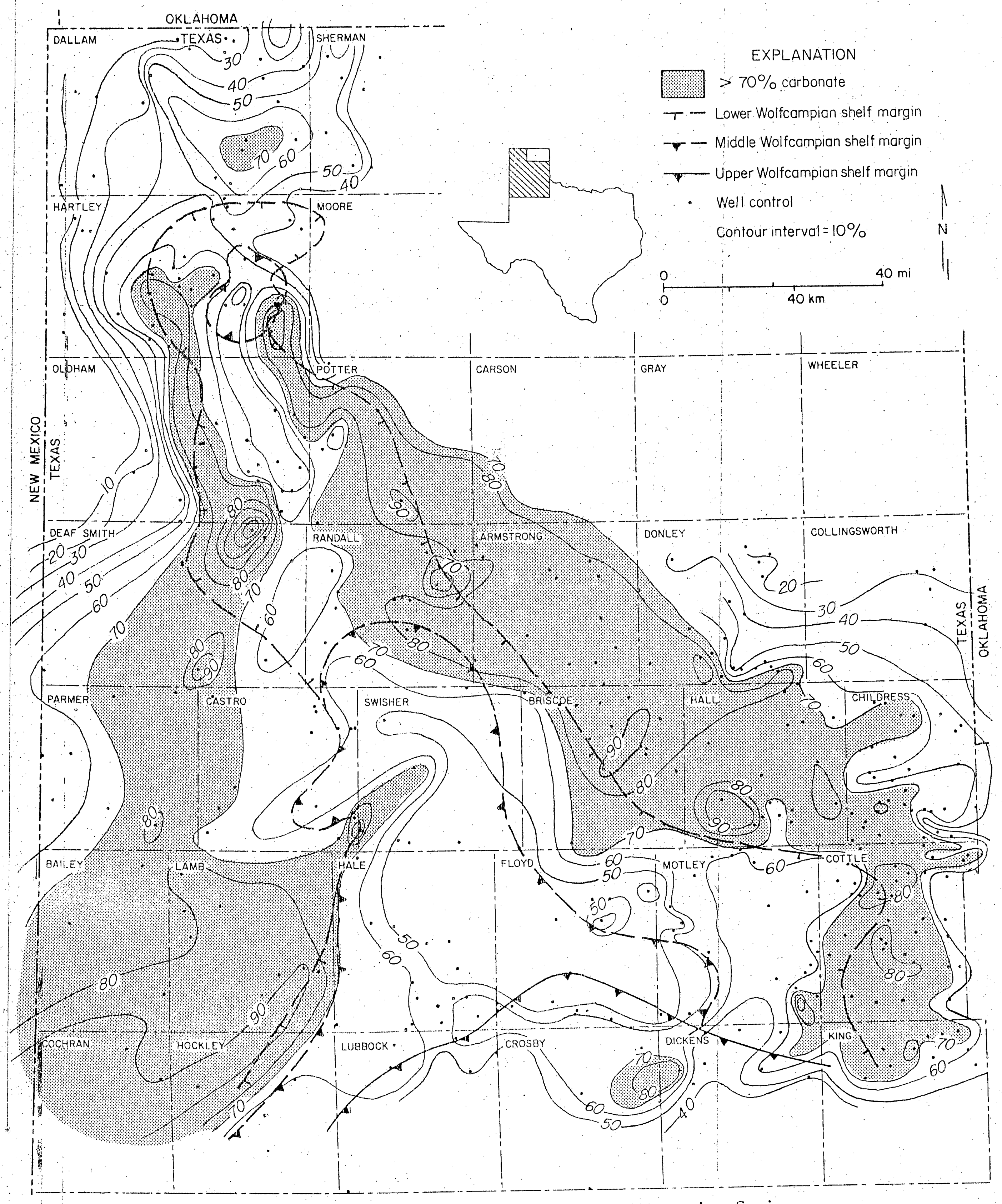

Figure 18. Carbonate percent map of Wolfcampian Series.

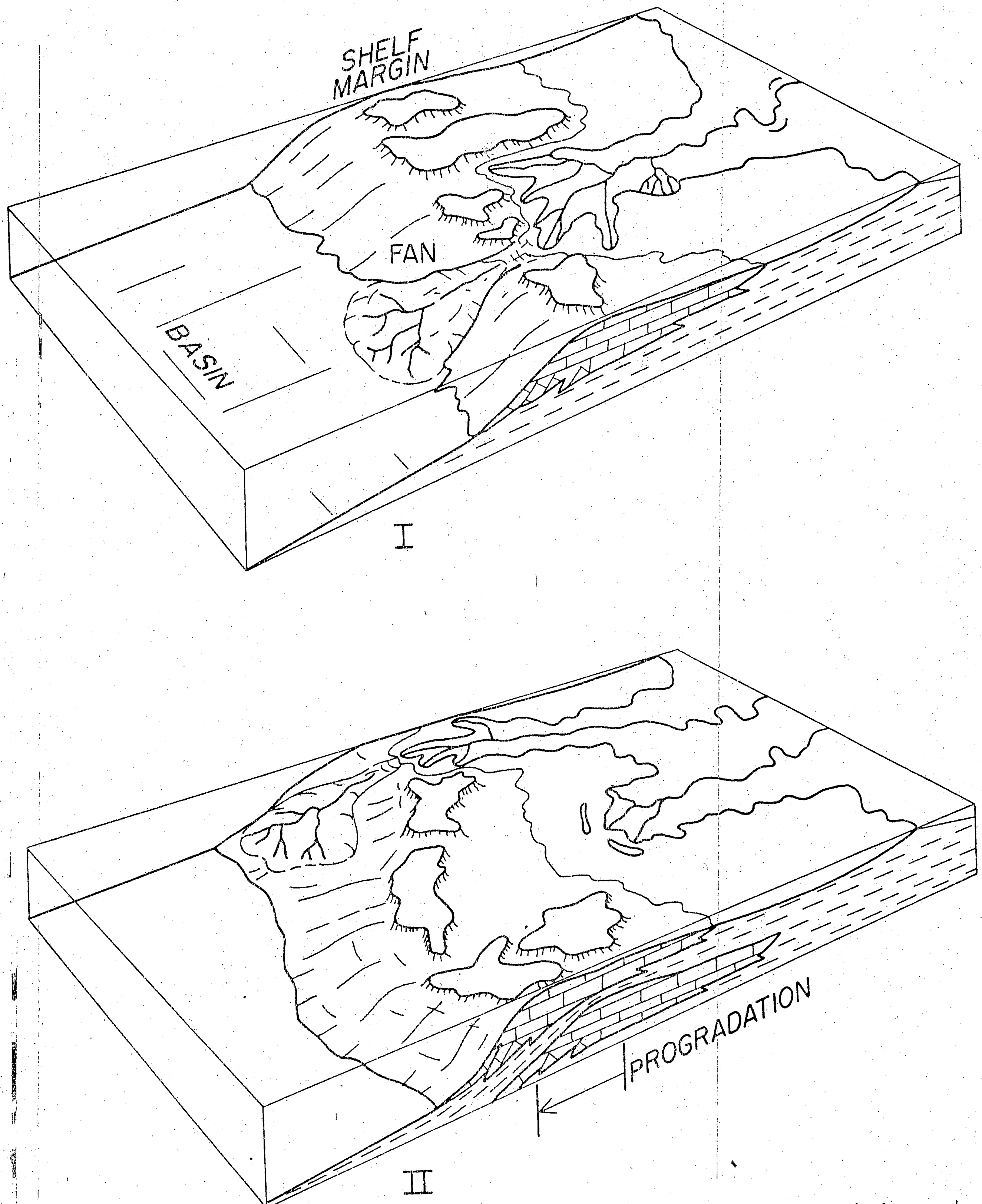

Figure 19. Model of shelf margin development. Phase I: delta progradation and formation of slope wedge. Phase II: delta abandonment and seaward progradation of new carbonate banks and shelf margin.

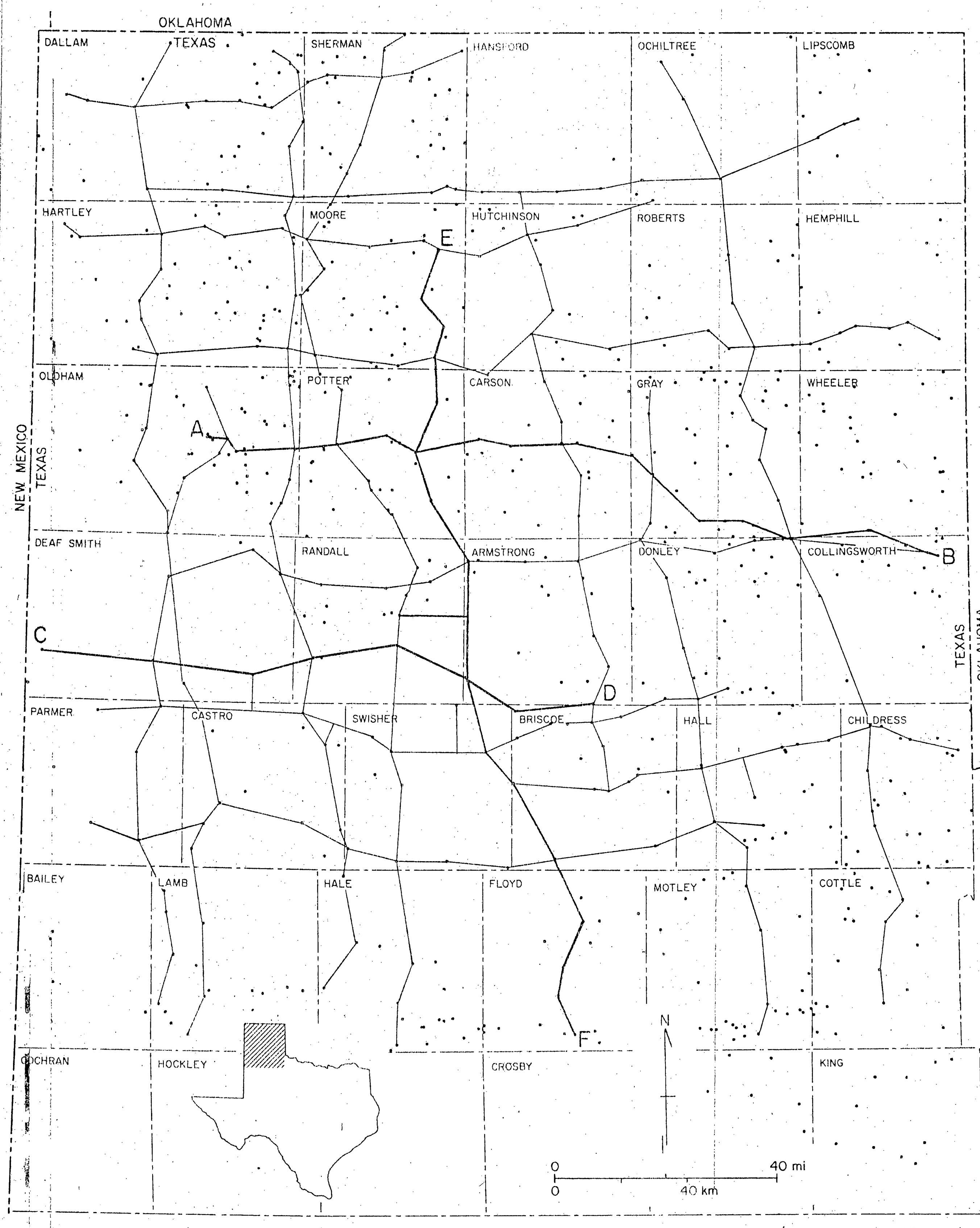

Figure 20. Index map showing locations of Leonardian cross-sections. Section E-F is published in this report.

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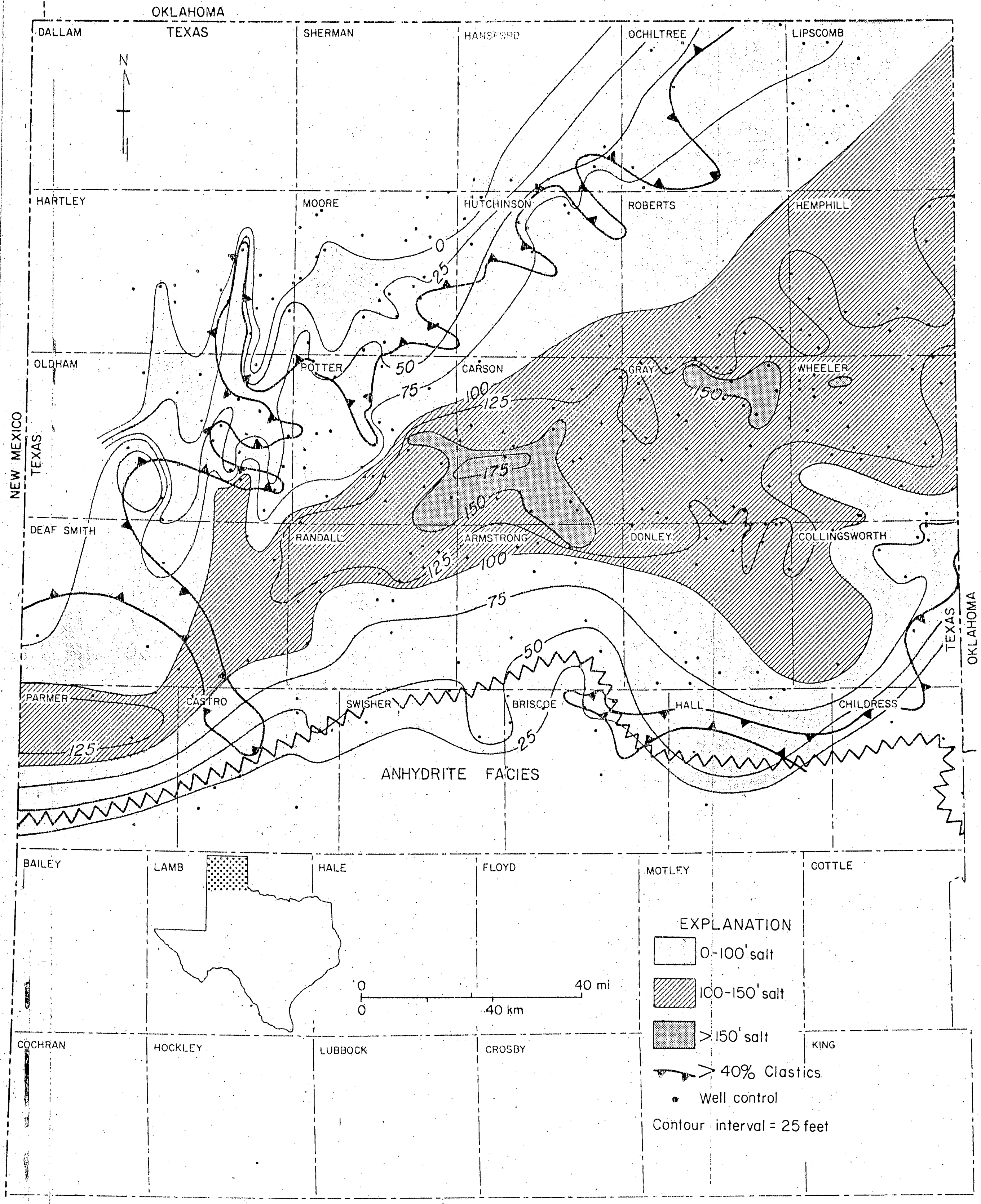


Figure 22. Net salt, upper cycle, lower Clear Fork Formation.

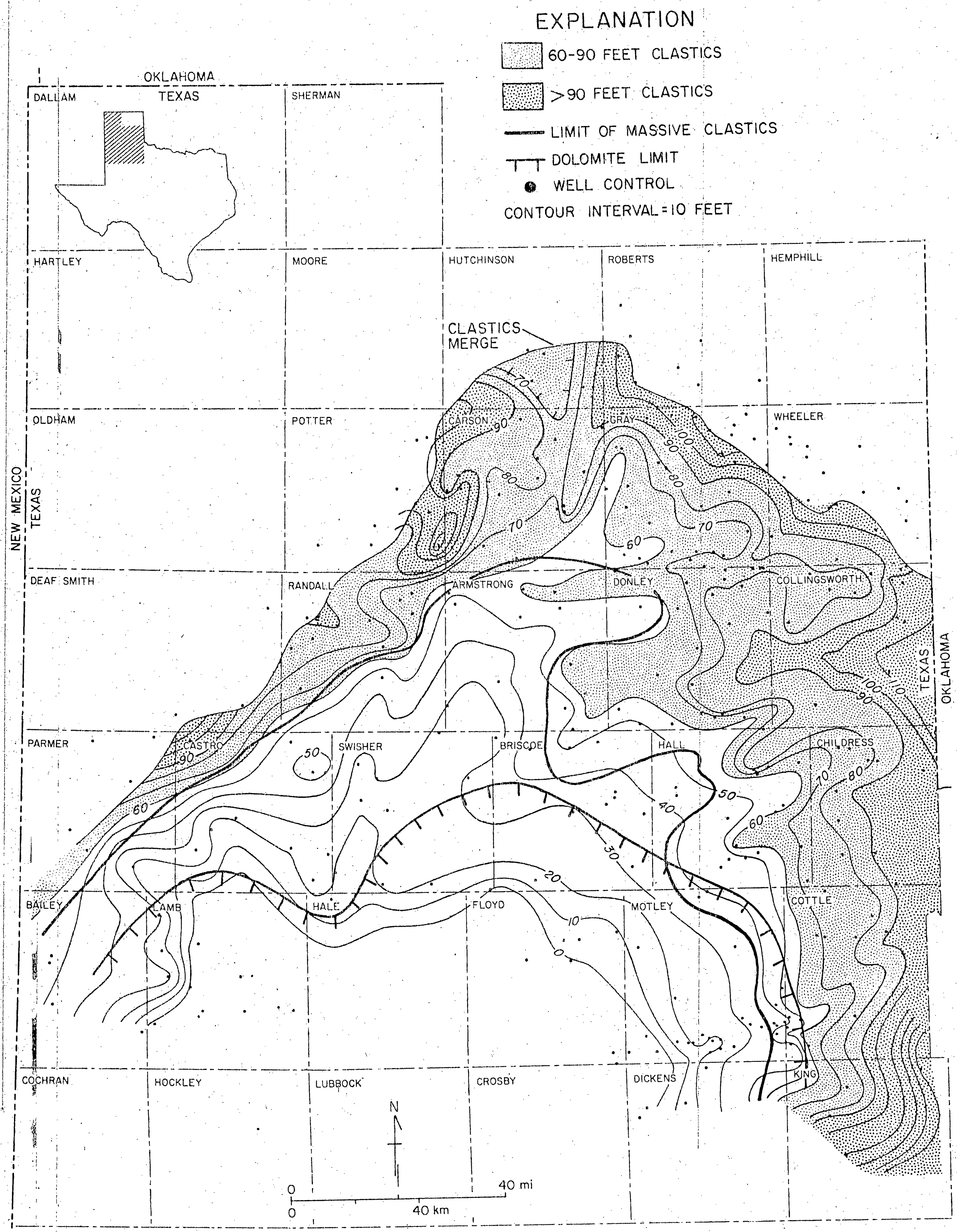


Figure 23. Net clastics, A-lobe of Red Cave Formation.

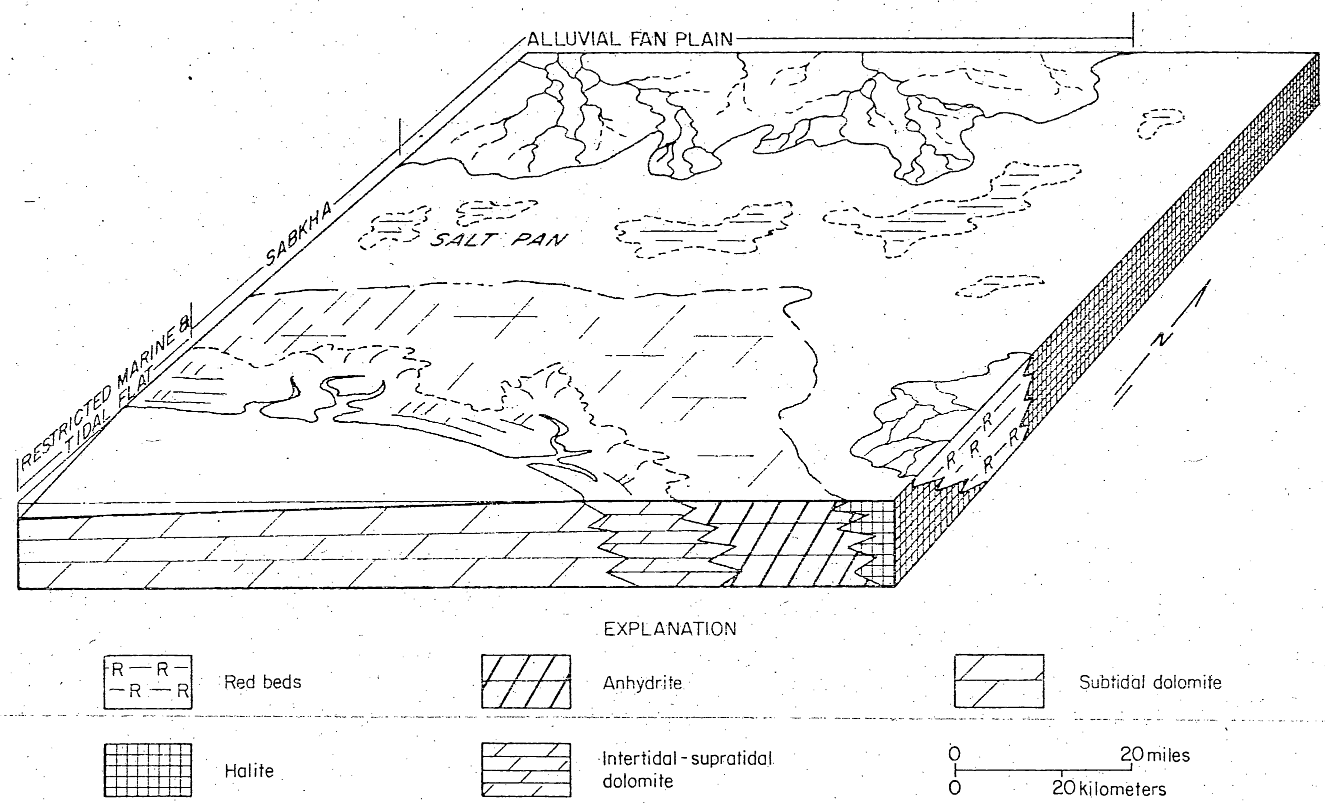


Figure 24. Facies model, deposition of lower Clear Fork Formation.

UPPER PERMIAN EVAPORITES AND RED BEDS

Four major genetic subdivisions of Upper Permian evaporite/red bed strata are recognized in the Palo Duro and Dalhart Basins. The overall aspect of the stratigraphy indicates a general southerly facies shift through time. Evaporite facies exhibit many of the features observed in modern coastal sabkhas.

Upper Permian strata in the Palo Duro and Dalhart Basins include salt, anhydrite, dolomite, rare limestone, and red beds. Evaporites and associated carbonates display basinward (southerly) facies changes from supratidal to subtidal; facies exhibit many features of modern, low relief, coastal sabkhas. Lithofacies include: (1) salt formed in upper sabkha brine ponds and evaporating pans, (2) lower sabkha anhydrite in bedded units, (3) supratidal to subtidal dolomite with nodular and bedded anhydrite, and (4) highly burrowed subtidal carbonates (see San Andres Formation example, figs. 4, 26, 27, and 28). Red beds occur as sheets (up to 300 feet thick) of shale and fine-grained sandstone, which intertongue basinward with dolomite/evaporites (see Tubb example, fig. 29). It is inferred that these deposits formed largely in tidal mudflats grading basinward into tidal sandflats. Clastic input was by aeolian and/or low energy alluvial processes.

The overall genetic aspect of the stratigraphy indicates a general southerly migration of facies through time. Four major genetic subdivisions are recognized:

1. Lower Clear Fork/Tubb strata--The lower part of the Clear Fork Group has been discussed. Tubb strata represent dominant late-stage red-bed deposition in the lower Clear Fork evaporite basin. Clastic environments prograded through time into the Palo Duro Basin center; transitional (intertonguing) evaporite environments retreated to the south.

2. Upper Clear Fork/Glorieta strata--Evaporites and dolomite of the upper part of the Clear Fork Group represent early dominance in the Palo Duro and Dalhart Basins of sabkha/shelf environments. Intertonguing red beds and salt of the Glorieta

Formation represent later dominance of clastic/upper sabkha environments in the basins. Both upper sabkha deposits and overlying red bed facies were deposited in environments that migrated through time from the Dalhart area to the Palo Duro Basin (fig. 30). Glorieta sandstones in the Dalhart Basin exhibit northeast-southwest isopach trends, extending into east-central New Mexico.

3. San Andres strata (fig. 31)--Lower San Andres strata include multiple cyclic units that are regressive to the south. Five cycles are recognized, each with basal dolomite (transgressive), grading upward into lower sabkha anhydrite, capped by upper sabkha salt. The upper sabkha terrane was centered in the northern part of the Palo Duro Basin at the close of each cycle. Upper San Andres strata include massively bedded anhydrite overlain by intertonguing anhydrite/salt, representing late-stage dominance of lower/upper sabkha environments.

4. Post-San Andres strata (fig. 32)--Post-San Andres strata include massive upper sabkha salt and red bed deposits. Salt is present only in the central and western parts of the Palo Duro Basin and is largely contained in two major salt units which correlate to the north in the Dalhart Basin with continuous gypsum marker beds. Upper boundaries of the salt units are transitional into red beds. Red bed units intertongue southward with salt.

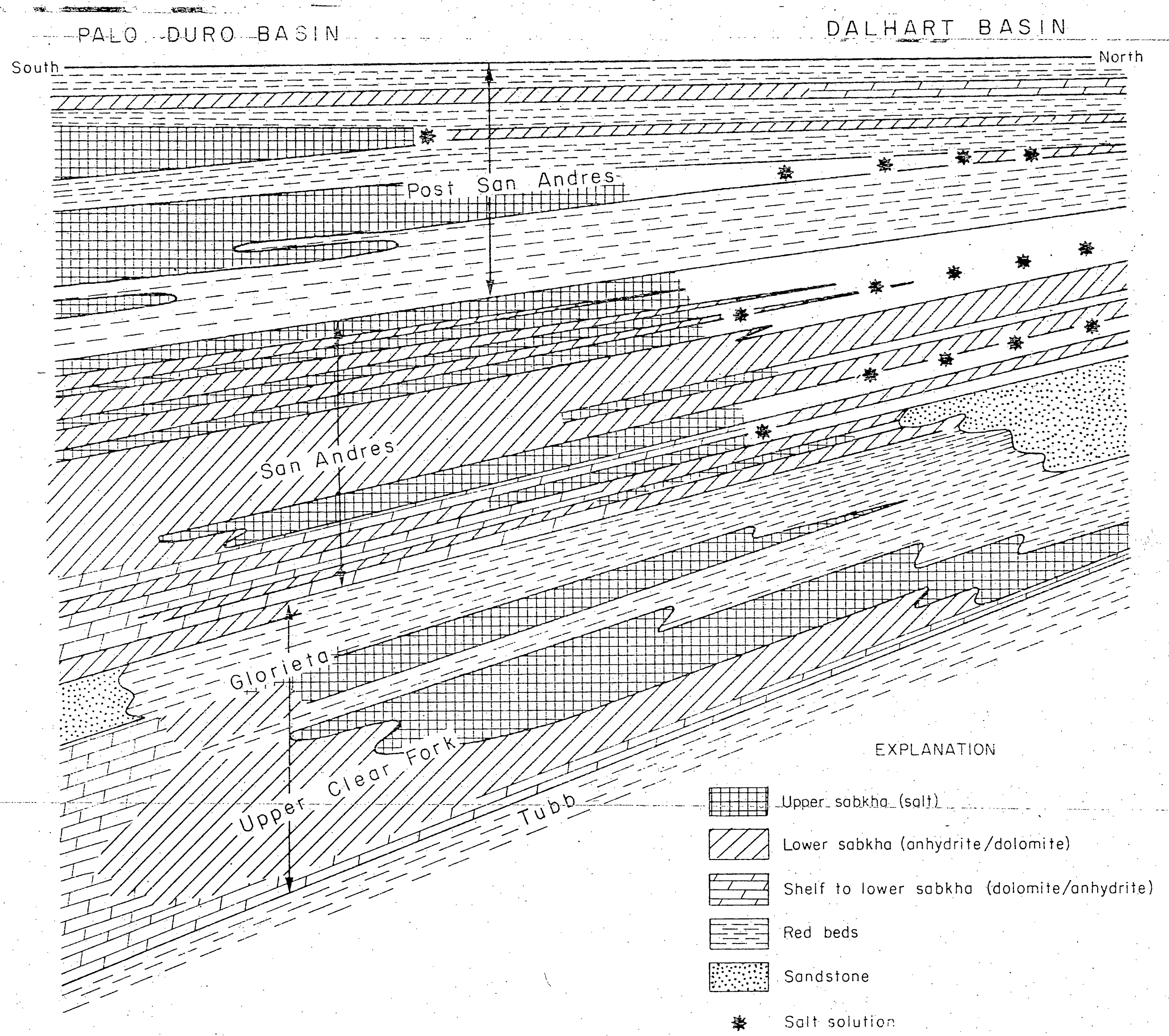


Figure 25. Generalized north-south cross-section, major genetic units, upper Permian salt-bearing strata, Palo Duro and Dalhart Basins.

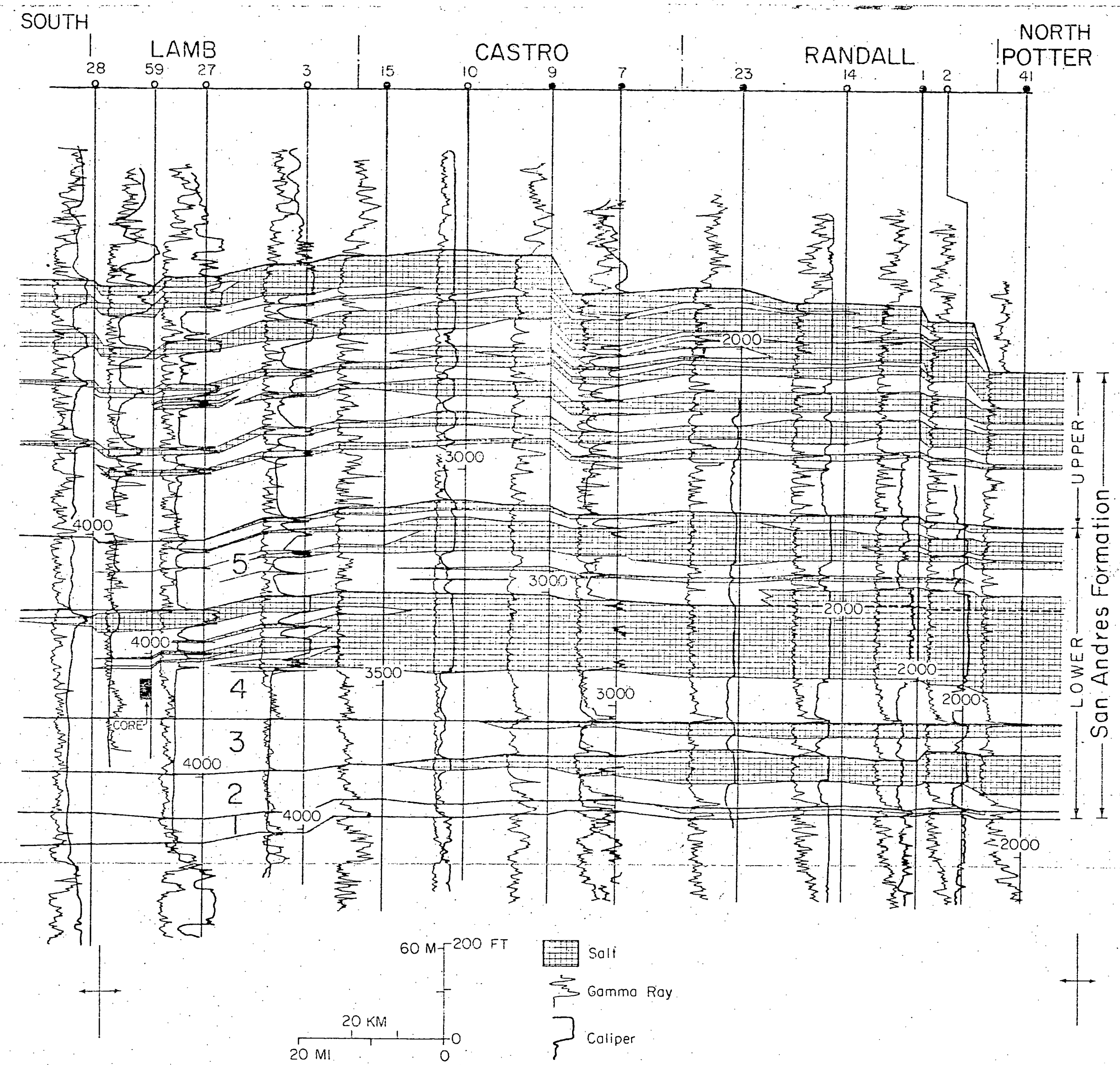


Figure 26. North-south cross-section, San Andres Formation, Palo Duro Basin. Salt beds that cap lower San Andres cyclic units 1-5 thin and pinch out to the south. Moderate to high radioactivity (higher to the north) in basal portions of the cycles diminishes upward into salt. Lithology and facies interpretations of gamma ray patterns are shown in figures 4 and 27.

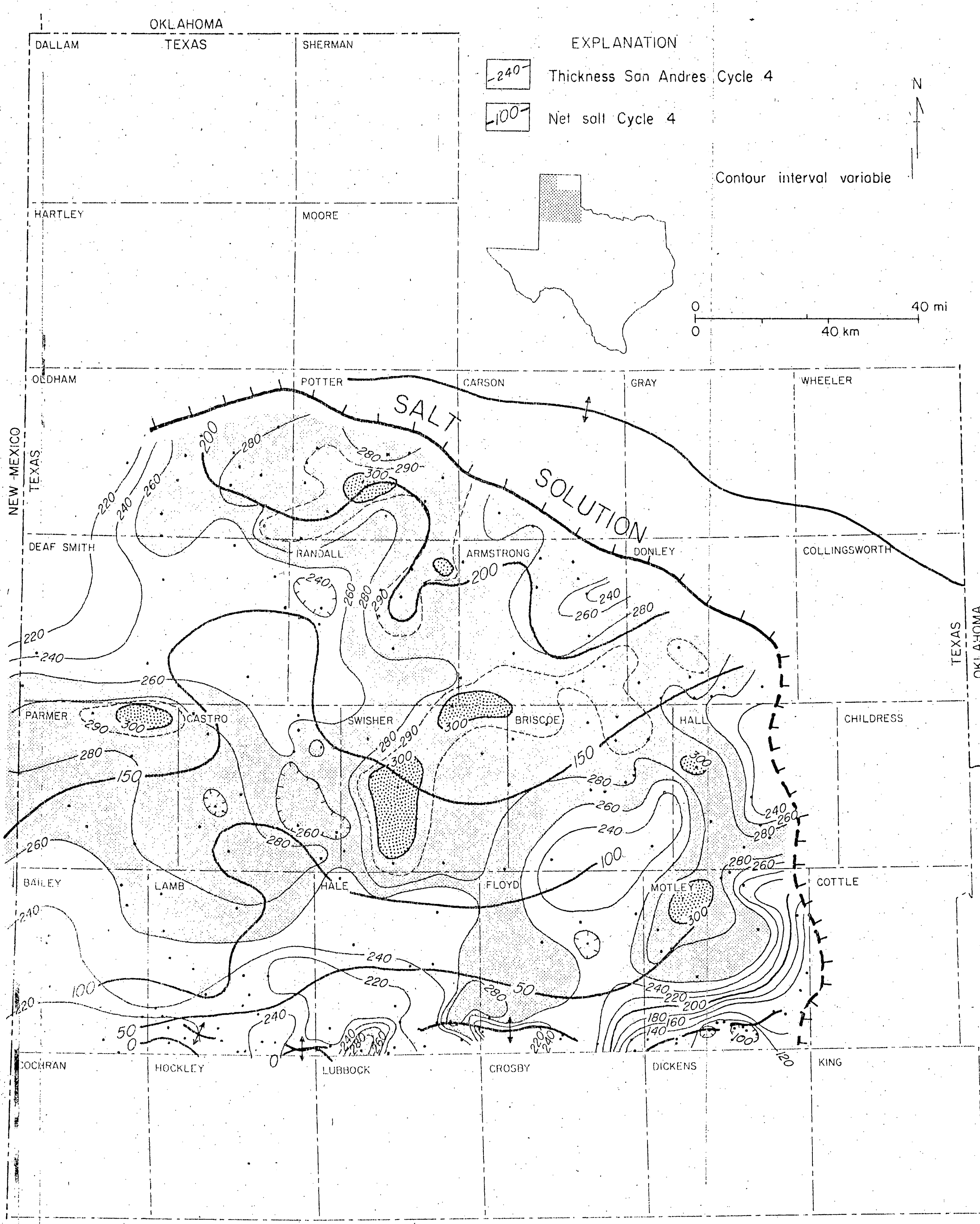


Figure 27. Isopach map, lower San Andres cycle 4 (fig. 25) showing net salt contained in cycle. Cycle exhibits relatively small variations in thickness (240-300 feet) in the basin. Net salt values increase to the north and reflect position of maximum development of upper sabkha salt terrane at close of cycle.

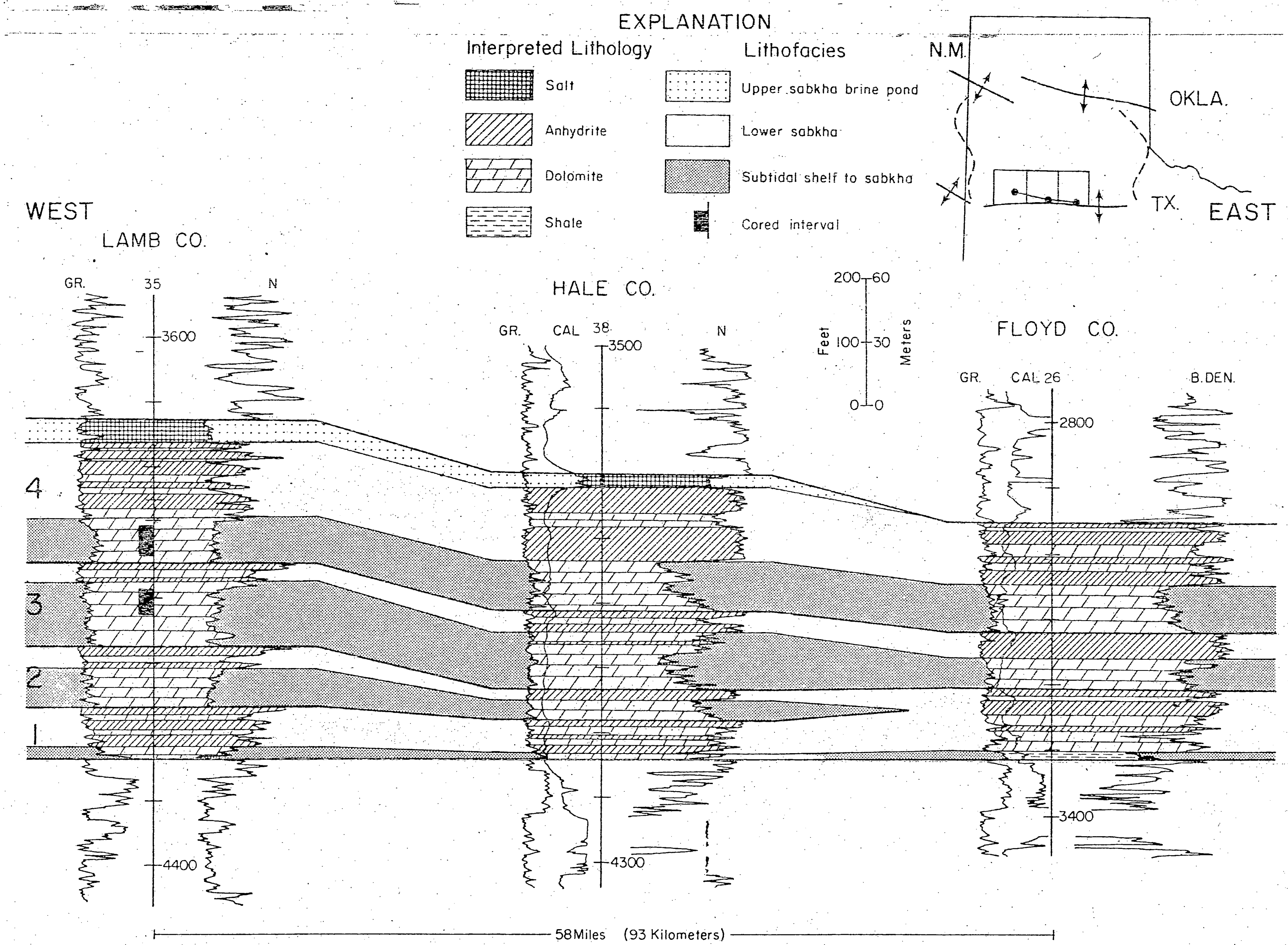


Figure 28. East-west cross-section, lower San Andres cyclic units, southern Palo Duro Basin. Both lithology and facies interpretatons are shown. Cores such as those in the Lamb County well suggest subtidal/intertidal deposition for basal dolomite of cycles (moderate radioactivity) grading upward into supratidal dolomite/anhydrite.

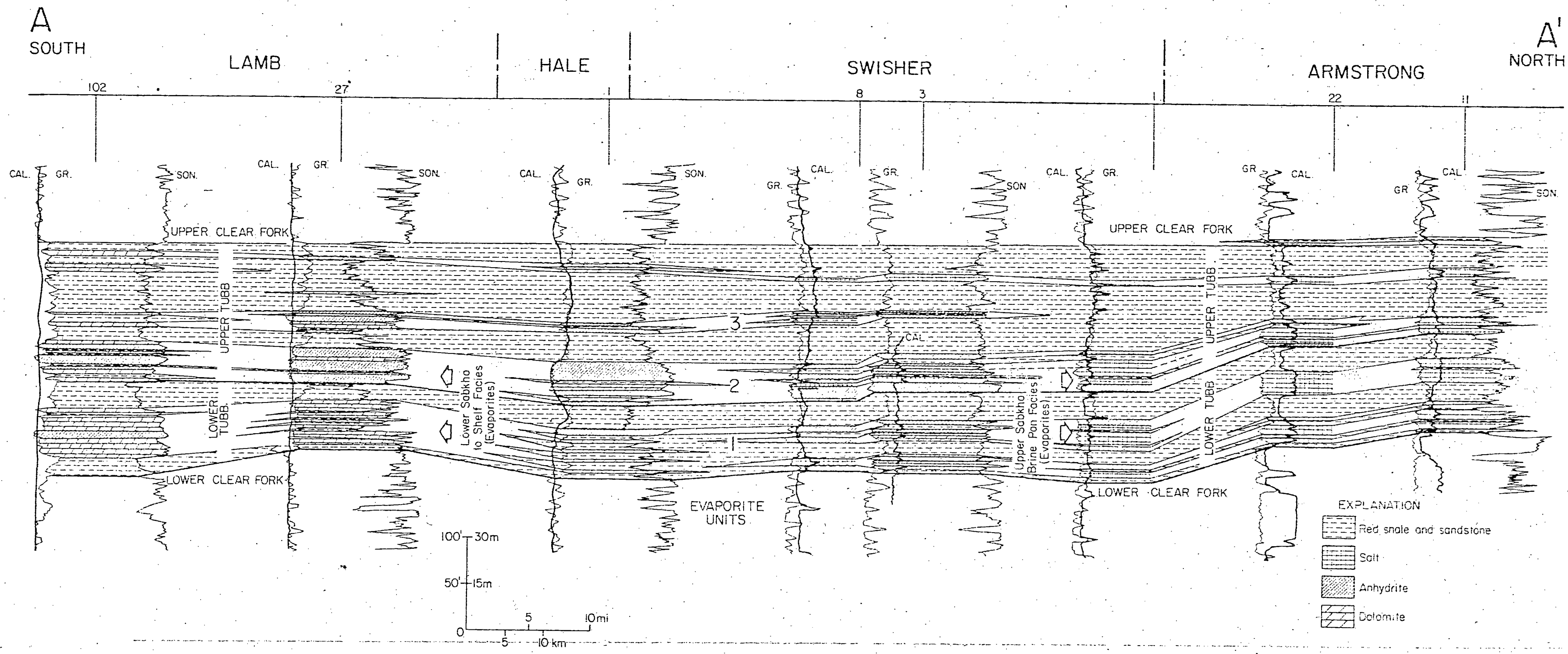


Figure 29. North-south cross-section, Tubb Formation, Palo Duro Basin. Evaporite units intertongue with clastics and exhibit basinward (southerly) lithofacies changes from upper sabkha salt to lower sabkha/shelf dolomite/anhydrite. Clastic tongues thin southeastward, perpendicular to line of section.

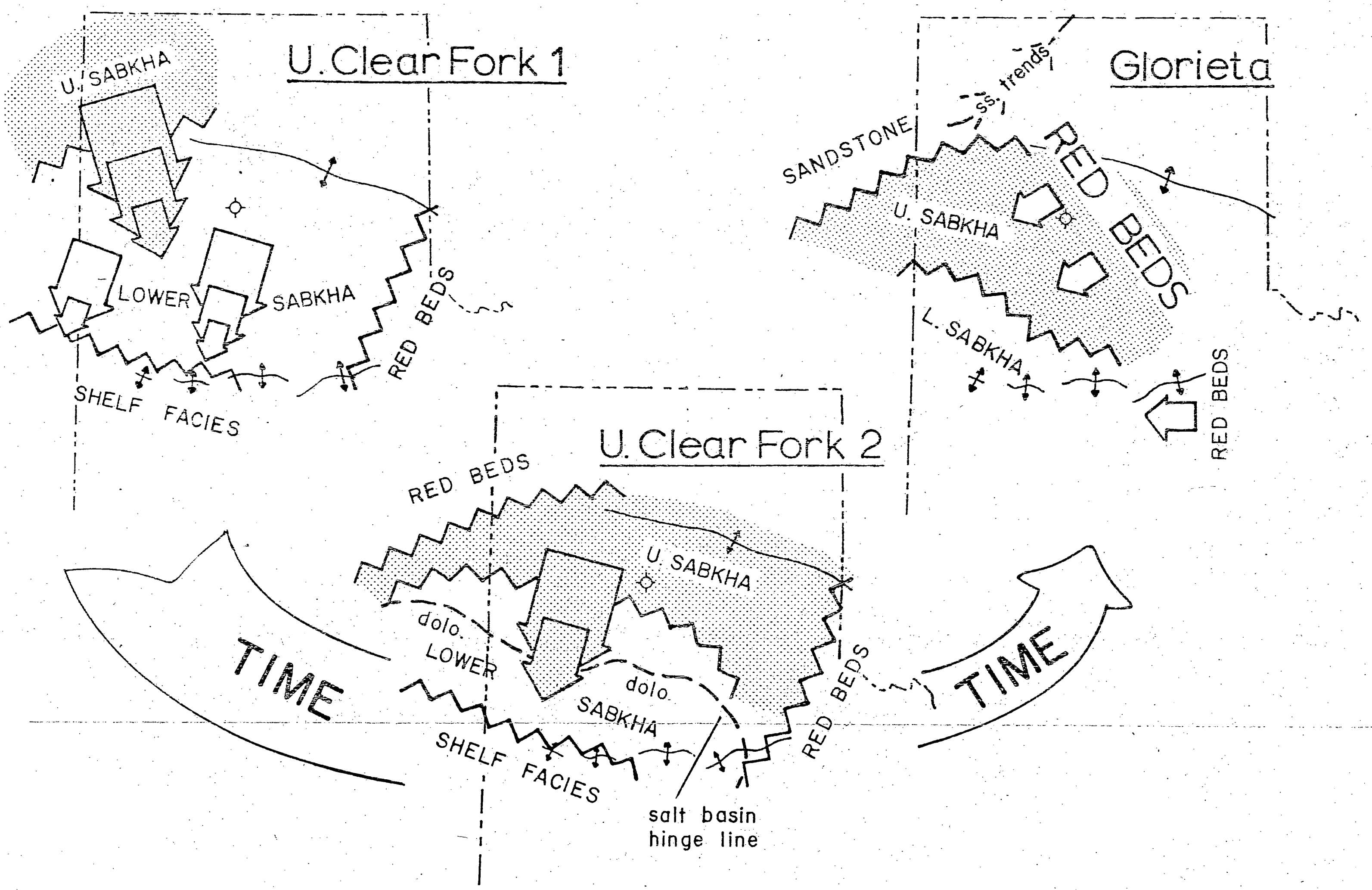


Figure 30. Paleogeography of upper Clear Fork/Glorieta genetic unit.

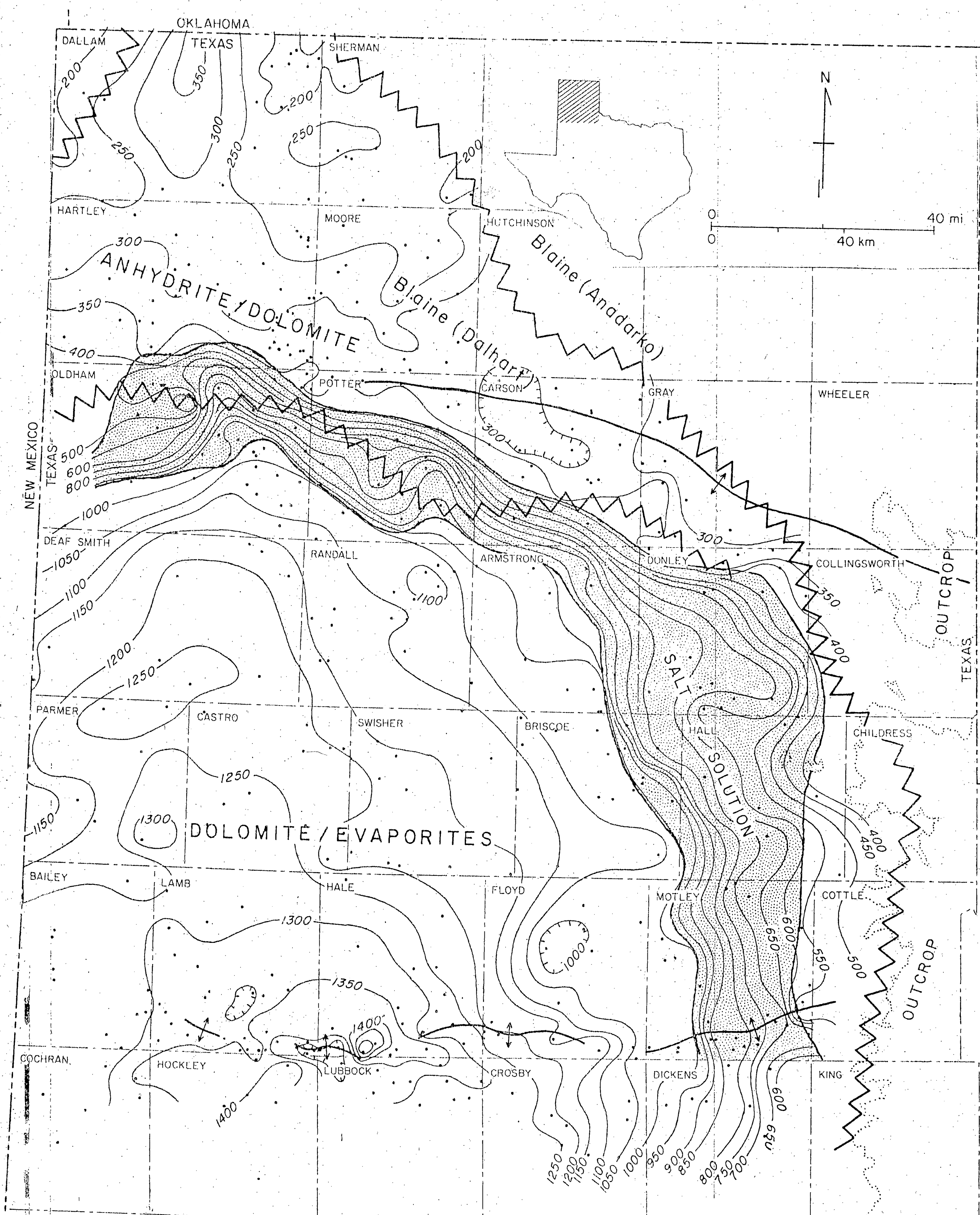


Figure 31. Isopach map, San Andres/Blaine Formations. Area of active salt solution is indicated. Boundaries between San Andres (Palo Duro), and Blaine (Dalhart and Anadarko) are marked by updip (northerly) change in basal beds from evaporites/dolomite to clastics.

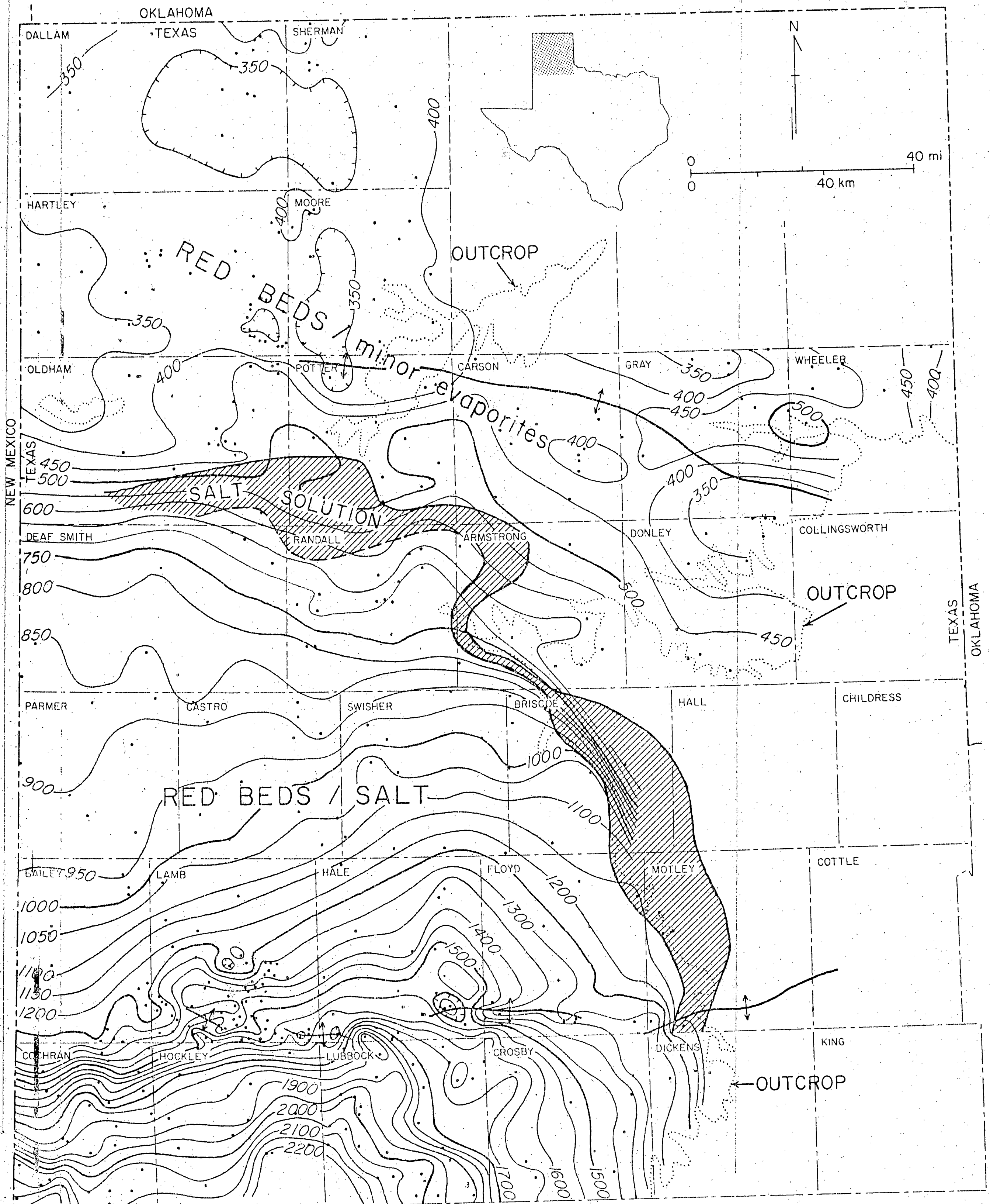


Figure 32. Isopach map, post-San Andres genetic unit. Area of active salt solution indicated.

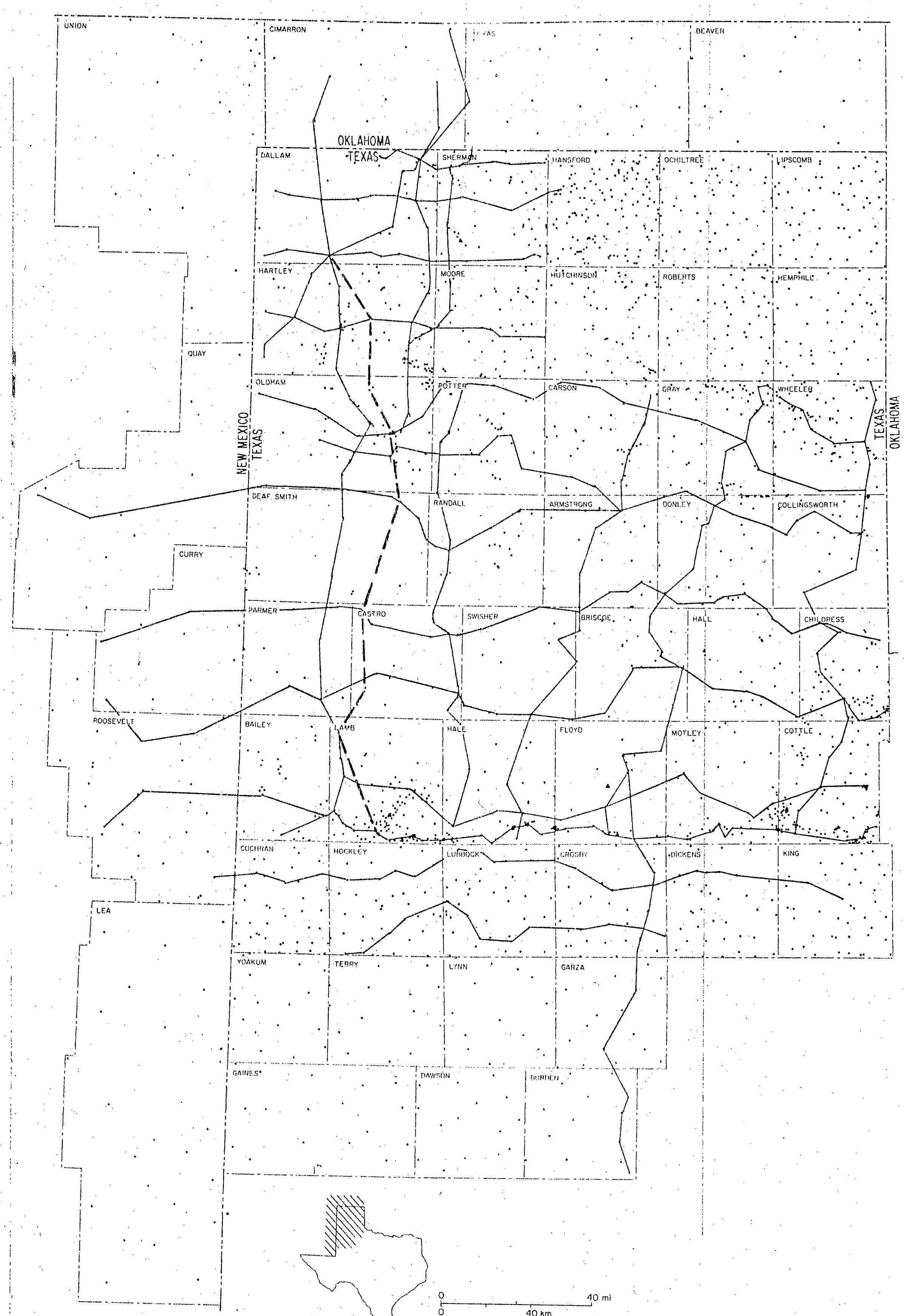


Figure 33. Lines of cross-sections with correlations of the upper Permian salt-bearing sequence constructed during investigation. Dashed line is cross-section shown in figure 34. Sections showing lithology interpretations of each major genetic unit were also prepared.

SALT DEPOSITS

Seven salt-bearing units are of interest as potential hosts for nuclear waste isolation in the Palo Duro and Dalhart Basins. Salt in each unit was deposited in upper sabkha (subaerial) environments. Salt lithofacies interfinger basinward with lower sabkha and shelf lithofacies and towards the margins of the basin with red beds.

Correlations of salt-bearing strata in the Palo Duro and Dalhart Basins are shown in figure 34. Most salt occurs in the Palo Duro area. Generalized data on each of seven salt-bearing units of interest are listed in table 1.

Lower Clear Fork salt--Two major salt depo-centers occur in the Anadarko Basin and Potter, Carson, and Randall Counties of the Palo Duro Basin, where total salt thickness reaches 300 feet. The lower Clear Fork Formation is composed of two offlapping evaporite cycles that record deposition in an upper sabkha salt pan flanked on the northwest and southeast by distal alluvial fan plain facies.

Upper Clear Fork salt (fig. 35)--Maximum salt development for: (1) lower salt units is in the Dalhart Basin, and (2) for upper salt units is in the northern Palo Duro Basin. In general, upper sabkha deposition shifted to the south through time. Salt units interfinger with red beds to the north and lower sabkha dolomite/anhydrite in the southern part of the Palo Duro Basin.

Glorieta salt--Salt with intertonguing massive red beds is present in the Palo Duro Basin. Evaporite tongues thin or pinch out to the northeast, reflecting control by the inferred paleoslope (downdip to the southwest). The position where individual tongues then shifted to the southwest through time. Evaporite facies were controlled by brine input from the open basin to the south; northern upper sabkha salt interfingers with lower sabkha dolomite/anhydrite at the southern margin of the Palo Duro Basin.

Lower San Andres (Flowerpot) salt--Salt is present in both the Palo Duro and Dalhart Basins (fig. 36). Lower San Andres shelf/sabkha cyclic units are capped by massive salt beds. Upper sabkha deposition was centered in the northern portion of the Palo Duro Basin at the close of each cycle. Lower San Andres (Blaine) shaly salt beds occur in the northwestern corner of the Dalhart Basin.

Upper San Andres (Yelton) salt--Salt is present in the Palo Duro Basin. These rocks exhibit cyclicity of anhydrite and salt but lack the massive dolomite lithofacies characteristic of the lower San Andres. Individual salt units are laterally persistent and coalesce near the northern and eastern limits of the basin where upper sabkha deposition was dominant.

Seven Rivers salt--Salt is present in the Palo Duro Basin (fig. 37). The lower portion of the unit contains intertonguing salt and red shale, with salt tongues thinning and pinching out to the northeast; the upper portion of the unit is massive salt. Upper sabkha deposition was dominant. The upper boundary of the unit is transitional into the overlying Yates red beds.

Salado/Tansill salt--Salt is present in the south-central Palo Duro Basin, where the unit composes a single massive salt sequence with intercalated shale. Upper sabkha deposition was dominant, and the upper boundary is transitional into red beds.

Table 1. Character and position of salt-bearing units, Palo Duro and Dalhart Basins.

Salt-bearing unit *(youngest to oldest)*	Thickness and extent of salt beds	Character of interbeds	Adjacent strata U - *underlying* O - *overlying*	Salt solution
1. Salado/ Tansill	Unit with continuous salt section, south-central Palo Duro; net salt <340 ft: a. basal massive salt, 70-80 ft b. overlying salt/shale, 80 ft c. upper massive salt, 200 ft	Discontinuous shale breaks	U - massive Yates red beds O - red beds capped by Alibates	Active solution at position of Caprock Escarpment
2. Seven Rivers	Lower portion of formation—9-12 beds in south-central Palo Duro, average 10 ft, pinching out to north Upper portion—massive salt, <300 ft to south, 100 ft to north	Discontinuous shale breaks	U - red beds, with sandstone, inter-tonguing with lower salt beds O - massive Yates red beds	At position of Caprock Escarpment and south of Amarillo Uplift
3. Upper San Andres (Yelton)	South Palo Duro—6-10 salt units, average 25-30 ft North Palo Duro—4-5 salt units, range 10-130 ft	Salt units intertongue with anhydrite	U - massive bedded anhydrite (middle San Andres) O - red beds with sandstone	South of Amarillo Uplift, east of Caprock Escarpment
4. Lower San Andres (Flower-pot)	Salt beds capping 5 cycles: *Cycle 1*—minor salt *Cycle 2 and 3*—salt units averaging 45-50 ft, pinching out to south in central Palo Duro *Cycle 4*—salt unit 200 ft to north, pinching out upsection to Palo Duro *Cycle 5*—to north beds range 10-70 ft, with net salt 100-170 ft; to south, beds average 10 ft Northwest Dalhart—<150 ft salt-bearing strata	Salt in cycles inter-tonguing with anhydrite/dolomite; dolomite with some porosity	U - Glorieta red beds/evaporite O - massive bedded anhydrite Updip (in Dalhart)—Glorieta sandstone	South of Amarillo Uplift, east of Caprock Escarpment
5. Glorieta	3 salt units intertonguing with red beds: a. lower unit—average 20-25 ft in Donley County (northeast Palo Duro), 50-55 ft in Bailey County (southwest Palo Duro) b. middle unit—average 90 ft in Donley County, 150 ft in Bailey County c. upper unit—pinching out to northeast, average 45-50 ft in Bailey County Beds within units range 10-75 ft	Shale interbeds common; anhydrite with shale to south	U - Upper Clear Fork evaporite/shale O - Lower San Andres cyclic units Updip (in Dalhart)—Glorieta sandstone	In central Potter and Carson Counties; possible to east on south margin Amarillo Uplift and east margin Palo Duro
6. Upper Clear Fork	Dalhart—in basal portion beds up to 80 ft in section with net salt <125 ft Palo Duro—beds average 15 ft in section with net salt <280 ft Amarillo Uplift—beds <10 ft in section with net salt <200 ft	Shale interbeds, increase to north; anhydrite increase to south	U - Tubb red beds O - Glorieta red beds/ evaporite Updip (in Dalhart)—Clear Fork/Glorieta red beds with sandstone	Possible on eastern margin, Palo Duro
7. Lower Clear Fork	2 salt units intertonguing with red beds (northwest and southeast); beds up to 40 ft thick: a. lower cycle—150-200 ft net salt in Anadarko Basin; 0-150 ft in Palo Duro Basin b. upper cycle—150 ft net salt in Anadarko Basin; 0-150 ft in Palo Duro Basin	Shale interbeds increase to northwest and southeast; anhydrite-dolomite increases to south	U - Red Cave red beds O - Tubb red beds Updip—red beds Downdip—anhydrite-dolomite	No salt solution

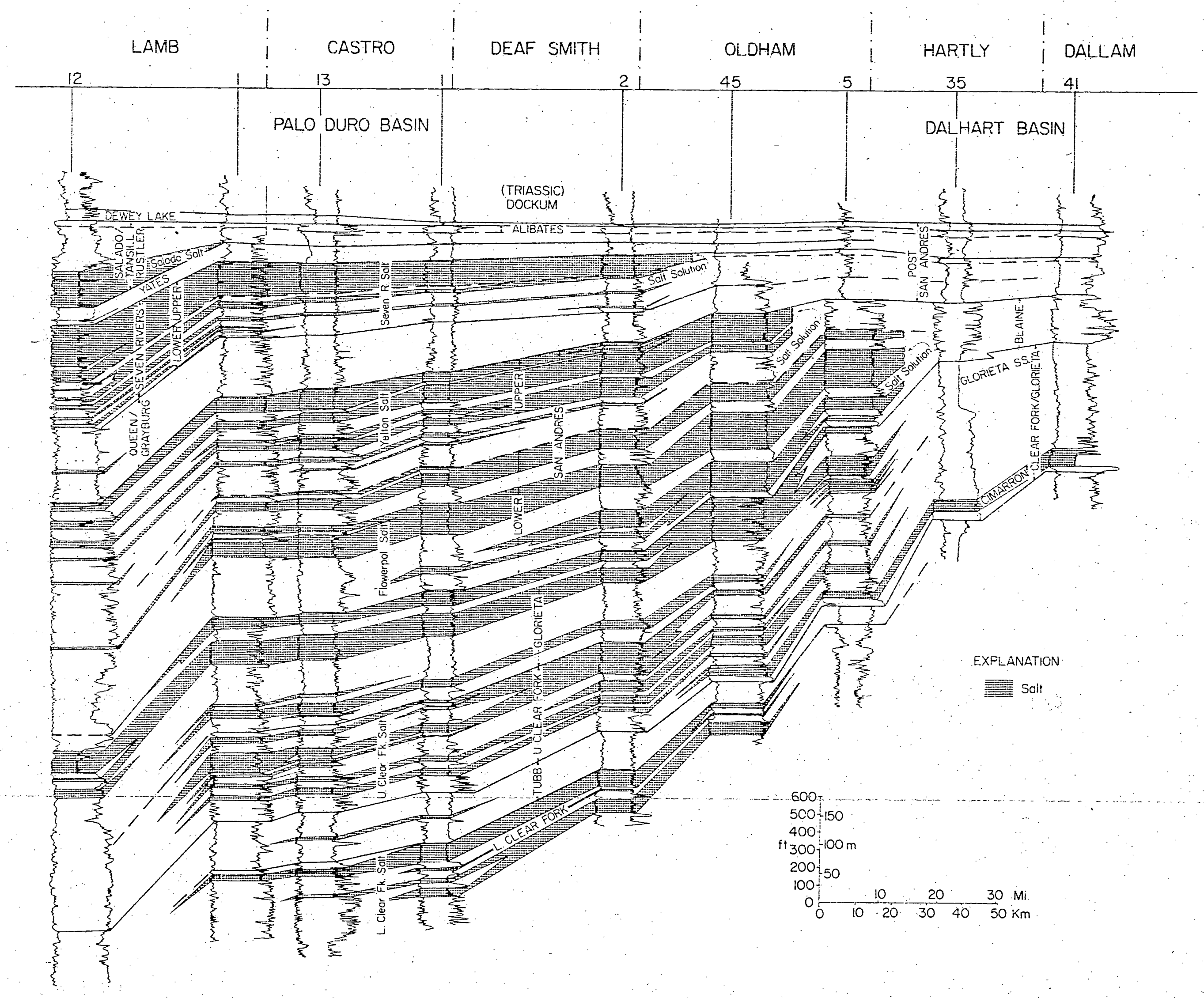


Figure 34. North-south cross-section, Upper Permian salt-bearing strata, Palo Duro and Dalhart Basins. Generalized salt units are correlated.

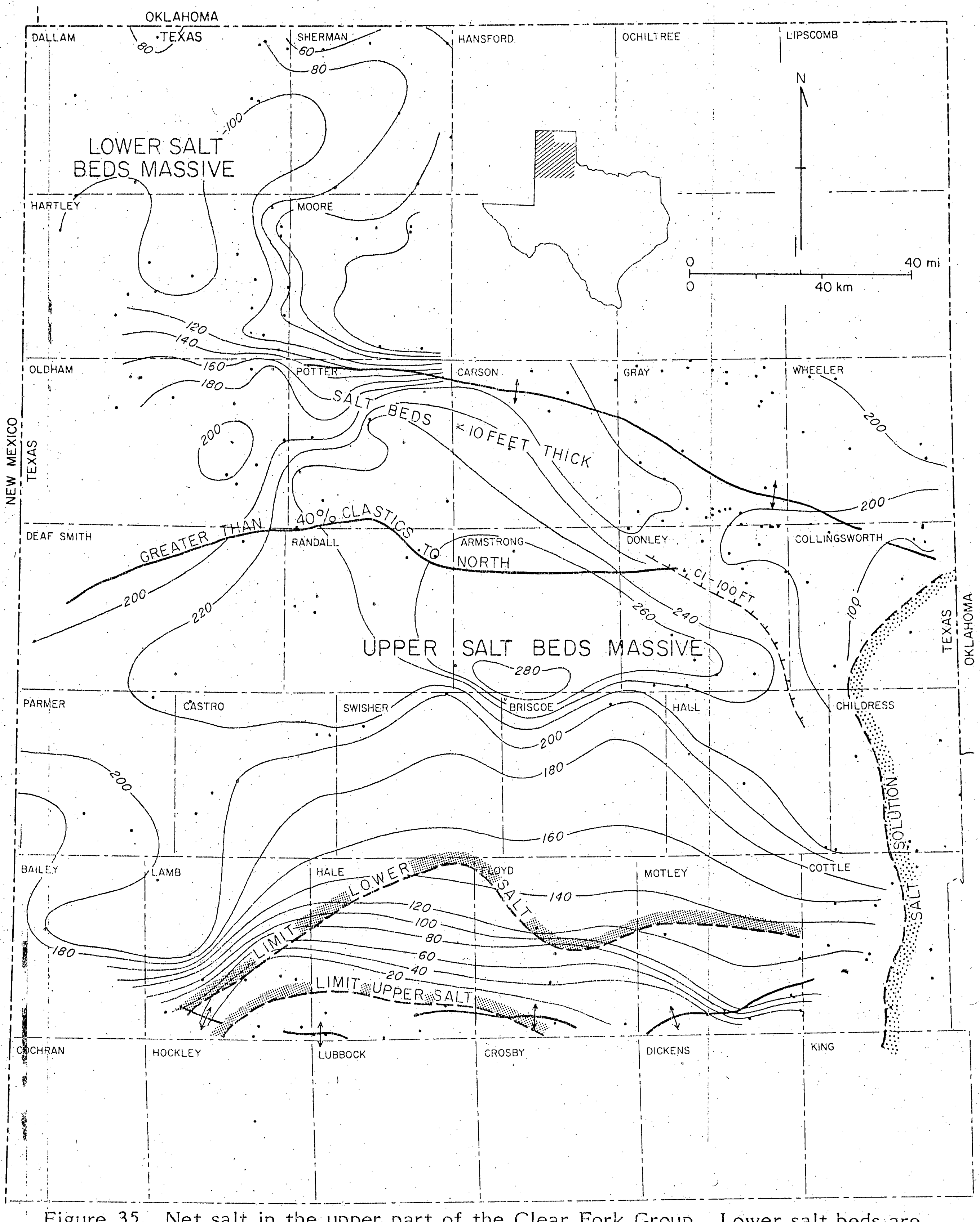


Figure 35. Net salt in the upper part of the Clear Fork Group. Lower salt beds are within the basal 100-200 feet of the units; upper salt beds are within the upper 300-400 feet of the unit.

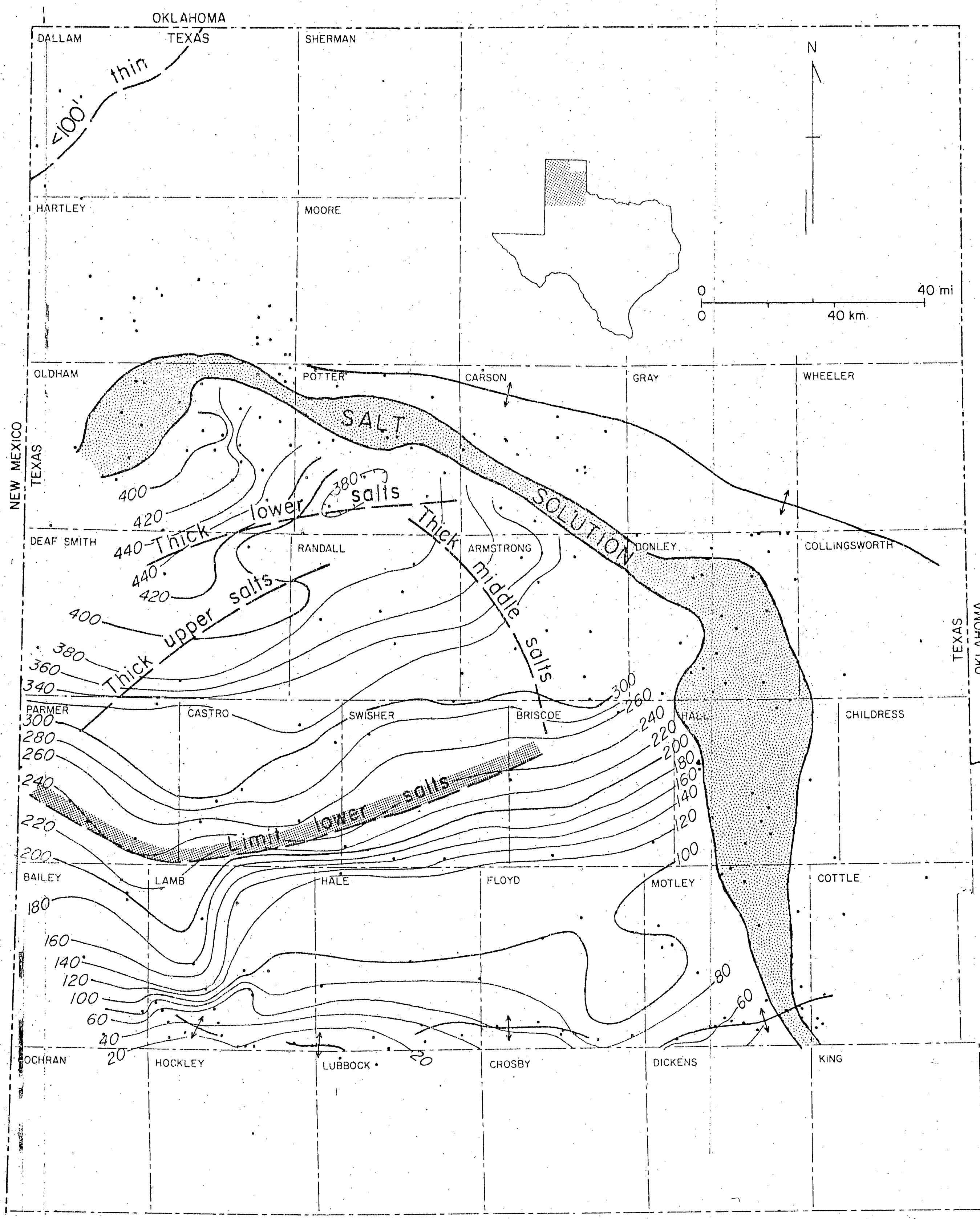


Figure 36. Net salt in the lower part of the San Andres Formation. Lower salt units cap cycles 1, 2, and 3 (fig. 26); middle salt is in cycle 4; the upper salt in cycle 5.

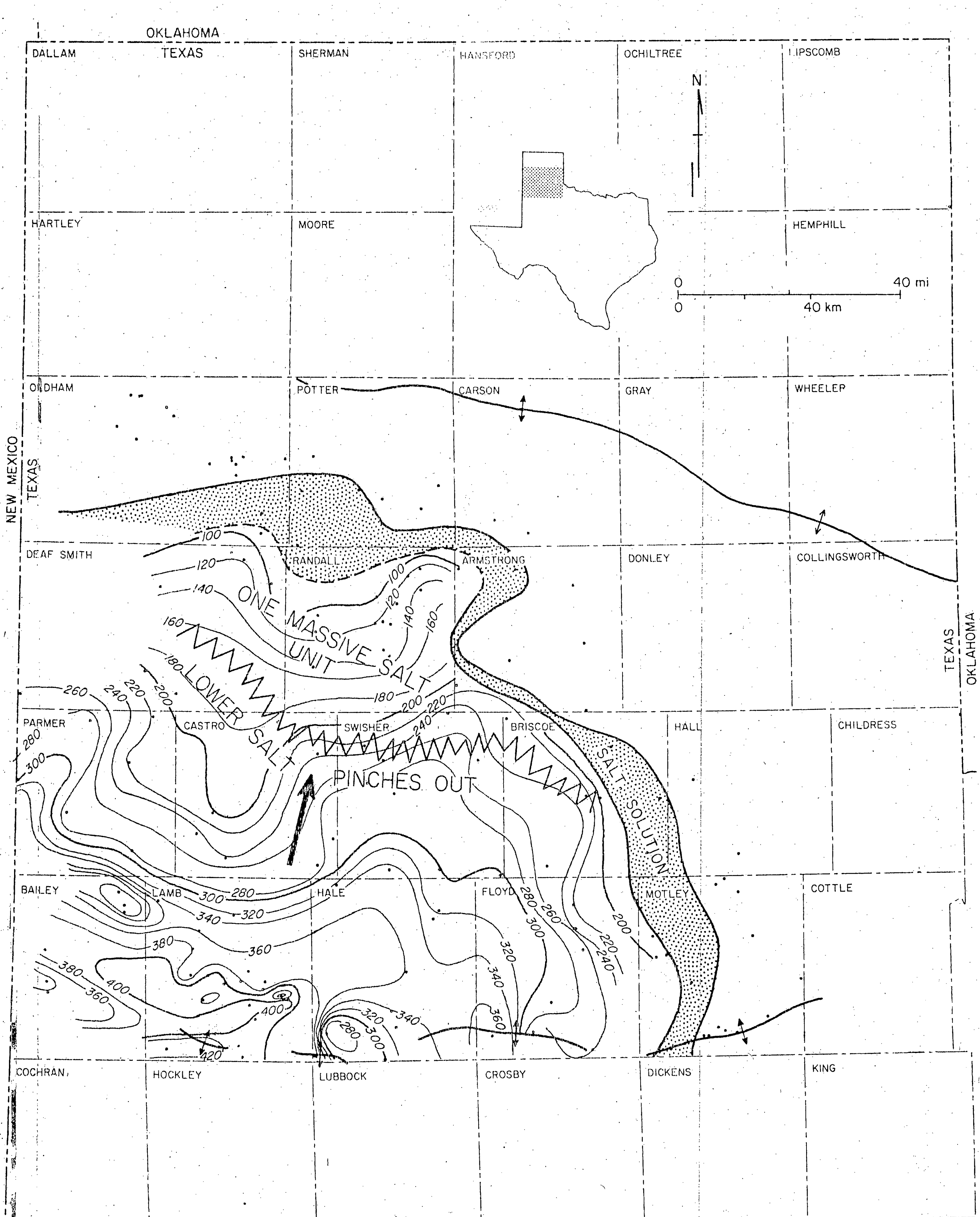


Figure 37. Net salt in Seven Rivers Formations. Lower salt intertongues with red beds to the north.

CORE HANDLING AND EVALUATION

A deep core hole (4000 feet), utilizing modern and innovative drilling methods, provides sample rock material for analytical studies. Additional core holes are underway or planned for the Palo Duro Basin.

Special core recovery and core handling techniques have been developed for the first 4000-foot stratigraphic test (DOE/Gruy Federal, Inc., Rex White, Jr., no. 1) drilled during August and September, 1978 in northeastern Randall County. During coring, the rock cores are enveloped by PVC pipe within 60-foot core barrels. Purpose of the PVC pipe is to prevent jamming of the core within the barrel and to firmly hold the core in place, thereby reducing movement and breakage. The pipe and core are removed together from the core barrel, marked and sliced into 6-foot segments while coring continues. Where possible, the core is extruded from the pipe briefly for on-site description, primarily to identify missing intervals. The core is replaced inside the PVC pipe which is then sealed at both ends, loaded onto a foam cushioned truck bed, and transported to The University of Texas Balcones Research Center, Austin, Texas for storage and analyses. At the research center the PVC pipe is split by a radial saw, and the core is removed for proper marking to record orientation. Three-foot segments per 50 feet of salt are sealed and set aside for rock mechanics, thermal, chemical and waste interaction studies. The remainder of the core is slabbed unequally, with the larger slab set aside for sampling, and the smaller slab is preserved as a permanent library sample. All of the core is being logged and photographed to obtain a complete lithologic description and visual record. Afterwards the salt cores are sealed in plastic bags to insure preservation and minimize dissolution and efflorescence. Numerous analyses and studies are planned for the core; they are outlined in table 2. Analyses will provide important data regarding lithology (especially character of the salt), hydrology and potential resources of the salt-bearing Permian section.

Table 2. Core tests, analyses and studies.

Depth	Randall County Well Site Stratigraphy	Fluid Tests	Porosity and Permeability	Evaporite Residue	Fluid Inclusions	Hydrocarbons	Petrography	Uranium and Molybdenum	Copper	Multielement Analysis
	Ogallala		Representative Non-Evaporitic Lithologies				Selected Intervals	X		Representative Lithologies
	Dockum	X						X		
	Dewey Lake							X	X	
	Alibates							X	X	
	Salado							X	X	
	Yates							X	X	
	Seven Rivers			X	X					
1000'	Queen/Grayburg	X						X	X	
	U. San Andres	X		X	X					
2000'	L. San Andres	X		X	X	X				
	Glorieta	X						X	X	
3000'	U. Clear Fork									
	Tubb	X						X		
	L. Clear Fork			X	X					
4000'	Red Cave							X	X	

RESOURCES

No economically recoverable deposits of petroleum, copper, uranium, or potash salts have been discovered in the Palo Duro Basin despite the fact that there are numerous favorable host and reservoir rocks throughout the basin.

Oil and gas--In decreasing order of importance, potentially suitable reservoirs may occur in the following depositional facies: (1) dolomitized shelf margins, (2) delta front sandstone, (3) evaporite cycle subtidal dolomites, (4) fan delta sandstones, and (5) sandy alluvial fan plain red beds. Porous dolomite trends (15 percent porosity) closely follow Pennsylvanian and Permian shelf margins (fig. 38), thus delineating narrow fairways for hydrocarbon exploration. Potential reservoirs may be sealed by contiguous and superjacent slope-basinal shale and impermeable shelf carbonates.

Numerous deltaic sandstones occur in the southeastern part of the basin and constitute potential reservoirs. Sandstone units range up to 200 feet thick and are surrounded by prodelta clays. Fan delta sandstones, commonly feldspathic, occur along tectonic uplifts and are characterized by high (15 percent) porosities. Abutment of these sandstones against basement rocks may form an updip seal to hydrocarbon migration.

In the Midland Basin and Central Basin Platform the San Andres Formation has produced millions of barrels of oil. These same carbonate strata occur in the Palo Duro Basin, but they are nonproductive at this time. Porous dolomitic strata near the base of several San Andres evaporite cycles constitute potential stratigraphic traps. Beds are sealed above by bedded salt and anhydrite.

Red beds normally are not regarded as favorable oil and gas exploration targets. However, alluvial fan plain red beds belonging to the Red Cave Formation have produced gas from the Panhandle Field and oil from the Anadarko Basin in Moore County. Production occurs from fine-grained sandstones and siltstones within the upper 100 feet of the formation.

Uranium and copper--Base metal mineralization occurs in outcrops of middle to upper Permian strata in Oklahoma and north Texas, but none have been discovered in the Palo Duro Basin. Absence in the Palo Duro Basin may be equally due to subsurface burial, lack of outcrops, and insufficient mineral exploration, as well as to actual absence of mineralization.

Chalcocite, malachite, carnotite, and uraninite are concentrated in channel sandstones (fluvial and tidal), and tidal mud flat deposits of Permian age in Oklahoma and north Texas (Al-Shaieb, 1978; Smith, 1974). Mineralization is thought to have occurred as a result of diagenesis accompanying ground-water movement through channel sandstones and evaporative discharge on sabkha surfaces.

In addition to the possibility of uranium and copper deposits in middle and upper Permian strata, fluvial-deltaic facies of the Triassic Dockum Group and fan delta granite wash (arkosic sandstones) deposits of Pennsylvanian and Early Permian age may be potential host units for uranium minerals. Presently, the National Uranium Resource Assessment, Department of Energy, is evaluating uranium resources in surface and shallow subsurface deposits in the Panhandle region of Texas.

Potash salts--Detailed subsurface correlation and mapping of Permian evaporite units have not revealed any proven occurrences of potash deposits, although potash has been reported from wells drilled in Potter, Randall, and Oldham Counties (Cunningham, 1934).

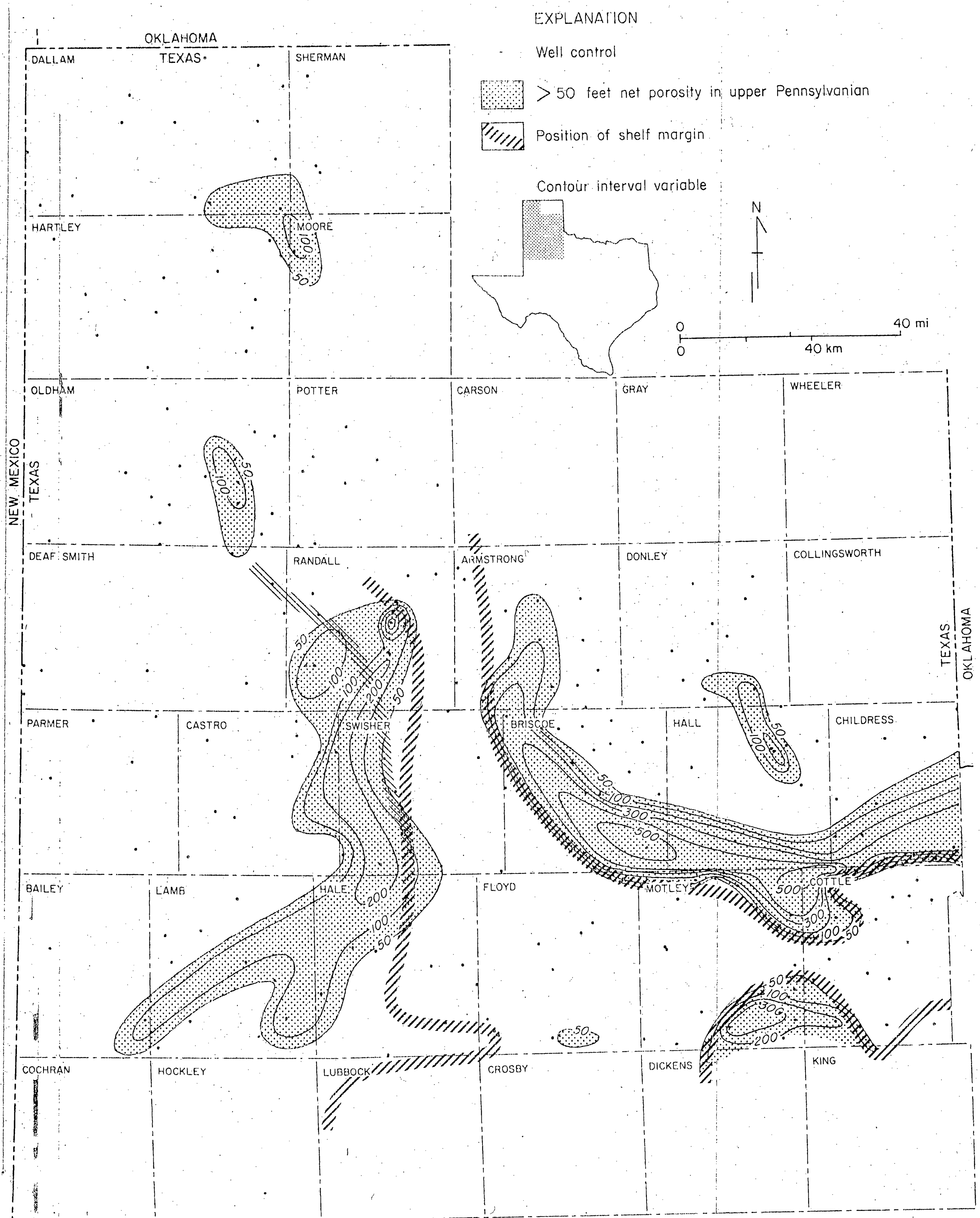


Figure 38 (a). Porosity map of Pennsylvanian carbonates. Data was obtained from sample log descriptions.

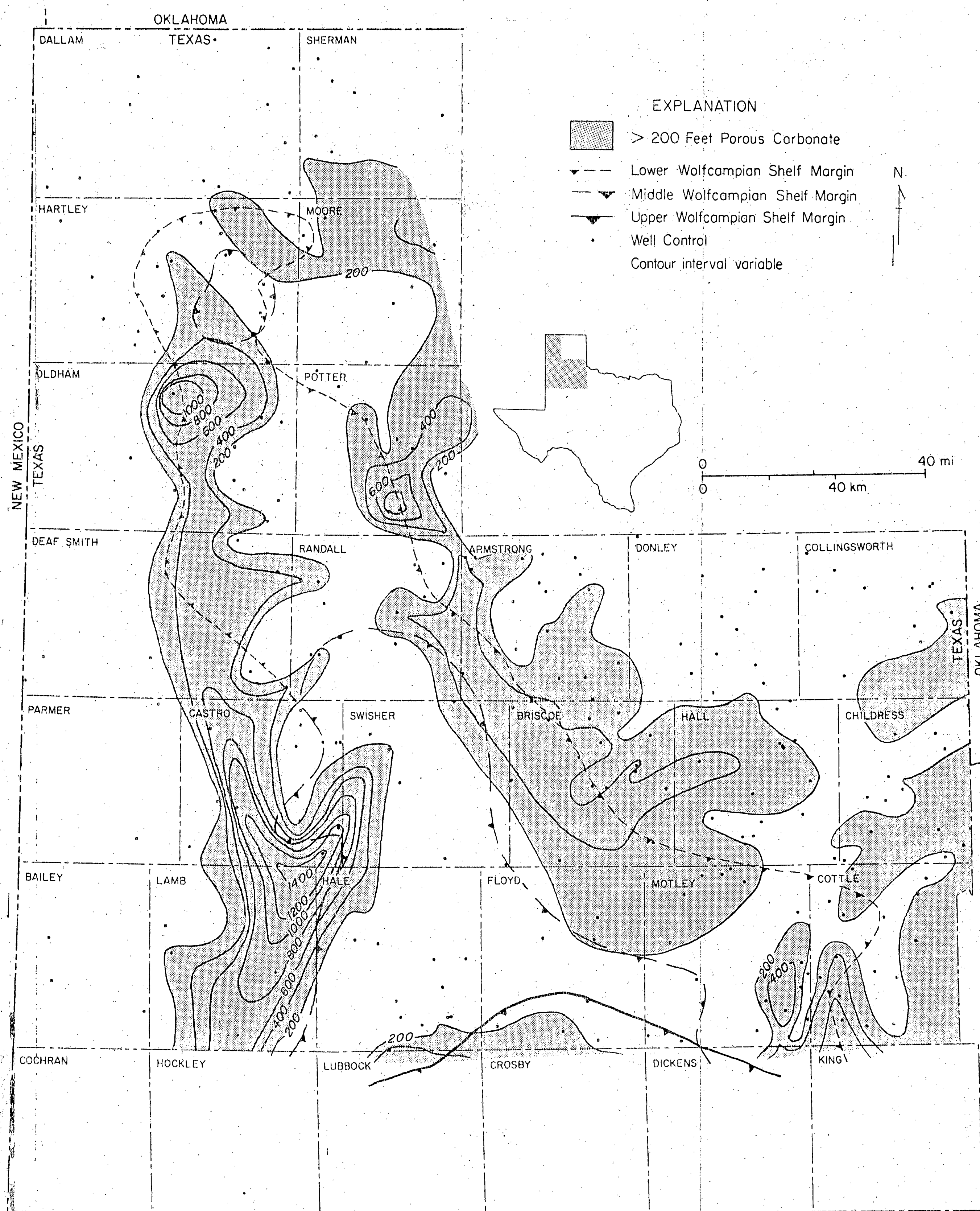


Figure 38 (b). Porosity map of Lower Permian carbonates. Data was obtained from sample log descriptions.

BASIC OBJECTIVE OF GEOMORPHIC STUDIES--TO INSURE THAT THE INTEGRITY OF A POTENTIAL NUCLEAR WASTE MANAGEMENT SITE IS SECURE FROM EROSION, STREAM INCISION, AND SALT DISSOLUTION

A methodology was developed to provide an integrated program of geomorphic and shallow stratigraphic studies to determine rates of surface erosion, stream incision and development, rates and direction of movement of salt dissolution fronts, fracture analysis, land resources and paleoclimatology.

To insure the integrity of a potential nuclear waste management site from erosion, stream incision and salt dissolution requires an understanding of processes and rates of sediment removal, stream propagation, slope retreat and salt dissolution. The following discussions of geomorphic mapping, linear element analysis, climate and erosion monitoring, salt dissolution and a major flood event on the Llano Estacado are the initial results of studies designed to understand these processes (fig. 39).

A preliminary discussion of the geomorphic methods used to evaluate the Llano Estacado area for suitable waste isolation sites has been presented earlier by Gustavson and others (1978b).

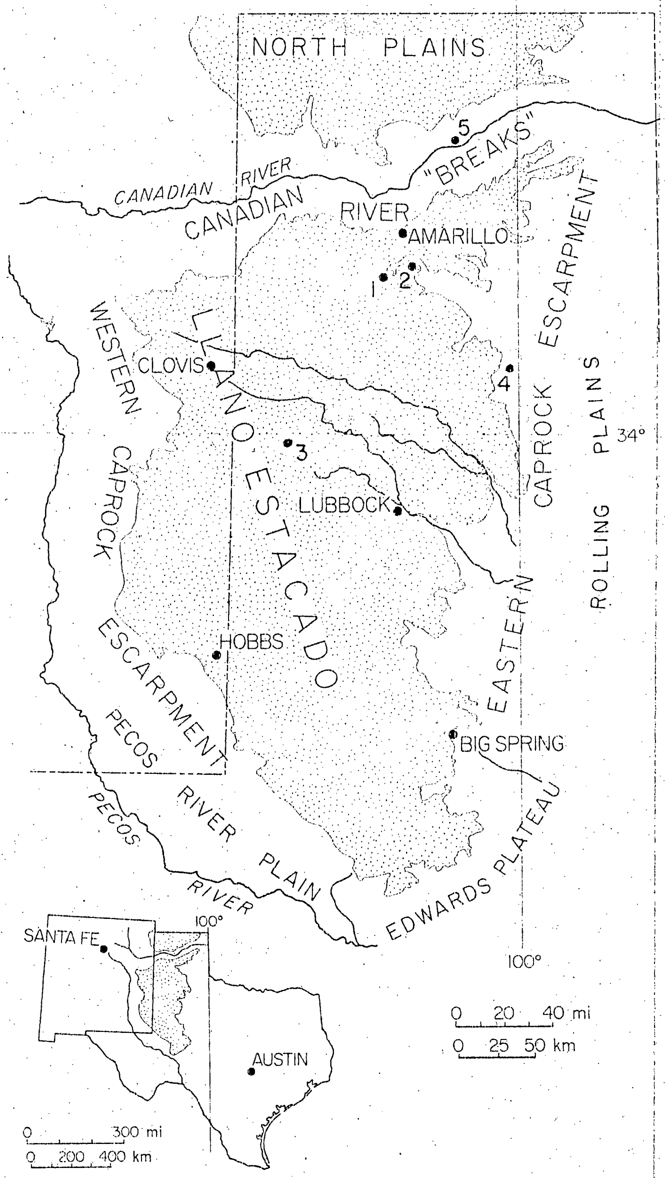


Figure 39. Physiographic units in the Texas Panhandle and adjacent areas. Numbers 1-5 indicate climate monitoring stations: (1) Buffalo Lake National Wildlife Refuge, (2) Palo Duro Canyon State Park, (3) Muleshoe National Wildlife Refuge, (4) Caprock Canyon State Park, and (5) Lake Meredith National Recreation Area.

CLIMATIC CHARACTERISTICS OF THE TEXAS PANHANDLE

Precipitation in the Southern High Plains is primarily from thunderstorms, resulting in brief, localized, and intense rainfall events which produce runoff within restricted areas and result in effective erosional processes.

In the Texas Panhandle 43 percent of the average annual precipitation falls during May through July, primarily from thunderstorms, while 72 percent falls during April through September (Haragan, 1976). Extreme rainfall events are of great significance. Within the past 33 years at Amarillo the months of May through August have seen maximum 24-hour rainfalls in excess of 17.1 cm (6.75 inches) in May, 1951; 15.6 cm (6.15 inches) in June, 1960; 10.4 cm (4.09 inches) in July, 1943; and 10.8 cm (4.26 inches) in August, 1945. These events are closely related to the frequency of thunderstorm events. In the Southern High Plains (fig. 40) data from 3 locations show that the percentage frequency of thunderstorms at Amarillo, Texas, is greatest in May through August and on an annual basis is slightly greater than either Lubbock, Texas or Clovis, New Mexico. The month of July usually includes 11 thunderstorm days (fig. 41), although Orton (1964) notes that on the average May brings the most frequent and violent thunderstorms over northwest Texas.

Intense rainfall events are important because they result in significant surface runoff which dominates the overall erosion process. A single thunderstorm with total rainfall on the order of 3 cm (1.2 inches) has resulted in observed surface denudation of 1 to 2 mm at the Palo Duro Canyon field study location. While these values are at the limit of reliable detection using erosion pins, they demonstrate the potential cumulative importance of frequent and intense, but not catastrophic, rainfall events.

Rainfall records within a 22-county area of the Texas Panhandle overlying the Palo Duro Basin show significant concentrations of rainfall within limited areas and locally high precipitation gradients. Figure 42 typifies this pattern with a gradient from 12.9 cm (5.08 inches) of rainfall at Turkey, Hall County, Texas, to zero rainfall at Quitaque, Briscoe County, Texas, over a distance of only 16 km (10 miles). Kinetic energy of a rainfall event is related to the sum of successive increments of rainfall intensity during the total period of rainfall. This factor, multiplied by maximum 30-minute rainfall intensity, has an 0.96 to 0.93 correlation coefficient with individual-storm soil loss over a ten-year period (Wischmeier and Smith, 1958). Locally intense rainfalls such as those that occur in the Texas Panhandle also tends to have larger size raindrops capable of displacing larger grains of surface material as a result of greater fall velocities (Laws and Parsons, 1943). The semiarid climate of the Texas Panhandle hampers the growth of vegetation, hence plant cover does not unduly restrict raindrop impact and surface flow processes. Furthermore, cultivation and grazing further reduce or tend to stress the vegetation cover.

Field evidence suggests that surface sediment is stored within stream channels of higher order as gradients decrease and flow infiltrates the channel bottom. Subsequent rainfall of differing intensity or spatial distribution may then move stored material and, consequently, contribute new sediment for transport by the drainage system. In the absence of resistant lithologies east of the Caprock Escarpment, fluvial processes are sufficiently active to permit streams such as the Little Red River to efficiently export sediment eroded from the Caprock Escarpment area. Efficient transport is indicated by smooth longitudinal stream profiles that lack local base levels which will slow sediment transport.

Langbein and Schumm (1958) suggest that maximum sediment yield from a drainage basin occurs at a value of 25.4 to 35.6 cm/year (10 to 14 inches/year) of effective precipitation. Because mean annual temperatures in the Texas Panhandle range from 59.7°F at Lubbock to 57.4°F at Amarillo (National Oceanic and Atmospheric Administration, 1977a and b), effective precipitation over the Palo Duro Basin would be less than the 40.6 to 50.8 cm (16 to 20 inches) of precipitation received due to evapotranspiration. Rainfall in a grassland environment combined with the intensity typical of thunderstorm precipitation makes the Rolling Plains, the Pecos Plains, and the Caprock Escarpment (fig. 39) climatically favorable for active erosion. A relatively low degree of induration of some rock units and local topographic relief enhance the erodibility of surface soil and sediments along the Caprock Escarpment.

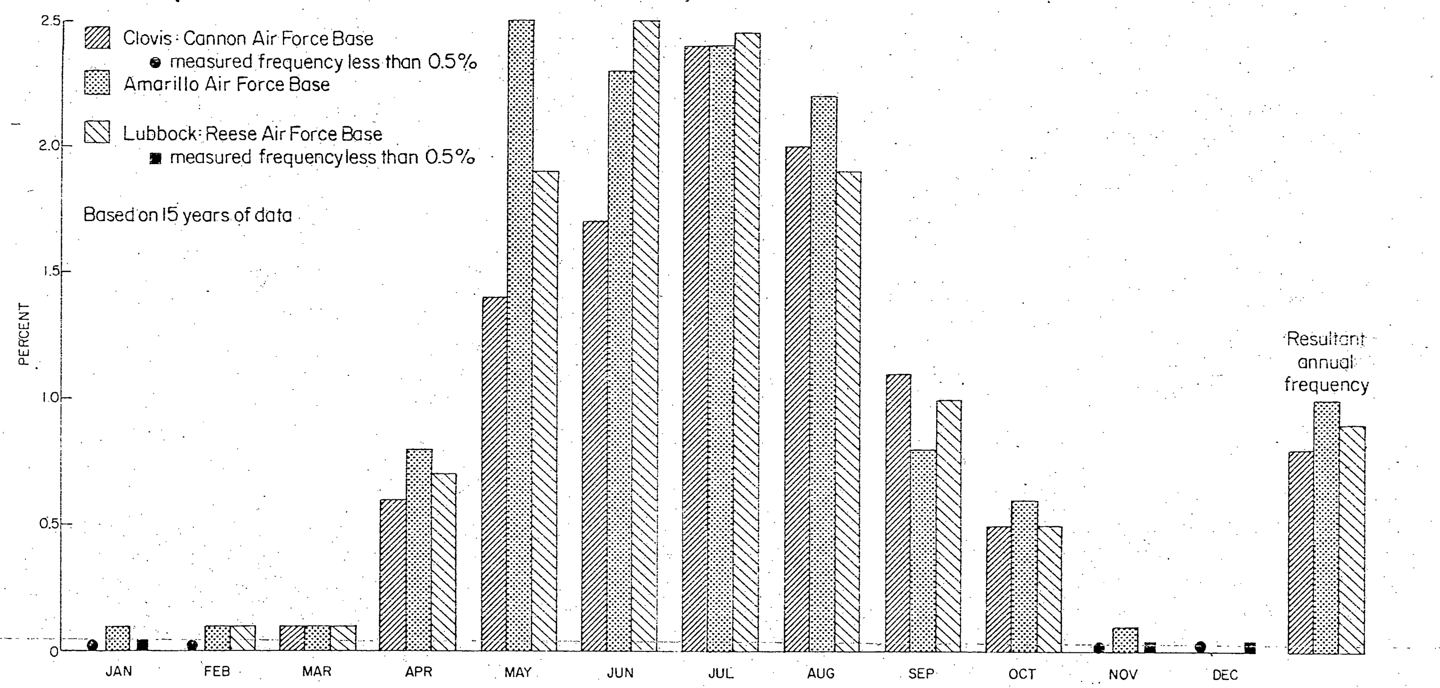


Figure 40. Percentage frequency of thunderstorms in the region of the Palo Duro Basin based on hourly observations (compiled from Orton, 1964).

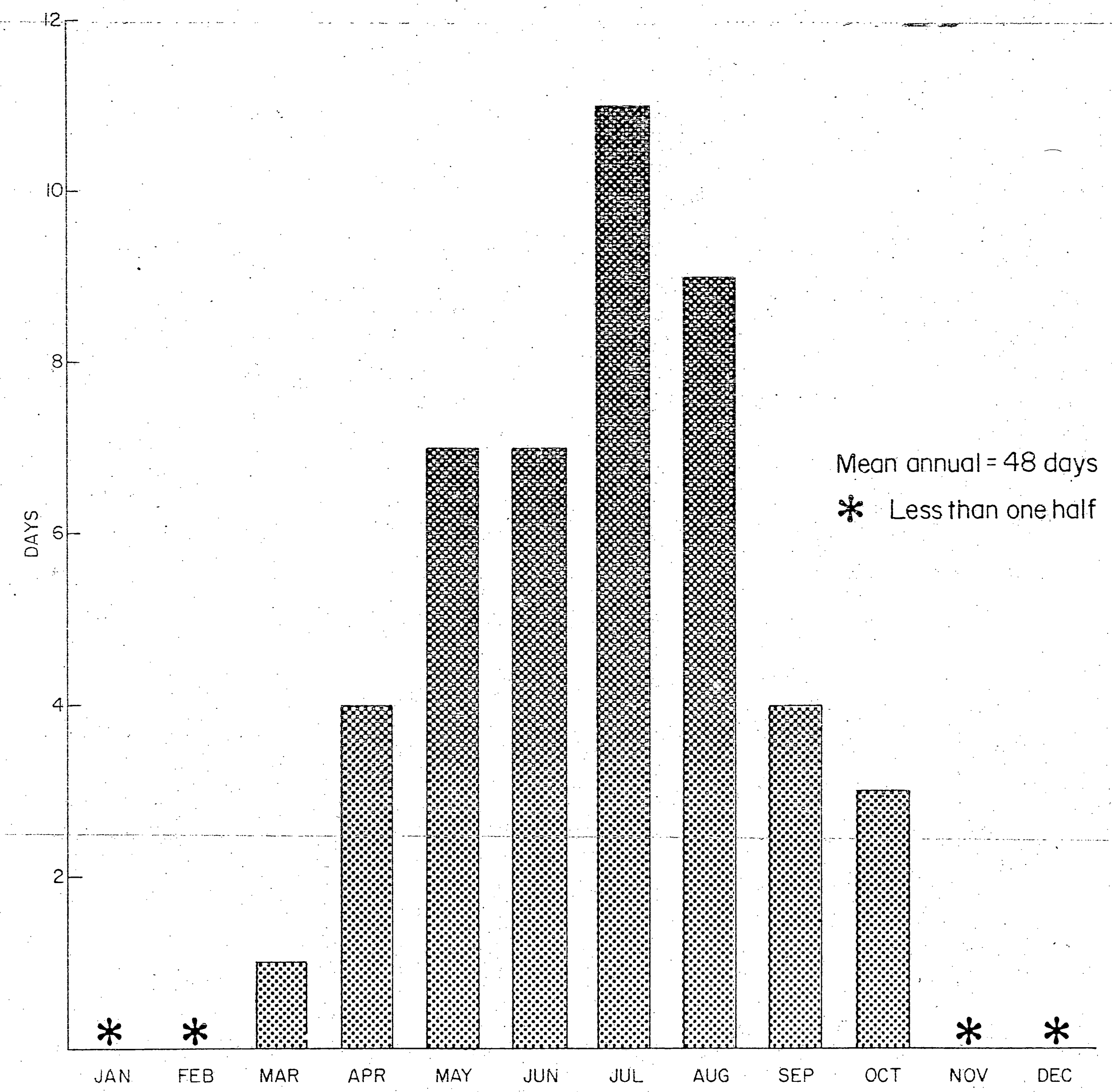


Figure 41. Thunderstorm days per month, Amarillo, Texas (data from Orton, 1964).

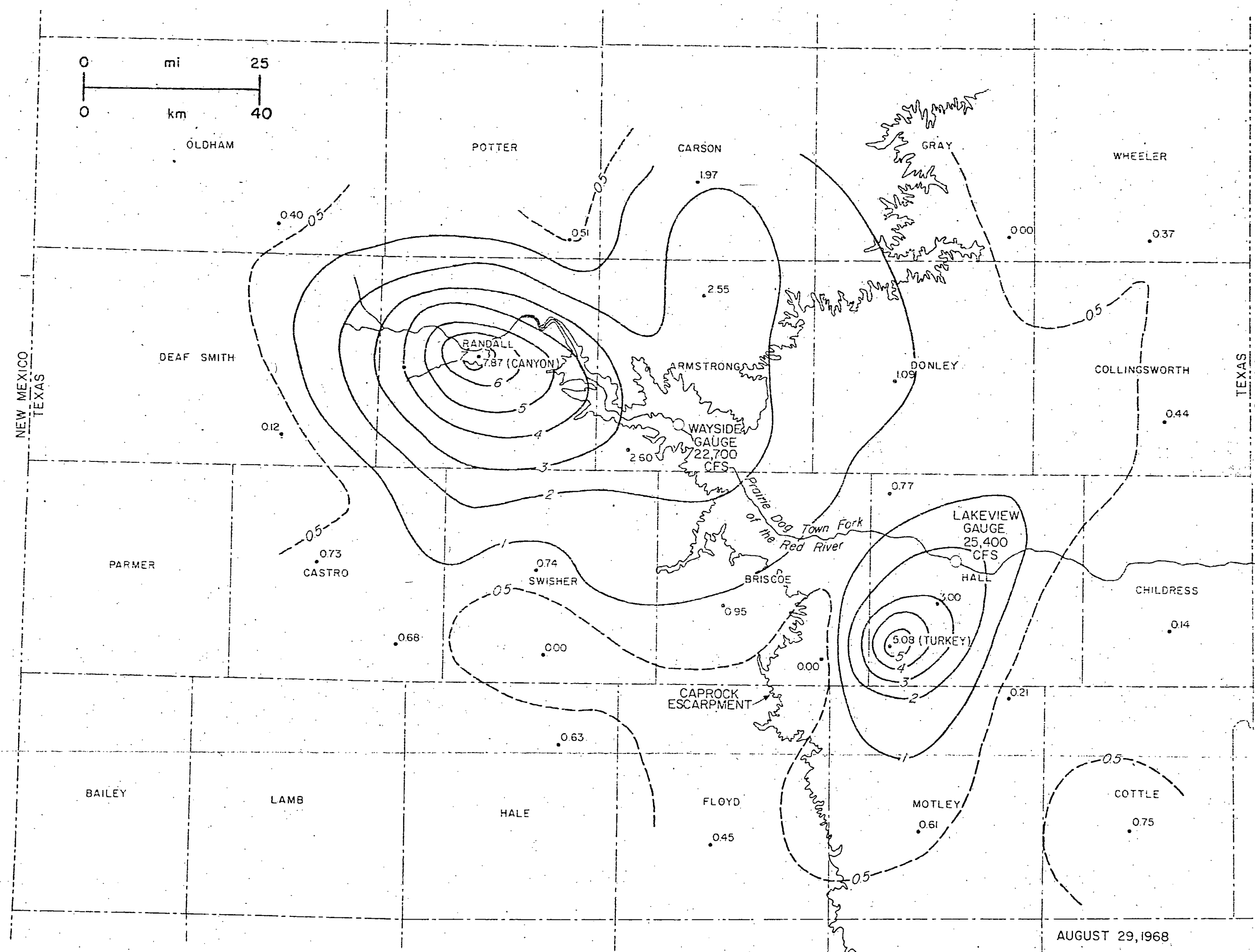


Figure 42. Isohyetal map (contours in inches) based on 24-hour rainfall ending 7 a.m., August 29, 1968. River discharge (ft.^{3}/sec.) is mean daily flow for 24 hours ending midnight, August 29, 1968.

RUNOFF CHARACTERISTICS AND A FLOOD IN THE TEXAS PANHANDLE

Limited discharge records on the Prairie Dog Town Fork of the Red River illustrate exceptional flood return frequency trends and peak discharges, such as occurred during the flood of May 27, 1978.

Return frequencies for floods on the Prairie Dog Town Fork of the Red River have been calculated. A plot of instantaneous discharge for the May 27, 1978 flood (fig. 43) shows the "flashy" intermittent flow characteristic of the Prairie Dog Town Fork. The occurrence of such high peak discharges during a relatively short period of record affects the shape of the flood return frequency plots (figs. 44 and 45) for this stream. High rainfall intensity and differences in the geomorphic configuration of contributing areas may be among the variables which contribute to an upper, steeper segment of flood frequency curves for the Texas Panhandle.

If the May 27, 1978 event is typical of high discharge events in this region, then their occurrence is a significant factor in sediment export from the Southern High Plains region. Under the present climatic regime major erosion, deposition and stream propagation seem to occur in discrete steps related to storm events. Analysis of such events in conjunction with historic records is one phase of geomorphic analysis of the Texas Panhandle region which relates to fluvial terrace deposits and the westward retreat of the Caprock Escarpment.

On May 26, 1978, heavy rains from thunderstorm activity fell in northwest Randall County in the upstream reaches of Palo Duro Creek. Rainfall distribution as a result of this storm (fig. 48) shows a peak at Canyon, Texas of 13 cm (5.1 inches); 7.1 cm (2.80 inches) of rain fell at the Buffalo Lake erosion monitoring location 16 km (10 miles) southwest of Canyon. These parameters typify the intense, localized rainfall characteristic of the Texas Panhandle region. Rainfall intensity at Buffalo Lake briefly exceeded 10.2 cm/hour (4.0 inches/hour), and the maximum intensity for a 30-minute period was on the order of 6.4 cm/hour (2.5 inches/hour) (fig. 47).

Published return frequencies for rainfall events (table 3) suggest that precipitation at Buffalo Lake had a return period just under 10 years for an event of 3 hours duration. The 24-hour rainfall total at Canyon, Texas would have a return period of just under 25 years; however, calculation of return frequencies for 24-hour rainfall totals at Canyon (55-year period of record) suggests that Hershfield's (1961) data (table 2) are somewhat low. A 12.9 cm (5.1 inches) daily rainfall has a return frequency of 19 years compared to the published value of 23 years, while a 14.7 cm (5.8 inches) daily rainfall has a return frequency of 28 years compared to the published value of 50 years.

As a result of the 12.9 cm (5.1 inches) of rainfall at Canyon on May 26, 1978 (a 19-year storm), significant erosion and sediment transport took place in Randall and Armstrong Counties. At the Buffalo Lake erosion monitoring station, erosion pin fields showed average net erosion of 1.45 to 3.06 cm (0.57 to 1.2 inches) with a maximum value of 6.2 cm (2.4 inches) (table 4). Erosion pins were set in February and March, 1978 and remeasured June 3-4, 1978. Deposition followed erosion at some erosion pins. Headcuts in alluvial/colluvial material in the study canyon migrated up to 12 m (39.4 feet) headward, and large volumes of caliche rubble were carried down the canyon. Largest blocks moved were on the order of 1 m (3.3 feet) in size (intermediate axis). Stream incision into alluvial/colluvial material in a canyon adjacent to the canyon being monitored revealed alternate layers of caliche gravel and finer materials, probably resulting in the past from similar repetitive events with high capacity for sediment transport.

A bar consisting predominantly of gravel-sized caliche fragments (fig. 48) illustrates the morphology assumed by sediment delivered during this storm from a tributary canyon to the main study canyon at Buffalo Lake. Intermediate-axis lengths of five of the largest clasts on the bar range from 46 to 70 cm (18.1 to 27.6 inches) and the thickness of sediment varies from 30 to 50 cm (11.8 to 19.7 inches) over most of the bar. Spot thicknesses of up to 1 m (3.3 feet) were noted where groups of cobbles and boulders are present.

The very heavy precipitation in the watersheds of Palo Duro and Tierra Blanca Creeks produced a flash flood along the Prairie Dog Town Fork of the Red River, the higher order trunk stream fed by Palo Duro Creek. Water crossing no. 1 within Palo Duro Canyon State Park was covered by 4.2 m (13.7 feet) of water, as indicated by flood debris surveys. Up to 1 m (3.3 feet) of sediment was deposited by overbank flow in some areas. A spatially variable pattern of deposition, followed by scouring of the newly deposited sediment, was documented by detailed studies within a single meander bend of the river. Flood events of this magnitude result in significant bedload transport, undercutting of canyon walls with subsequent slumping, and delivery of sediment to the stream channel, which may, in turn, be transported by runoff events at lower flow stages. Study of overbank deposits will assist interpretation of fluvial deposits along the Canadian River and the Prairie Dog Town Fork east of the Caprock Escarpment. An understanding of the age, position, and slope of terrace surfaces is one approach to determine erosion rates for the Southern High Plains.

Table 3. Rainfall frequency for Randall County, durations of 30 minutes, 3 hours, and 24 hours; return periods of 1 to 100 years (data from Hershfield, 1961).

Return Period (years)	Duration	Magnitude (inches)
1	30 minutes	0.9
2	30 minutes	1.1
5	30 minutes	1.5
10	30 minutes	1.8
25	30 minutes	2.1
50	30 minutes	2.4
100	30 minutes	2.7
1	3 hours	1.45
2	3 hours	1.75
5	3 hours	2.4
10	3 hours	2.9
25	3 hours	3.4
50	3 hours	3.9
100	3 hours	4.3
1	24 hours	2.2
2	24 hours	2.8
5	24 hours	3.8
10	24 hours	4.6
25	24 hours	5.2
50	24 hours	5.8
100	24 hours	6.6

Table 4. Erosion pin measurements at the Buffalo Lake monitoring station following the May 26, 1978 storm.

Slope Class	Number of Pins in Class	Net Erosion Average	Net Erosion Maximum	Net Erosion Minimum
0-9°	15	1.45 cm	5.9 cm	0.0 cm
10-19°	7	3.06 cm	5.4 cm	0.9 cm
20-29°	14	2.41 cm	6.2 cm	0.3 cm
30-39°	6	2.00 cm	6.0 cm	0.7 cm

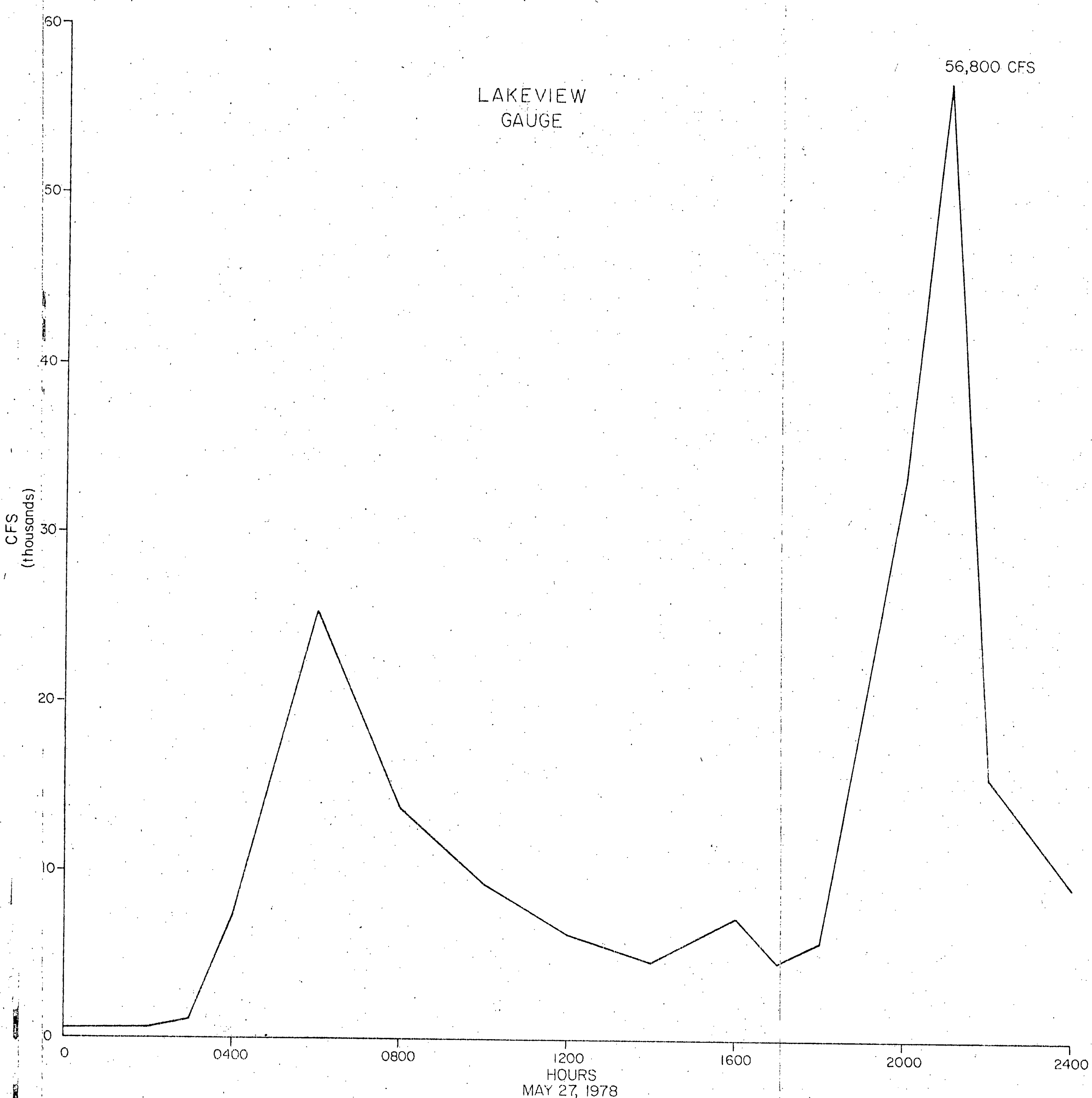


Figure 43. Instantaneous discharge based on hourly computations, Lakeview gauge, Prairie Dog Town Fork of the Red River.

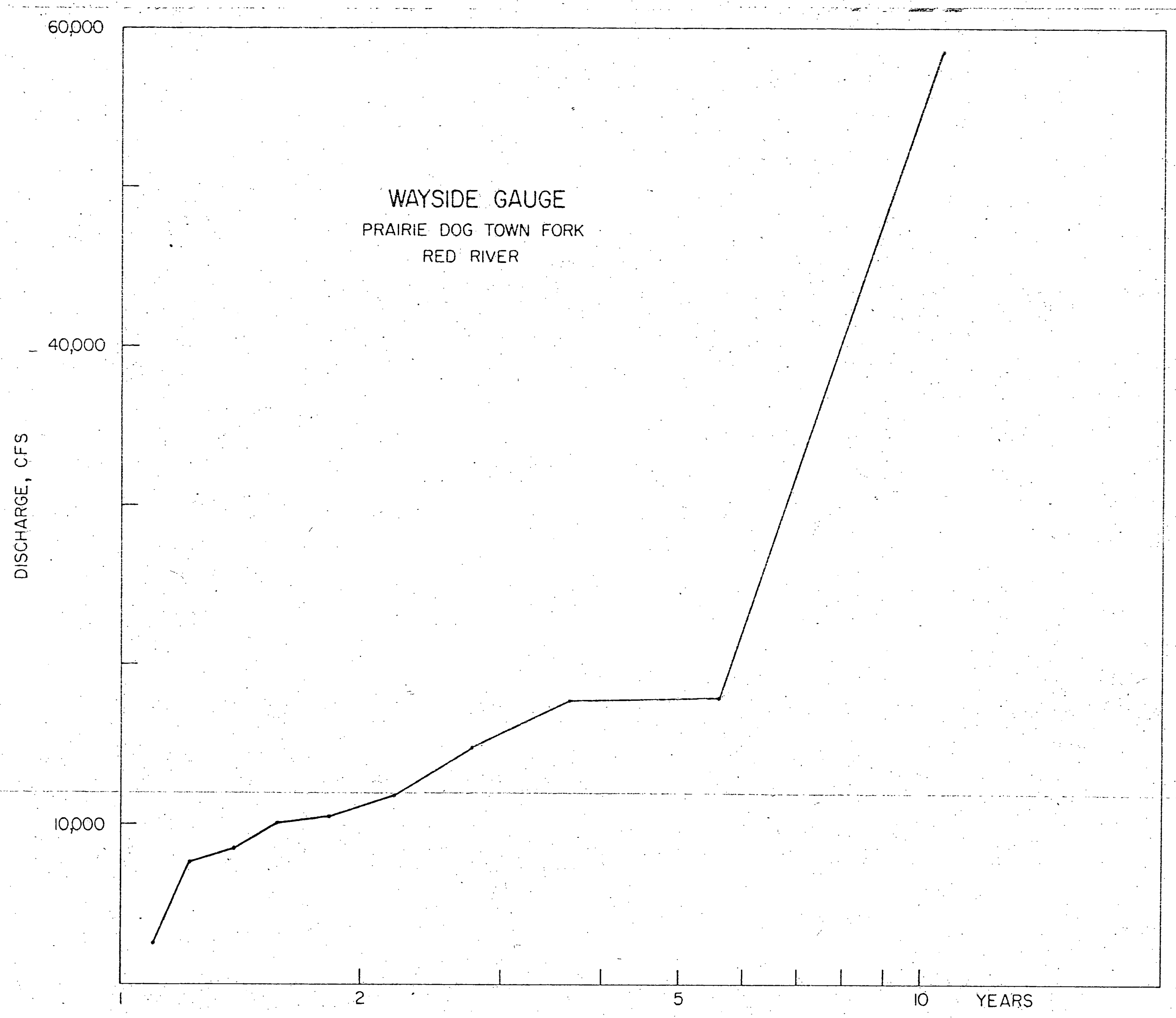


Figure 44. Return interval of annual peak discharge based on 1968-1976 water years.

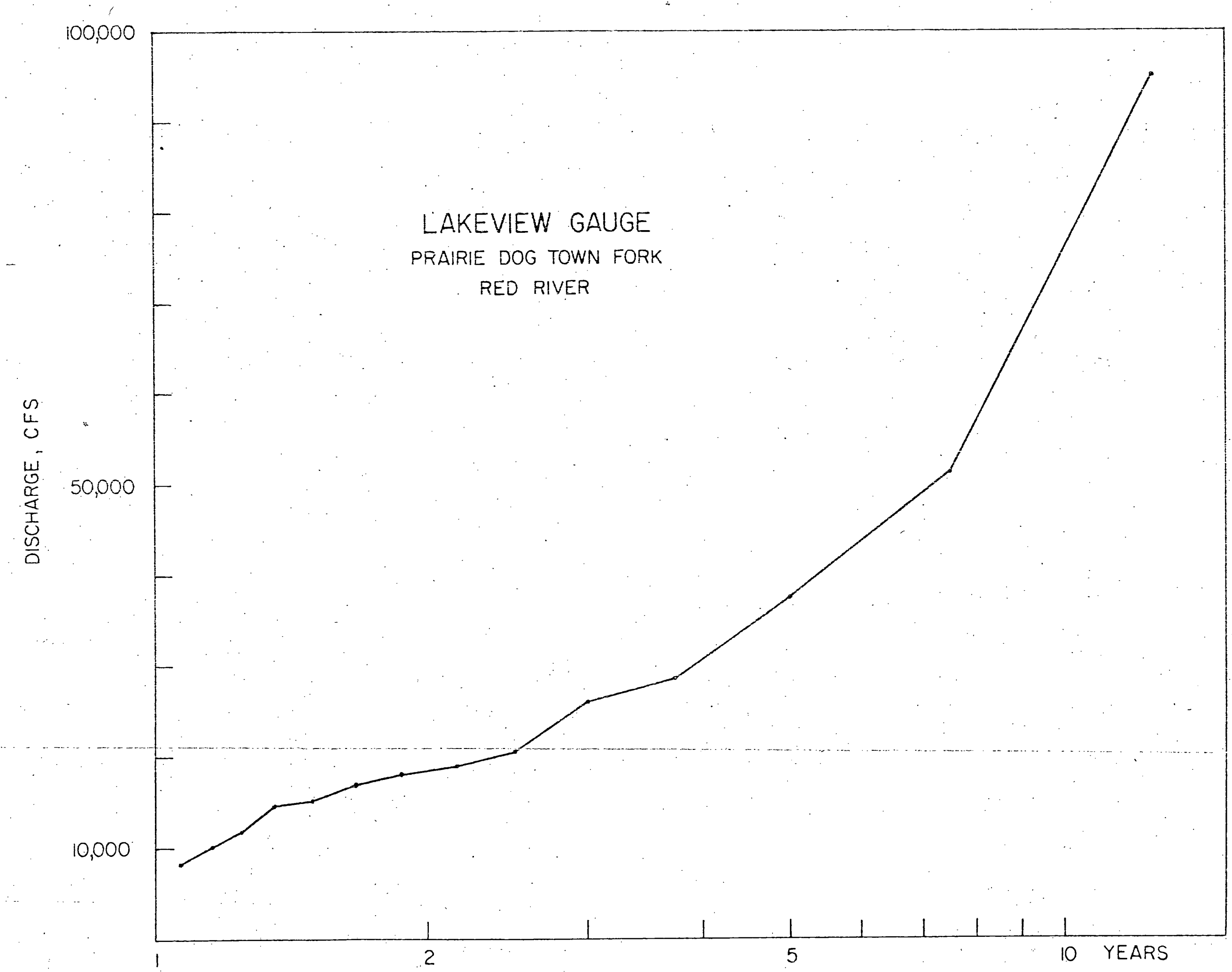


Figure 45. Return interval of annual peak discharge based on 1964-1976 water years.

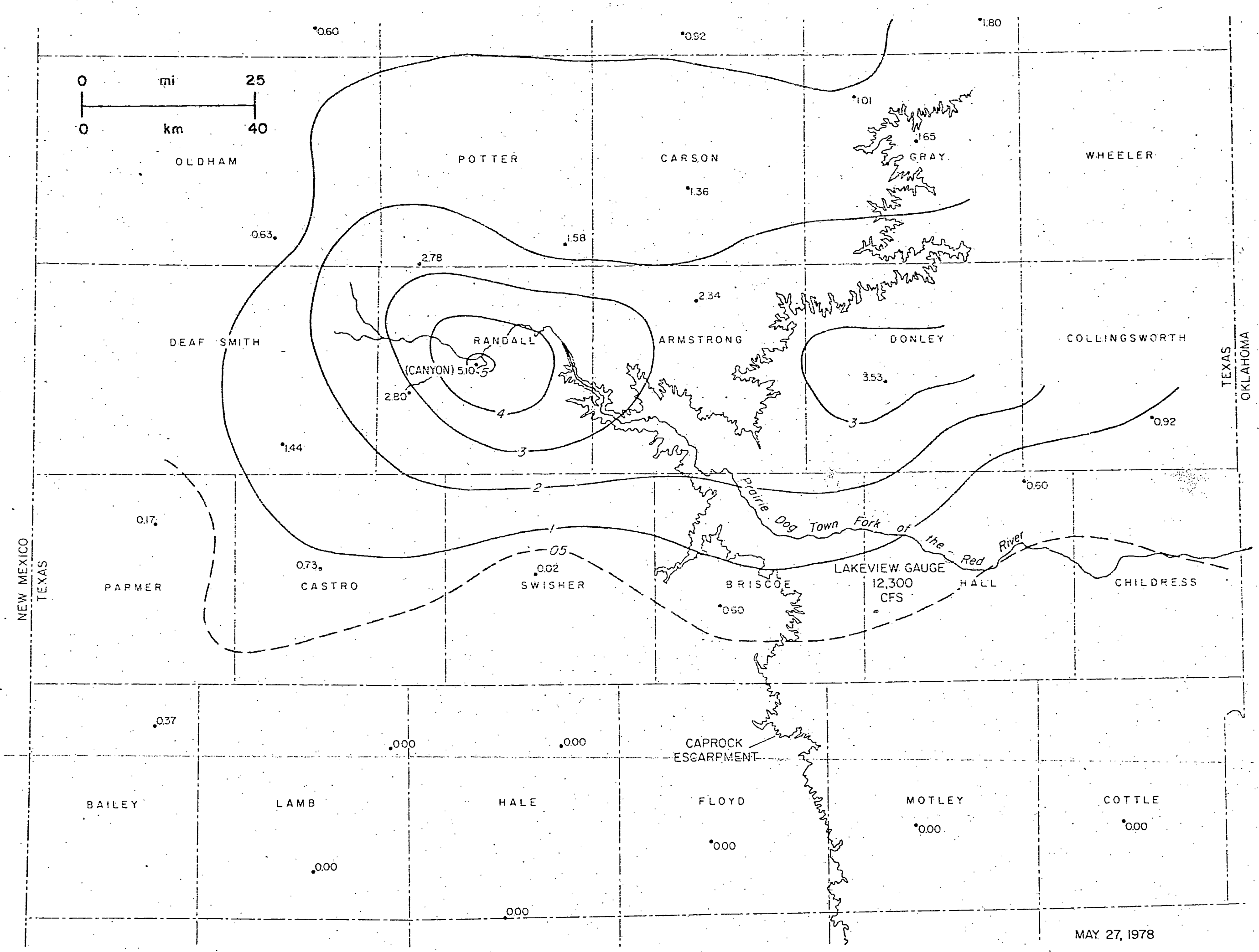


Figure 46. Isohyet map (contours in inches) based on 24-hour rainfall ending 7 a.m., May 27, 1978. River discharge (ft.^{3}/sec.) is mean daily flow for 24 hours ending midnight, May 27, 1978.

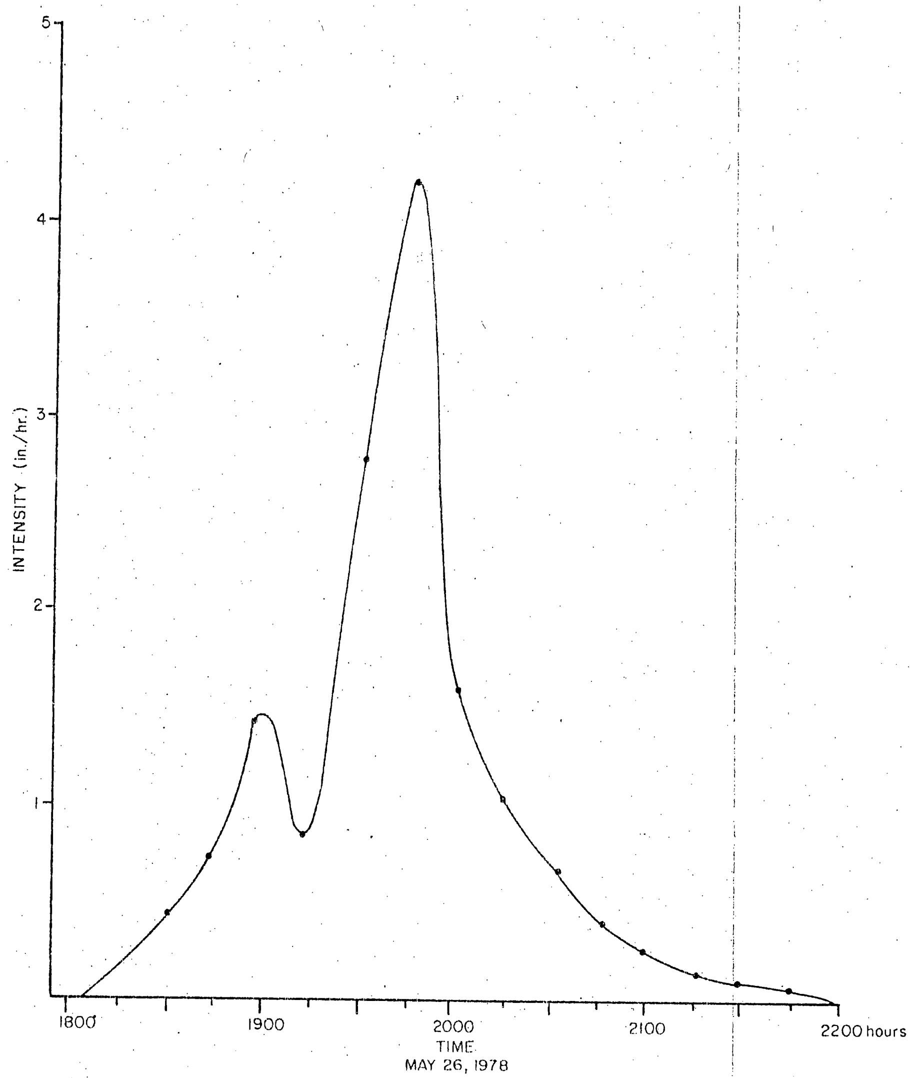


Figure 47. Rainfall intensity curve from Buffalo Lake erosion monitoring location.

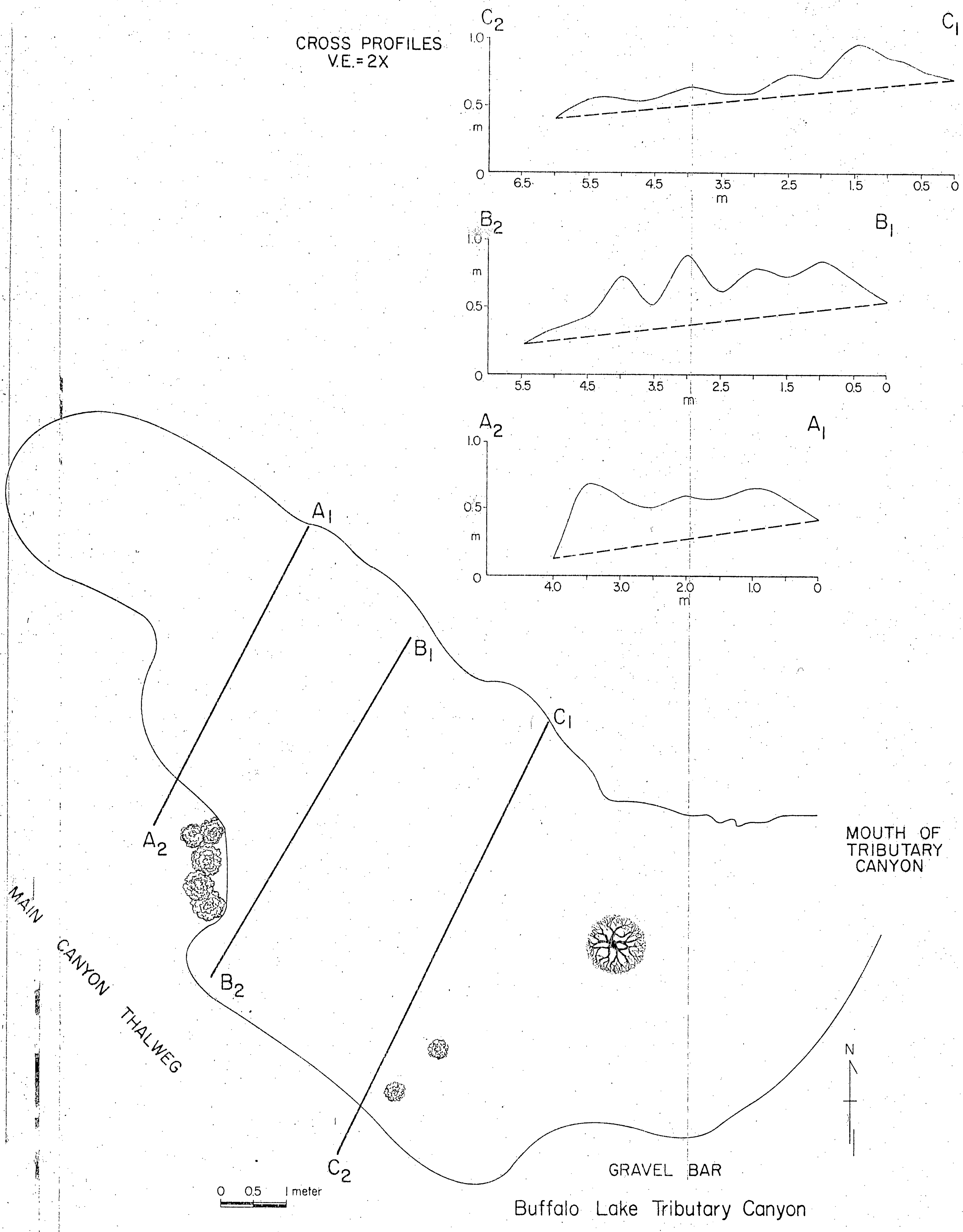


Figure 48. Plan view and selected cross profiles for gravel bar deposited during May 27, 1978 storm, Buffalo Lake monitoring station.

GEOMORPHIC MAPPING

Geomorphic mapping of the Llano Estacado and adjacent areas provides a means to extrapolate modern geomorphic process and rate data from process study sites to other areas of the High Plains--an example of the role that playas play in development of High Plains drainage.

Based on the analyses of 1:24,000 topographic maps, black-and-white controlled aerial photo mosaics (1:24,000) of various vintages, and colored infrared aerial photography (1:80,000; 1977), geomorphic map units for the High Plains were defined which are based on unique combinations of geologic substrate and soil, land form morphology and topography, geologic process, and biota (Gustavson and Cannon, 1974; Wermund and others, 1974; and Brown and others, 1971).

The Llano Estacado is a broad flat plain sloping gently to the south and east at about 1.5 m/km (8 feet/mile). It is broken locally by numerous, small, internally drained, ephemeral lake basins (usually called playa lakes). Regional drainage is rectilinear to the southeast and east, consisting of draws that extend entirely across the Llano Estacado. Interfluve areas, which account for the majority of the Llano Estacado surface, do not exhibit integrated drainage.

Characteristic geomorphic units of the Llano Estacado are illustrated in figure 49.

1. Ph--Playa bottoms include either dry or water-filled ephemeral ponds that cover from 1-15 ha and are commonly up to 10 m deep.
2. Ps--Playa sides are the catchment area for deeper (greater than 5 m deep) playas.
3. Ld--Lee dunes are low topographic rises (commonly only about 3 m of relief) adjacent to some of small playas.
4. Swales are long, narrow (straight or sinuous), nearly flat areas with concave-up slopes. They occur along either bottoms of draws or are short, narrow, poorly formed areas between or draining into playas.

5. Swale sides are water-gathering slopes for swales.

6. The High Plains surface is composed of flat, gently sloping surfaces that surround major drainage features and playa lakes.

Playa lakes are aligned in a northwest-southeast direction in many areas of the Llano Estacado, and they are approximately parallel to regional slope. Elements of rectilinear drainage on the High Plains probably developed from interconnection of playas. Playas filled during storms, overtopped divides, and flowed into the next playa downslope. Many repetitions of this process led to formation of a surface drainage network consisting of interconnecting swales, playas, and draws, ultimately producing the present rectilinear drainage.

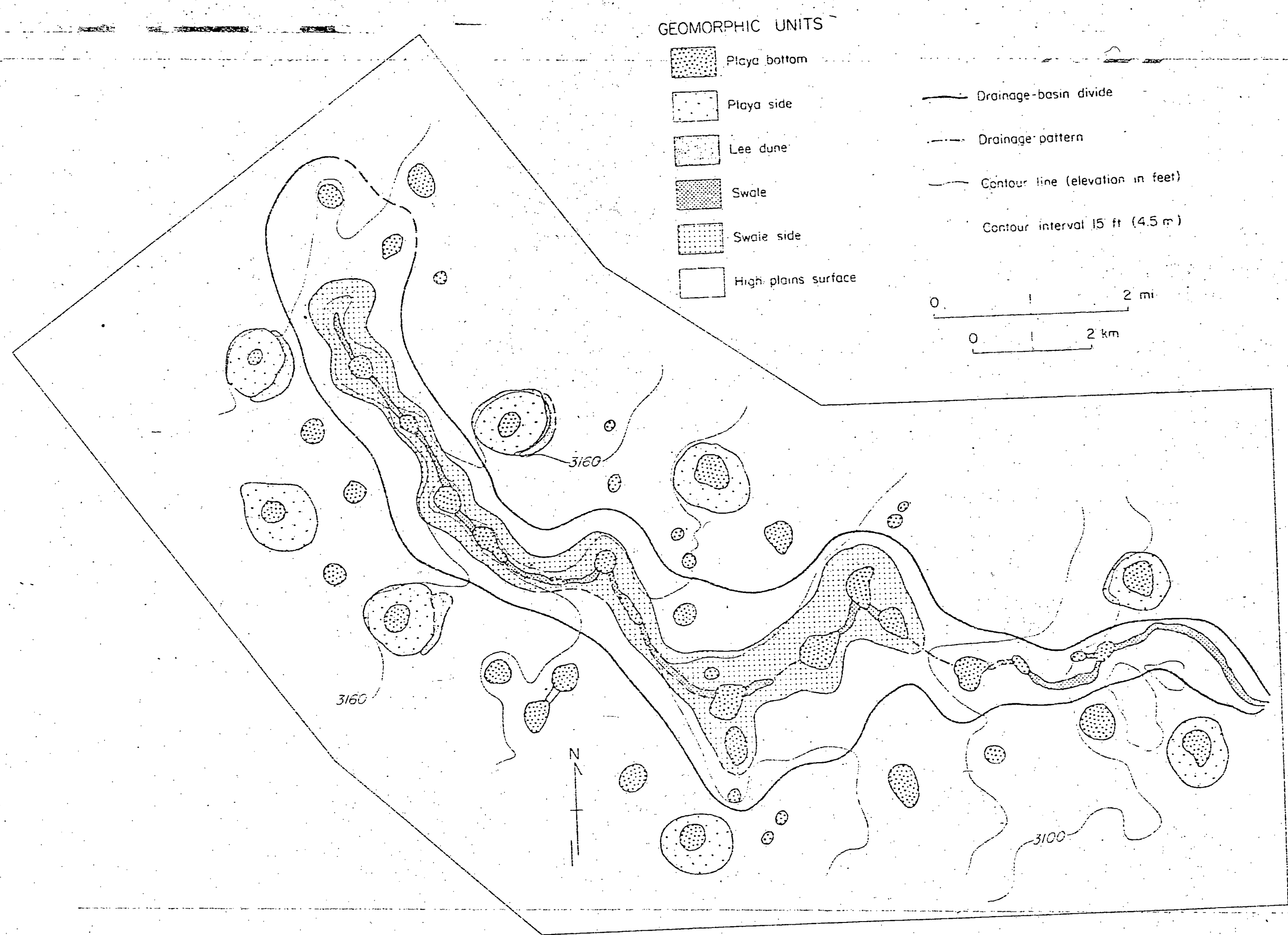


Figure 49. Geomorphic map of a small drainage basin approximately 50 km east-northeast of Lubbock.

ANALYSES OF LINEAR ELEMENTS, SURFACE AND JOINTING, TEXAS PANHANDLE

Landsat imagery of the Texas Panhandle has been used to define linear physiographic elements, or lineaments; the Amarillo-Plainview area exhibits lineaments typical of High Plains and Rolling Plains physiographic regions.

An examination of 1:250,000-scale geologic maps of the Panhandle of Texas reveals a notable linearity of stream segments and scarps and an alignment of playa lake depressions. Specially enhanced satellite imagery was used in a comprehensive study of a 600,000 square km area including the High Plains over the Palo Duro Basin (fig. 50). More than 4,650 linear features were delineated from Landsat imagery.

This study was undertaken to examine: (1) the prevalent orientations of linear physiographic trends, and (2) the relationship between these trends and geologic structural elements of northwest Texas and eastern New Mexico. Good correlation between orientation of straight physiographic features and structural elements, ranging from joints to basement features, suggests that there is some degree of structural control of surface geomorphology. Lineaments in the Texas Panhandle defined from Landsat imagery range in length from 2 to 40 km.

Each Landsat image was analyzed in conjunction with 1:250,000-scale topographic and geologic maps to develop lineament categories and to avoid inclusion of man-made features in the analysis. Five categories of lineaments were noted, including surface drainage, scarps, playa alignments, linear geologic contacts, and tonal anomalies. Special effort was made to exclude roads and field boundaries and to detect apparent lineaments from agricultural practices. Analysis of three Landsat scenes (blocks 3, 4, and 6, fig. 50) was completed on specially enhanced false-color composite imagery.

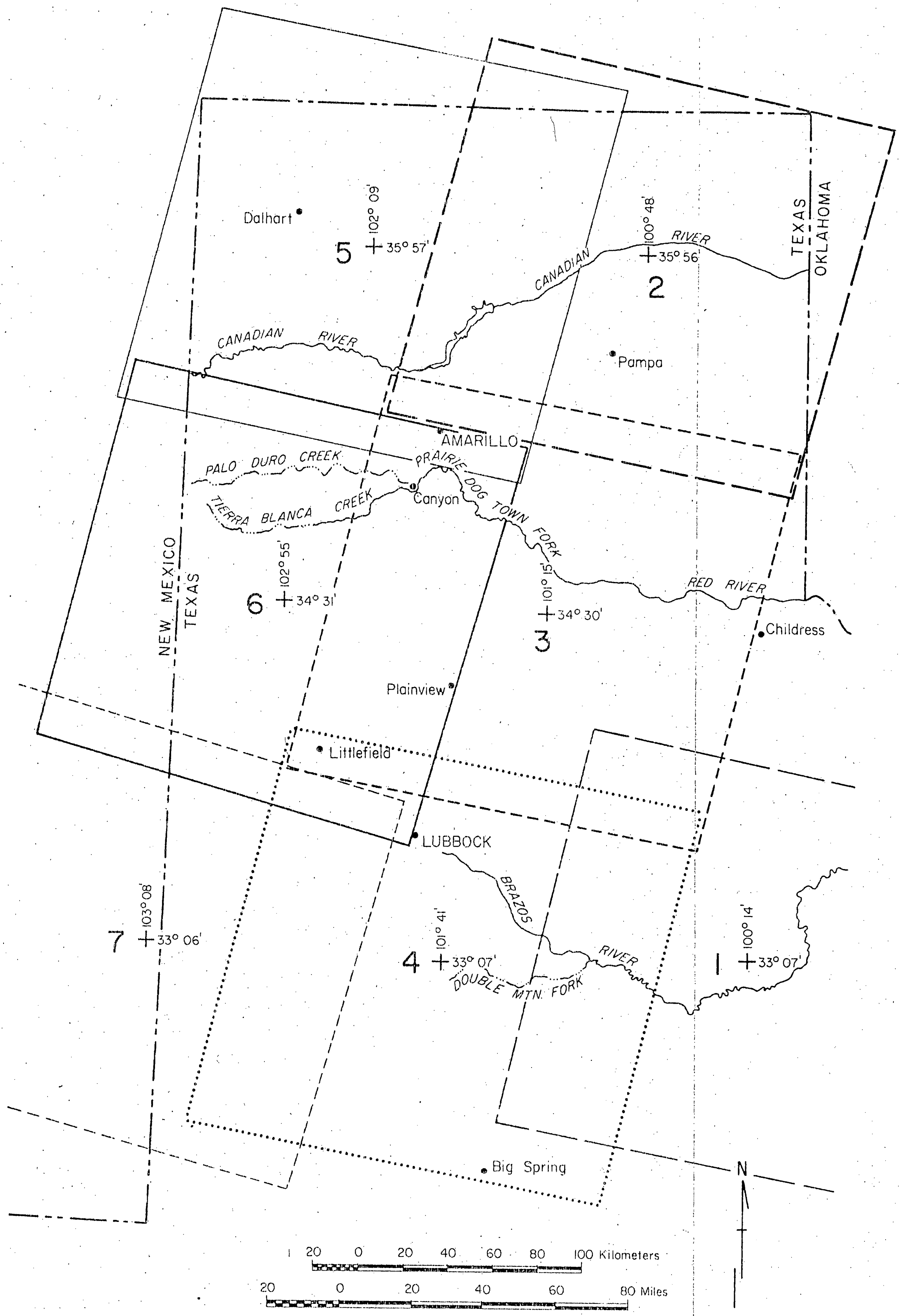
Block 3, covering the Amarillo-Plainview area (fig. 51), includes 1,286 lineaments. Of these, 522 are on the High Plains, 726 are on the Rolling Plains, and 38 are related specifically to the Caprock Escarpment. High Plains lineaments are dominantly drainage features (56 percent) and playa alignments (31 percent). In the Rolling Plains, where an integrated drainage system is developed, 95 percent of the lineaments are drainage features. Tonal anomalies, probably representing low swales or poorly developed drainage features, are much less frequent in the Rolling Plains physiographic province; playa lakes are absent. Linearity of many stream segments in the Rolling Plains is striking, as is the overall symmetry of the North and Middle Pease Rivers in Motley County (fig. 51). Control of physiography by a joint pattern persistent over the area of a county and perhaps a region is indicated.

Lineament orientations. Azimuth frequency diagrams illustrate the orientation of lineaments derived from Landsat imagery (fig. 52). The High Plains data show a trend centered at 300°-320° and a subordinate, orthogonal trend at 30°-50° (fig. 52). Lineaments on the Caprock Escarpment, which have here been separated from the High Plains data, are derived from blocks 3, 4, 6, and 7 (fig. 50). Drainage features, playa alignments, and tonal anomalies contribute to these trends. Most tonal anomalies represent incipient drainage or swales which carry intermittent flow between playas. Drainage orientation along regional slope commonly assumes a modified rectilinear pattern suggesting structural control by orthogonal jointing. This hypothesis is supported by a similar trend of orthogonal joint sets measured in outcrops.

Lineaments defined off the High Plains are primarily from the Rolling Plains and the Pecos Plains, and from the Canadian Breaks and a small part of the Edwards Plateau (fig. 39). These data define a predominant trend at 0°-20° and subordinate trends at 60°-70° and at 300°-330°. Two types of drainage features are common: stream segments and drainage lines. Stream segments are relatively short, straight channel reaches normally connecting at sharp, angular junctions suggesting joint intersections. These are among the shortest lineaments recognized with lengths down to 2 km (1.2 miles); they represent less vegetated, high-reflectance active fluvial channels. Drainage lines denote linear valley trends which may be independent of the orientation or linearity of smaller stream segments within the trend. Vegetation, minor topographic scarps, and overall integrated drainage patterns are useful in recognizing drainage lines. A stream in north-central Donley County (fig. 51) illustrates how a series of linear stream segments can be defined within a longer, linear trend of a drainage line. Commonly both long trends of a drainage line and short stream segments coincide with prevalent lineament orientations, indicating possible control by primary and secondary joint sets.

Jointing. Over 1,100 joint measurements have been recorded from near-vertical joint faces of the Tertiary Ogallala, Triassic Dockum, and Permian Quartermaster Formations. Joints in the Ogallala Formation are poorly developed, irregular and confined to the caliche caprock. Caliche caprock outcrops locally exhibit a regular sawtooth, exposed face with roughly cubic caliche blocks on scree slopes below, suggesting that joints in the Ogallala caprock enhance weathering and erosion.

Joints are well defined in sandstones of both the Dockum and Quartermaster Formations and most of the joint data were recorded from these two units. Extension fractures near canyon walls were not measured. Graphic plots of joint orientations (figs. 53 and 54) and joint plots on geologic maps (figs. 55 and 56) indicate that: (1) major joint trends vary geographically and are westerly, northwesterly, northerly, and northeasterly directions, parallel to major basement structural trends (fig. 1); (2) stream and valley segments and escarpments tend to parallel major joint orientations; and (3) trends of playa alignments and draws on the Llano Estacado parallel both regional slope and major northwesterly joint orientations. Development of streams and scarps on and off the Llano Estacado is related, in part, to joint orientations. That joints act as preferred zones of ground-water movement is indicated by solution cavities in the Ogallala caliche caprock and by local, preferential solution of cements along joints in the Dockum Formation.



LANDSAT FRAME COVERAGE AND APPROXIMATE CENTER POINTS, TEXAS PANHANDLE

Figure 50. Generalized frame boundaries for Landsat coverage of the Texas Panhandle, numbered for reference to text discussion.

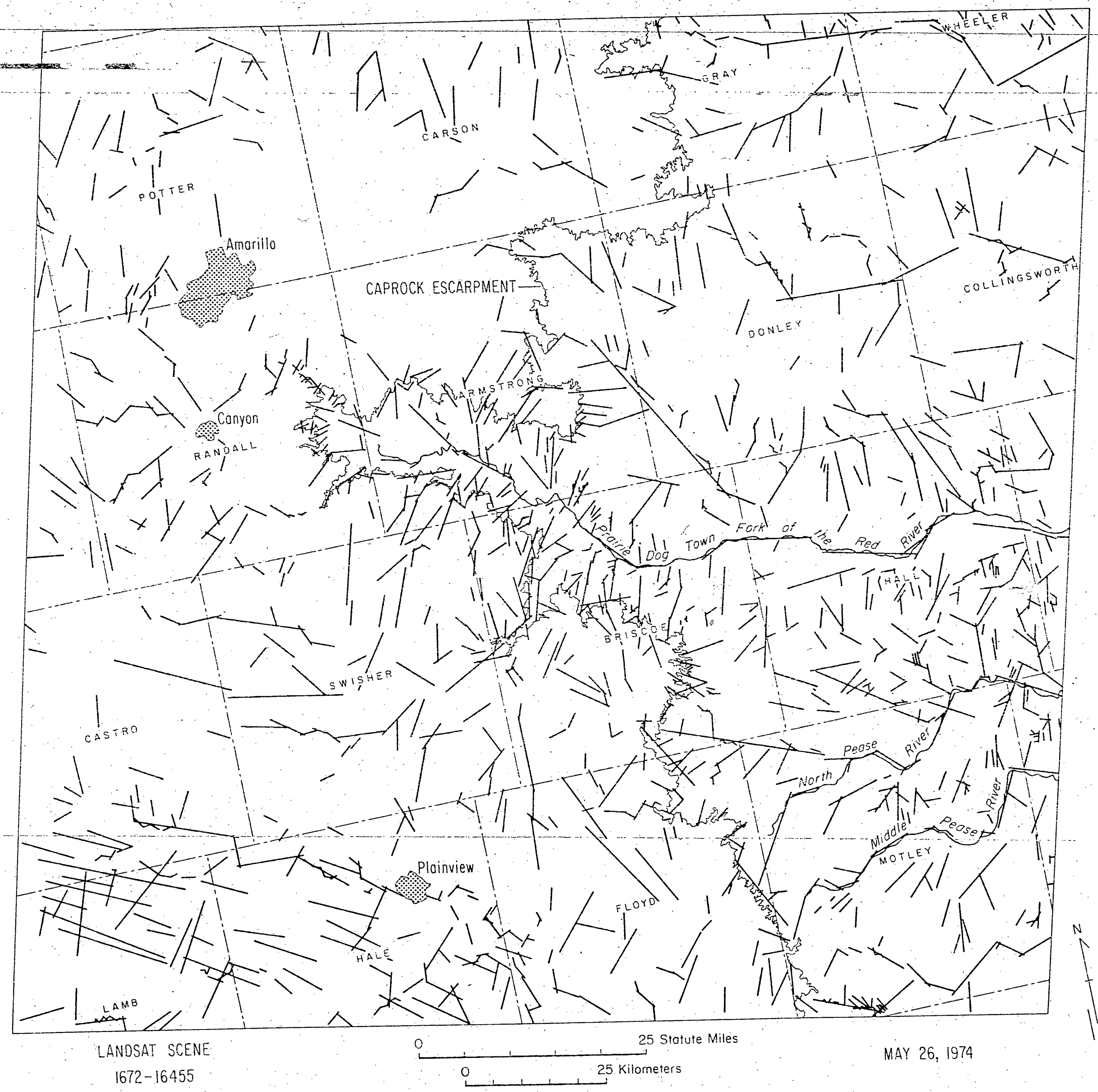


Figure 51. Lineaments derived from false-color composite Landsat imagery, Texas Panhandle region.

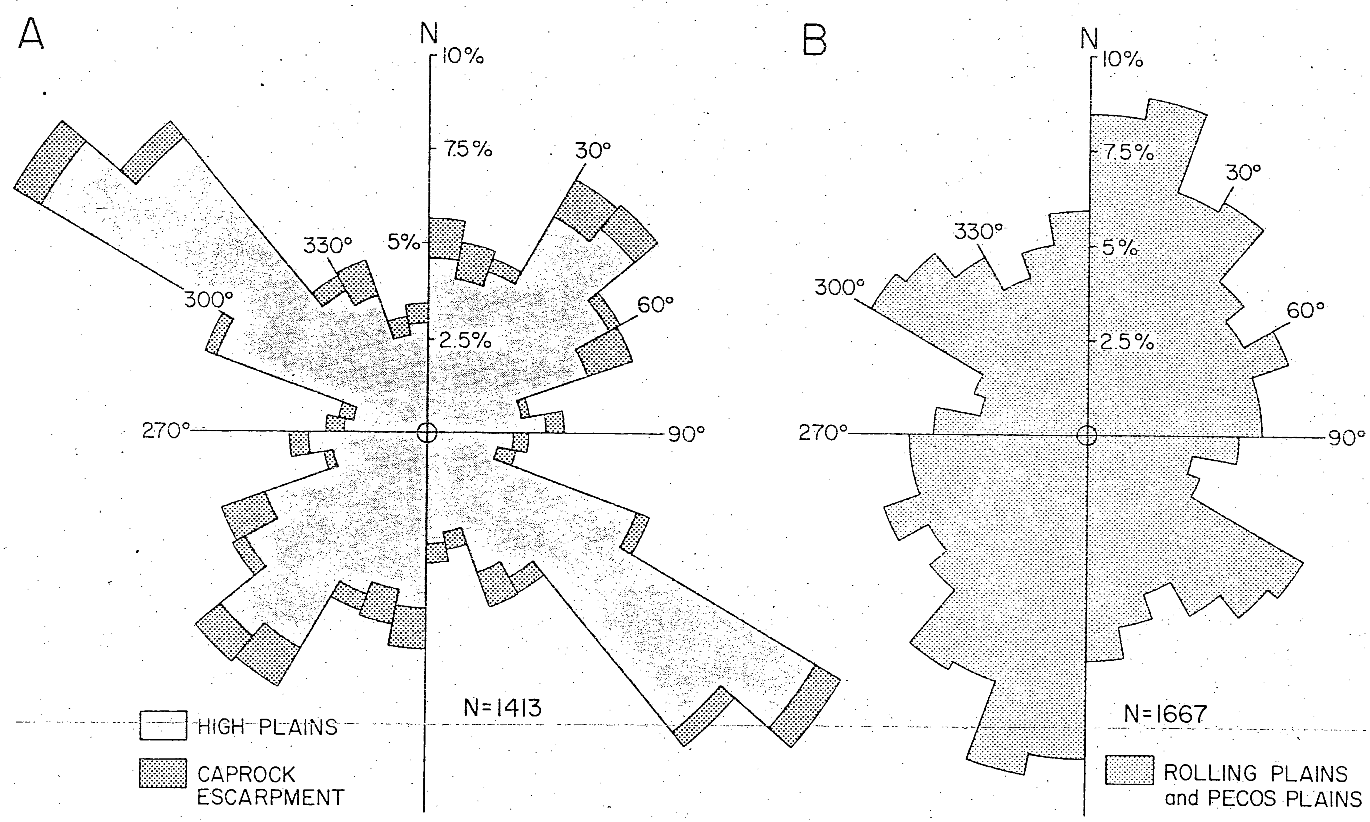


Figure 52. Lineament trends in the central Texas Panhandle and adjacent New Mexico.

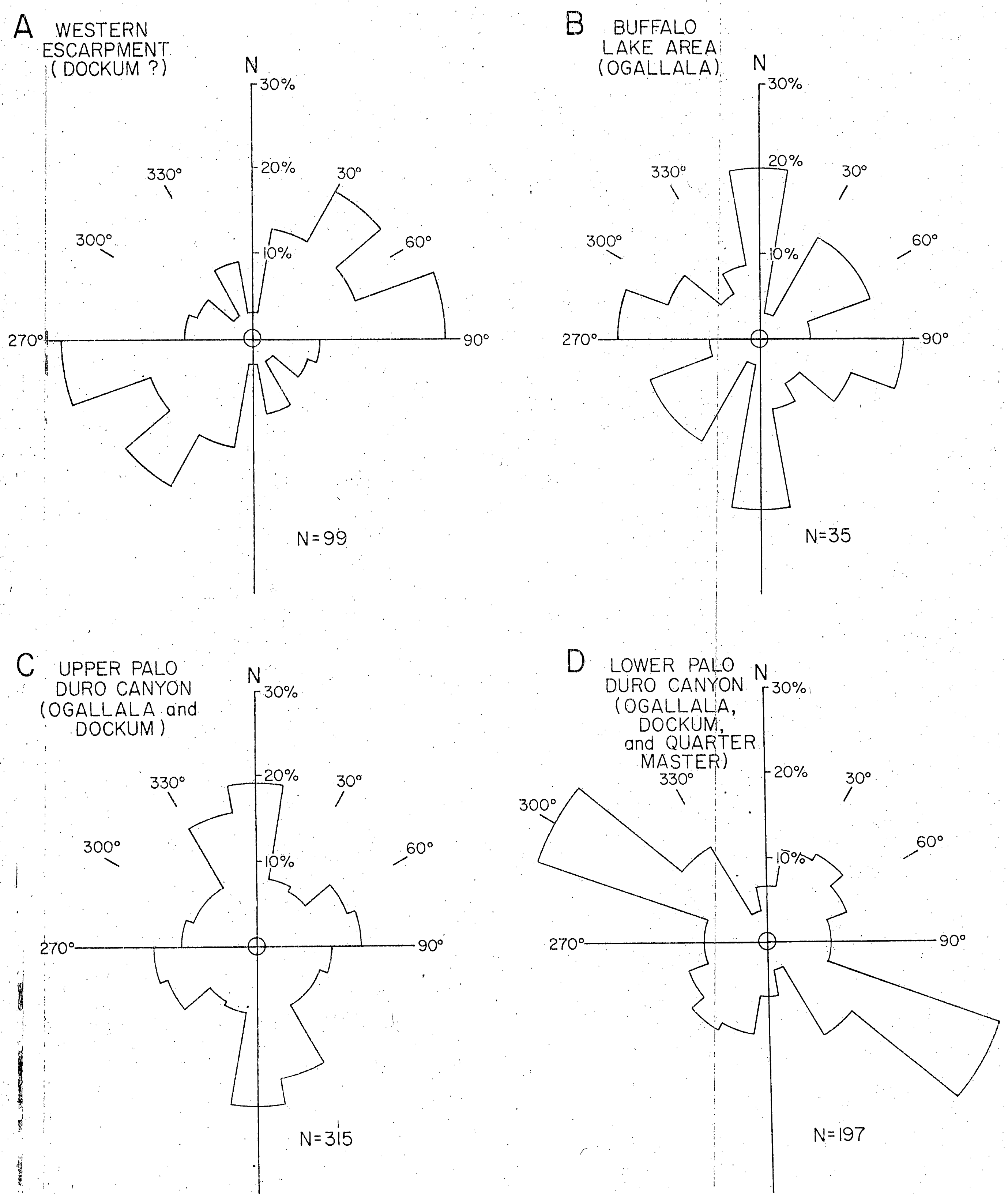


Figure 53. Summary of joint orientations grouped by locality, Texas Panhandle region.

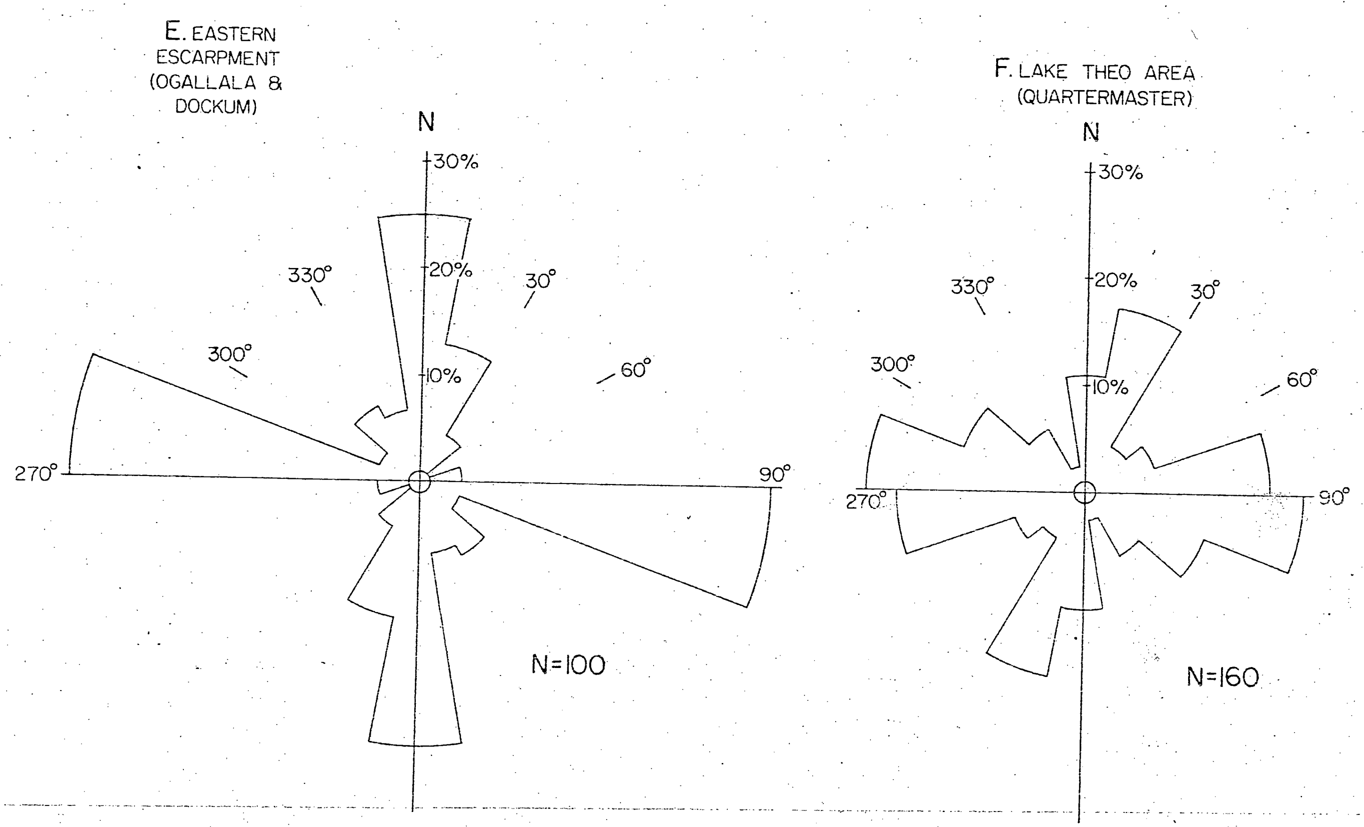


Figure 54. Summary of joint orientations grouped by locality, Texas Panhandle region.

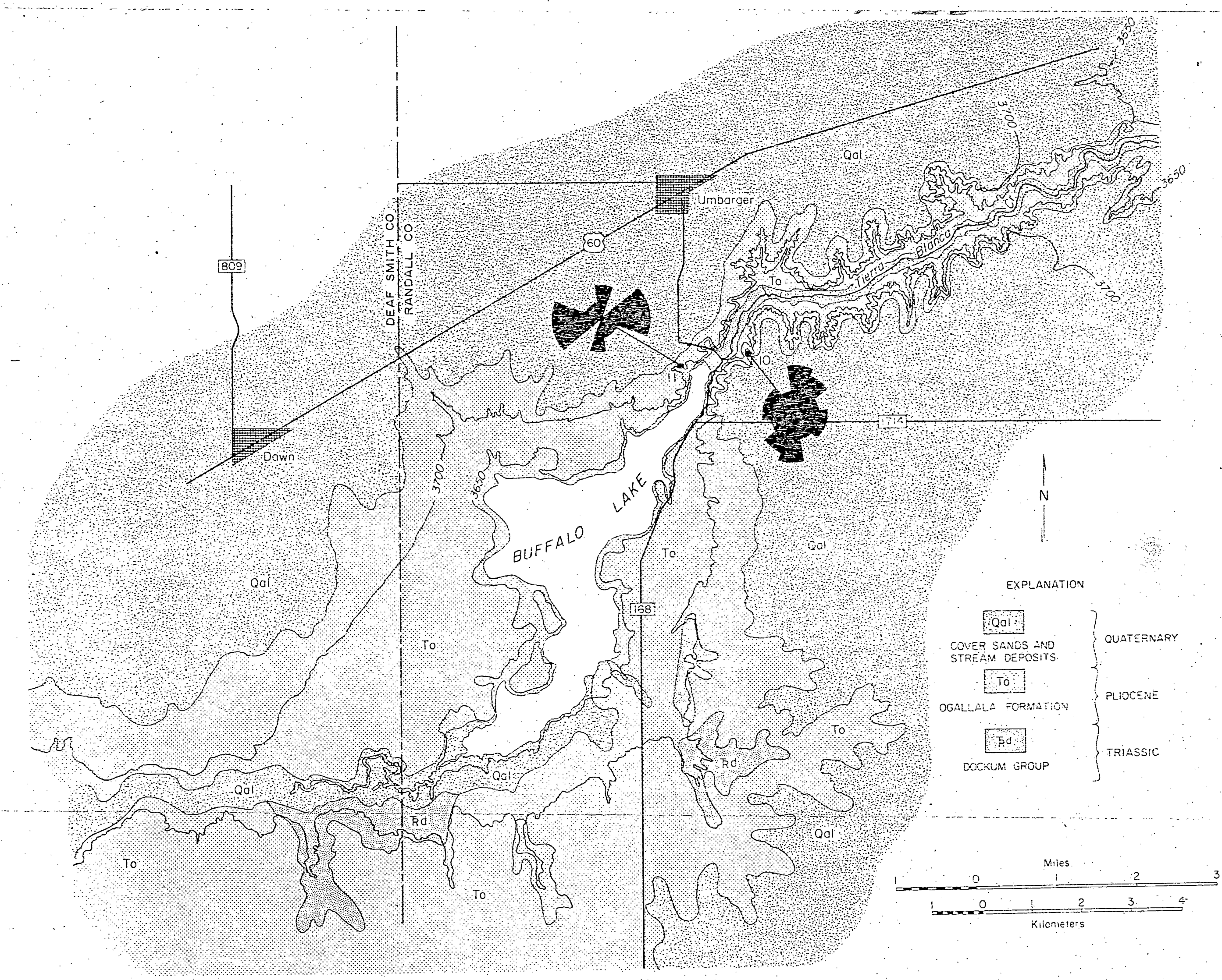


Figure 55. Geologic map and joint distribution, Buffalo Lake area, Texas Panhandle region.

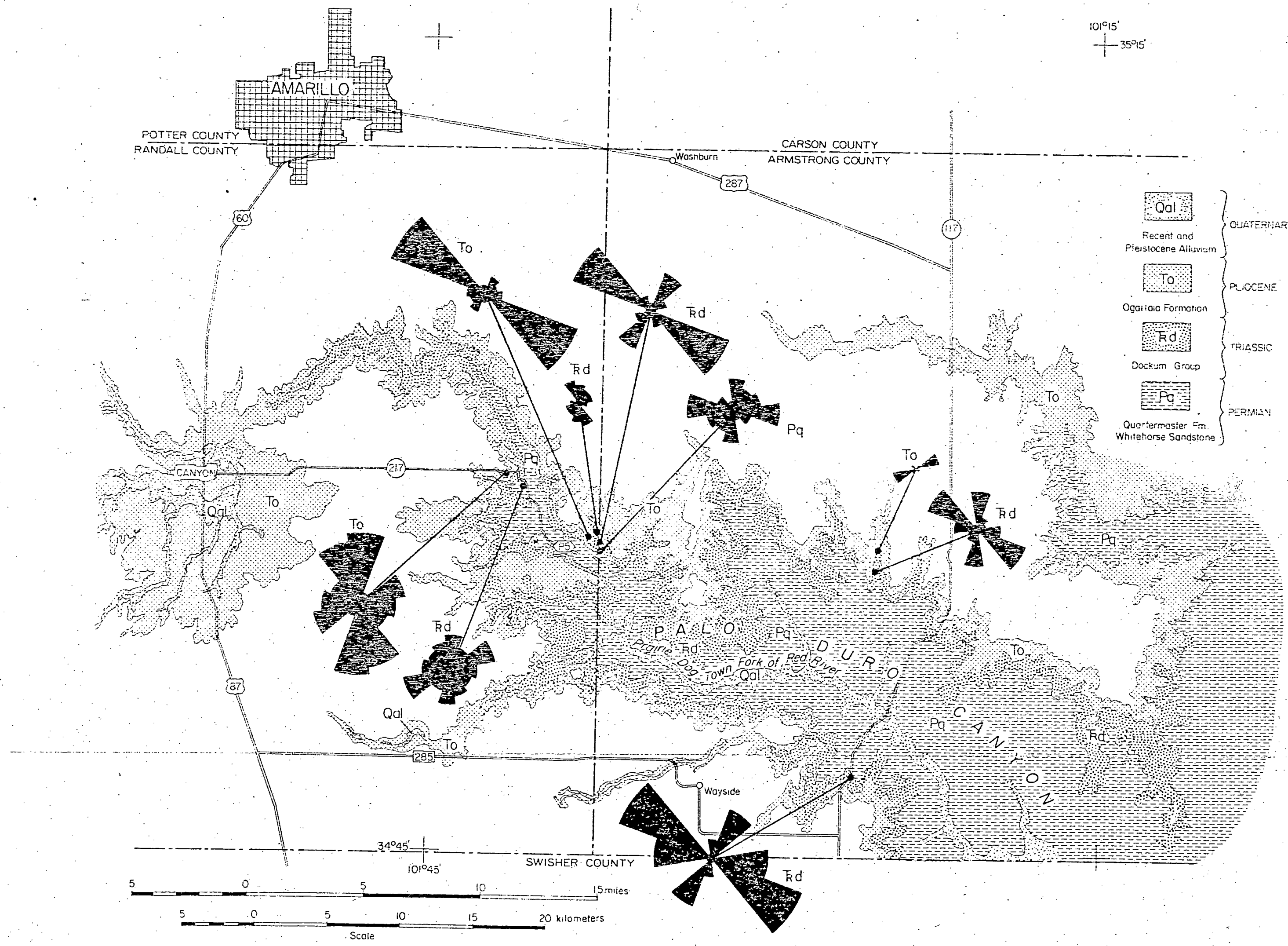


Figure 56. Joint orientations and geologic map, Palo Duro Canyon, Texas Panhandle region.

SALT DISSOLUTION

Dissolution of Permian bedded salt is an active process that has resulted in major post-Permian structures and is the source of high dissolved loads in streams draining the Llano Estacado and Rolling Plains.

Salt dissolution has been identified along the eastern escarpment of the Llano Estacado and along the southern margin of the Canadian River Valley where salt beds lie between 150-600 m (500-2,000 feet) deep (fig. 57). The coincidence of dissolution zones and major surface erosional features strongly indicates that there is a causal interrelationship between processes and areas of surface erosion and the location of subsurface dissolution zones. Unless the coincidence of surface erosional features and dissolution zones is entirely fortuitous, rates of surface scarp retreat and subsurface dissolution zone retreat from the Late Tertiary to the present must have been approximately equal. Reentrants in the dissolution zone occur below reentrants in the eastern escarpment of the Llano Estacado where major streams, the Canadian River, Prairie Dog Town Fork of the Red River, and Quitaque Creek pass through the escarpment. Thus, stream development and incision are probably influenced by the position of the salt dissolution zone.

Post Permian structure. In order to understand regional geologic structural changes that have occurred since the Permian Period, a structure contour map (sea level datum) of the top of the Alibates Dolomite was prepared (fig. 58). The Alibates Dolomite consists of one or two tin dolomitic anhydrite beds (approximately 50 feet) and is a persistent marker bed in Upper Permian strata of the Texas Panhandle. Its thin but widespread distribution indicates that the depositional topography of the Permian evaporite basin in the Texas Panhandle was relatively flat. If large depressions or highs were present during deposition, the Alibates Dolomite would exhibit significant thickening into paleotopographic depressions or thinning over paleotopographic highs.

Major structural depressions are defined by elevations on the upper surface of the Alibates Dolomite in Oldham, Hartley, Moore, and Carson Counties. A basin defined by the Alibates structure map in Oldham, Hartley, and Moore Counties, which were infilled by Triassic and Tertiary sediments, was formed in part by salt dissolution and collapse/subsidence of the subjacent Permian evaporite sequence. The southern basin margin, defined by post-Permian dissolution, coincides with the trend of underlying dissolution zones Upper Permian strata (fig. 57). The structural basin and salt dissolution fronts parallel and underlie a segment of the Canadian River and its valley, suggesting that dissolution also may have influenced the location of this river segment.

In Carson County, a large closed basin defined by the Alibates structural map exhibits approximately 300 feet of relief. The basin is filled with clastic sediments of the Ogallala Formation and lies within and to the north of the dissolution zone of the subjacent Permian salts. It is probable that this post-Permian basin also resulted from salt dissolution. Presence of thicker Ogallala deposits in the basin indicates that the basin existed prior to Ogallala time and that local dissolution was underway prior to or during deposition of the Ogallala Formation.

Along the eastern margin of the Palo Duro Basin in Briscoe, Armstrong, Donley, and Grey Counties, the dip of the Alibates Formation shifts from south to east, and a structural trough is defined by the 2,500-foot contour on the upper surface of the unit. The post-Permian trough underlies the valley of the Prairie Dog Town Fork of the Red River, an indication that the Alibates has been structurally depressed here, probably from dissolution of underlying bedded Permian salts.

Small-scale salt dissolution structures. Twenty-seven filled collapse chimneys were discovered in the Permian Whitehorse Formation during construction of the Sanford Dam on the Canadian River, 40 miles northeast of Amarillo (fig. 59). Chimneys are circular to eliptical in cross section and are filled with slumped and brecciated sediments from the overlying Triassic Dockum Group and Tertiary and Ogallala Formation. Chimneys apparently formed when Permian sediments collapsed into voids formed from dissolution of Permian salt.

Several classes of playa lakes occur on the Llano Estacado, the largest of which occur only over zones of salt dissolution or where salt dissolution has probably occurred in the past. Comparison of a structure contour map of the Blaine/San Andres Formation and a topographic map for an area including a large lake in Grey County shows that a structural depression of the Blaine/San Andres Formation underlies the lake (fig. 60). A gamma-ray log cross-section shows that the Blaine thins under the lake probably as a result of salt dissolution.

Topography on the Alibates Formation, structure contour map, the filled chimneys in the vicinity of Sanform Dam, and large lake depressions all suggest that major structural collapses of as much as 300 feet have occurred around the margin of the Palo Duro Basin as a direct result of salt dissolution.

Stream discharge of solution derived salts. The average annual solute discharged from the Llano Estacado from 1969-1974 was 2,749,000 tons of dissolved solids per year including 1,161,000 tons of chloride and 507,900 tons of sulfate (U.S.G.S., 1969-1974). Nearly half of this dissolved load is supplied by the Prairie Dog Town Form of the Red River where the average load for the same period was 1,033,500 tons dissolved solids including 425,300 tons of chloride and 155,800 tons of sulfate. Thus, dissolution of Permian salts is an active process in the Palo Duro Basin.

Solute load is described in terms of sulfate (SO_4^{--}), chloride (Cl^-), and total dissolved solids (TDS) (fig. 61, table 5). In nearly every case Cl^- load, which represents solution of bedded salts at depth, exceeds SO_4^{--} load. The SO_4^{--} content of these waters is derived from solution of gypsum or anhydrite. Since solution-modified gypsum outcrops (karst) are common along the High Plains Escarpment, at least some of the SO_4^{--} content of these waters is the result of surface solution processes.

Nevertheless, surface solution does not preclude the possibility that some SO_4^{--} is derived by subsurface dissolution of gypsum and anhydrite. The drainage basin of the Prairie Dog Town Fork of the Red River carries the largest solute load, and it is the drainage system that has eroded the greatest distance westward into the High Plains. This further illustrates a close coincident between stream incision, scarp retreat, and the westward migration of subsurface salt dissolution zones.

Table 5. Water Quality (6-year average).

	10^3 tons per year		
	TDS	CHLORIDE	SULFATE
1 A	96.2	25.2	34.0
1 B	133.1	34.2	31.5
1 C[a]	67.3	26	8.3
2	104.4	19.0	46.5
3	68.4	8.3	35.9
4 A	24.5	6.6	7.9
4 B	252.5	94.7	74.7
5	129.4	58.6	22.8
4 C	1,0335	425.3	155.8
7[b]	47.1	16.7	12.3
8[b]	7.5	1.8	2.8
9	336	143.7	62.6
10	176.8	82.5	28.5
11	61.5	23.9	18.0
12	109.6	55.8	12.9
13	130.0	58.6	23.5
14	39.0	12.3	11.9
15	240.0	111.2	31.8
16	62.4	27.3	17.4
17	600	299.7	72.8
18	138.3	35.0	49.3
TOTAL AVERAGE ANNUAL SOLUTE EXPORT	2,739.1	1,121.2	520.9

a Two-year average
b Three-year average

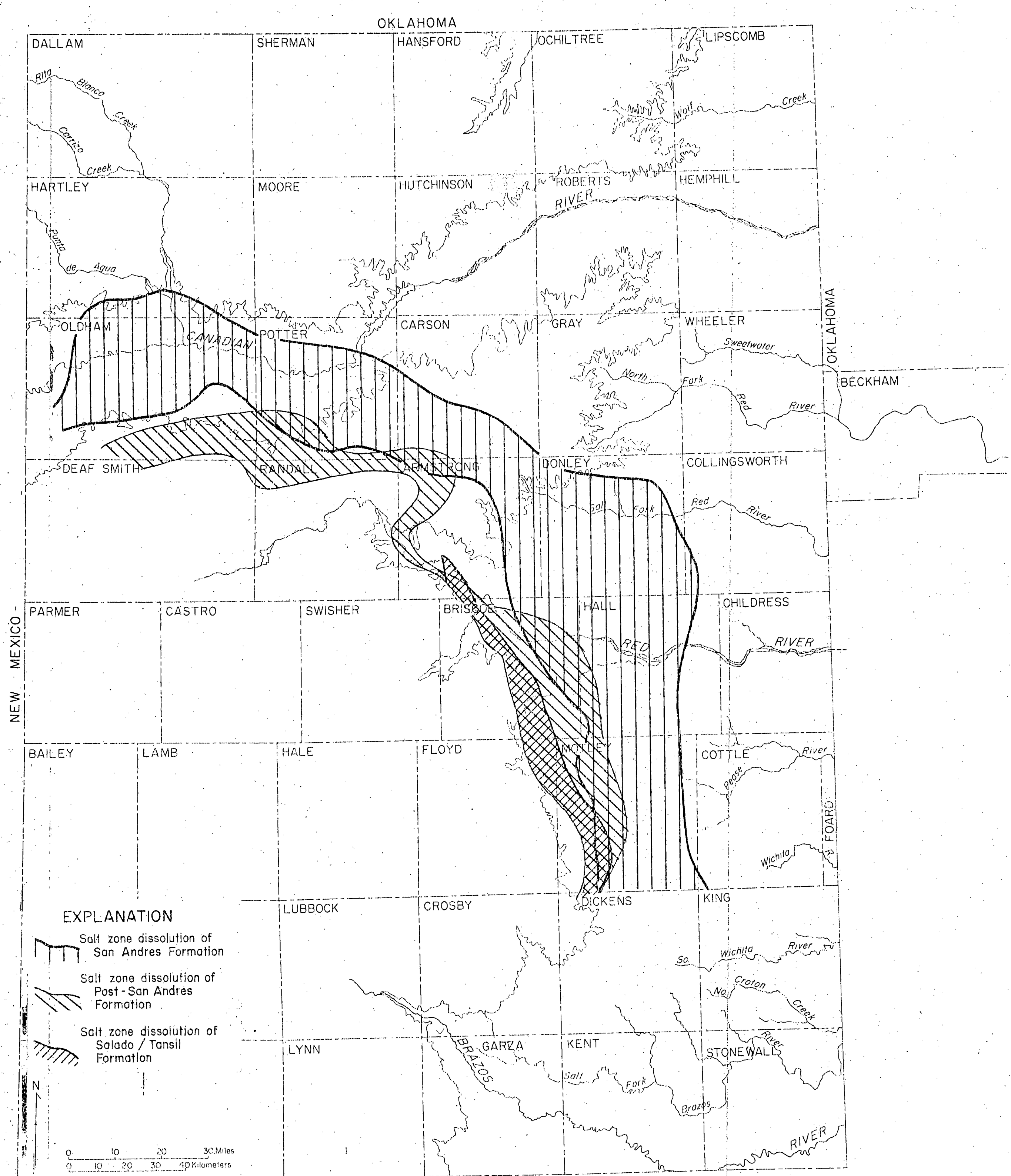


Figure 57. Salt dissolution zones, Texas Panhandle (also refer to figures 31 and 32).

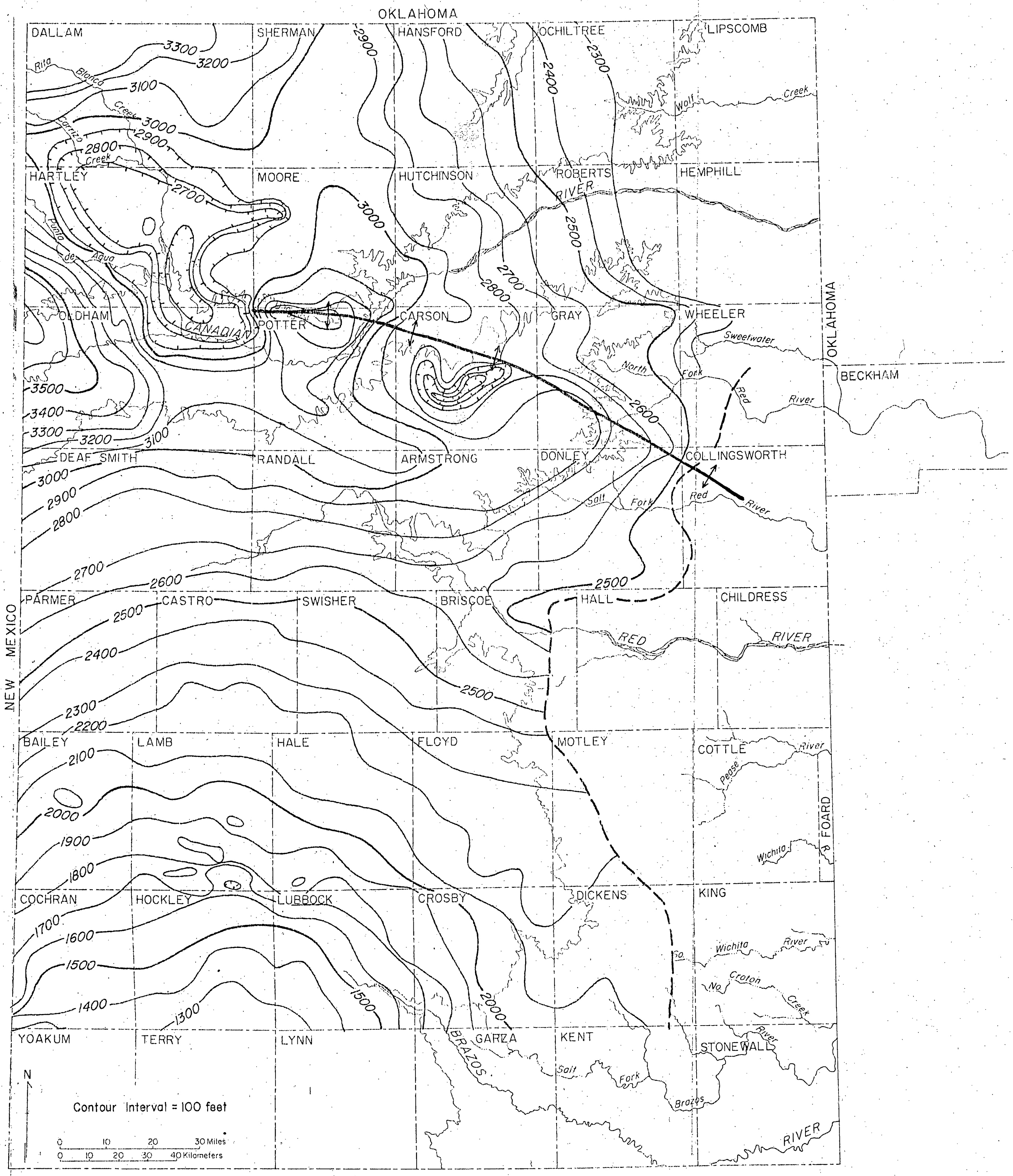


Figure 58. Structure contour map, Upper Permian Alibates Dolomite. Heavy line marks trace of Amarillo Uplift.

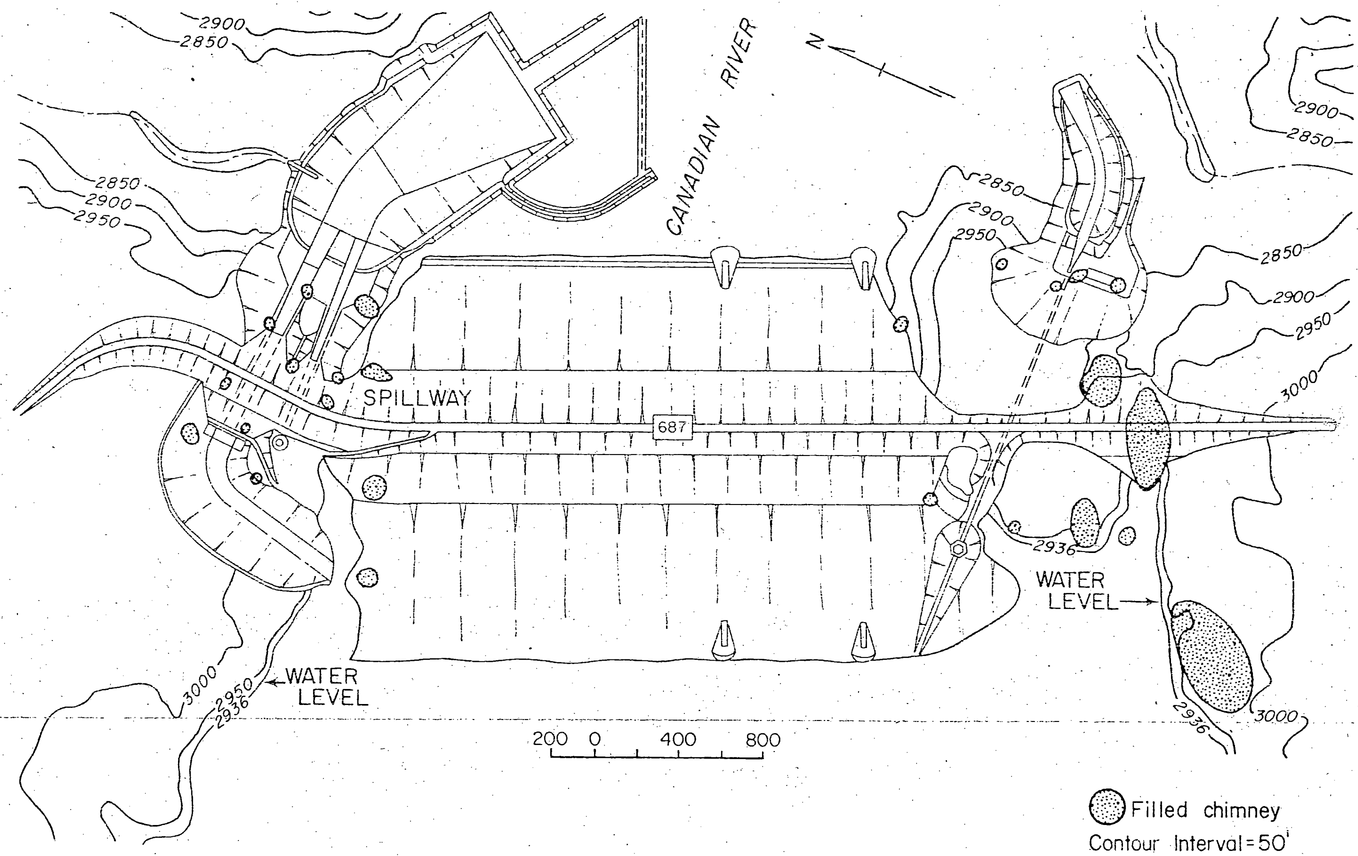


Figure 59. Sanford Dam, Texas. Twenty-seven filled collapse chimneys were discovered during construction of the dam (from Bock and Crane, 1963).

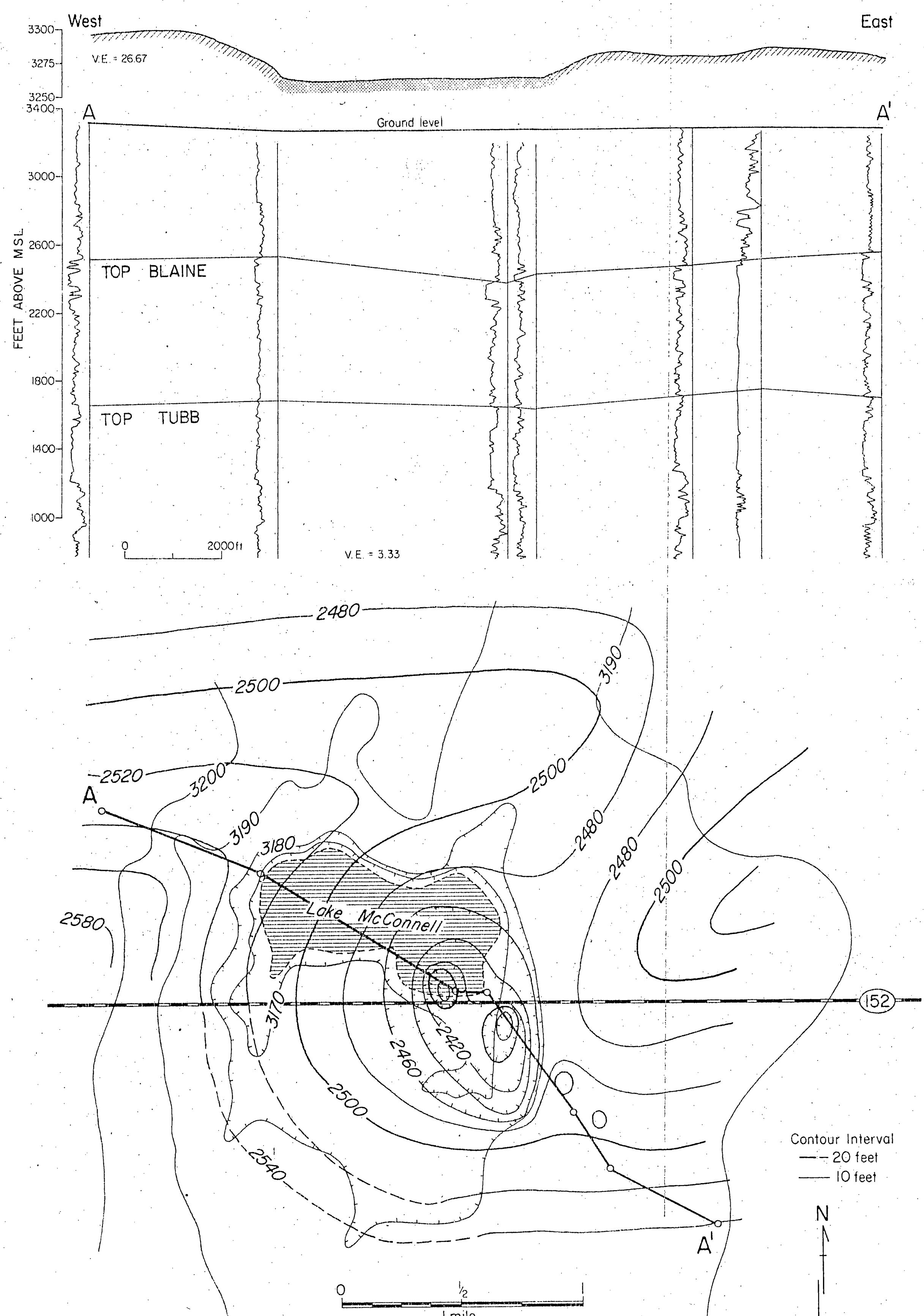


Figure 60. Topographic map of Lake McConnell overlying a structure contour map of a subsidence bowl on the top of the Blaine Formation. The cross section A-A' shows thinning of the Blaine Formation due to salt solution.

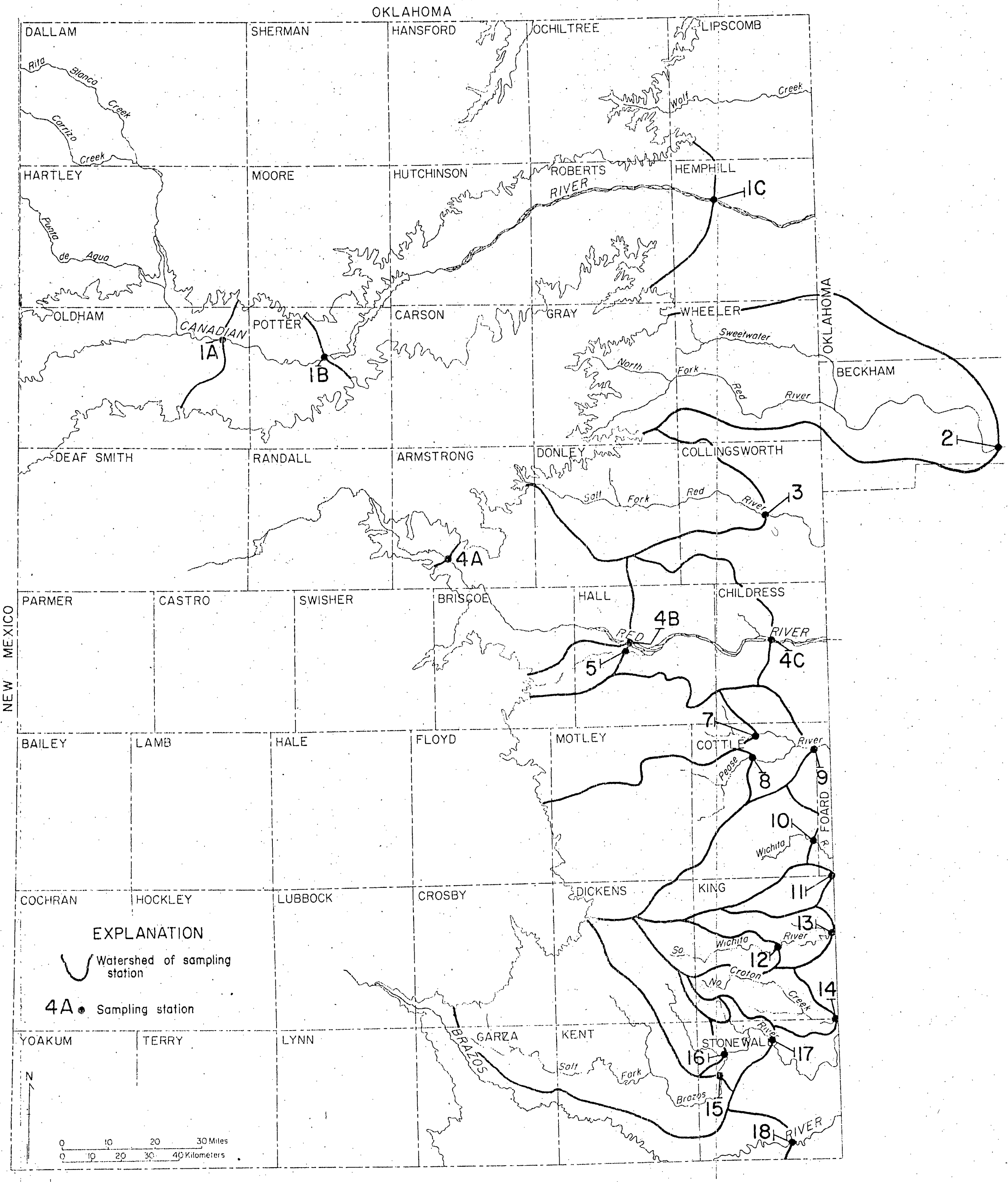


Figure 61. Drainage sub-basins and water-quality monitoring stations, Canadian River Valley and Rolling Plains (see table 4 for water quality data).

FUTURE RESEARCH GOALS

The continued goal of nuclear waste management studies in the Texas Panhandle is a comprehensive, detailed, integrated, and balanced program that is designed to foresee and address all problems that might conceivably affect safe isolation of nuclear materials.

Research to determine if potentially suitable areas for nuclear waste isolation exist in the Palo Duro and Dalhart Basins has been underway since 1977, and the program will probably continue at least through 1982. Funded by the Department of Energy, this program is being conducted by the Bureau of Economic Geology, The University of Texas at Austin.

As outlined in this report, in the early phases of the program subsurface research has included regional stratigraphic studies of all major strata in the basins, as well as descriptions of all major salt sequences, including their geometry, distribution, composition, and facies associations. Continuing studies will provide detailed description and genetic interpretations of the salt using core data to characterize salt quality and define specific salt depositional and predictive models. Presently it is possible to predict facies and salt quality variations on a basin-wide level; ideally a primary goal of the research is to develop predictive capability at a detailed level.

Hydrologic studies are being designed to determine where water occurs in the basins, where it is moving, and how fast it is moving. A principal requirement in secure isolation of waste is that water must not invade the repository unit and that water will not transport radioactive materials away from a potential storage site. Because subsurface aquifers are so essential to agriculture, it is absolutely vital to insure that water quality will not be affected and that possible undiscovered water supplies will not be contaminated.

A thorough understanding of resource potential in the basins is necessary for future, potential site evaluation. A potential site should not coincide with significant reserves or potential resources of energy and minerals so that the area will be protected from future mineral and energy exploration.

Basic objectives of surface geomorphic studies have been to insure that any future, possible nuclear waste isolation sites are secure from erosion, stream incision, and salt dissolution. Continuing studies are designed to predict accurately rates of slope retreat, stream development, and measurement of surface erosion and sediment transport. These values will indicate if or how soon, even if considered in terms of tens of thousands of years, surface erosion might affect a waste repository site. Because surface linear elements are present in the region, continuing research is designed to establish cause-effect relationships between the linear anomalies and possible fracture systems which may affect erosional and hydrologic processes. Using the present geometry and position of active salt solution fronts and volumes (rates) of salt being removed from the basin by streams, it is anticipated that salt solution rates can be accurately determined.

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