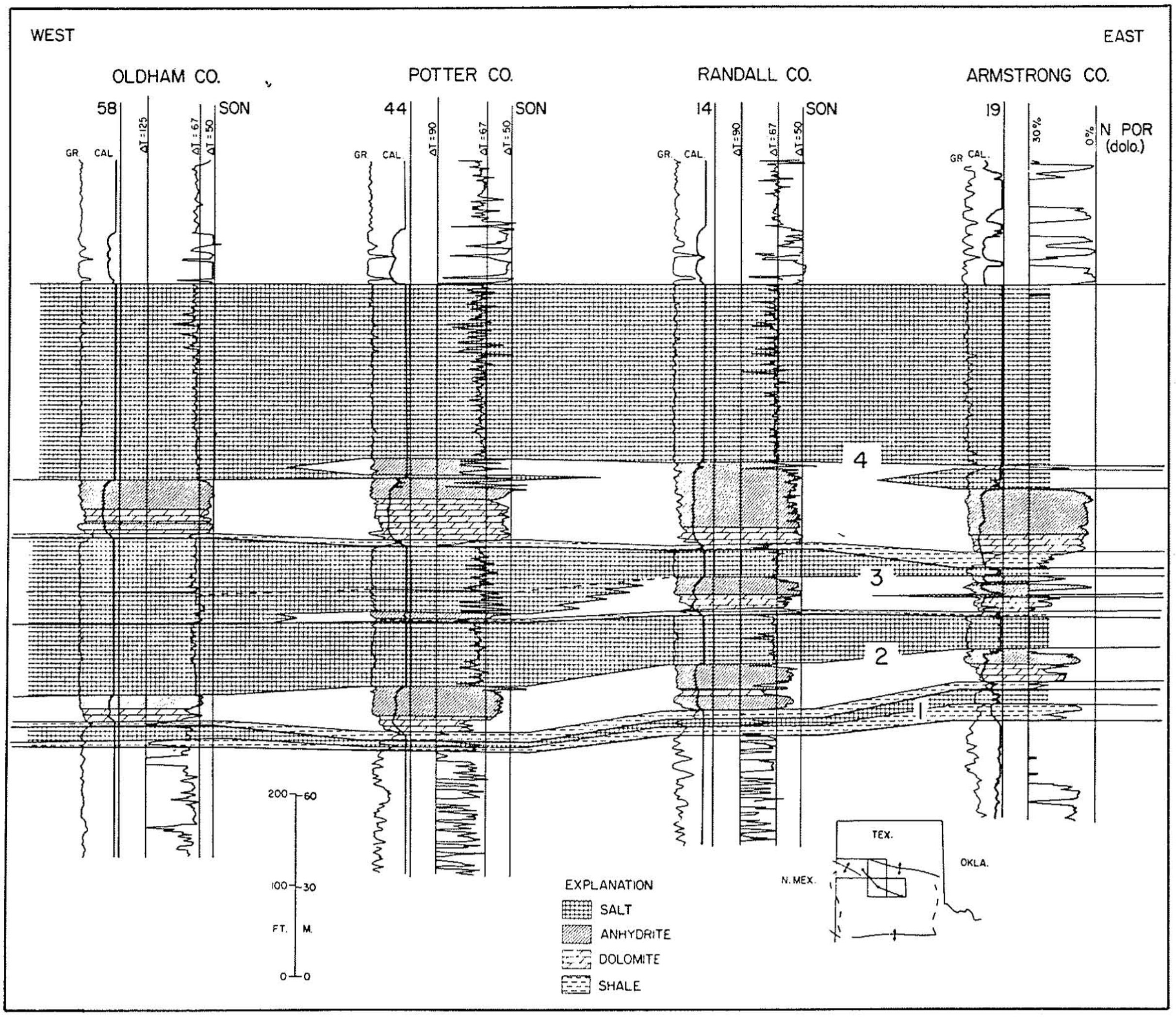
Geological Circular 79-1

1979

Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle

A Report on the Progress of Nuclear Waste Isolation Feasibility Studies (1978)



by S. P. Dutton, Robert J. Finley, W. E. Galloway, Thomas C. Gustavson, C. Robertson Handford, and Mark W. Presley

Bureau of Economic Geology
W. L. Fisher, Director

The University of Texas at Austin
Austin, Texas 78712

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GEOLOGY AND GEOHYDROLOGY OF THE PALO DURO BASIN, TEXAS PANHANDLE

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PURPOSE AND SCOPE

W. E. Galloway and Thomas C. Gustavson

Integrated, detailed, and comprehensive study of the physical stratigraphy, tectonic history, hydrogeology, geomorphology, and resource potential of the Palo Duro and Dalhart Basins, Texas Panhandle, is part of 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 of Texas 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 in the Panhandle area.

The technical program can be subdivided into three broad research tasks, which are addressed by a basin analysis group, a surface studies group, and a basin geohydrology group (fig. 1). The 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 (2,400 m) of core material for analysis and testing of the various lithologies overlying and interbedded with salt units. Concurrently, the surface studies group has collected ground and remotely-sensed data to describe surficial processes, including carbonate and evaporate solution, geomorphic evolution, and fracture system development. The newly formed basin geohydrology group will evaluate both shallow and deep circulation of fluids within the basins.

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

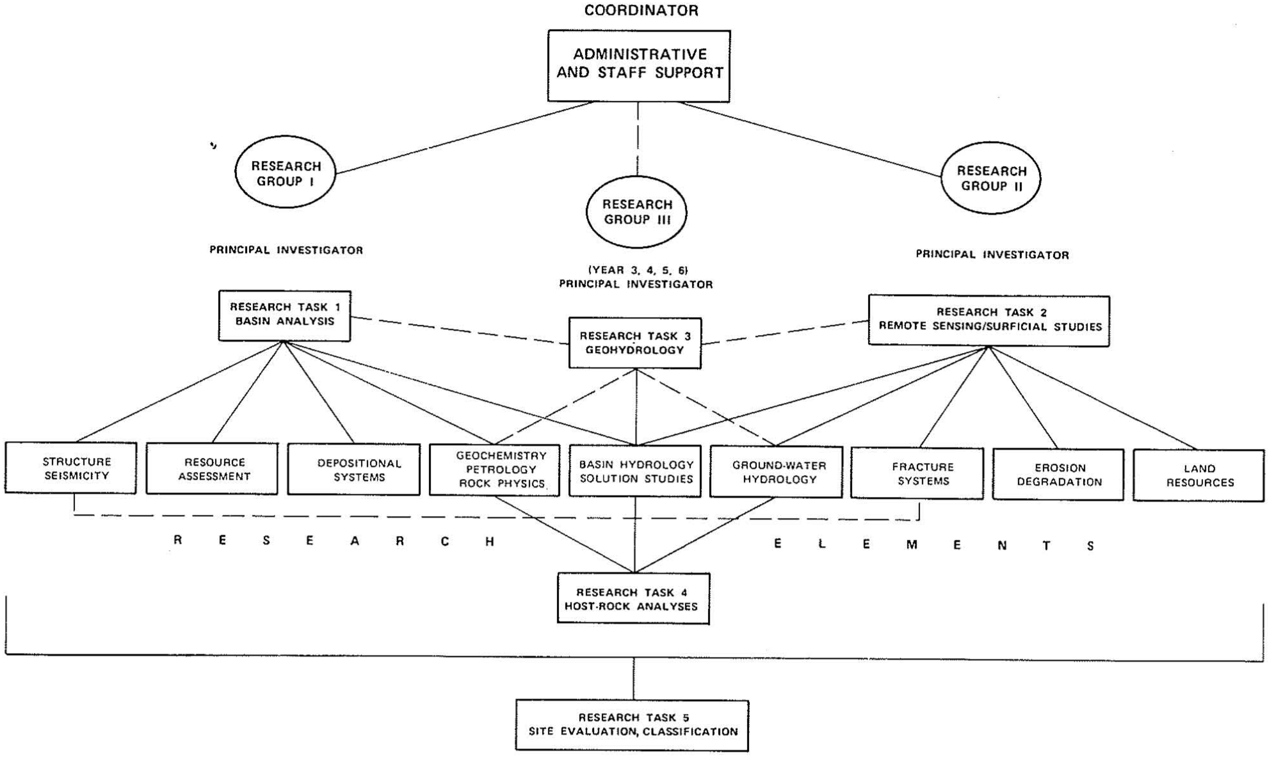


Figure 1. Structure of Texas Panhandle Program.

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

W. E. Galloway

This phase of the project describes the stratigraphy, composition, and extent of salt-bearing Permian strata, provides a three-dimensional description of lithofacies properties required for hydrologic studies, and forms 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 lie primarily in older, deeper rocks. The principal objective of the initial phase of the examination of the Palo Duro and Dalhart Basins (fig. 2) to determine potential suitability for isolation of nuclear wastes was description of major salt sequences--their distribution, thickness, composition, and lateral and vertical facies associations. At the same time, the subsurface data base was also used to carry out genetic stratigraphic studies of all major underlying older Paleozoic and overlying Triassic and Pliocene strata (fig. 3). Stratigraphic units provide potential hosts or reservoirs for various deposits, including petroleum, uranium, base metals, evaporite minerals, and most importantly, fresh water. Consequently, assessment of resource potential, or resource fairways within the basins, is the second principal objective.

Initial subsurface analysis provided the basis for selection of several 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 from cores are being described and analyzed using various techniques. Geophysical well logs will enable geologists to calibrate responses of various downhole measurements (natural gamma radiation, formation density, interval travel time, electrical properties) with actual rock types. Calibrated logs can then be used to improve interpretations of rock composition and thickness previously made using logs from numerous petroleum test wells.

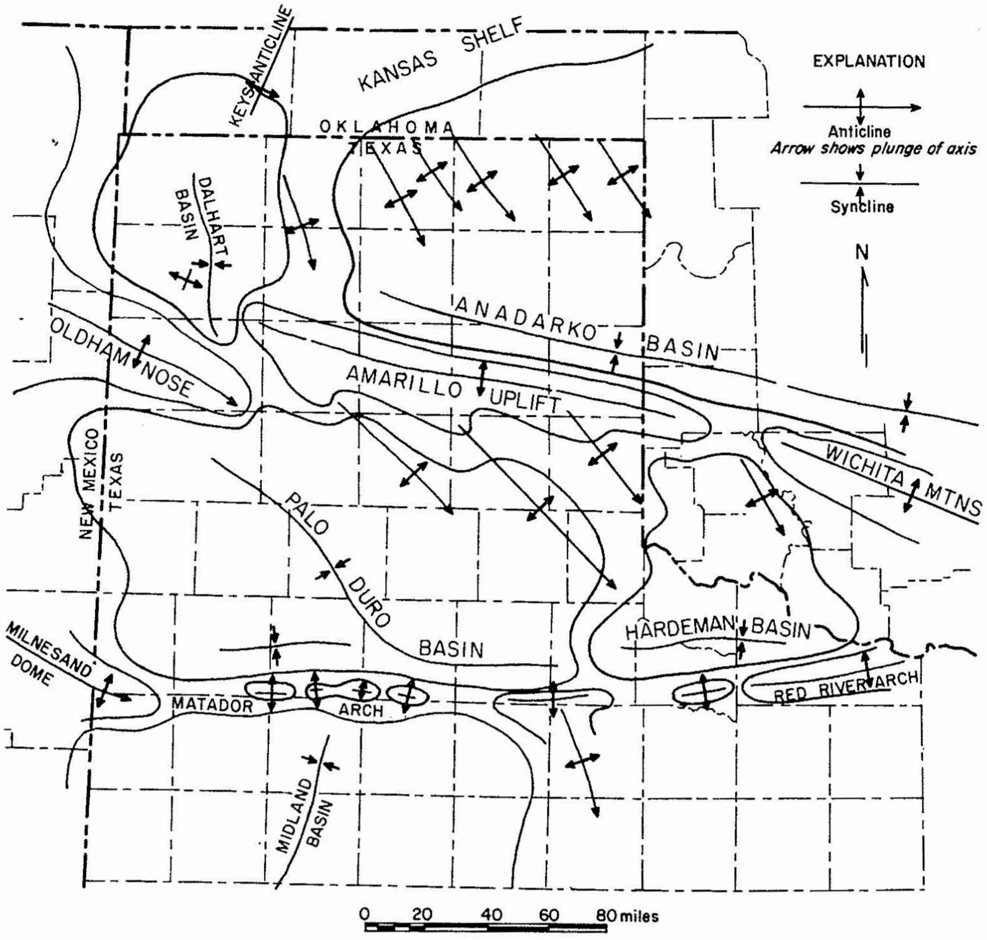
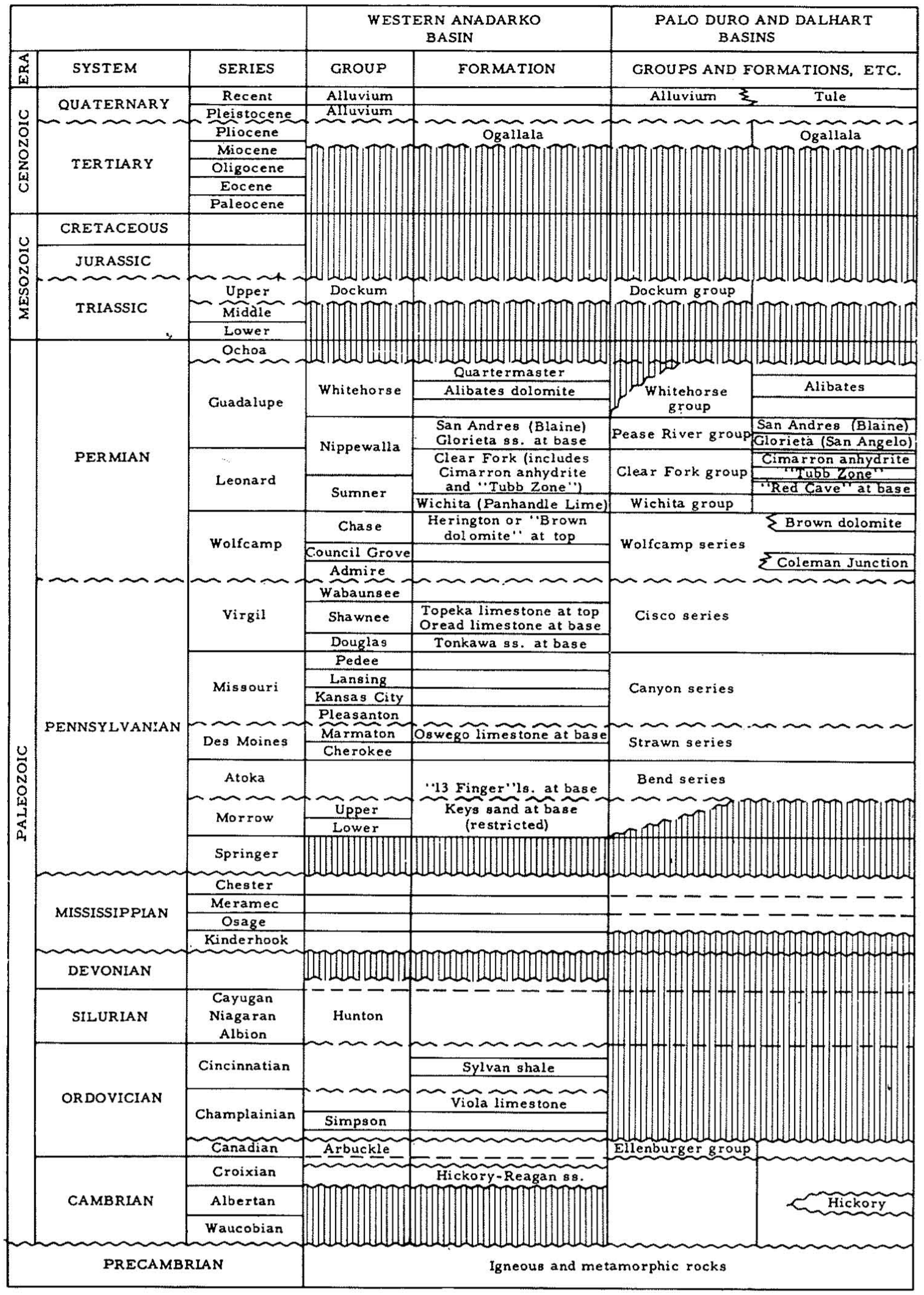


Figure 2. Structural elements and general index map of the Texas Panhandle (from Nicholson, 1960).



			WESTERN ANADARKO BASIN		PALO DURO AND DALHART BASINS	
ERA	SYSTEM	SERIES	GROUP	FORMATION	GROUPS AND FORMATIONS, ETC.	
CENOZOIC	QUATERNARY	Recent	Alluvium		Alluvium	Tule
		Pleistocene	Alluvium			
	TERTIARY	Pliocene		Ogallala		Ogallala
		Miocene				
		Oligocene				
		Eocene				
		Paleocene				
MESOZOIC	CRETACEOUS					
	JURASSIC					
	TRIASSIC	Upper	Dockum		Dockum group	
		Middle				
		Lower				
PALEOZOIC	PERMIAN	Ochoa				
		Guadalupe	Whitehorse	Quartermaster	Whitehorse group	Alibates
				Alibates dolomite		
			Nippewalla	San Andres (Blaine) Glorieta ss. at base	Pease River group	San Andres (Blaine) Glorieta (San Angelo)
		Leonard		Clear Fork (includes Cimarron anhydrite and "Tubb Zone")	Clear Fork group	Cimarron anhydrite "Tubb Zone" "Red Cave" at base
			Sumner	Wichita (Panhandle Lime)	Wichita group	
		Wolfcamp	Chase	Herington or "Brown dolomite" at top	Wolfcamp series	Brown dolomite
			Council Grove			Coleman Junction
			Admire			
	PENNSYLVANIAN	Virgil	Wabaunsee		Cisco series	
			Shawnee	Topeka limestone at top Oread limestone at base		
			Douglas	Tonkawa ss. at base		
		Missouri	Pedee		Canyon series	
			Lansing			
			Kansas City			
			Pleasanton			
		Des Moines	Marmaton	Oswego limestone at base	Strawn series	
			Cherokee			
		Atoka		"13 Finger" ls. at base	Bend series	
		Morrow	Upper	Keys sand at base (restricted)		
			Lower			
		Springer				
	MISSISSIPPIAN	Chester				
		Meramec				
		Osage				
		Kinderhook				
	DEVONIAN					
	SILURIAN	Cayugan Niagaran Albion	Hunton			
	ORDOVICIAN	Cincinnatian		Sylvan shale		
		Champlainian		Viola limestone		
			Simpson			
		Canadian	Arbuckle		Ellenburger group	
	CAMBRIAN	Croixian		Hickory-Reagan ss.		
		Albertan				Hickory
		Waucobian				
PRECAMBRIAN			Igneous and metamorphic rocks			

Figure 3. Stratigraphic names applied to the Palo Duro and western Anadarko Basins, Texas (from Nicholson, 1960).

DATA

Mark W. Presley

The subsurface 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 (fig. 4) includes logs from downhole geophysical probes (well logs) and described well cuttings (sample logs). Each of the 2,280 data points represents 1 or more log types, for a total of 4,500 well logs and 888 sample logs (fig. 4).

The data base was chosen to include all available logs in the counties in the central parts of the Palo Duro and Dalhart Basins (fig. 4). 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. Well names and operators for all wells used in this report are shown in table 1.

Standard log interpretation techniques were used for lithostratigraphic mapping and construction of cross sections. Criteria for defining salt are shown in figure 5. 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 5, in which values are anomalous or missing owing to the enlarged borehole.

Table 1. Well names and operators corresponding to Bureau of Economic Geology numbering system. These wells are used on all cross sections in this report.

County	BEG number	Operator	Well name
Armstrong	1	Standard Oil	No. 1-A Palm
	11	Ketal Oil	No. 1 F. B. Massie-Mo.
	16	Hassie Hunt Trus.	No. 1 J. A. Cattle
	19	Texaco	No. 1 Ritchie
	22	W. V. Harlow	No. 1 Mattie Hedgecoke
	23	Burdell Oil	No. 1 McGehee Strat Test
Briscoe	20	Gulf Oil	No. D-1 Rodgers
	21	Cockrell	No. 1 Allard
	23	Amerada	No. 1 Hamilton
Castro	1	Amarillo Oil	No. 1 C. R. Veigel
	7	Union of Cal.	No. 1 Formwalt
	9	Ashmun & Hilliard	No. 1 Willis
	10	Phillips	No. 1 Morris "J"
	11	Sun Oil	No. 1 Herring
	13	Amarillo Oil	No. 1 L. C. Boothe
	14	Sun Oil	No. 1 Haberer
	15	Sun Oil	No. 1 Uselton
	16	Ashmund & Hilliard	No. 1 J. L. Merritt
	17	Standard of Texas	No. 1 Steakley
	18	Anderson-Prichard	No. 1 Fowler-McDaniel
Childress	29	Claud Hamill	No. 1 Kent McSpadde
	34	O. P. Leonard	No. 1 J. E. Turner
	37	Perkins-Prothro	No. 1 Howard
	40	R. D. Gunn	No. 1 G. B. Dorsey
	42	Kay Kimbell	No. 1 J. Rhea
	48	U. H. Griggs	No. 1 Smith
	49	Sinclair Oil	No. 1 Willard Mullins
	74	British-American Oil	No. 1 E. V. Perkins
Dallam	5	Royal Resources	No. 31 Sneed
	41	Skelly Oil	No. 1 E. J. Dixon
Deaf Smith	2	Frankfort Oil	No. 1 Allison-Hayes
Floyd	4	Lovelady	No. 1 E. E. Wells
	12	Perry Larson	No. 1 Goins
	13	Cockrell Corp.	No. 1 Karstetter
	26	Soderstrom	No. 1 Battey
	30	Standard Oil	No. 1 Minnie Adams
Hale	1	El Ray Petr.	No. 1 Whitten
	38	Henderson & Erickson	No. 1 Overton
Hall	18	Amerada Petr.	No. 1 LaFayette Hughes
	19	Midwest Oil	No. 1 Hughes
	22	R. D. Gunn	No. 1 T-Bar Ranch
	23	Robinson Bros. Oil	No. 1 Hughes
Hartley	35	Whitehall	No. 1 Reynolds Cattle
Lamb	1	Gulf Oil	No. 1 L. E. Bartlett
	3	Steve Gose	No. 1 J. E. Busby
	12	DEPCO, Inc.	No. 10 Young
	27	Vaughn Petr.	No. 1 Eva Wells
	28	R. H. Fulton	No. 1 Cowen
	35	Shell Oil	No. 1 Ivey & McCary
	59	Humble Oil	No. 1 Fowler
	102	Cherry Petr.	No. 1 Middlebrook
Moore	8	Continental Oil	No. 1 E. L. Amis
	29	Gabe D. Anderson	No. 1-24 Bennett
	43	Grady L. Fox	No. 1 Sneed
	46	Colorado Interstate	No. 36-A Masterson
Oldham	5	Shell Oil and Atlantic	No. 98-1 Fulton
	45	Shell Oil	No. 315-4 Alamosa
	58	Shell Oil	No. 1 Taylor
Parmer	8	Texaco	No. 1 Owen Patton
	10	Sunray Oil	No. 1 Kimbrough
Potter	10	Sinclair	No. 17 Bivins
	25	Bivins	No. 1 LX Shell
	41	Asarco	No. 1-29 WDW
	44	Humble	No. 1 O. H. Gouldy
Randall	1	Frankfort Oil	No. 1 H. L. Erwin
	2	Burdell Oil	No. 1 Winters
	14	Shell Oil	No. 1 Nester
	23	Frankfort Oil	No. 1 Stinnett
Swisher	1	Frankfort Oil	No. 1 Wesley
	2	L. A. Helms	No. 1 Harris
	3	Frankfort Oil	No. 1 Culton
	6	Standard Oil	No. 1 A. B. Johnson
	8	Burdell Oil	No. 1 Bradford
	9	Humble Oil	No. 1 A. B. Nanny
	10	Consolidated Gas	No. 1 Patton
	11	Consolidated Gas	No. 1 H. O. Thompson
	12	Frankfort Oil	No. 1 Sweatt
	13	Sinclair Oil	No. 1 Savage

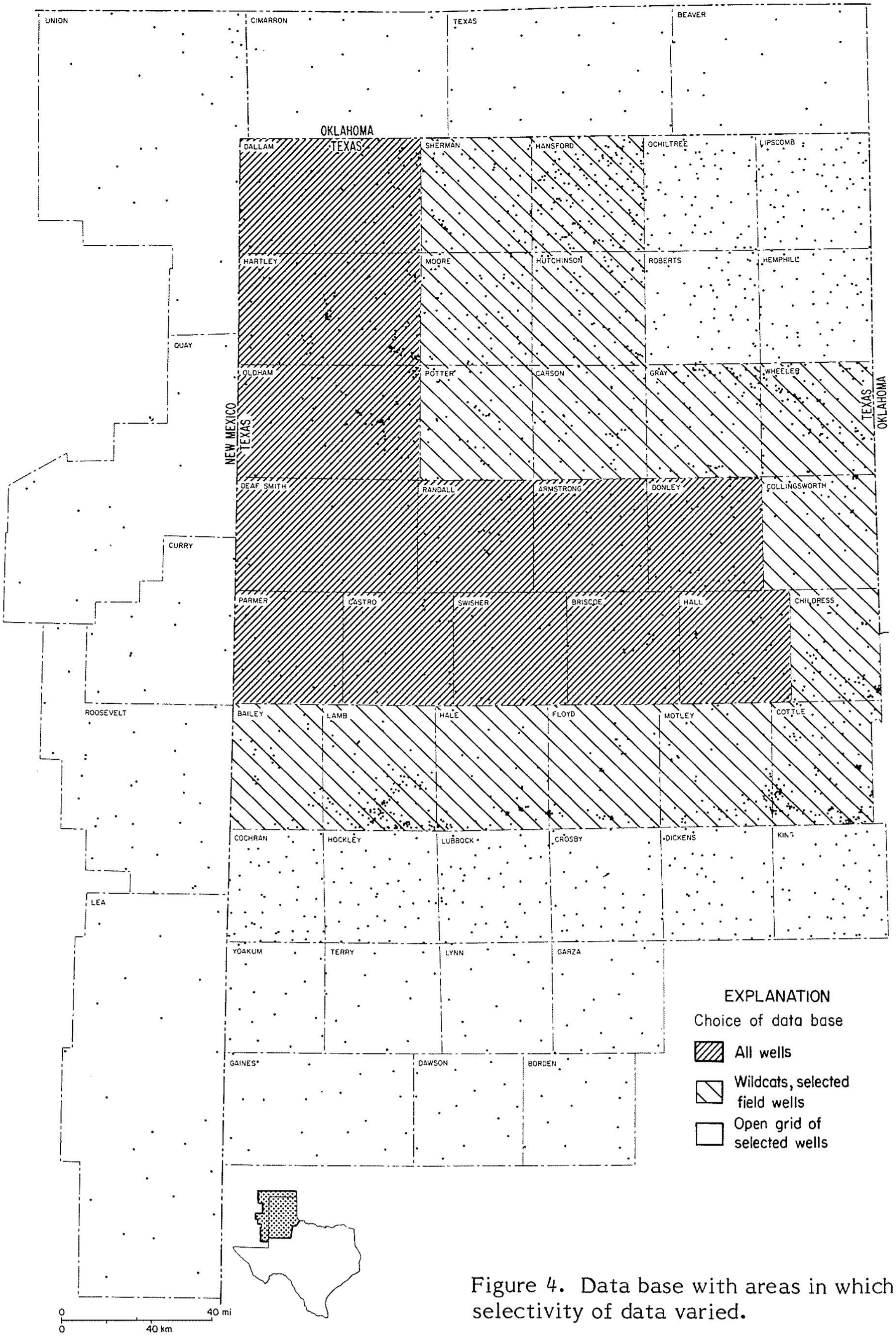


Figure 4. Data base with areas in which the selectivity of data varied.

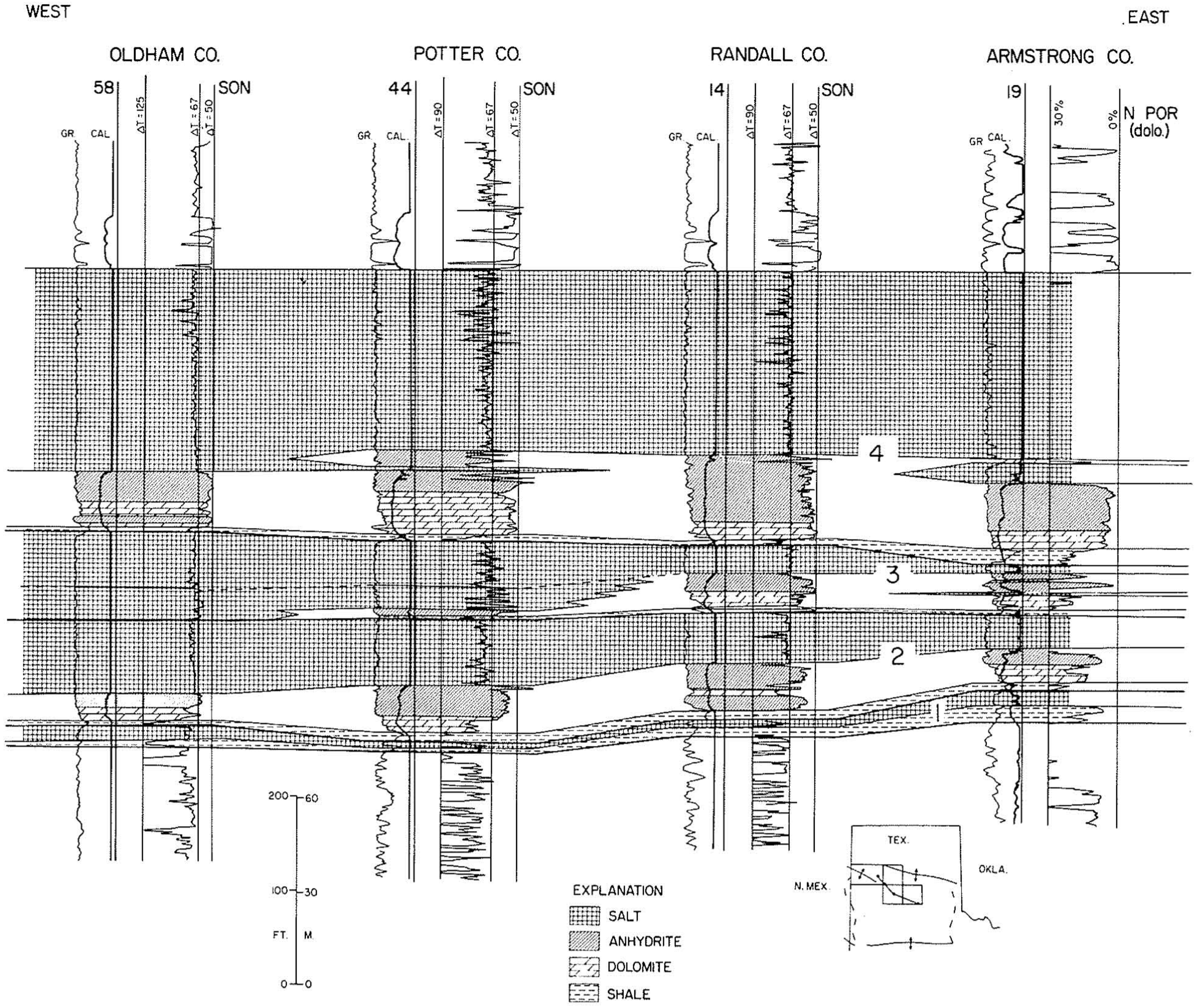


Figure 5. East-west cross section, lower San Andres cyclic units, northern Palo Duro Basin--an example of log-lithology interpretations in the salt-bearing sequence. Log types include gamma ray (GR), caliper (CAL), sonic (SON), and neutron porosity (NPOR).

BASIN STRUCTURAL AND STRATIGRAPHIC FRAMEWORK

S. P. Dutton

The stratigraphic sequence of the Palo Duro Basin is 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 (3,000 m) below the surface. The basin is asymmetrical, with the deepest part immediately north of the Matador Arch, the southern boundary of the basin (fig. 6). The basin axis trends east-west in the eastern part and northwest-southeast in the western part of the basin. Several faults strike northwest just south of the Amarillo Uplift, but the rest of the basin lacks evidence of significant faulting.

Strata in the Palo Duro Basin range in age from Precambrian to Plio-Pleistocene (figs. 7 and 8). The sequence can be subdivided into six genetically related units: pre-Pennsylvanian, Pennsylvanian, lower Permian, upper Permian, Triassic, and Plio-Pleistocene. Each unit exhibits distinctive facies tracts, depositional style, geohydrology, and resource potential.

(1) The pre-Pennsylvanian section consists of a basal marine sandstone and shallow shelf carbonates. These were deposited before the Palo Duro and Dalhart Basins developed. Only eroded remnants of these older rocks remain. This section is separated from overlying Pennsylvanian strata by a major unconformity.

(2) The Pennsylvanian section composed of mixed carbonate-clastic rocks records the initial development of the present Palo Duro structural and sedimentary basin. Tectonic activity strongly influenced sedimentation patterns. Marine transgression occurred throughout this period as the basin subsided.

(3) The 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) The upper Permian evaporite - red bed clastic sequence records the final filling of the Paleozoic marine-influenced basin. Deposition occurred in restricted, back-shelf - sabkha environments.

(5) Triassic strata consist of continental clastics deposited in a major lacustrine basin by rivers, deltas, and fan deltas. Remnants of Cretaceous rocks are preserved in the southwestern part of the Palo Duro Basin.

(6) The Plio-Pleistocene section contains continental clastics deposited by fluvial and eolian processes. Caliche at the top of this sequence comprises the caprock of the Panhandle High Plains.

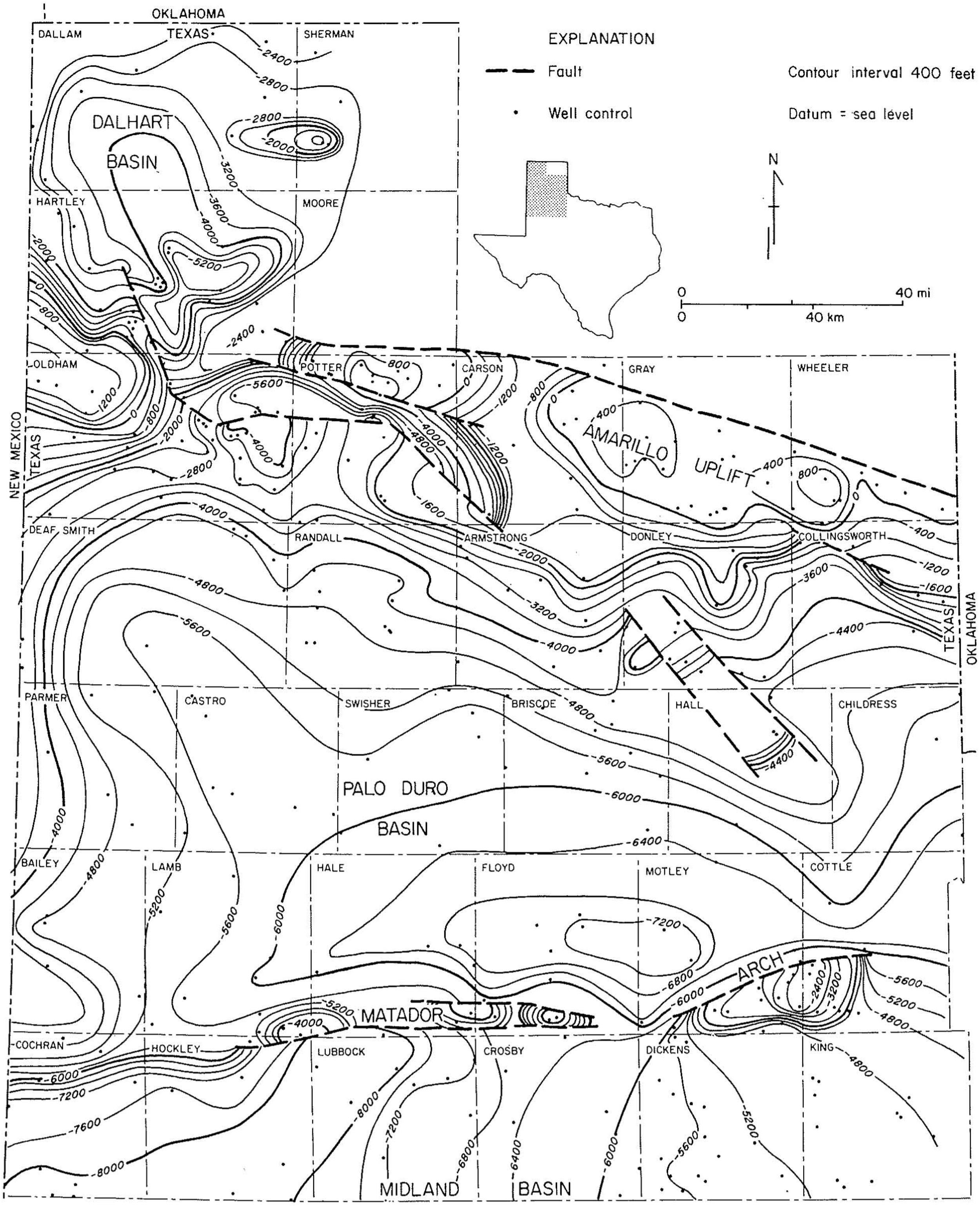


Figure 6. Structure contour map on the top of Precambrian basement, illustrating basement structure in the Palo Duro and Dalhart Basins.

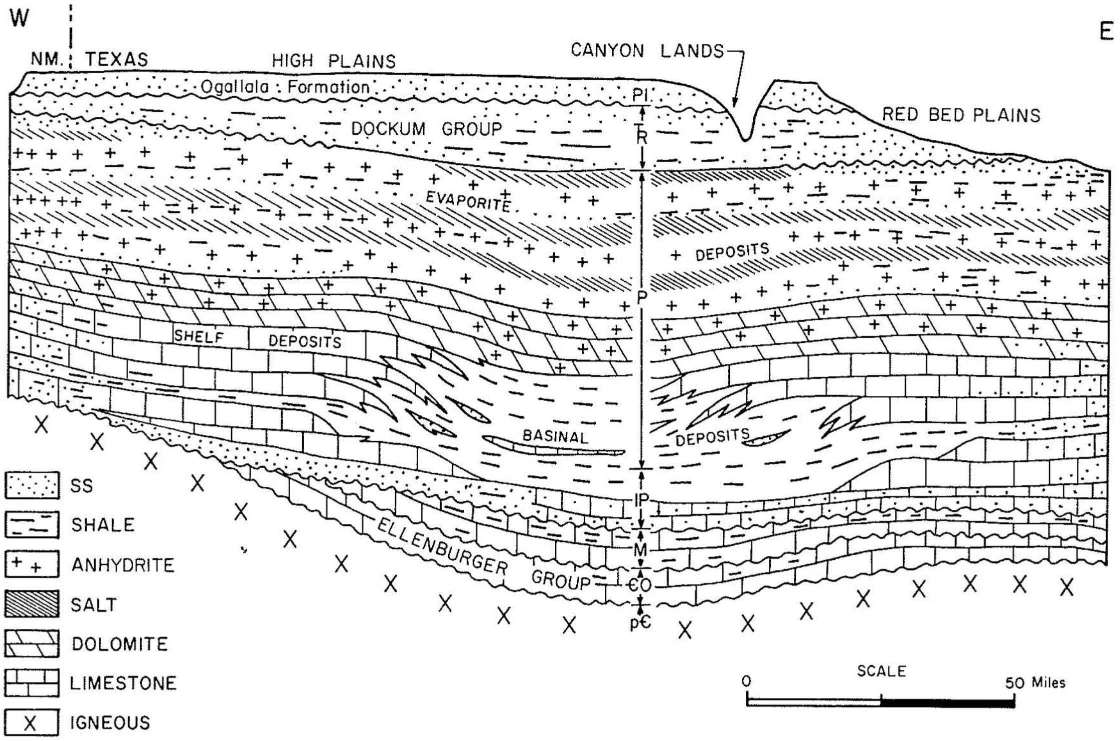


Figure 7. Schematic east-west section across Palo Duro Basin, Texas Panhandle.

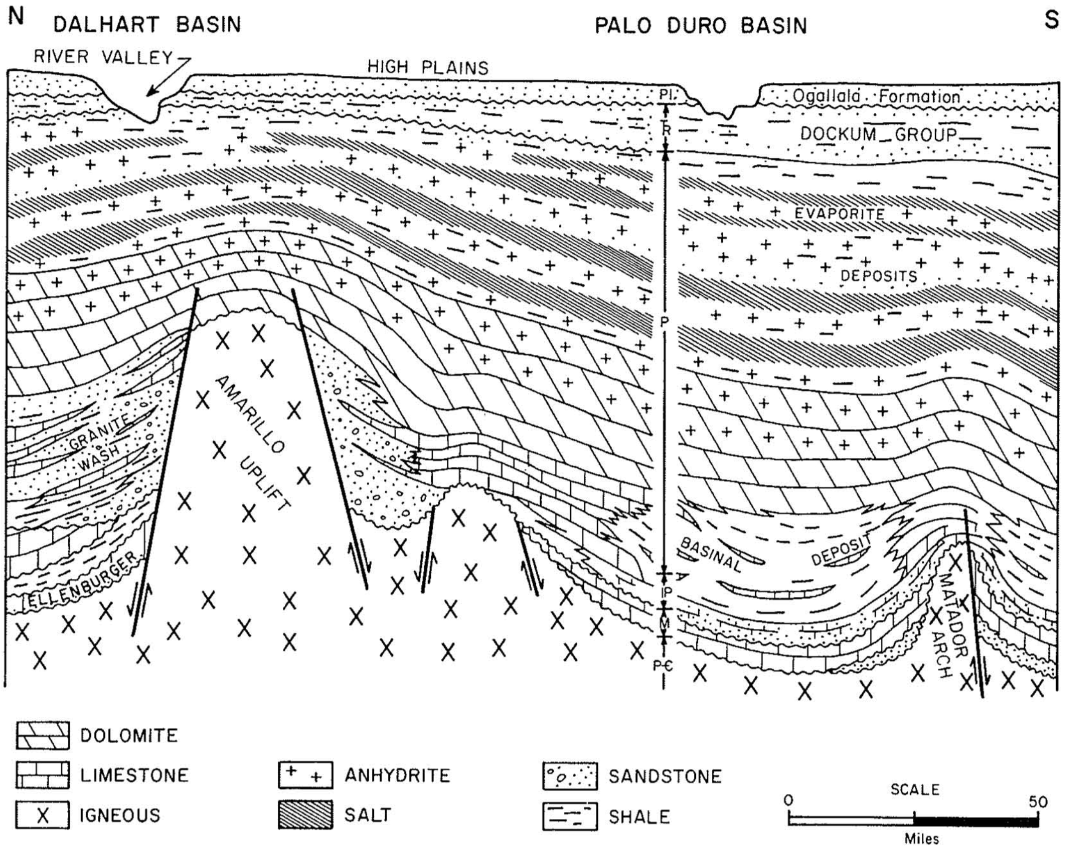


Figure 8. Schematic north-south section across Dalhart Basin, Amarillo Uplift, Palo Duro Basin, and Matador Arch, Texas Panhandle.

PRE-PENNSYLVANIAN EROSION AND SHALLOW SHELF DEPOSITION

S. P. Dutton

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

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

By Ordovician time the entire 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. 9).

Upper Ordovician, Silurian, and Devonian strata in the Palo Duro Basin have been eroded or were never deposited. A broad arch ("the Texas Peninsula") trending north-northwest through the central part of the Palo Duro Basin (Nicholson, 1960), was uplifted sometime after deposition of the Ellenburger Group. Lower Paleozoic rocks on the arch were eroded to basement. This extensive erosion left isolated remnants of Upper Cambrian basal sandstone and Ellenburger strata along the east and west flanks of the former arch (fig. 9).

By Mississippian time, the Texas Peninsula was no longer a positive element, and marine-shelf carbonates were deposited across the entire region. A maximum thickness of 1,100 feet (330 m) of Mississippian rocks occurs in Childress County (fig. 10). Like the Ellenburger, Mississippian deposits formed in a shallow marine-shelf environment. Carbonates in the lower part of the Mississippian sequence have been dolomitized, 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. Major deformation began late in the Mississippian Period and continued through the Pennsylvanian Period. Principal positive features that surround and define the Palo Duro Basin--the Amarillo-Wichita Uplift, Matador Arch, Bravo Dome (Oldham Nose), and Milnesand Dome (fig. 2)--were uplifted early in the Pennsylvanian Period. The newly formed 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 were eroded in the exposed highland areas but 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 pre-Pennsylvanian unit were also constructed.

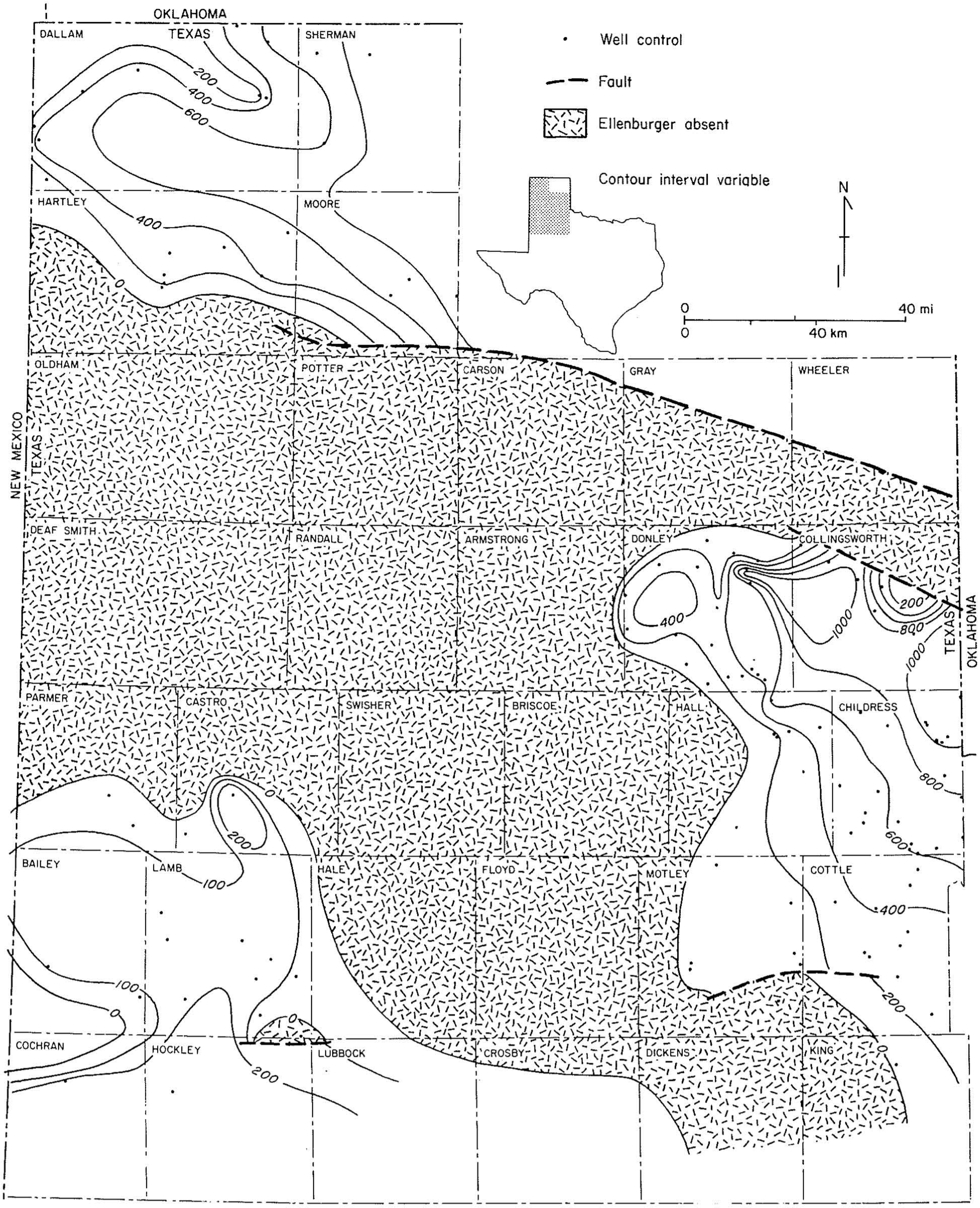


Figure 9. Isopach map of Ellenburger Group.

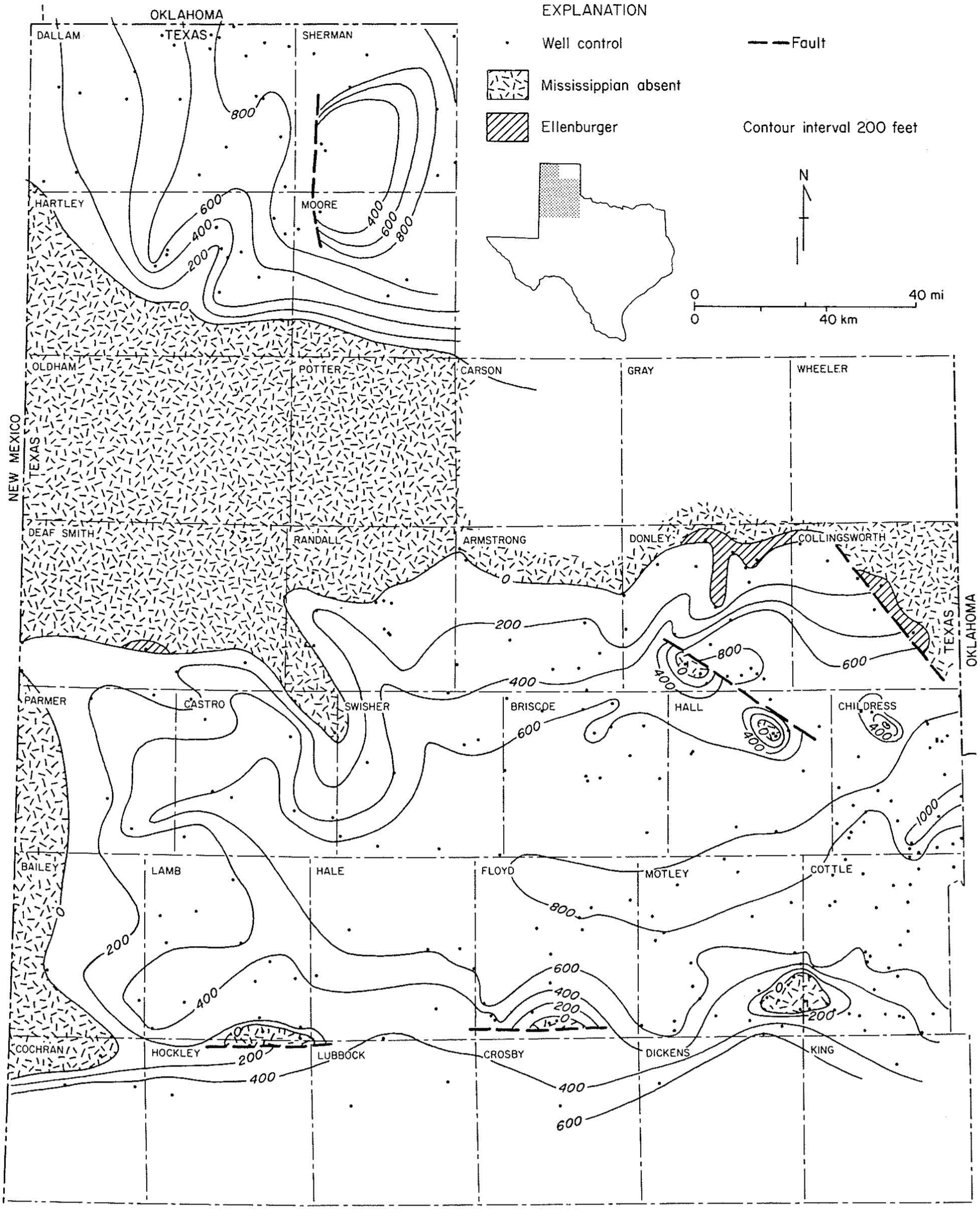


Figure 10. Isopach map of Mississippian section. Mississippian sediments are preserved in the Palo Duro and Dalhart Basins but have been eroded off of adjacent structural uplifts.

DEVELOPMENT OF THE PALO DURO BASIN DURING THE PENNSYLVANIAN PERIOD

S. P. Dutton

During the Pennsylvanian Period the Palo Duro Basin deepened and developed a well-defined, mud-filled basin facies surrounded by carbonate shelf-margins. 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 facies patterns and thickness of sediments. Marine transgression continued throughout the Pennsylvanian Period. There are no widespread marker beds or unconformities in the section. However, there was a noticeable change in depositional style evidenced by differences between lower and upper Pennsylvanian strata. Early Pennsylvanian sedimentation was dominated by terrigenous clastics, but in late Pennsylvanian time carbonate buildups dominated sedimentation, and clastic influence was greatly reduced (figs. 11 and 12).

Twenty-one cross sections of Pennsylvanian strata were constructed for this study (fig. 12), as well as nine isolith maps, seven lithologic percent maps, five porosity maps, a total Pennsylvanian isopach map, and a structure contour map on top of the Pennsylvanian sequence.

Early Pennsylvanian Period--Sediments were deposited in three principal environments: alluvial fan and fan delta, shallow marine shelf, and deep basin (seaward of the marine shelf). Erosion of Precambrian basement that was exposed in the Amarillo Uplift and the Sierra Grande Uplift of eastern New Mexico supplied coarse arkosic sand and gravel ("granite wash") to alluvial fans and fan deltas located along the northern boundary of the basin (fig. 13). Downdip, distal fan sands were interbedded with mud and thin carbonate deposits. Carbonate and clastic sedimentation alternated, and following abandonment each fan became the site of subsequent carbonate deposition.

Most of the Palo Duro was occupied by a shallow shelf, similar to the pre-Pennsylvanian structural setting. The southern part of the region was sufficiently removed from terrigenous clastic source areas so that few sands reached it. Shallow marine carbonates and terrigenous mud were deposited in shallow shelf environments. Basinal shales were deposited only in a small deeper water area immediately north of the Matador Arch.

Late Pennsylvanian Period--A large, well-defined, mud-filled basin developed during late Pennsylvanian time. Carbonate shelf-margin buildups rimmed the basin and stood several hundred feet above the central basin floor (fig. 11). Along the eastern and southwestern basin margins the shelf-edge position remained stationary, and more than 1,000 feet (300 m) of carbonates were deposited. However, two relict shelf margins are recognized in the northern part of the western shelf (fig. 14). The younger shelf is 18 miles (28.9 km) west, or landward, of the older shelf. Retreat of this shelf margin may have been caused by subsidence, as well as an influx of clastic sediment from the Amarillo Mountains.

Basin filling occurred in the Late Pennsylvanian Period when sediment entered the basin through breaches and low areas along shelf-margin trends. Large feeder channels that supplied clastics to the basin were present in the north-central and southeastern Palo Duro area (fig. 15). Basin fill was mostly fine-grained clastics, but sand was also deposited (fig. 15). The areal and cross-sectional geometry of some sandstone units suggests that they were deposited as bar finger sands in high-constructive elongate deltas.

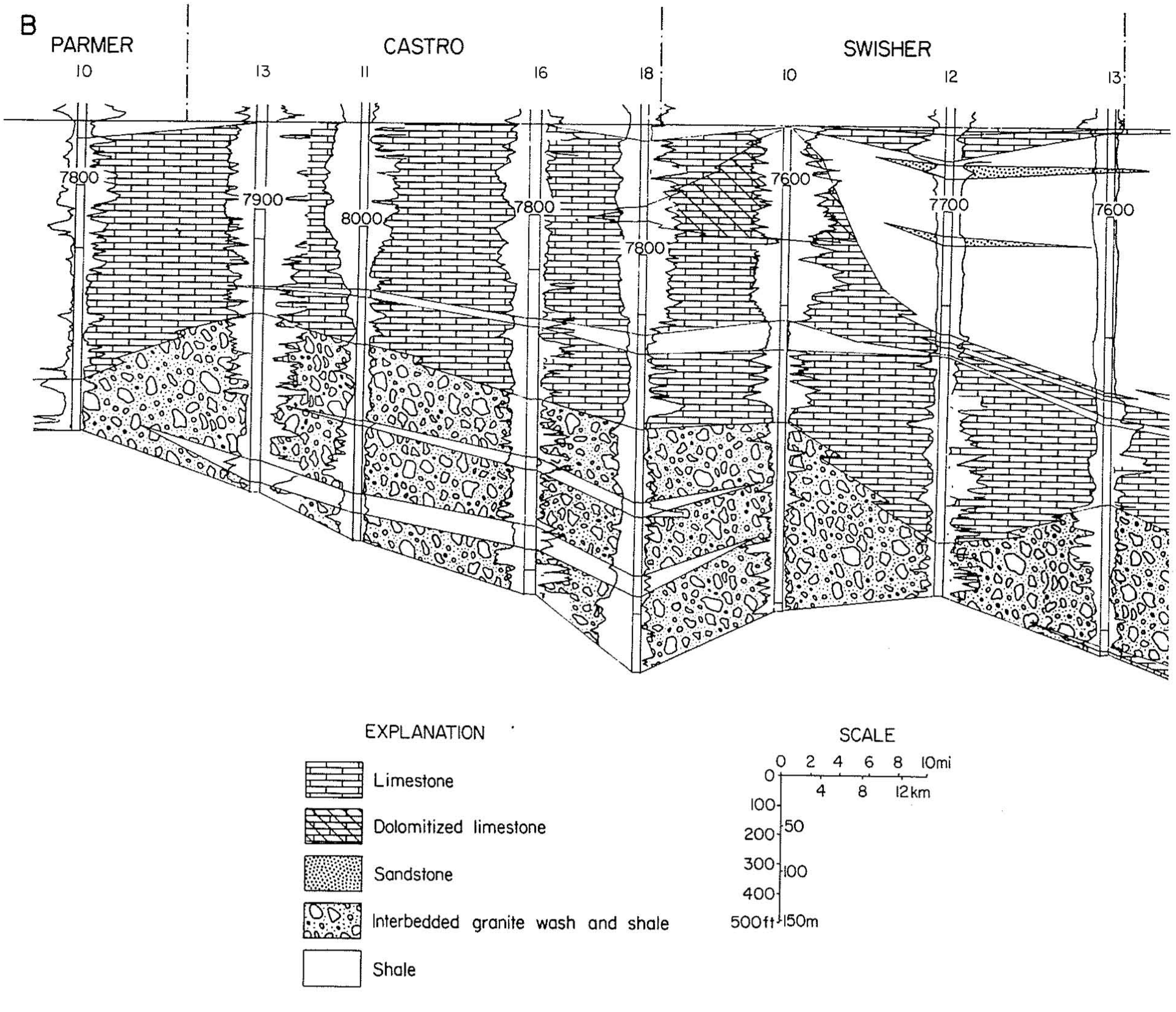
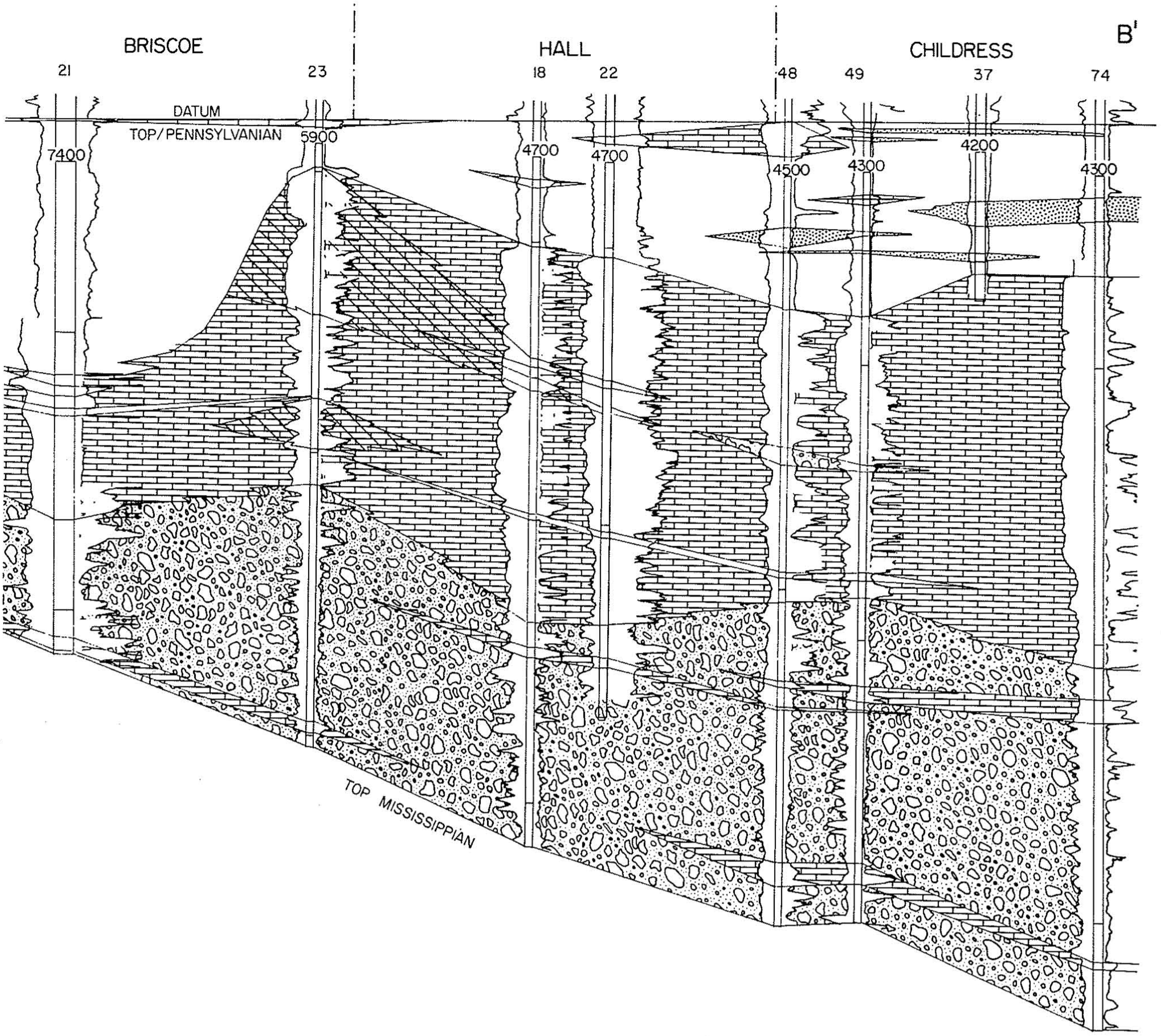


Figure 11. East-west Pennsylvanian cross section B-B^1.


BRISCOE
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DATUM
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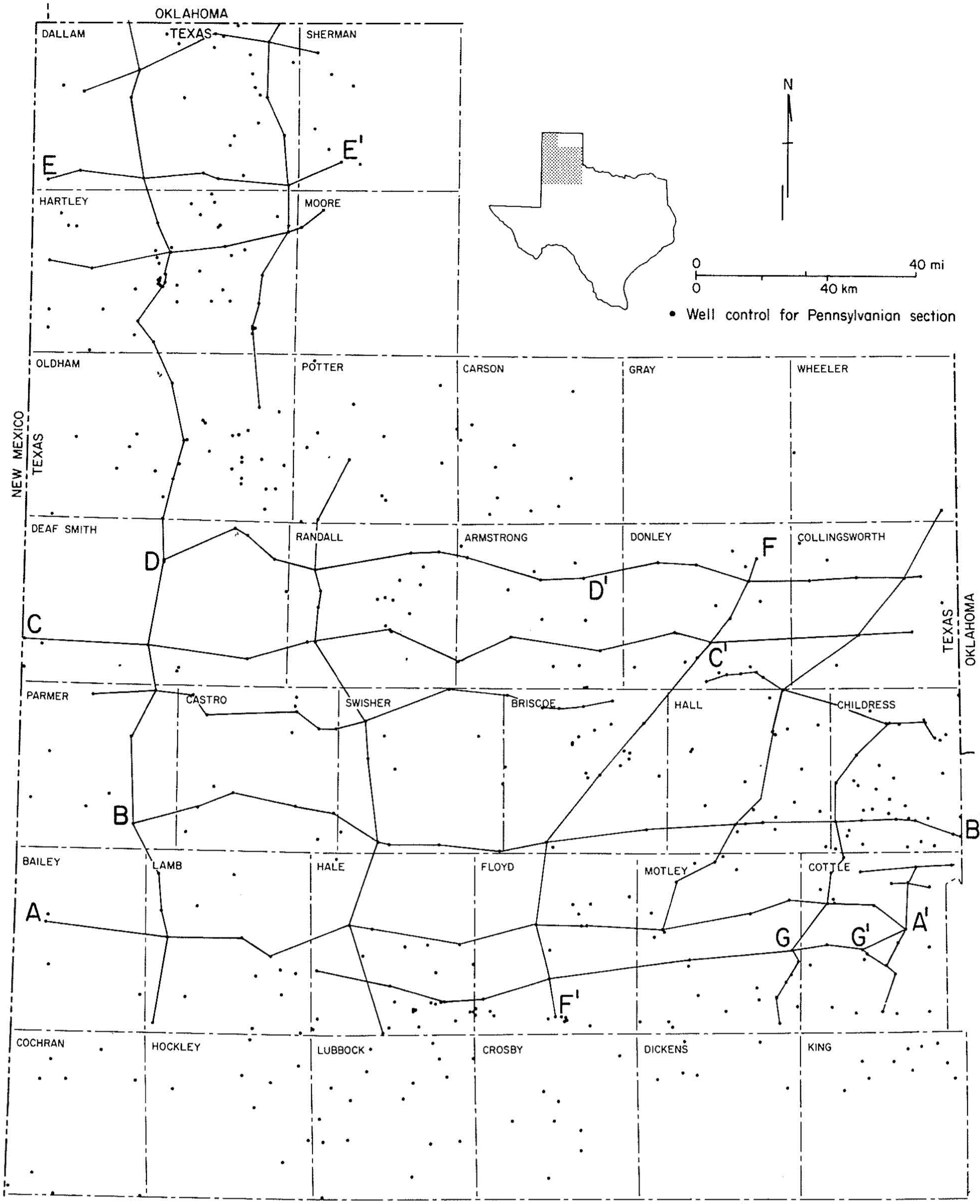


Figure 12. Index map of study area showing Pennsylvanian well control and locations of cross sections.

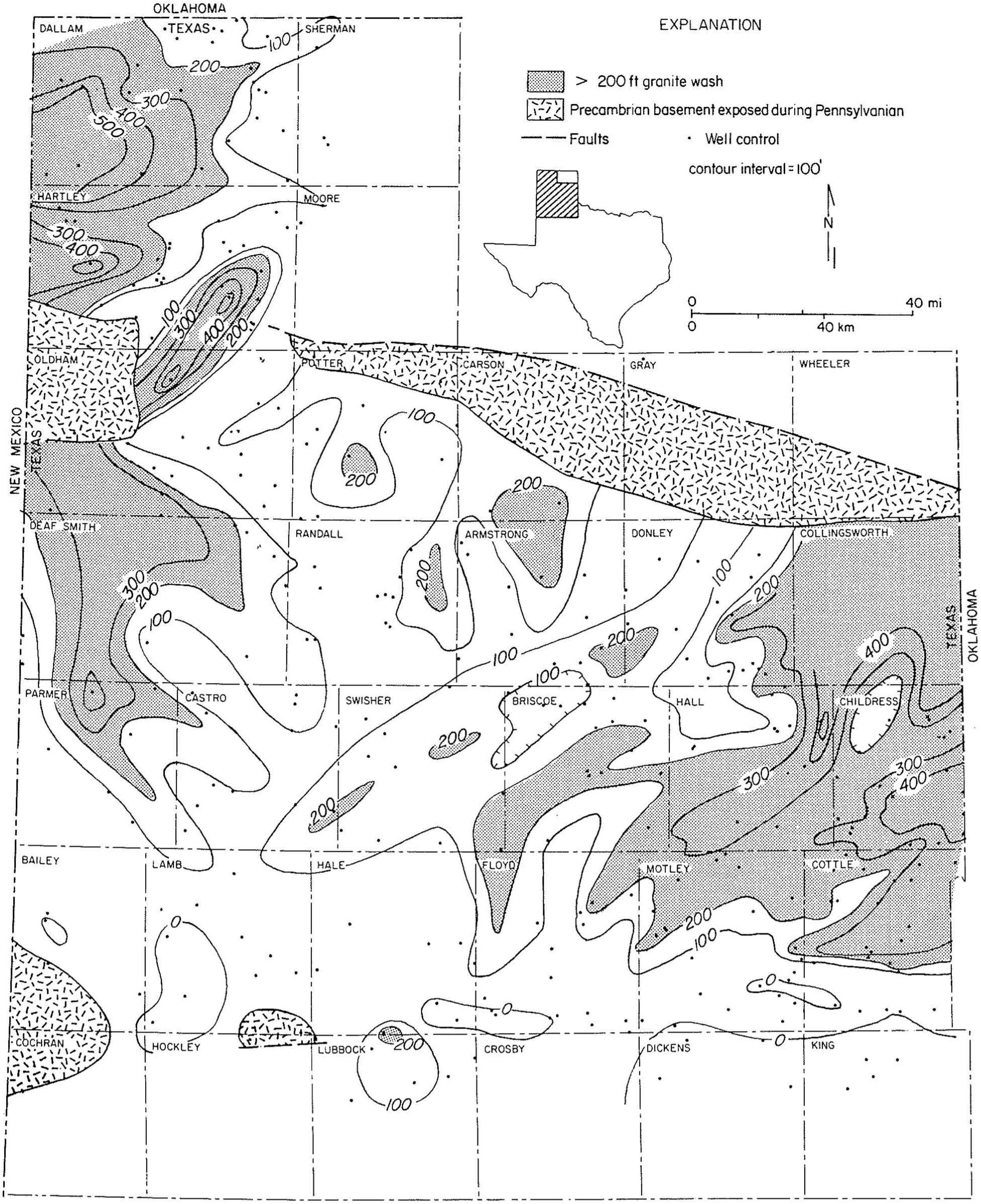


Figure 13. Net granite wash map of lower Pennsylvanian section.

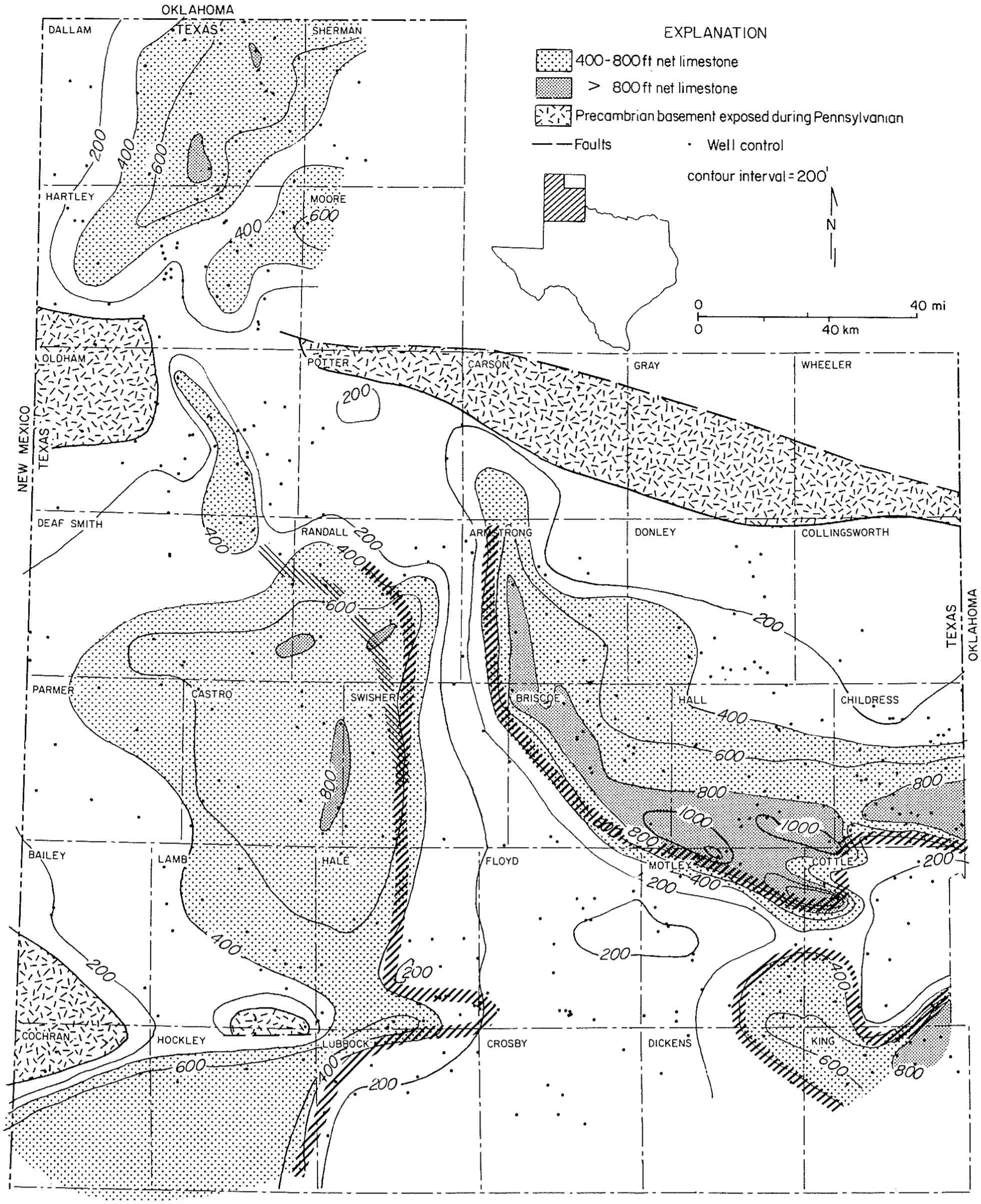


Figure 14. Net limestone map of upper Pennsylvanian section. Position of the shelf margin is shown by dark hachured line. The retreated shelf-edge position is shown by the lighter hachures.

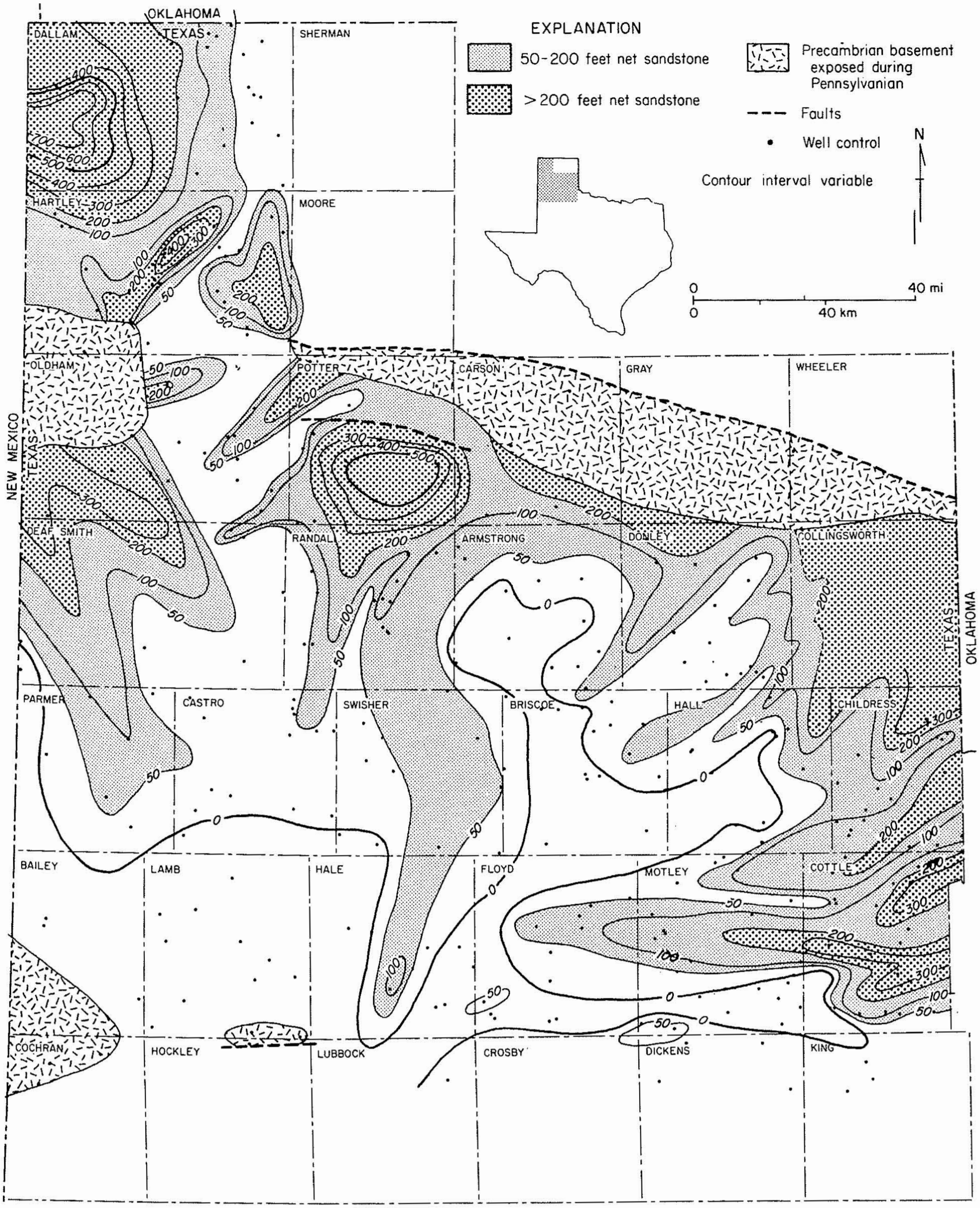


Figure 15. Net sandstone map of upper Pennsylvanian section.

LOWER PERMIAN DEPOSITIONAL SYSTEMS

C. Robertson Handford

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

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

Representative cross sections illustrate the stratigraphic framework (figs. 16, 17, 18, and 19). Lithologic data were interpreted from electric logs and used to construct facies maps (figs. 20, 21, 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. 24 and 25).

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 deposited an arcuate, carbonate shelf-margin complex 400 to 1,800 feet (120 to 548 m) thick that separated the deep basin from shallow shelf environments. Initially the shelf margins were widely separated, but they closed rapidly during Wolfcampian time. Progradational shelf-margin sequences range from 200 to 400 feet (60 to 120 m) thick, implying that each shelf-margin bank stood 200 to 400 feet (60 to 120 m) above the adjacent basin floor.

Slope and basinal system--Black shales and micritic limestones compose the bulk of sediments deposited in basin and slope environments. Terrigenous sediments were introduced by deltas that prograded to the shelf margin and were reworked and transported downslope by suspension settling, turbidity currents, and debris flows or slumping. Thick slope wedges provided foundations for subsequent shelf-margin development and progressively filled the deeper part of the basin.

Sabkha system--Strata belonging to the Wichita Group and lower Clear Fork Formation (an unnamed formation within the Clear Fork Group, herein called the "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 Panhandles into southern Kansas. The Wichita sabkha consisted 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 (91 m) of upper sabkha, bedded salt in 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.

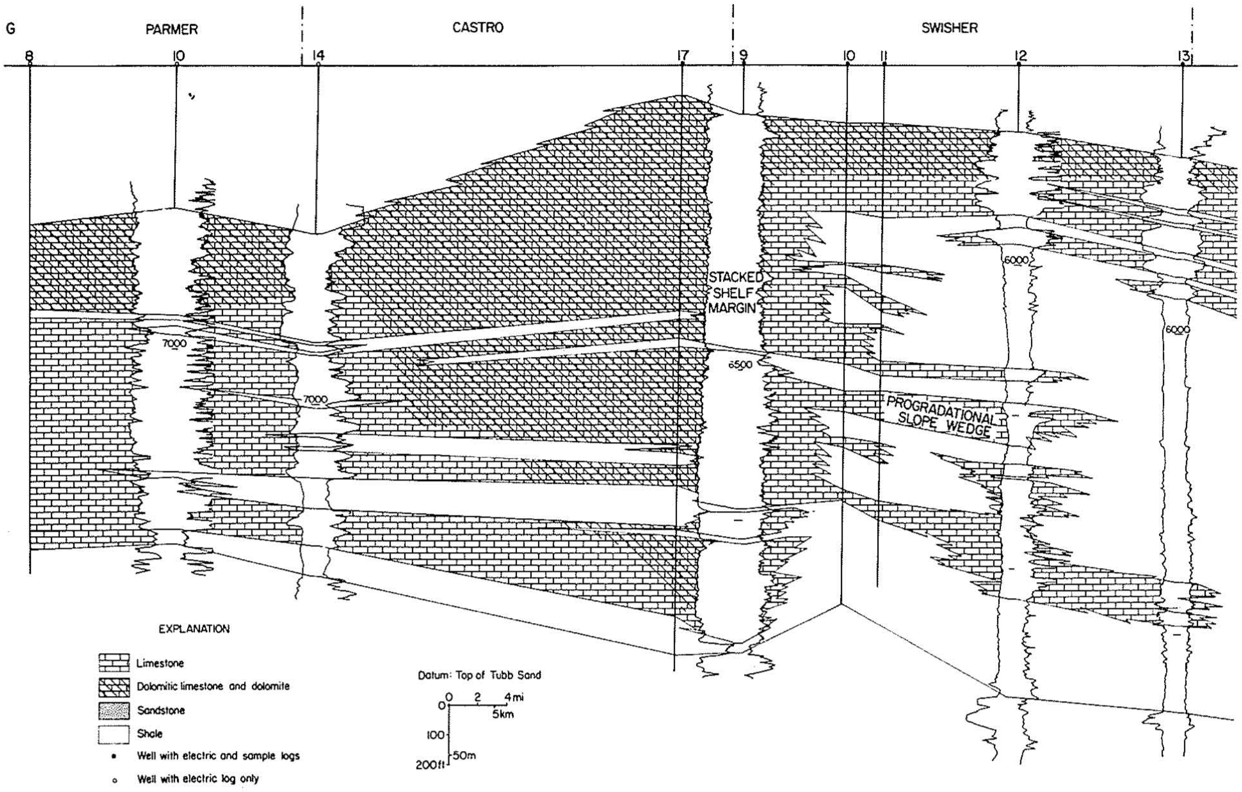
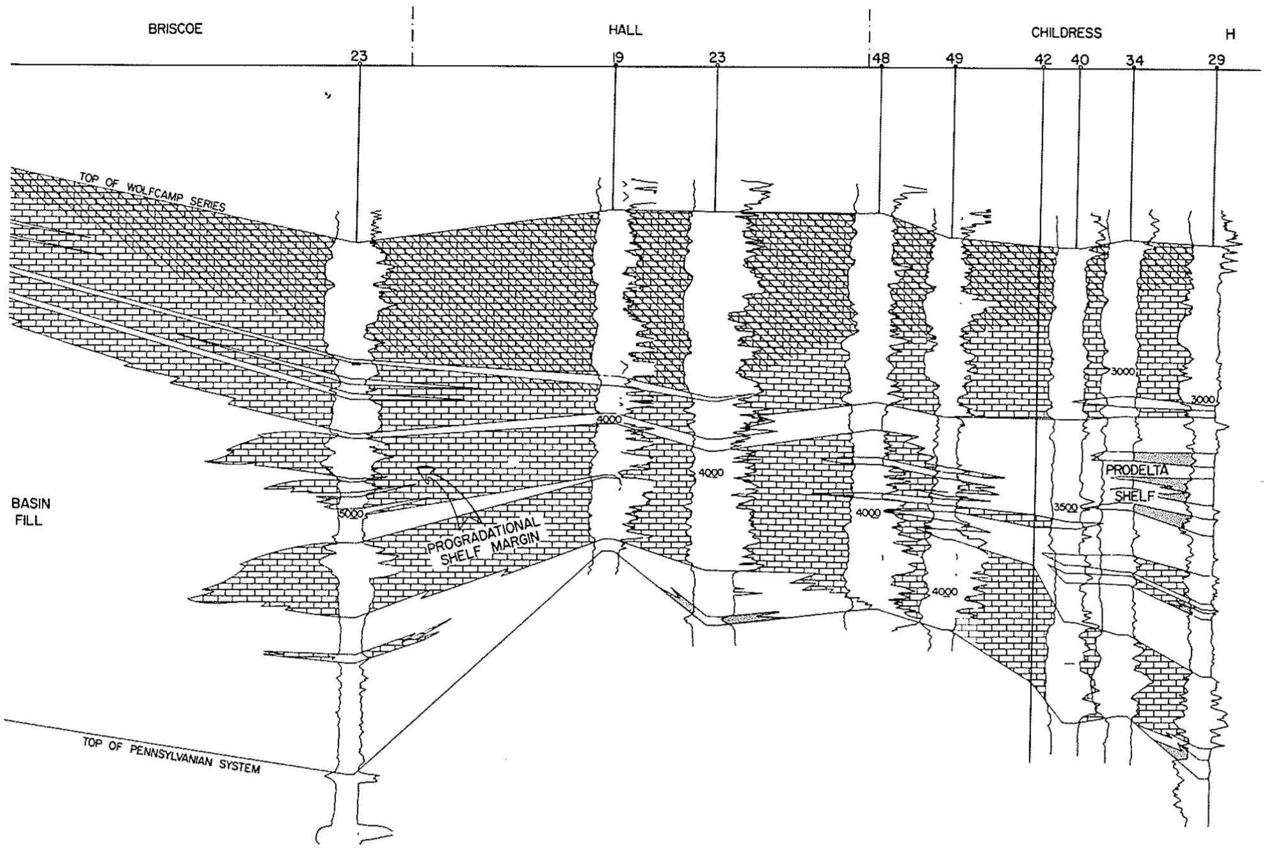


Figure 16. Wolfcampian cross section G-H.


BRISCOE
HALL
CHILDRESS
H
23
19
23
48
49
42
40
34
29
TOP OF WOLFCAMP SERIES
4000
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BASIN FILL
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PROGRADATIONAL SHELF MARGIN
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TOP OF PENNSYLVANIAN SYSTEM

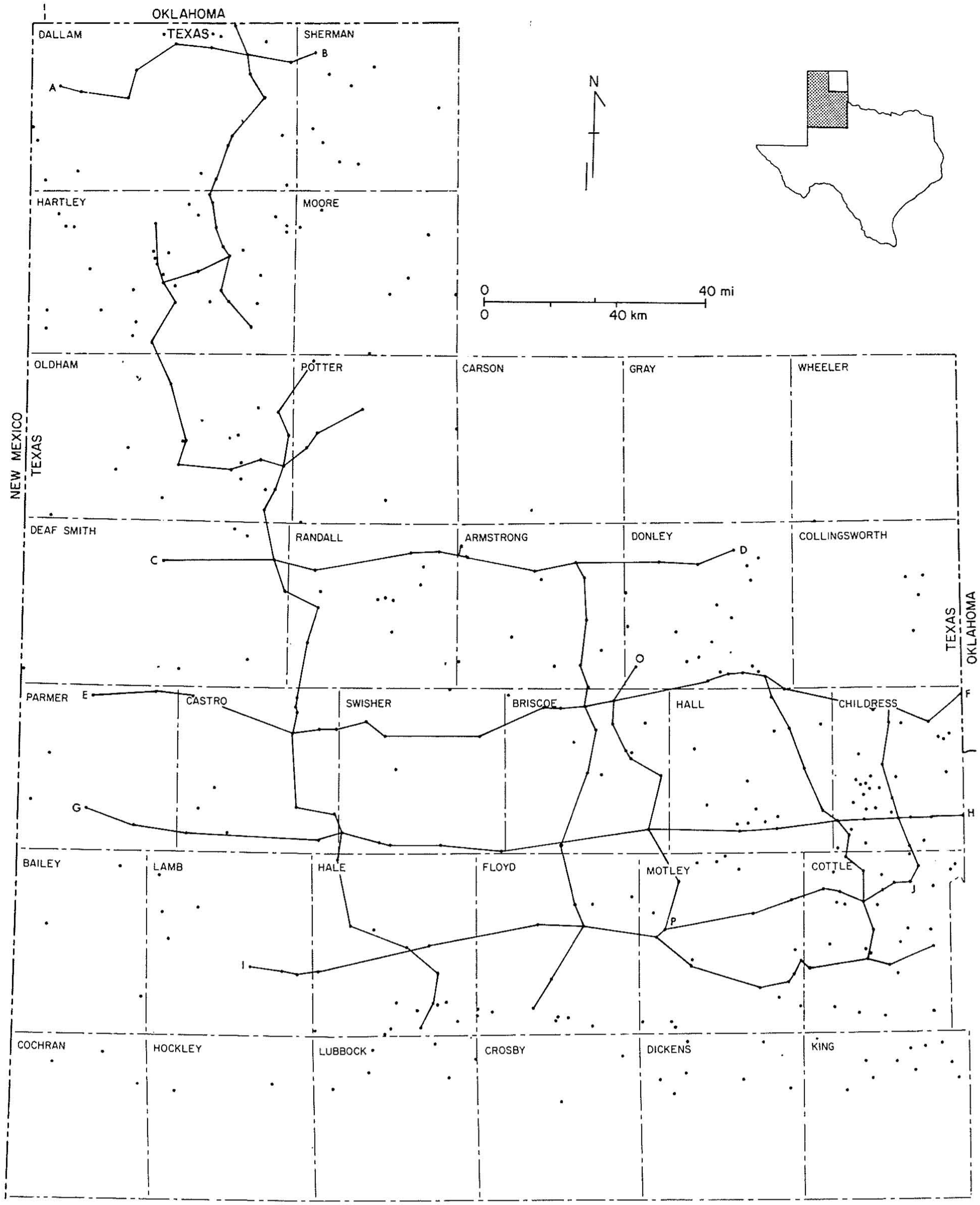


Figure 17. Index map of study area showing locations of Wolfcampian cross sections. Section G-H is published in this report (fig. 16).

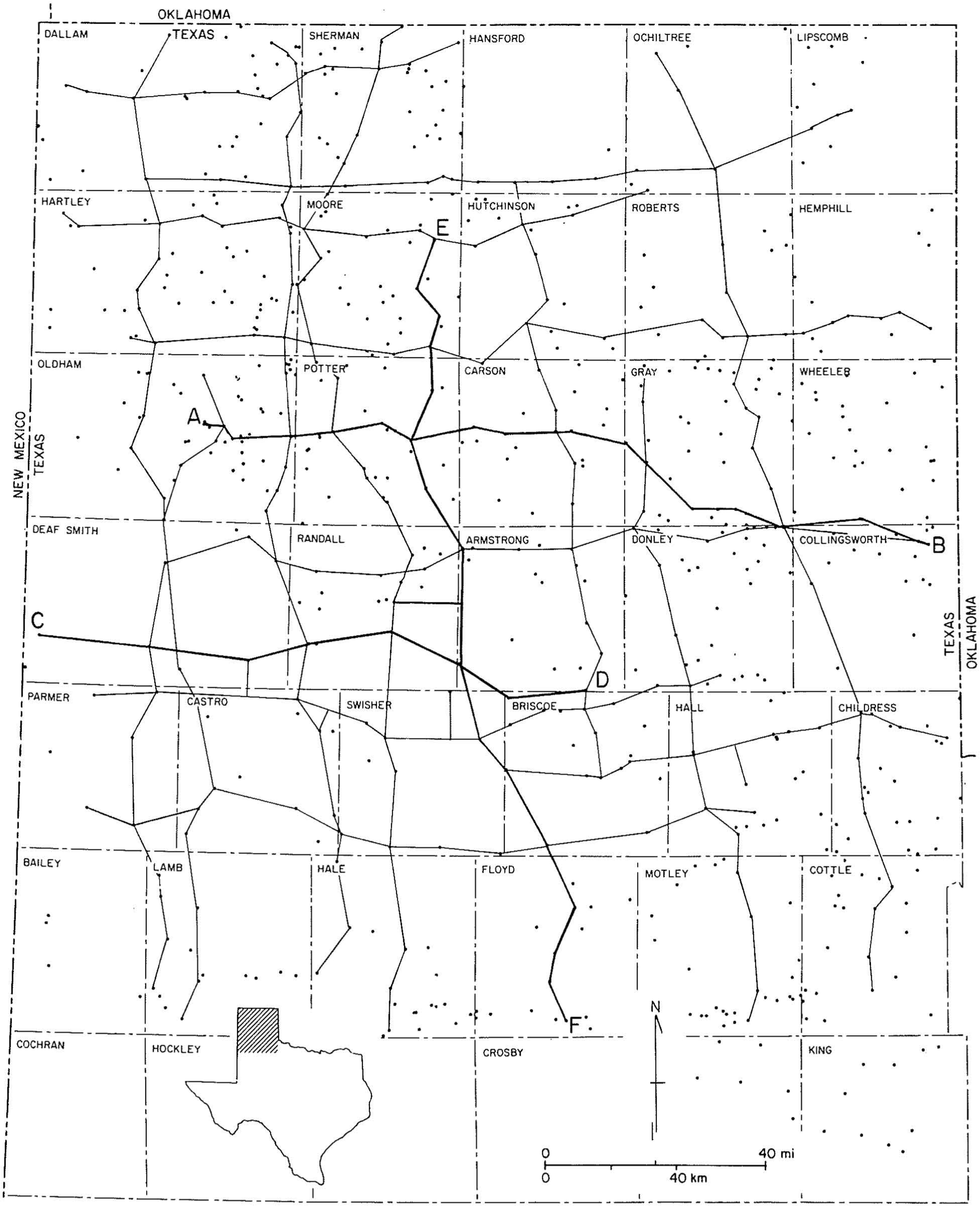


Figure 18. Index map showing locations of Leonardian cross sections. Section E-F is published in this report (fig. 19).

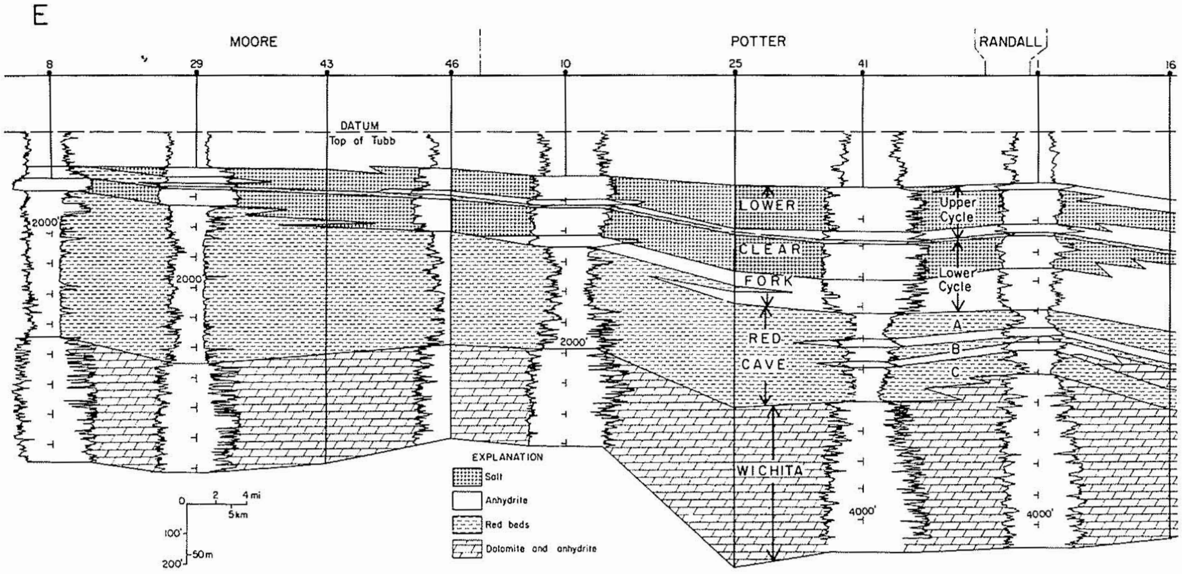
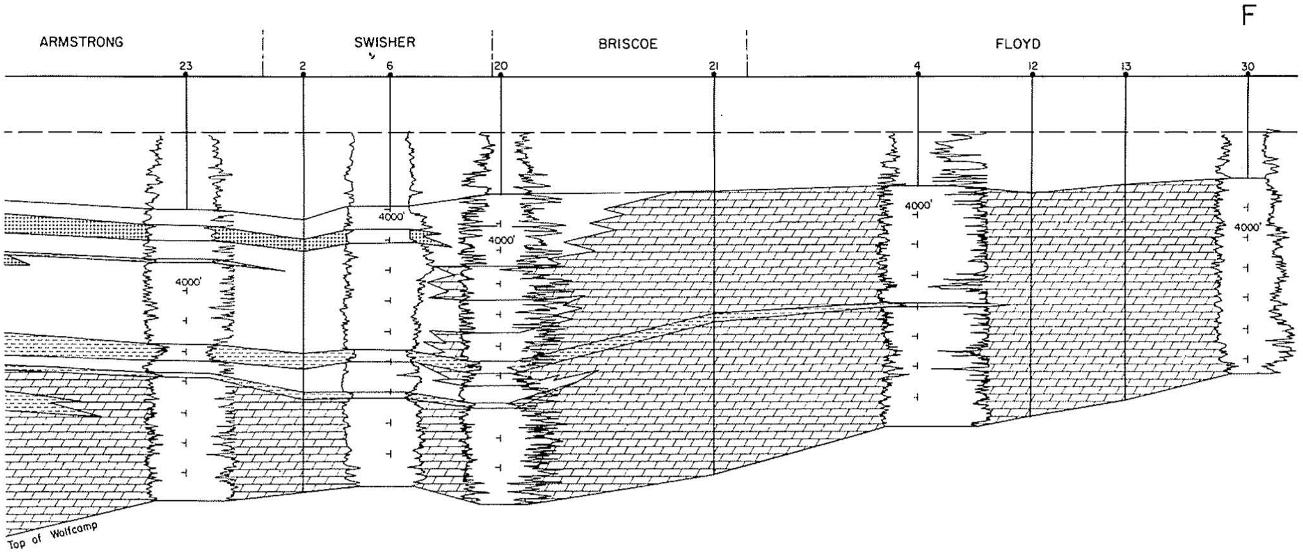


Figure 19. Leonardian cross section E-F.


F
ARMSTRONG
SWISHER
BRISCOE
FLOYD
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2
6
20
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4
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13
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4000'
4000'
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4000'
4000'
Top of Wolfcamp

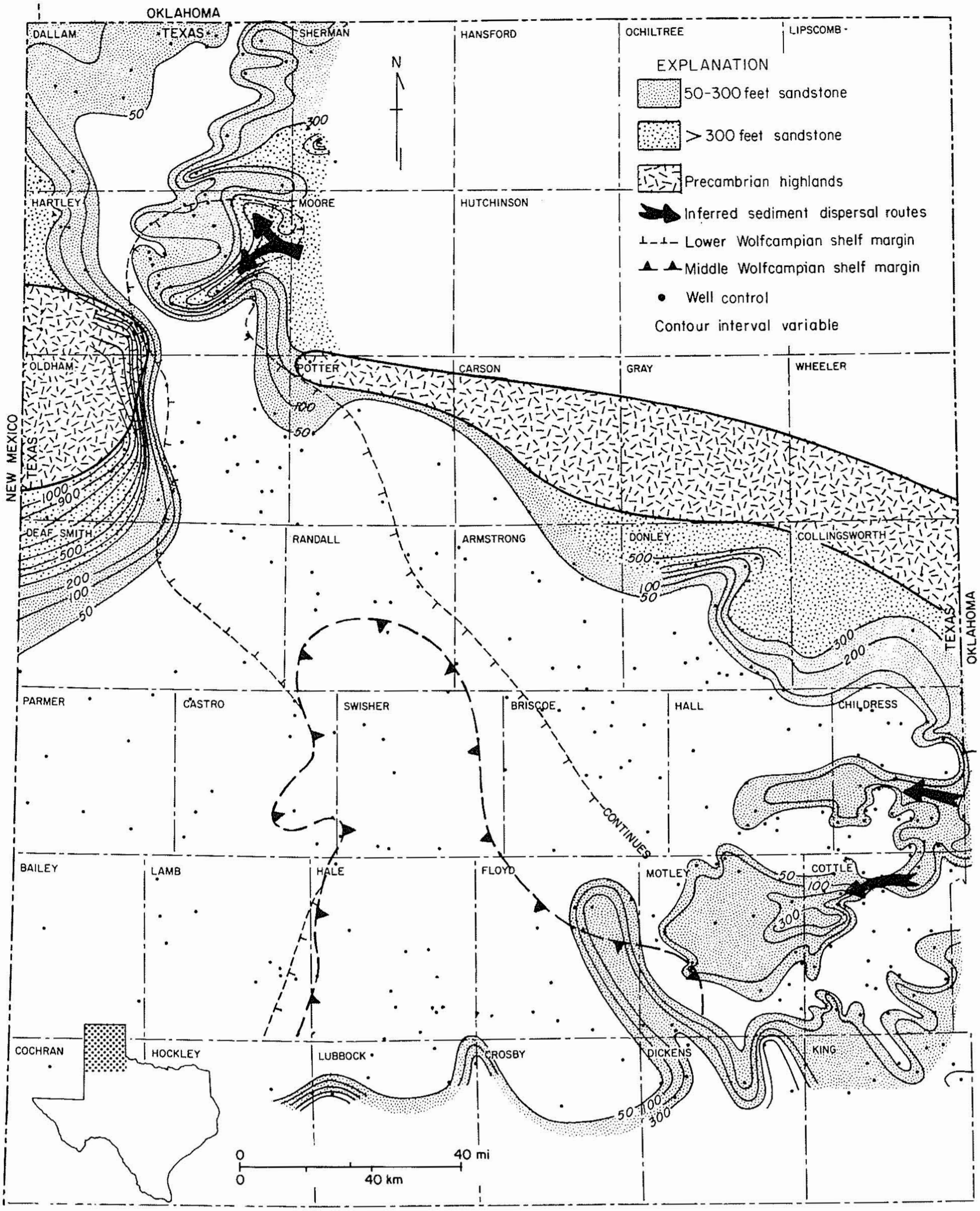

Figure 20. Net sandstone map of Wolfcampian Series.

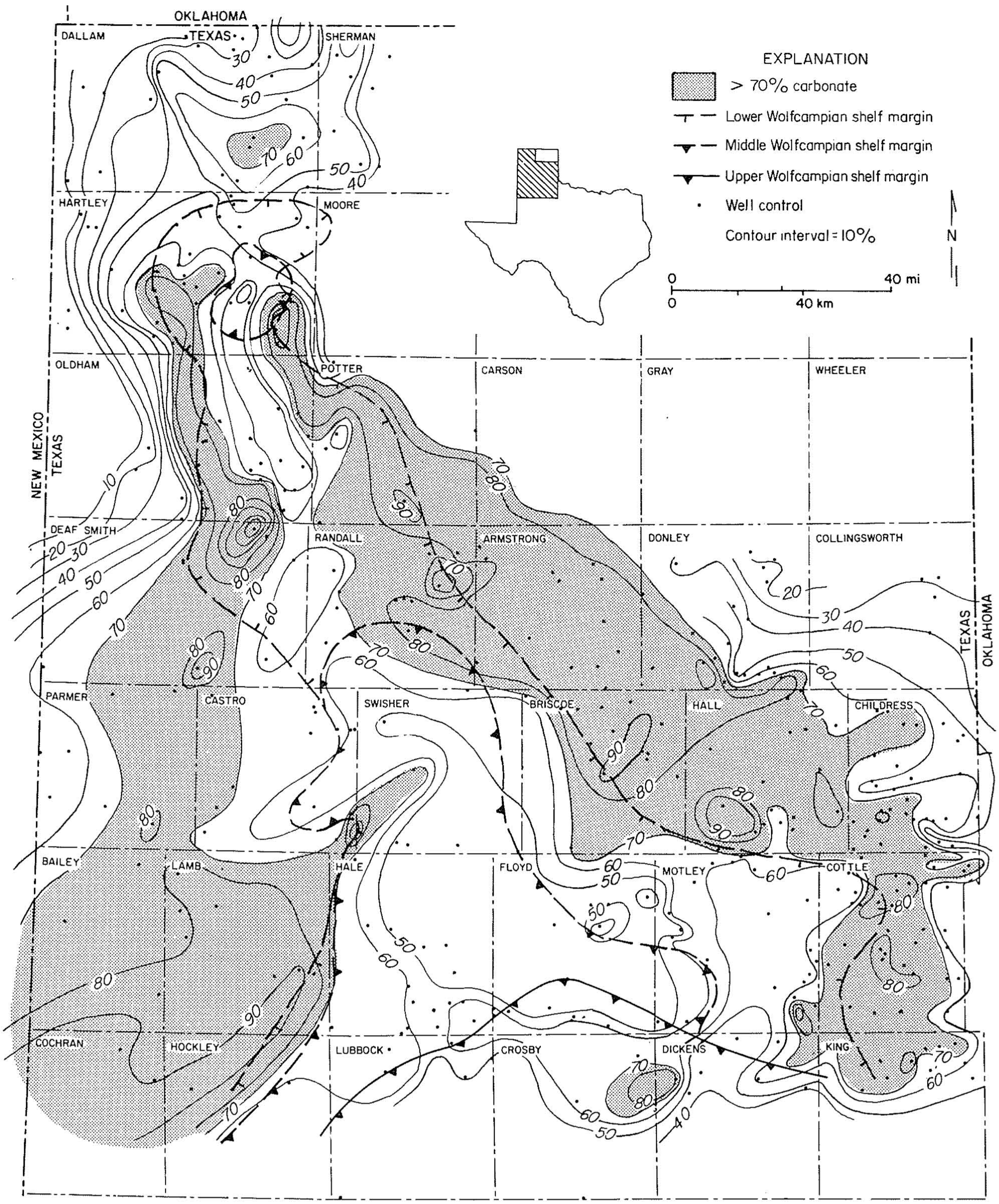

Figure 21. Carbonate percent map of Wolfcampian Series.

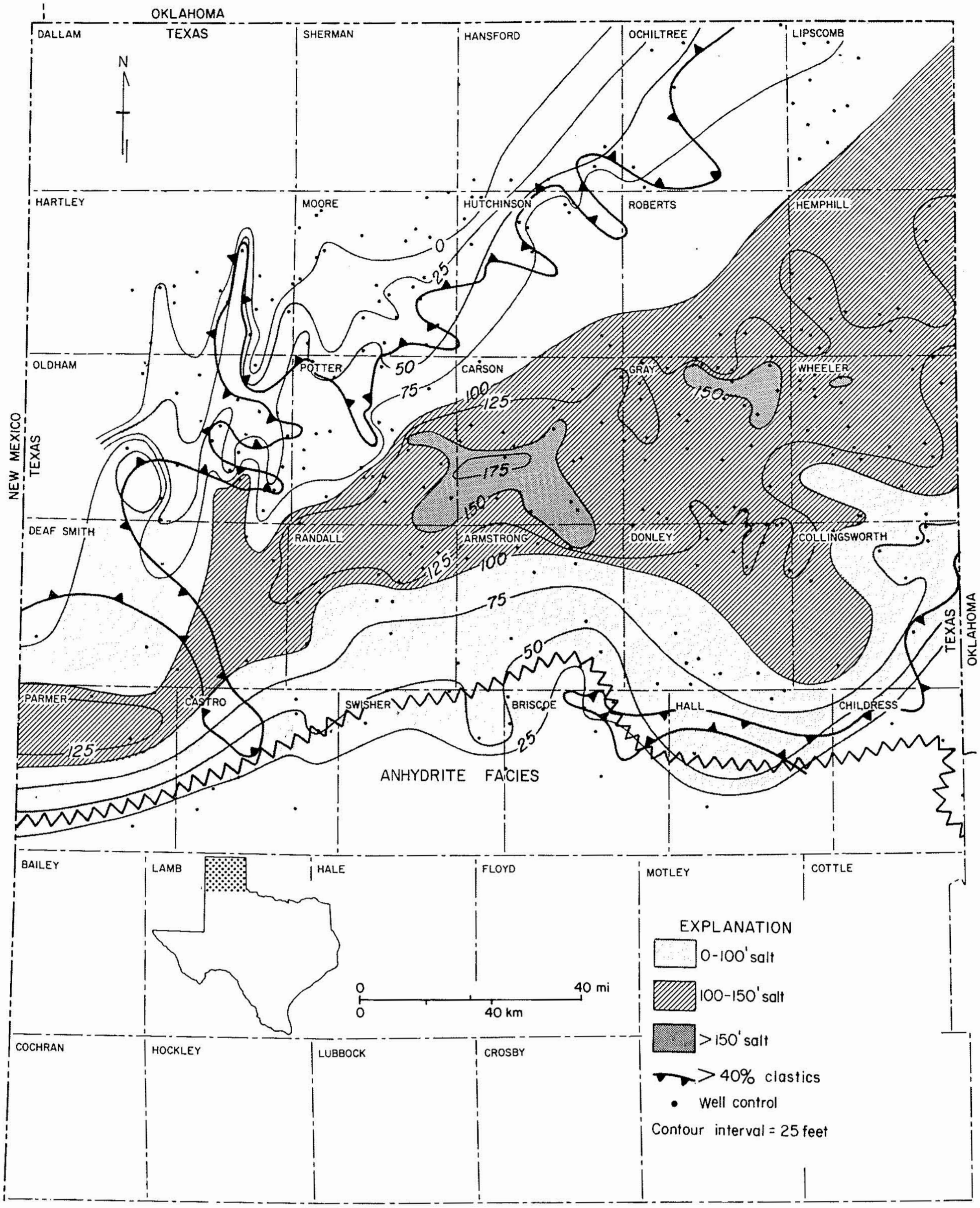

Figure 22. Net salt, upper cycle, lower Clear Fork Formation.

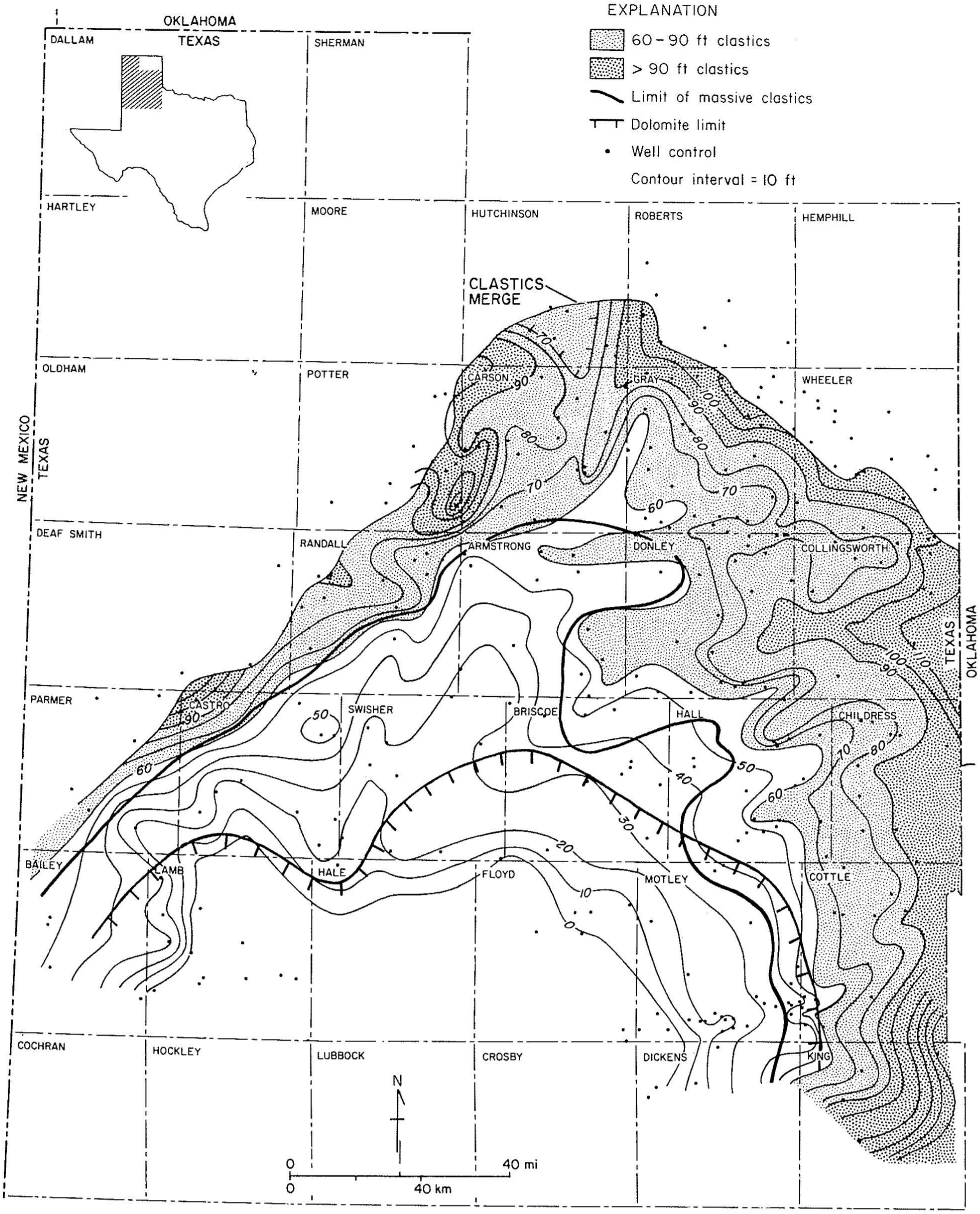

Figure 23. Net clastics, A-lobe of Red Cave Formation.

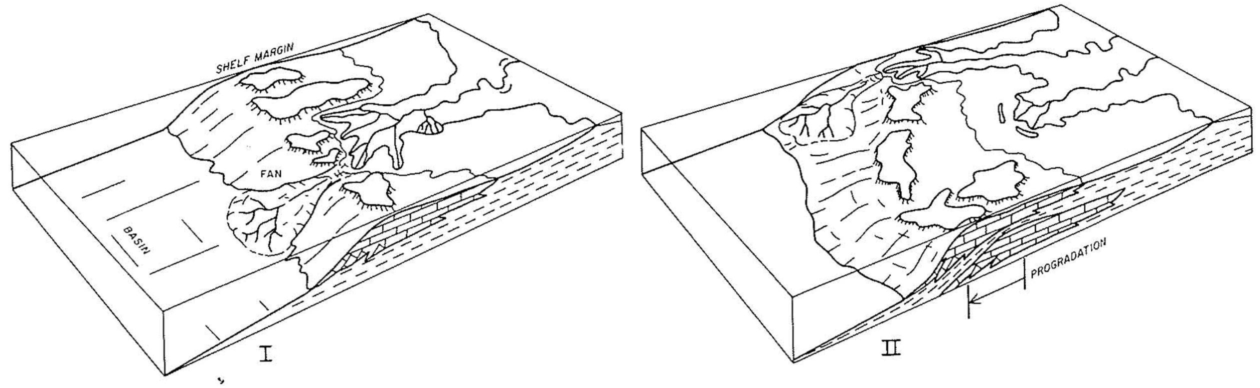

Figure 24. Model of shelf-margin development. Phase I: delta progradation and formation of slope wedge. Phase II: delta abandonment and seaward progradation of new carbonate banks and shelf margin.

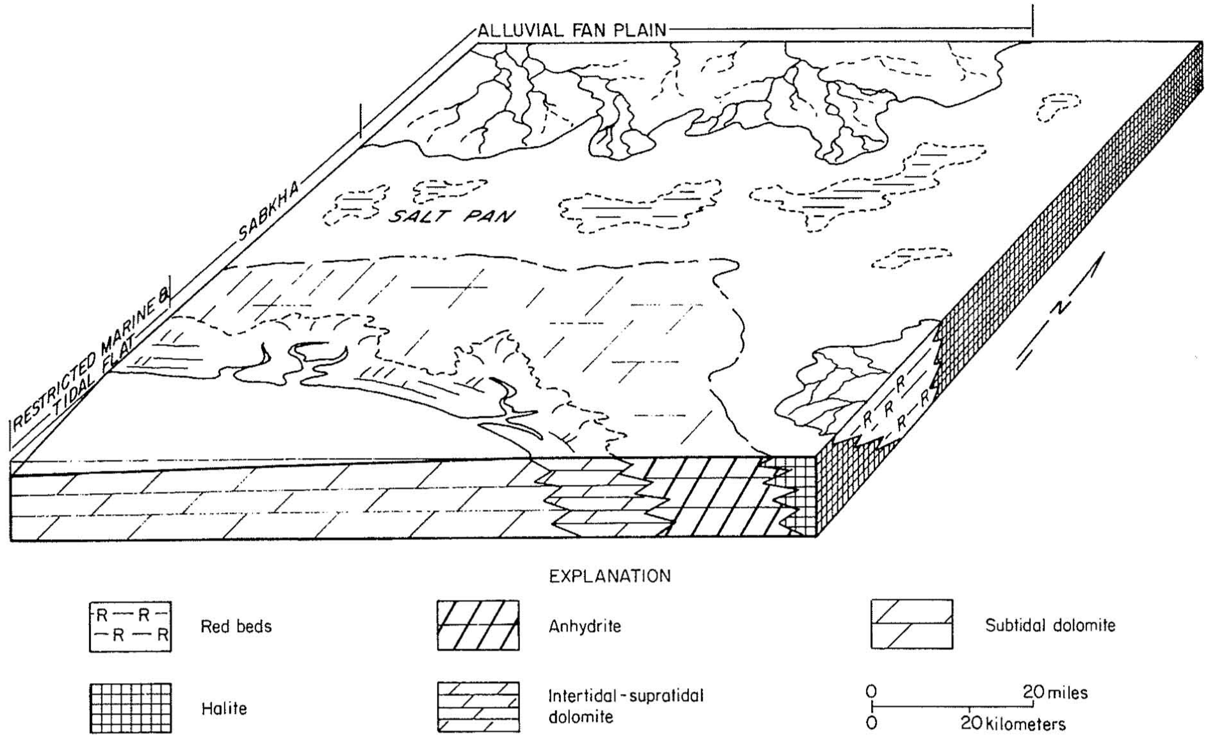

Figure 25. Facies model, deposition of lower Clear Fork Formation.

UPPER PERMIAN EVAPORITES AND RED BEDS

Mark W. Presley

Four major upper Permian genetic sequences composed of evaporite and 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 (fig. 26). 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. 5, 27, 28, and 29). Red beds occur as sheets of shale and fine-grained sandstone up to 300 feet (91 m) thick, which intertongue basinward with dolomite-evaporites (see Tubb example, fig. 30). It is inferred that these deposits formed principally in tidal mudflats grading basinward into tidal sandflats. Clastic input was by eolian and/or low-energy alluvial processes.

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

Lower Clear Fork-Tubb strata--The lower Clear Fork Formation has been discussed. Tubb strata represent dominant late-stage, red-bed deposition in the early Clear Fork evaporite basin. Clastic environments prograded into the Palo Duro Basin center; transitional (intertonguing) evaporite environments retreated to the south.

Upper Clear Fork-Glorieta strata--Evaporites and dolomite of the upper Clear Fork Formation (an unnamed formation within the Clear Fork Group, herein called "upper Clear Fork Formation") represent early dominance of sabkha and shelf environments in the Palo Duro and Dalhart Basins. Intertonguing red beds and salt of the Glorieta Formation indicate later dominance by clastic-upper sabkha environments in the basins. Both upper sabkha deposits and overlying red-bed facies were deposited in environments that prograded from the Dalhart area and the region of the Amarillo Uplift to the Palo Duro Basin (fig. 31). In the Dalhart Basin, the Glorieta is composed principally of thick sandstones which trend southwesterly and extend into east-central New Mexico.

San Andres strata--The San Andres Formation is composed of dolomite, anhydrite and salt (fig. 32). Lower San Andres strata are composed of multiple cyclic units that are regressive to the south. Five cycles are recognized, each with basal dolomite (transgressive), grading upward into lower sabkha anhydrite-dolomite, 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 contain massively bedded anhydrite overlain by intertonguing anhydrite-salt, representing late-stage dominance of lower and upper sabkha environments.

Post-San Andres strata--Post-San Andres strata contain massive upper sabkha salt and red-bed deposits (fig. 33). Salt is present mainly in the southern and western parts of the Palo Duro Basin and principally occurs in two major salt units which correlate with continuous gypsum marker beds to the north in the Dalhart Basin. Upper boundaries of salt units are transitional into red beds. Red-bed deposits intertongue southward with salt. Trends of thinning to the southwest, observed from mapping of red-bed units, suggest that the paleoslope at this time was toward the region of the Delaware Basin in southeastern New Mexico.

Lines of cross sections on which correlations of upper Permian strata were based are shown in figure 34.

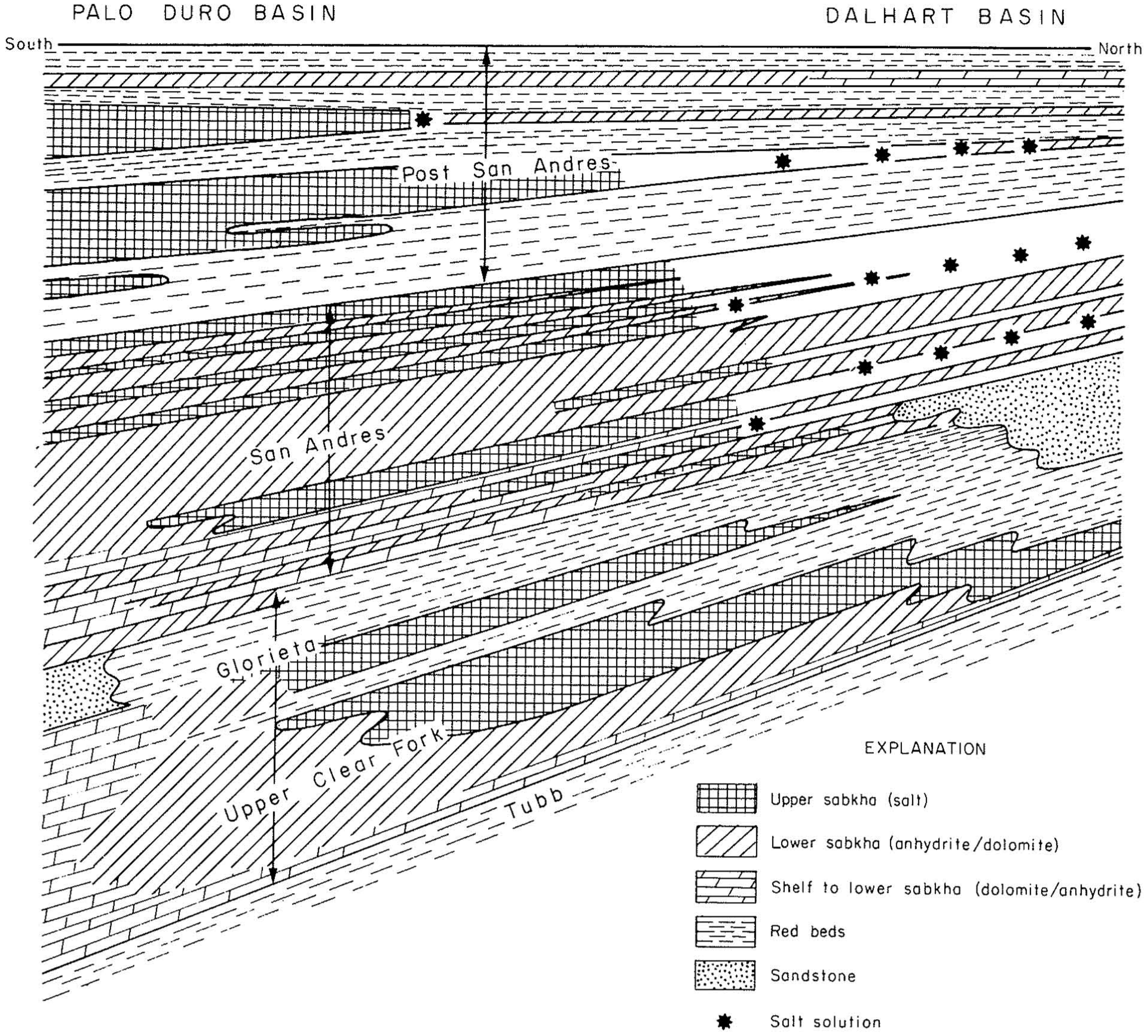

Figure 26. Generalized north-south cross section, major genetic units, upper Permian salt-bearing strata, Palo Duro and Dalhart Basins.

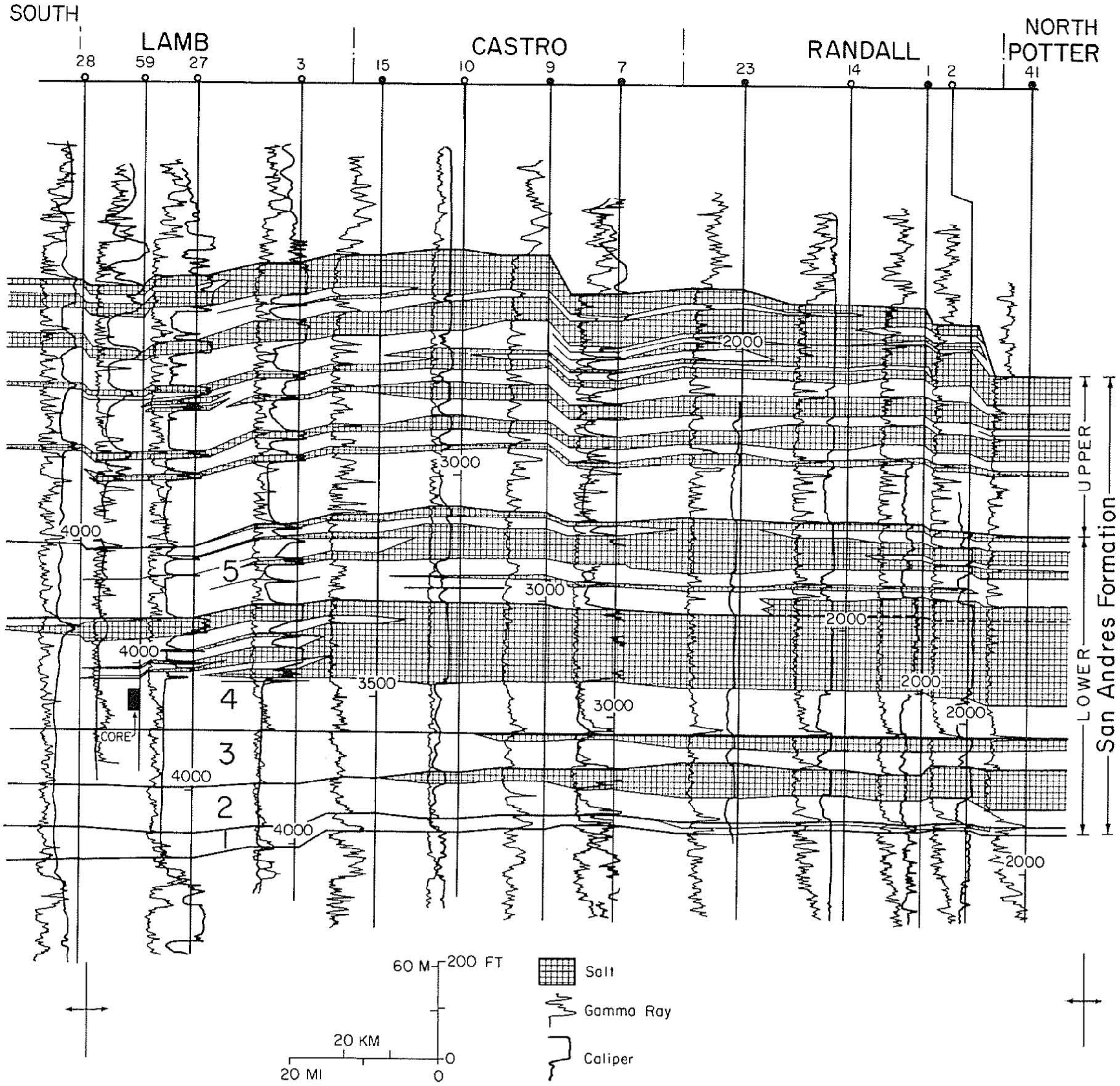

Figure 27. North-south cross section, San Andres Formation, Palo Duro Basin. Salt beds that cap lower San Andres cyclic units 1-5 thin and pinch out to the south. Moderate to high radioactivity (higher to the north) in basal portions of the cycles diminishes upward into salt. Lithology and facies interpretations of gamma ray patterns are shown in figures 5 and 29. Depths shown on logs (values range from 2,000 to 4,000) are in feet.

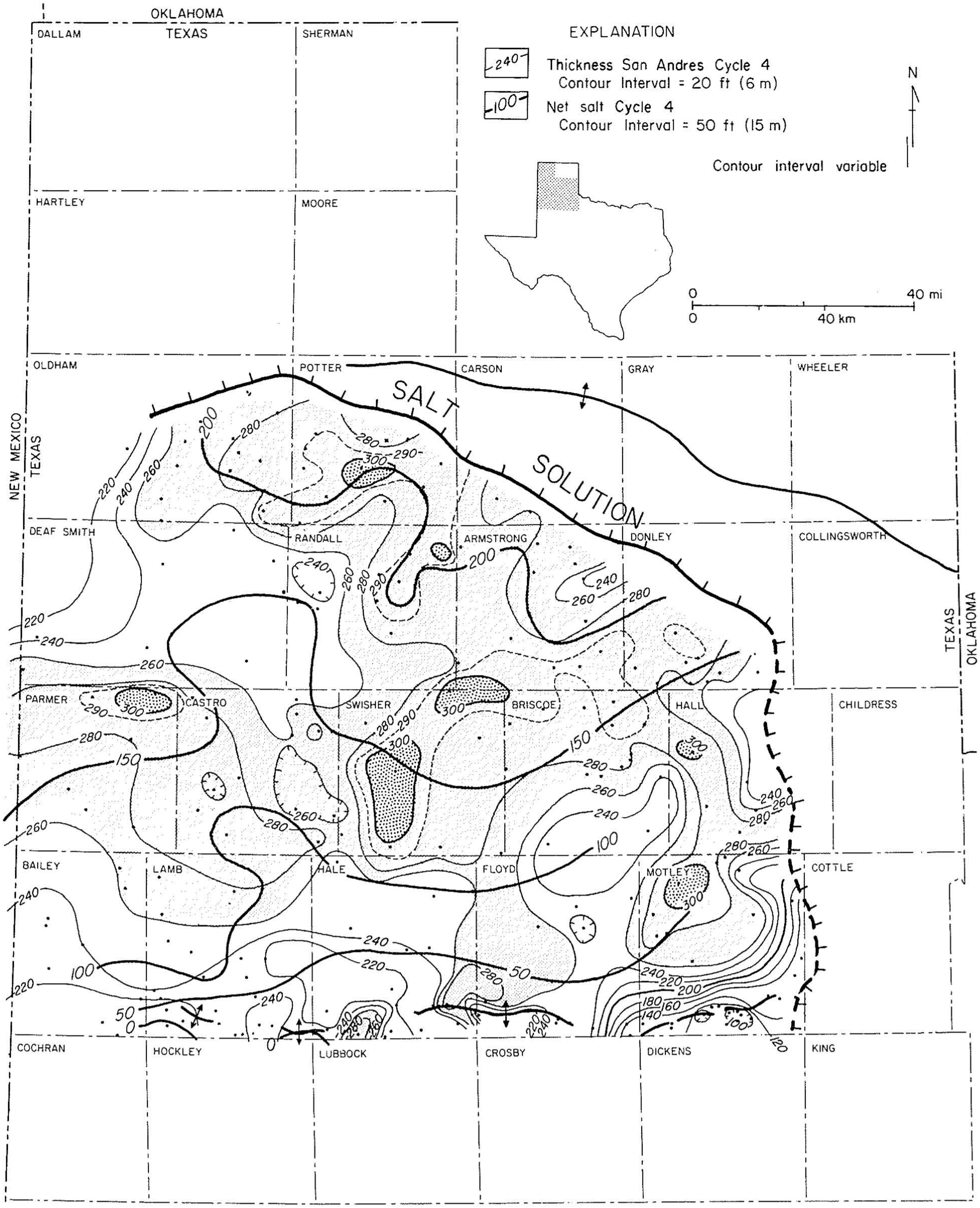

Figure 28. Isopach map, lower San Andres cycle 4 (fig. 27) showing net salt contained in cycle. Cycle exhibits relatively small variations in thickness (240 to 300 ft or 73 to 90 m) in the basin. Net salt values increase to the north and reflect position of maximum development of upper sabkha salt terrane at close of cycle.

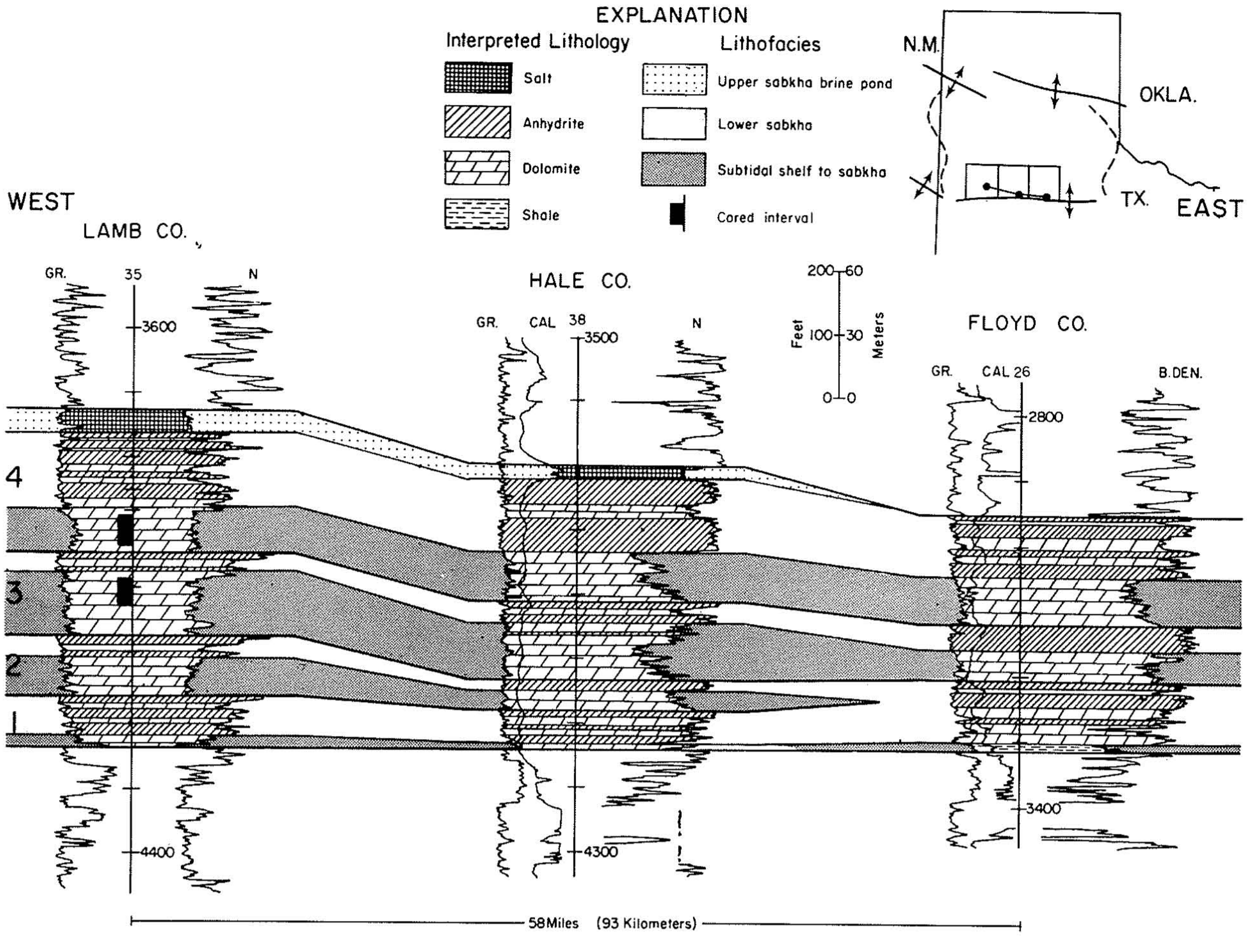

Figure 29. East-west cross section, lower San Andres cyclic units, southern Palo Duro Basin. Both lithology and facies interpretations are shown. Cores such as those in the Lamb County well suggest subtidal-intertidal deposition for basal dolomite of cycles (moderate radioactivity) grading upward into supratidal dolomite-anhydrite. Cycle 4 is capped by upper sabkha salt. Lower sabkha facies interfinger to the north with salt, and to the south with dolomite.

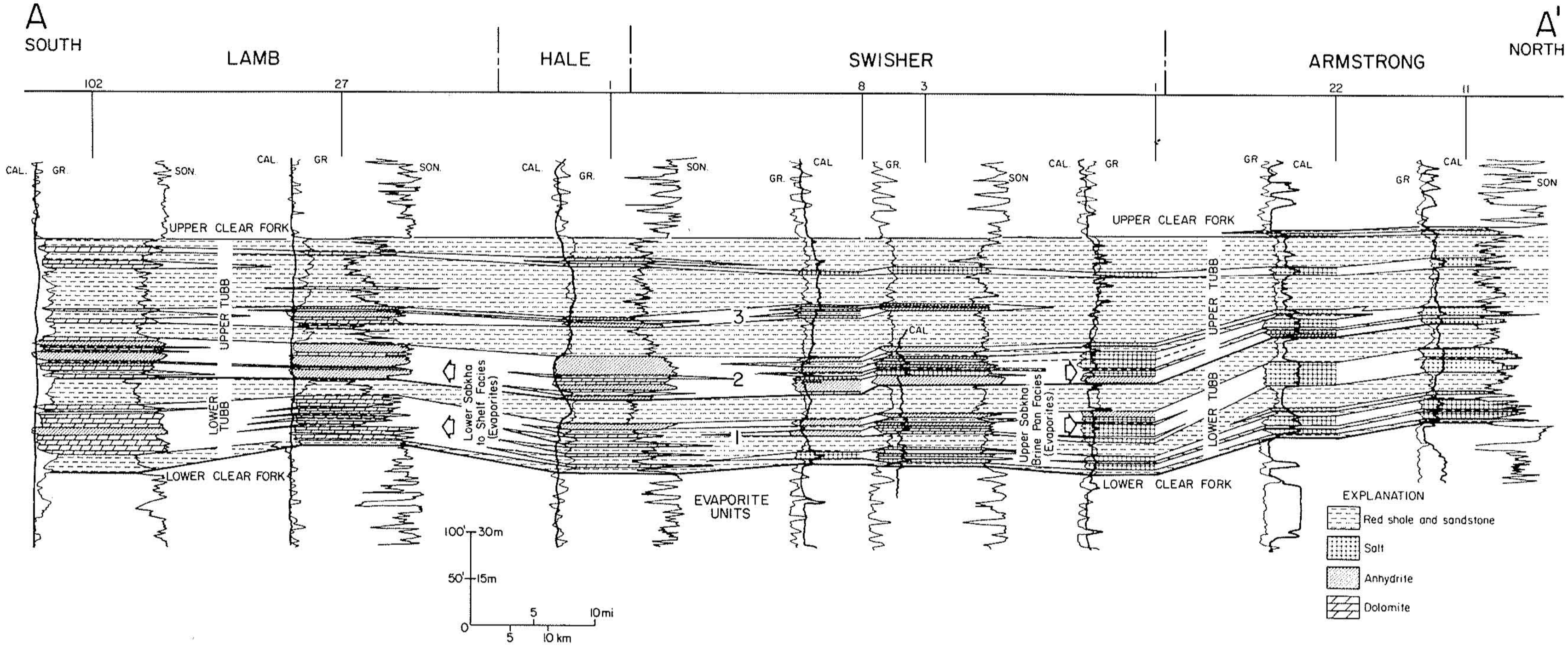

Figure 30. North-south cross section, Tubb Formation, Palo Duro Basin. Evaporite units intertongue with clastics and exhibit basinward (southerly) lithofacies changes from upper sabkha salt to lower sabkha and shelf dolomite-anhydrite. Clastic tongues thin southeastward, perpendicular to line of section.

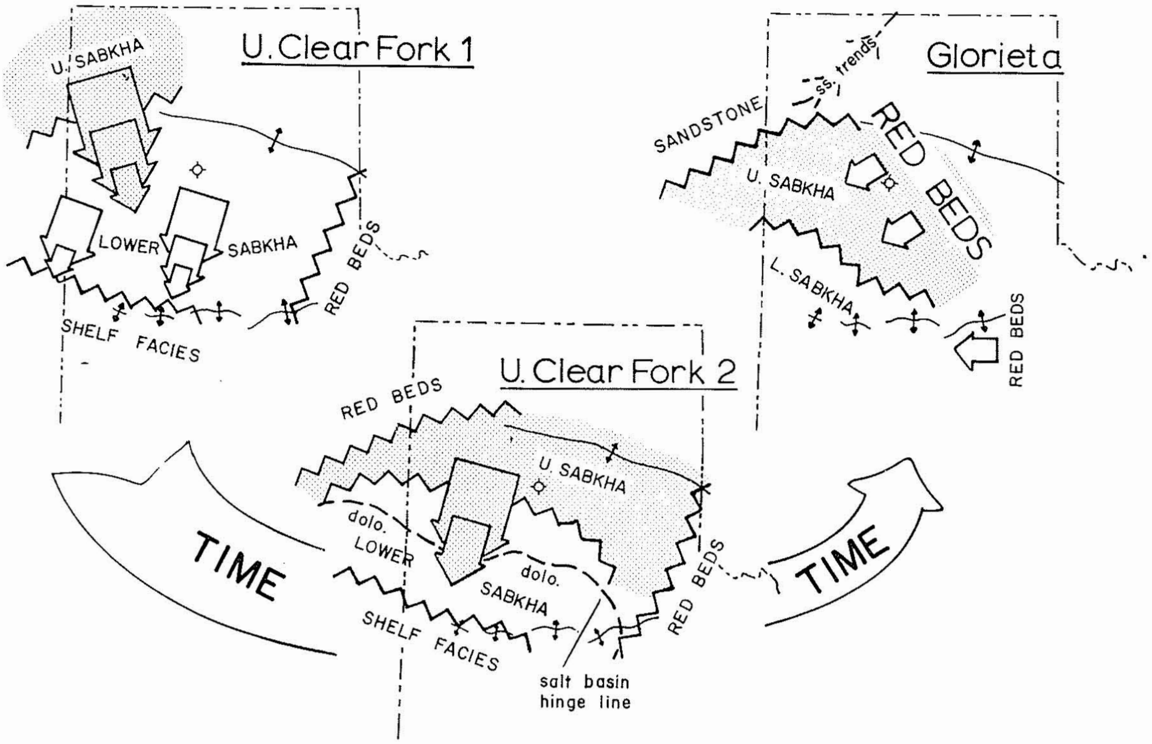

Figure 31. Paleogeography of upper Clear Fork-Glorieta genetic unit.

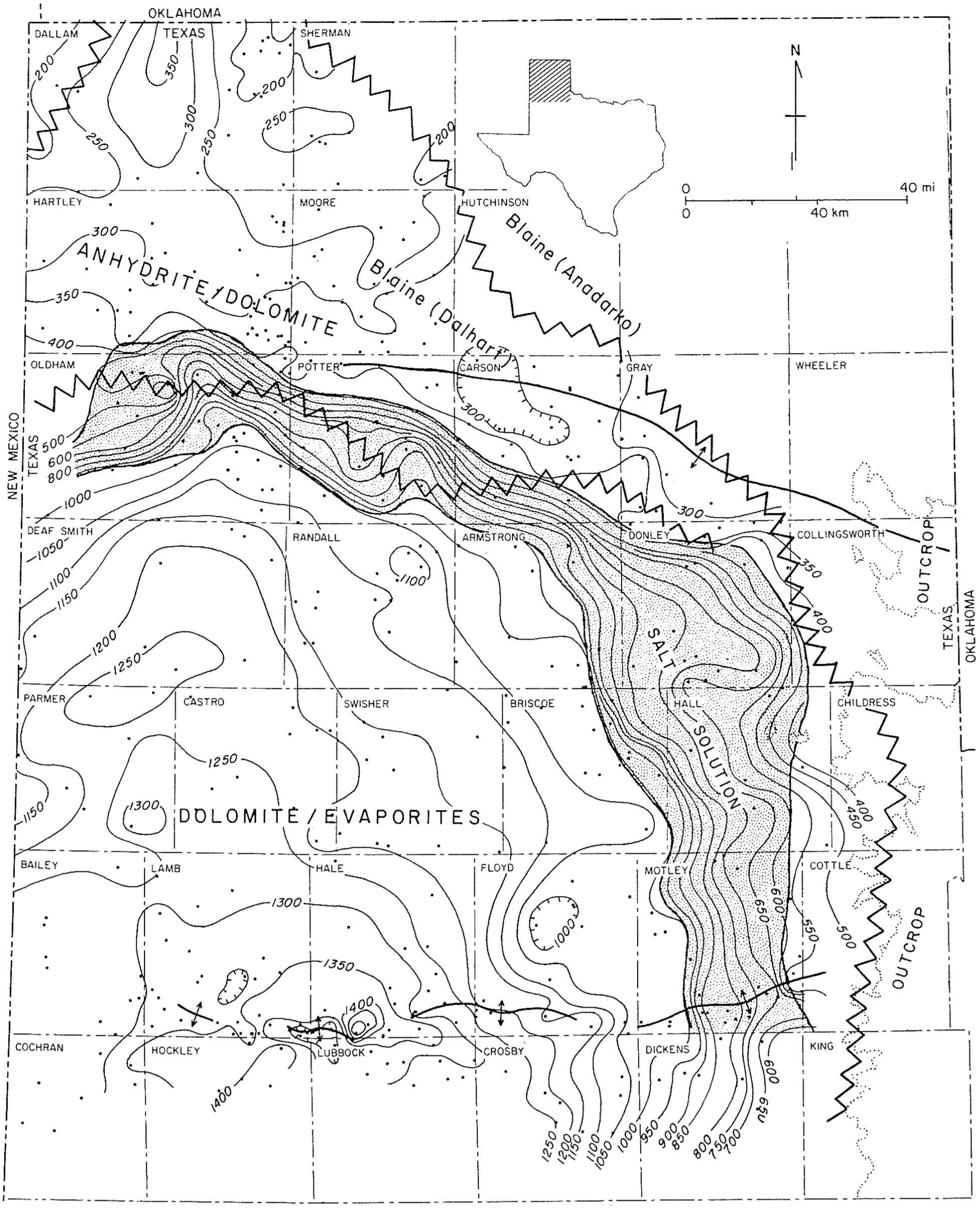

Figure 32. Isopach map, San Andres and Blaine Formations. Area of active salt solution is indicated. Boundaries between San Andres (Palo Duro), and Blaine (Dalhart and Anadarko) are marked by updip (northerly) change in basal cyclic units from evaporites-dolomite to clastics.

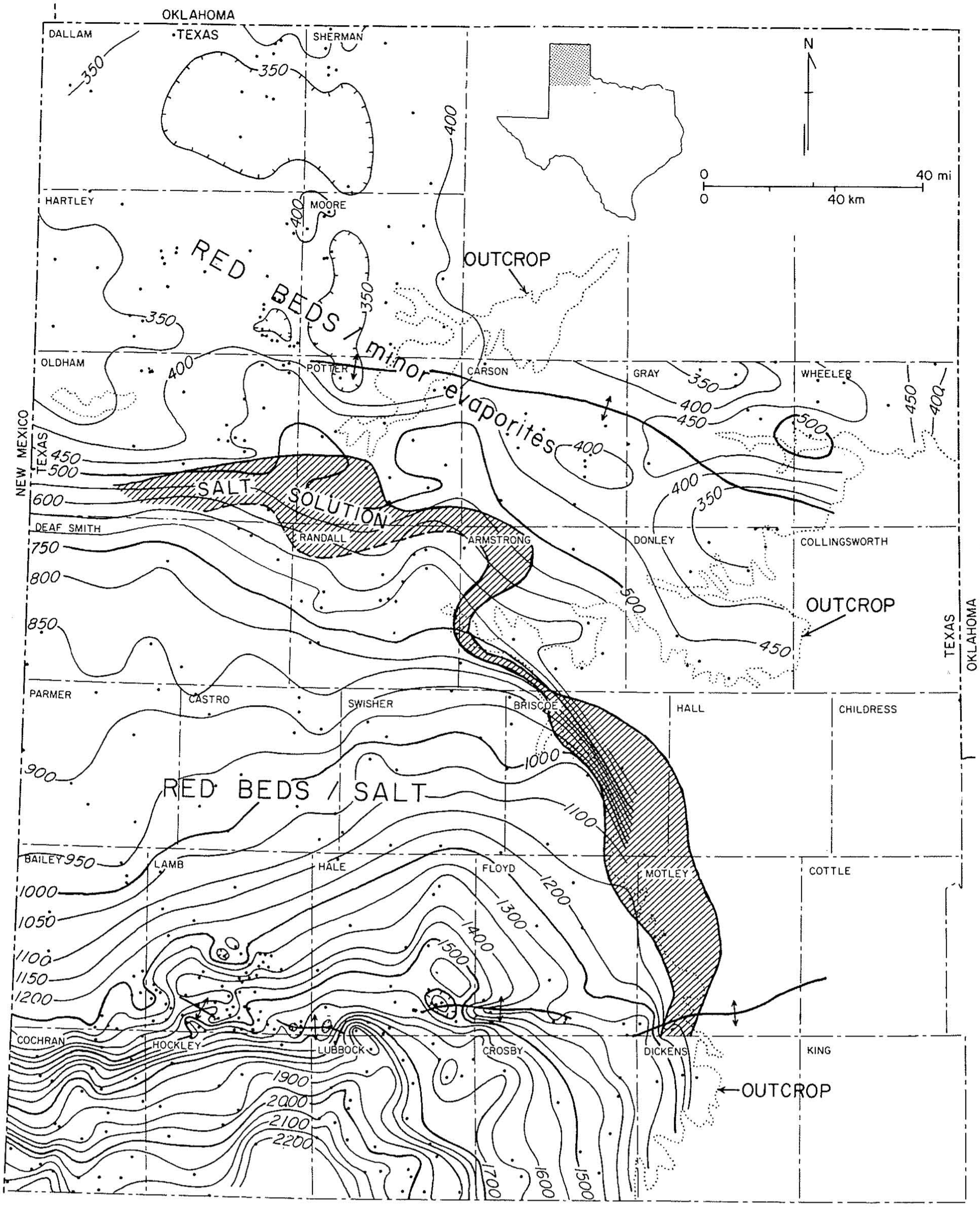

Figure 33. Isopach map, post-San Andres genetic unit. Area of active salt solution indicated.

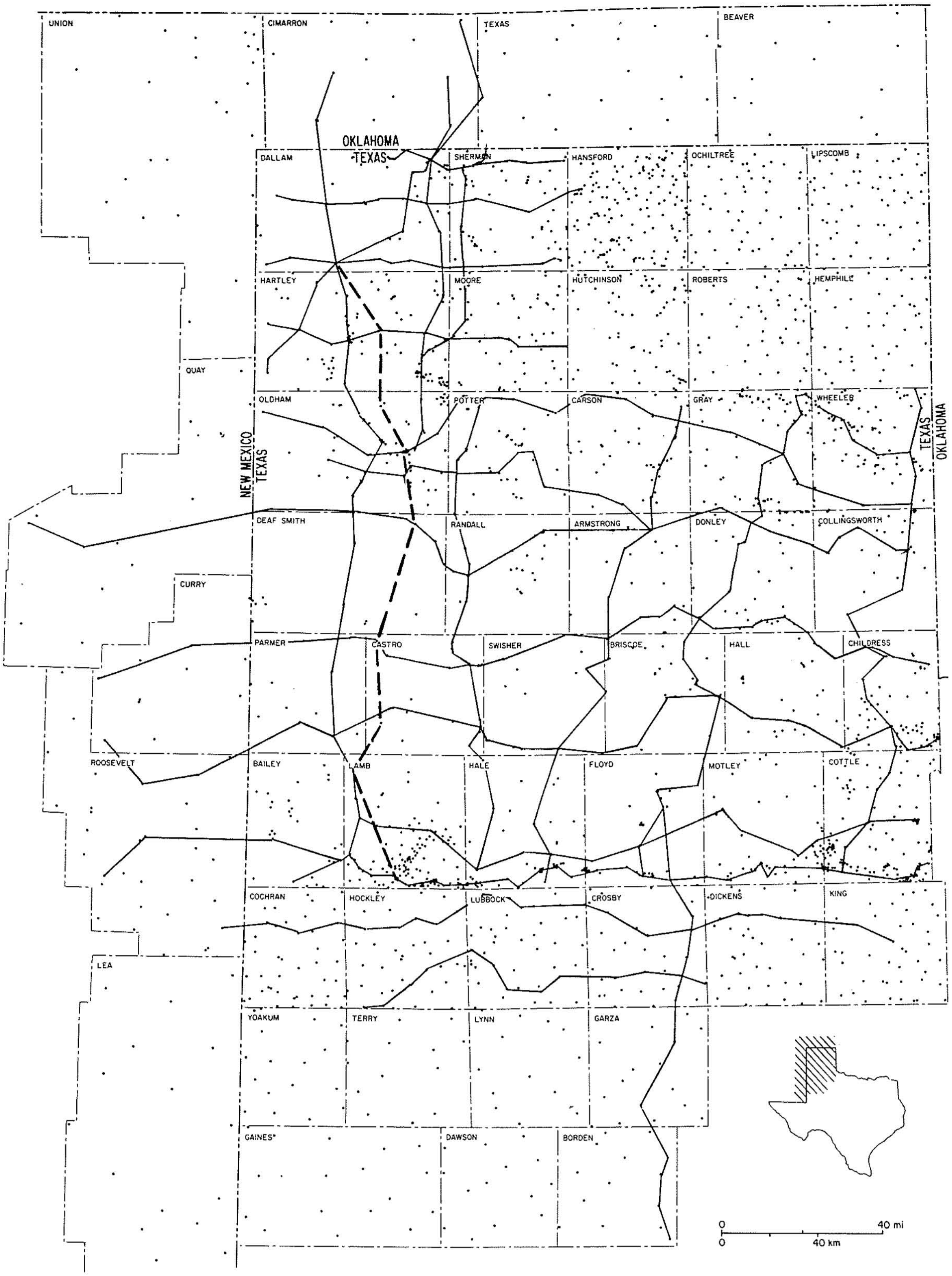

Figure 34. Lines of cross sections with correlations of the upper Permian salt-bearing sequence constructed during investigation. Dashed line is cross section shown in figure 35. Sections showing lithology interpretations of each major genetic unit were also prepared.

SALT DEPOSITS

Mark W. Presley

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 with lower sabkha and shelf lithofacies basinward and with red beds towards the margins of the basin.

Correlations of salt-bearing strata in the Palo Duro and Dalhart Basins are shown in figure 35. Most salt occurs in the Palo Duro area. Generalized data on each of seven salt-bearing units studied are listed in table 2. Following is a discussion of each salt-bearing unit from oldest to youngest.

Lower Clear Fork--Areas of major salt accumulation occur both in the Anadarko Basin and in Potter, Carson, and Randall Counties of the Palo Duro Basin, where total salt thickness reaches 300 feet (91 m). 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--Thickest salt in lower salt units of the upper Clear Fork (fig. 36) occurs in the Dalhart Basin. In upper salt units, maximum salt thickness is in the northern Palo Duro Basin. In general, upper sabkha deposition shifted progressively to the south. 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 with intertonguing massive red beds is present in the Palo Duro Basin. Evaporite tongues thin or pinch out to the northeast, progressively offlapping through time and reflecting depositional control by the inferred paleoslope (downdip to the southwest). Evaporite facies were deposited from brine 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 is present in both the Palo Duro and Dalhart Basins (fig. 37). 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 in this and younger salt-bearing units (Seven Rivers, Salado-Tansill) is present only in the Palo Duro Basin. These rocks exhibit cyclic 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 is thickest in the south-central portion of the Palo Duro Basin (fig. 38). 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--In the south-central part of the Palo Duro Basin, the unit is a single massive salt sequence with intercalated shale. Upper sabkha deposition was dominant, and the upper boundary is transitional into red beds.

Table 2. 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, intertonguing 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 (Flowerpot)	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 into southern 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 intertonguing 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 thick in Donley County (northeast Palo Duro), 50-55 ft thick in Bailey County (southwest Palo Duro) b. middle unit—average 90 ft thick in Donley County, 150 ft thick in Bailey County c. upper unit—pinching out to northeast, average 45-50 ft thick 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, and on Amarillo Uplift
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

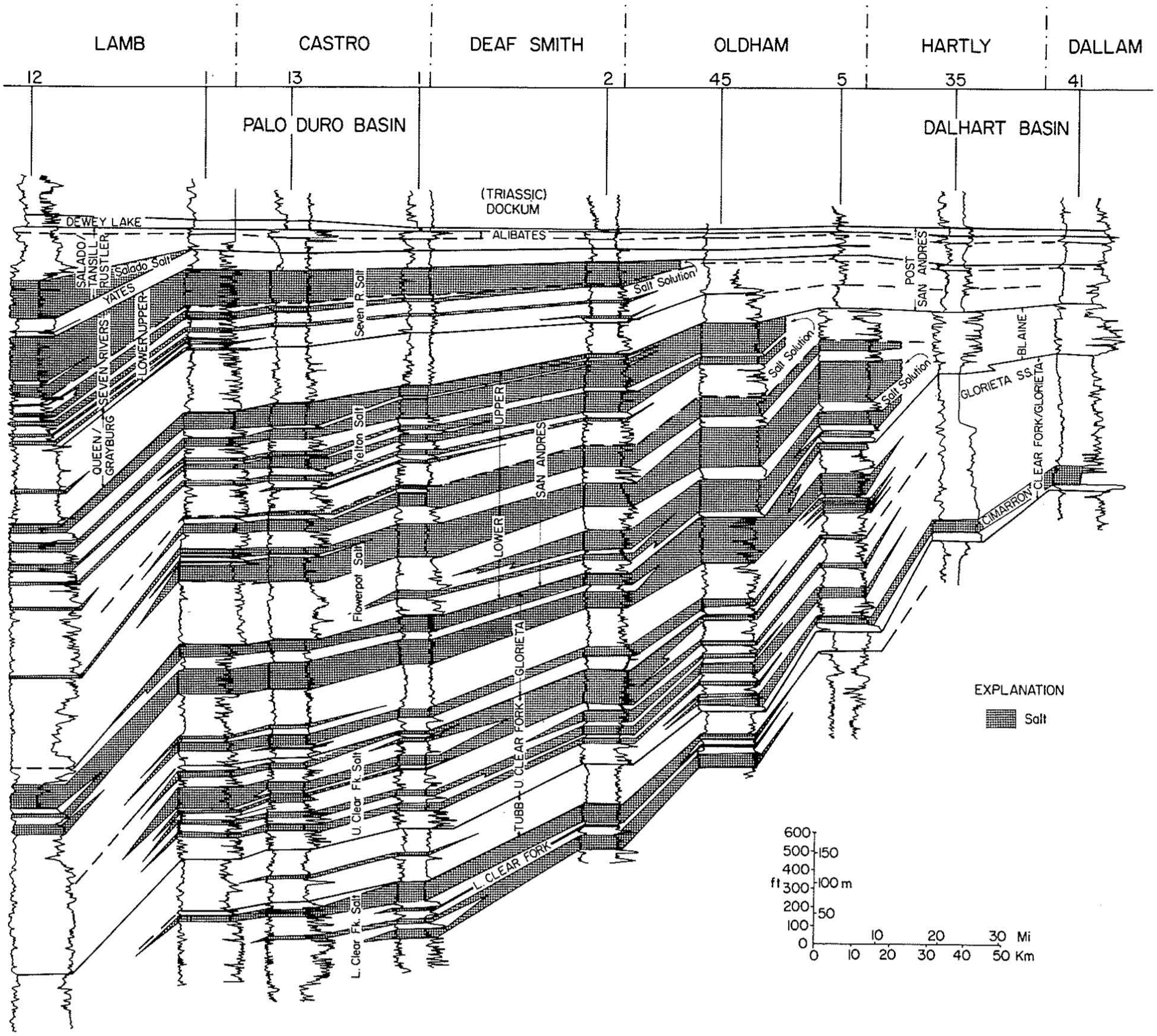

Figure 35. North-south cross section, upper Permian salt-bearing strata, Palo Duro and Dalhart Basins. Generalized salt beds are correlated. Line of section shown on figure 34.

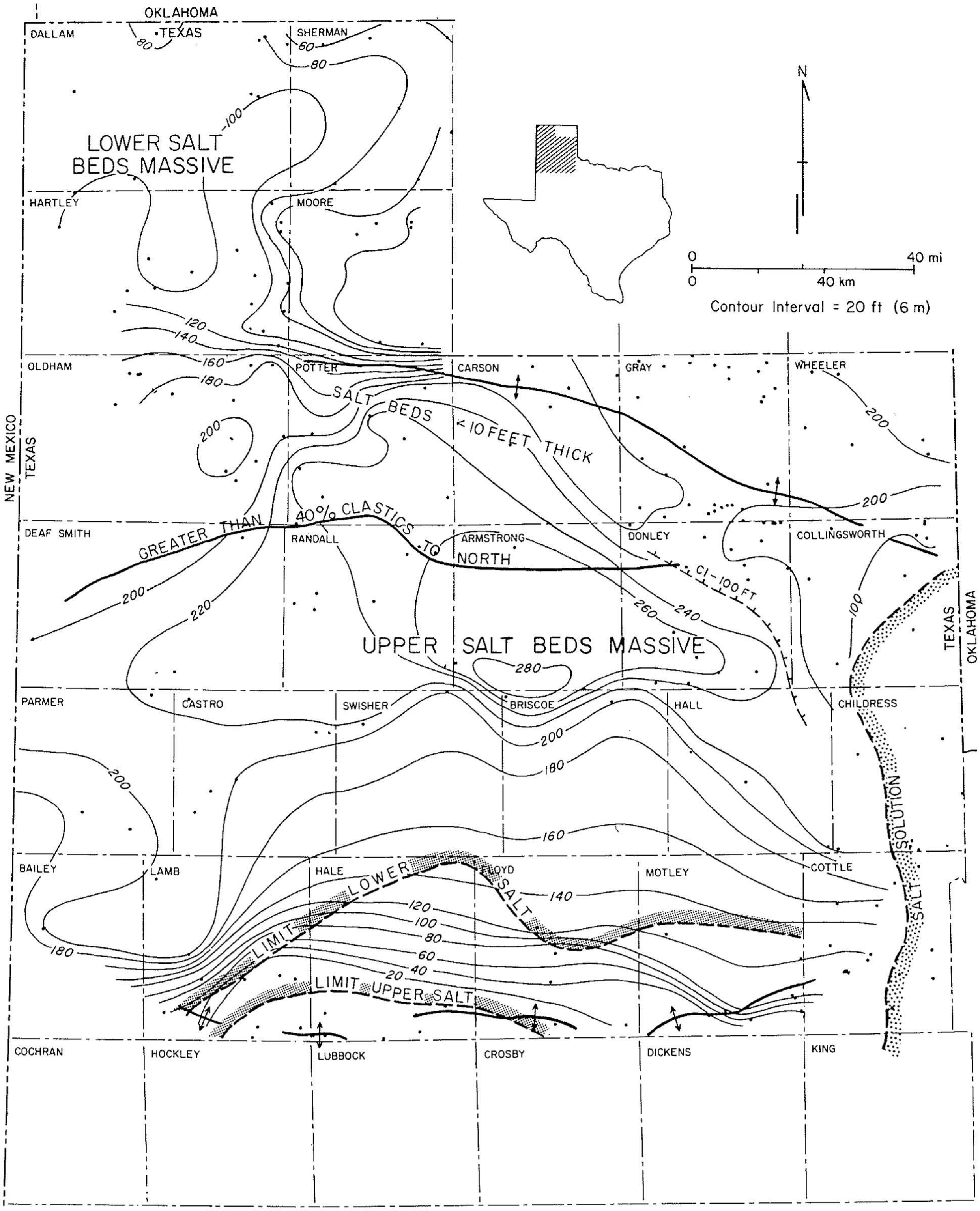

Figure 36. Net salt in the upper Clear Fork Formation. Lower salt beds are within the basal 100 to 200 feet (30 to 61 m) of the unit; upper salt beds are within the upper 300 to 400 feet (91 to 122 m) of the unit.

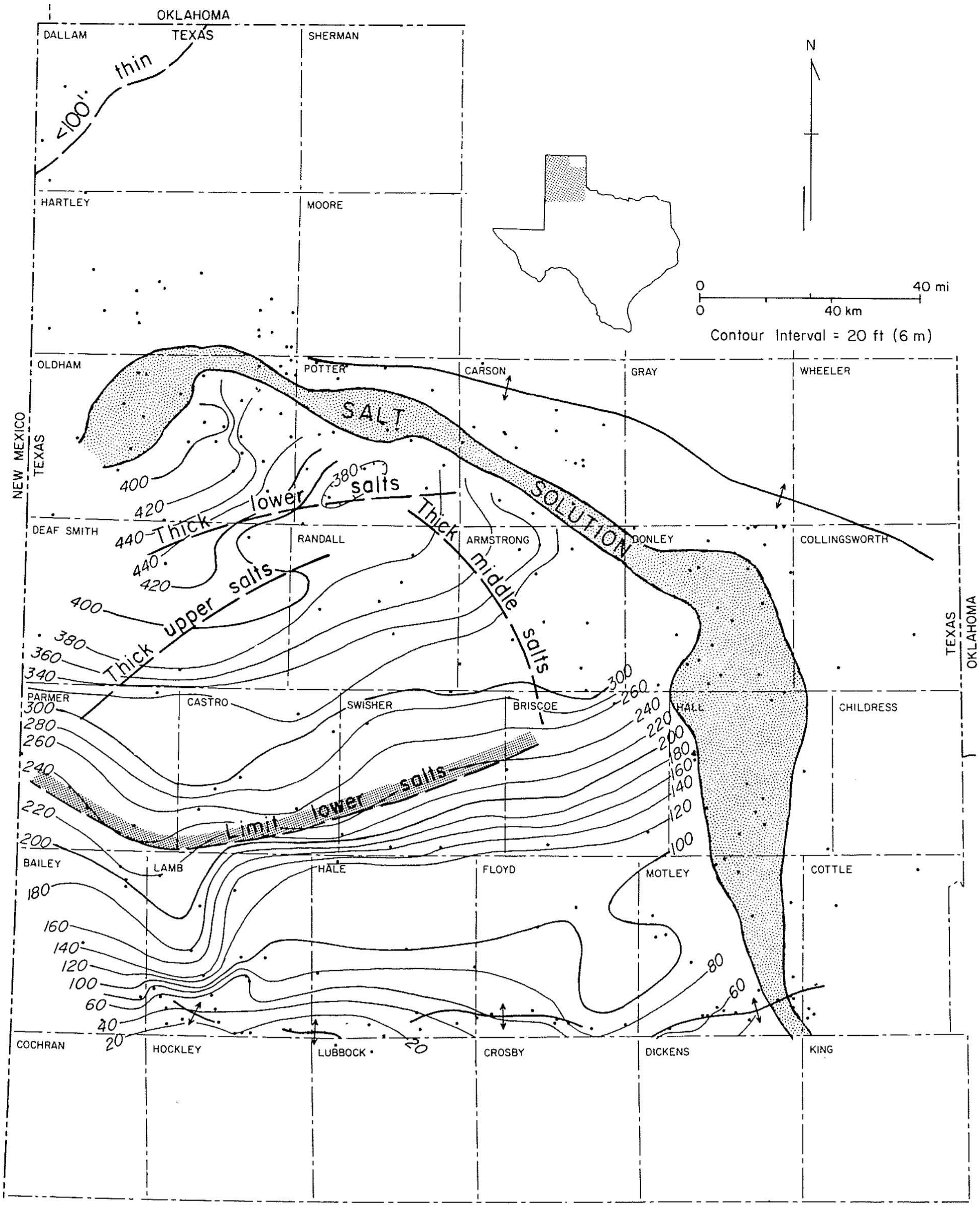

Figure 37. Net salt in the lower San Andres Formation. Lower salt units cap cycles 1, 2, and 3 (fig. 27); middle salt is in cycle 4 (figs. 27 and 28); the upper salt in cycle 5.

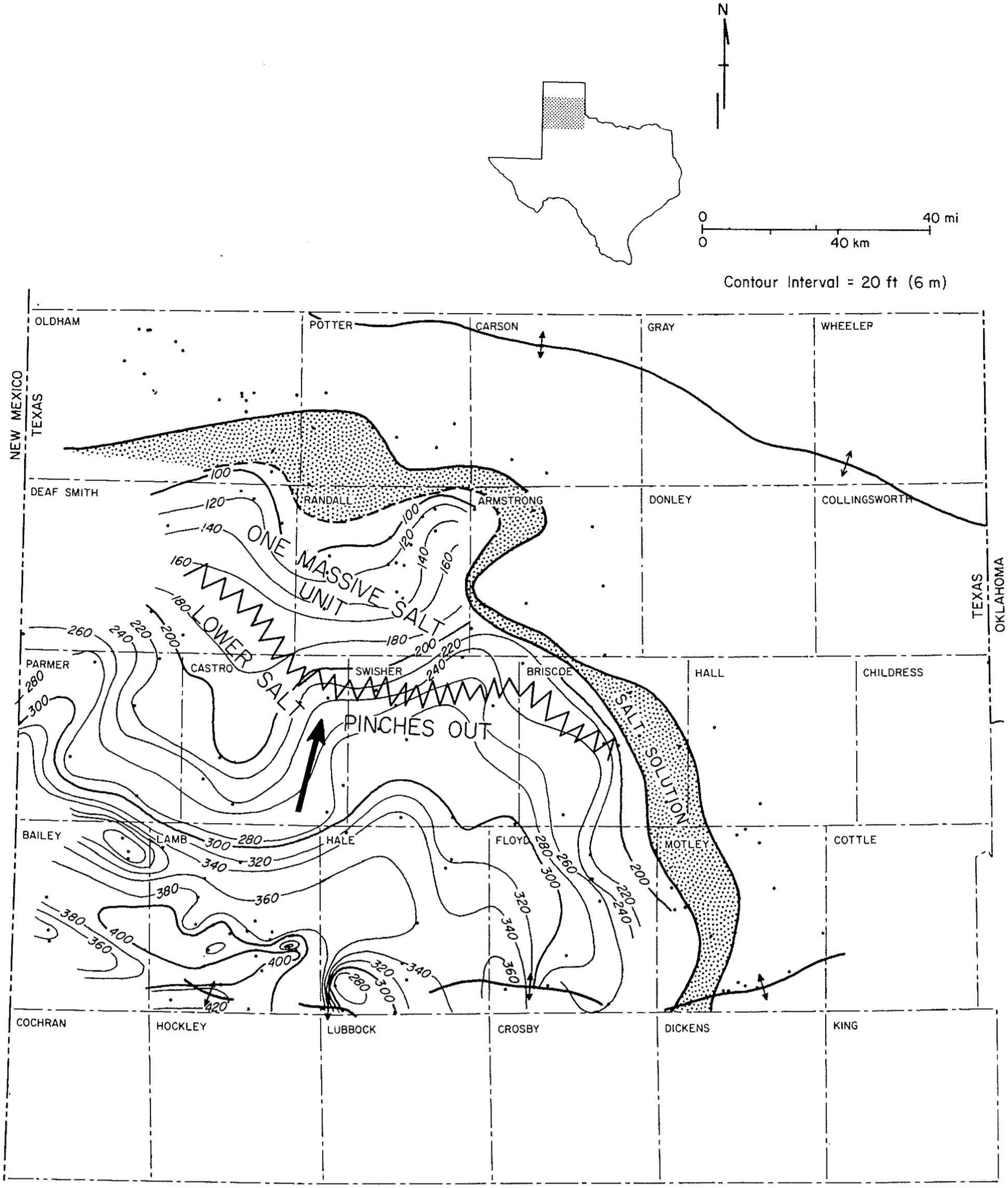

Figure 38. Net salt in Seven Rivers Formation. Lower Seven Rivers salt beds intertongue with red beds to the north. The upper Seven Rivers is a single, relatively massive salt unit.

CORE HANDLING AND EVALUATION

C. Robertson Handford

A deep core hole (4,000 feet or 1,200 m), which was drilled using modern and innovative methods, provided sample rock material for analytical studies. Additional core holes are planned for the Palo Duro Basin.

Special core recovery and core handling techniques were developed for the first 4,000-foot (1,200-m) stratigraphic test (DOE/Gruy Federal, Inc., Rex White, Jr., No. 1) drilled during August and September, 1978, in northeastern Randall County (see fig. 4). Late in 1978 a second stratigraphic test (DOE/Gruy Federal, Inc., D. M. Grabbe, No. 1) was drilled in northeastern Swisher County. Core samples from both wells are presently being analyzed.

During coring, the rock cores were enveloped by PVC pipe within 60-foot (18.2-m) core barrels. The PVC pipe prevented jamming of the core within the barrel and firmly held the core in place, reducing movement and breakage. The pipe and core were removed together from the core barrel, marked, and sliced into 6-foot (1.82-m) segments. Where possible, the core was extruded from the pipe briefly for on-site description, primarily to identify missing intervals. The core was replaced inside the PVC pipe. The pipe was 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 was split lengthwise with a radial saw, and the core was removed for marking to record top and bottom orientation. Where there was a section of 50 or more feet (15 or more m) of salt in the core, one uncut 3-foot (0.9-m) segment per 50 feet (15 m) of salt was sealed and set aside for rock mechanics, thermal, chemical, and waste interaction studies. All of the core but the 3-foot (0.9-m) salt segments was slabbed lengthwise into two parts, with a larger part (approximately two-thirds of the core) set aside for sampling, and a smaller part (approximately one-third of the core) preserved as a permanent library sample. All of the core has been logged and photographed to obtain a complete lithologic description and visual record. The salt cores are now sealed in plastic bags to insure preservation and minimize dissolution and efflorescence. Numerous analyses and studies planned for the core are outlined in table 3. Analyses will provide important data regarding lithology (especially character of the salt), hydrology, and potential resources of the salt-bearing Permian section.

Table 3. Core tests, analyses, and studies.

Depth	**Randall Well Site Stratigraphy**	**Fluid Tests**	**Porosity and Permeability**	**Evaporite Residue**	**Fluid Inclusions**	**Hydrocarbons**	**Petrography**	**Uranium and Molybdenum**	**Copper**	**Multi-element Analysis**
	Ogallala							X		
	Dockum	X	Representative Non-Evaporitic Lithologies					X		
	Dewey Lake							X	X	
	Alibates							X	X	Representative Lithologies
	Salado	X					Selected Intervals	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	
3000′	U. Clear Fork									
	Tubb							X	X	
	L. Clear Fork	X		X	X					
4000′	Red Cave							X	X	

RESOURCES

C. Robertson Handford

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

Basin analysis requires an assessment of the resources of the Palo Duro Basin. If potential economic deposits are present, they must be identified early so that all resource factors, which could preclude parts of the basin from nuclear waste isolation, can be thoroughly evaluated.

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 (figs. 39a and 39b), 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 that occur in the southeastern part of the basin constitute potential reservoirs. Sandstone units range up to 200 feet (60.9 m) 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.

The San Andres Formation has produced millions of barrels of oil in the Midland Basin and on the Central Basin Platform. San Andres carbonate strata occur in the Palo Duro Basin, but they are nonproductive. 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 (30 m) 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 has been discovered in the Palo Duro Basin. This may be due as much to subsurface burial, lack of outcrops, and insufficient mineral exploration, as it is 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 probably occurred as a result of diagenesis that accompanied 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 Evaluation Program, U. S. 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).

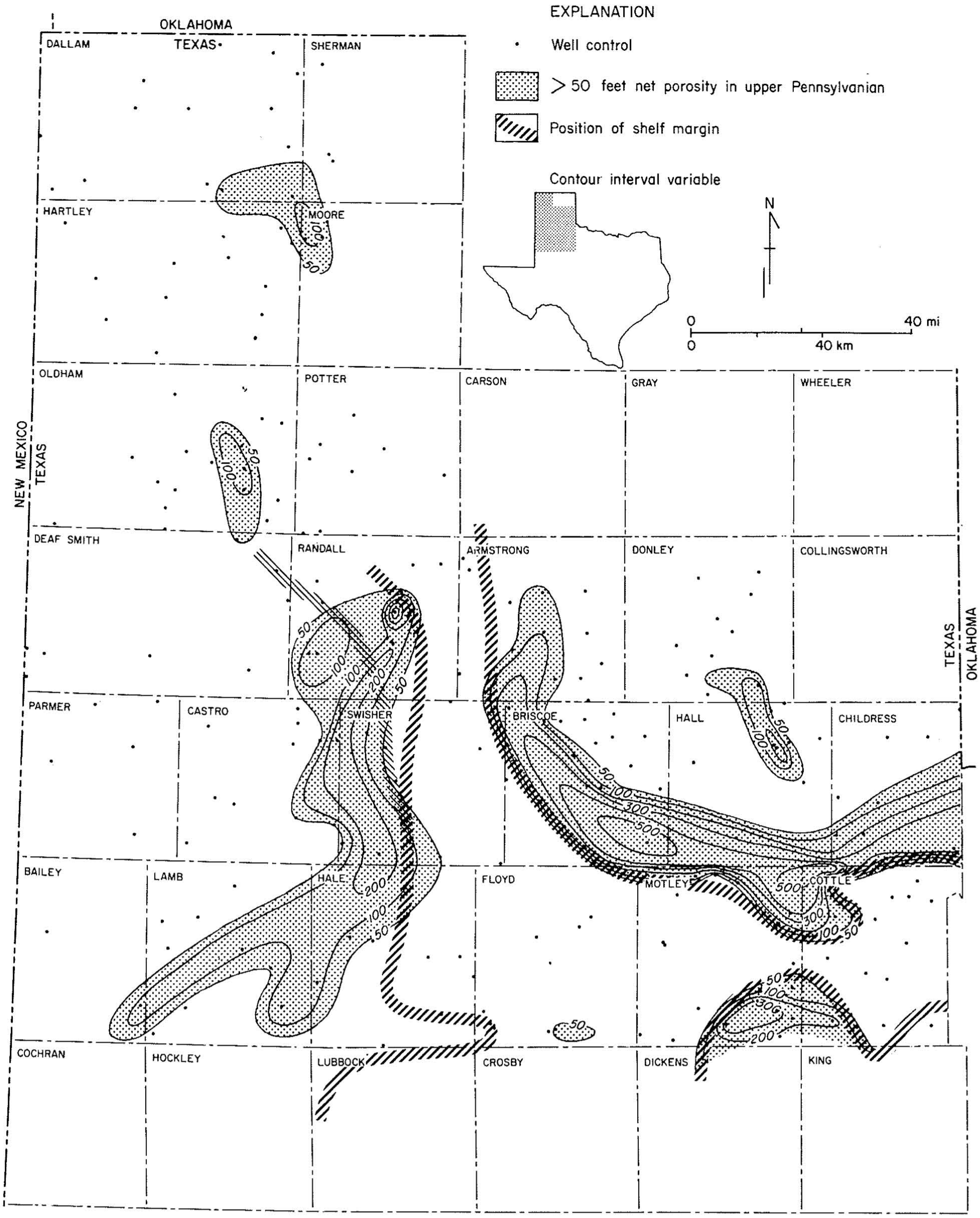

Figure 39a. Porosity map of Pennsylvanian carbonates. Data were obtained from sample log descriptions and represent intervals described as porous.

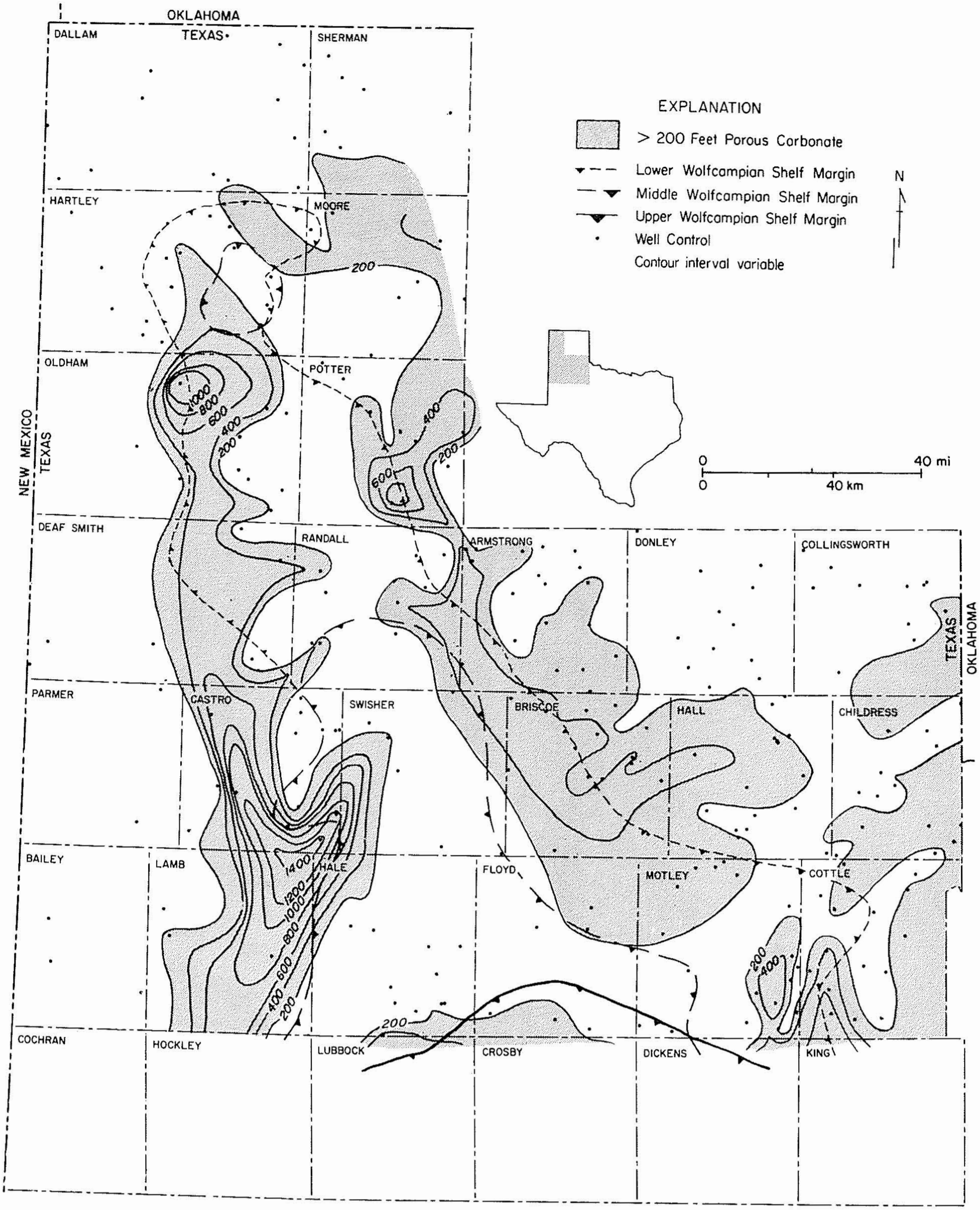

Figure 39b. Porosity map of lower Permian carbonates. Data were obtained from sample log descriptions and represent intervals described as porous.

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

Thomas C. Gustavson

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 surface erosion, stream incision, and salt dissolution requires an understanding of processes and rates of sediment removal, stream propagation, slope retreat, and salt dissolution. Climate, especially high-intensity rainfall, and jointing are the major controls of stream propagation and slope retreat. Salt dissolution at depth results in collapse of overlying sediments and strongly influences drainage and slope development. Quantitative measurements of erosion rates are obtained for various combinations of slope, vegetation, soil, and substrate lithology. Geomorphic mapping provides the mechanism for which erosion rate data for specific areas can be extrapolated to other similar areas of the Llano Estacado. 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 on-going studies designed to provide understanding of these processes (fig. 40). A preliminary discussion of the geomorphic methods used to evaluate the suitability of the Llano Estacado area or the Southern High Plains for use as waste isolation sites has been presented by Gustavson and others (1978b).

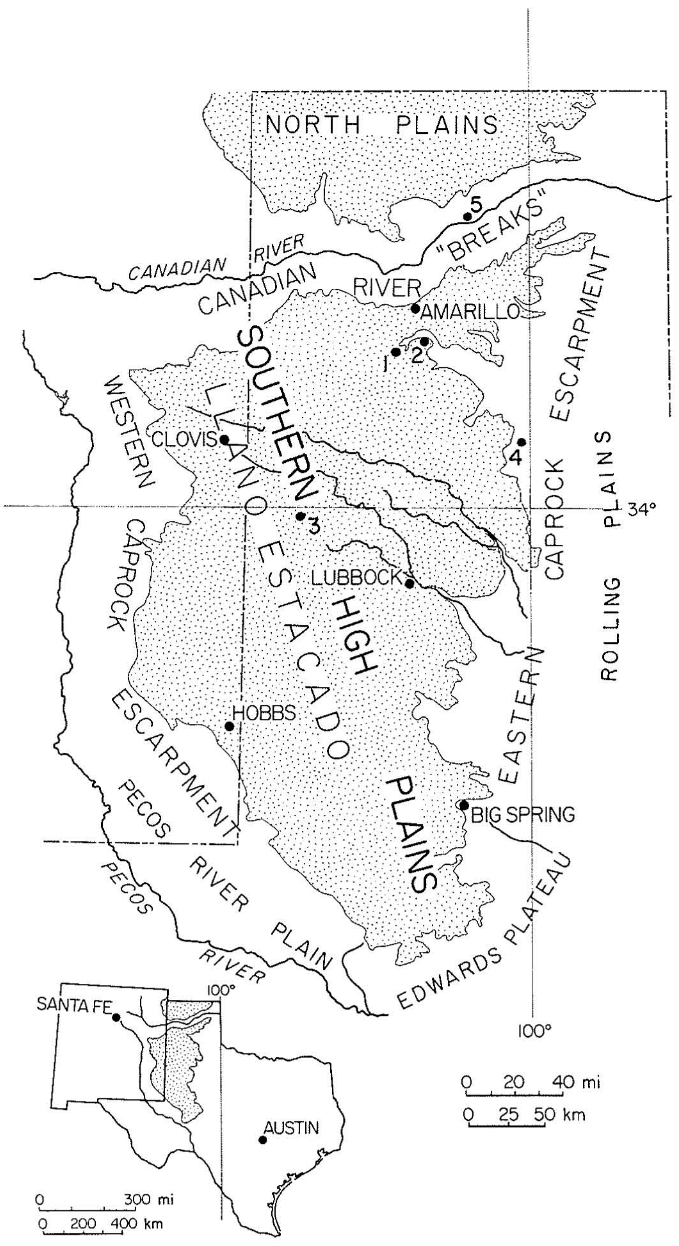

Figure 40. Physiographic units in the Texas Panhandle and adjacent areas. Numbers 1-5 indicate climate monitoring stations: (1) Buffalo Lake National Wildlife Refuge, (2) Palo Duro Canyon State Park, (3) Muleshoe National Wildlife Refuge, (4) Caprock Canyon State Park, and (5) Lake Meredith National Recreation Area.

CLIMATE OF THE TEXAS PANHANDLE AND ITS INFLUENCE ON EROSION

Robert J. Finley

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

In the Texas Panhandle 43 percent of the average annual precipitation falls during May through July, primarily from thunderstorms, and 72 percent falls during April through September (Haragan, 1976). Extreme rainfall is greatly significant because of intense erosion. Within the past 33 years at Amarillo the months of May through August have had maximum 24-hour rainfalls 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 thunderstorms. In the Southern High Plains (fig. 41) data from three 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 at either Lubbock, Texas, or Clovis, New Mexico. July in Amarillo usually includes 11 thunderstorm days (fig. 42), 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 is the dominant erosional process. A single thunderstorm with total rainfall of approximately 3 cm (1.2 inches) resulted in observed surface denudation of 1 to 2 mm (0.04 to 0.08 inches) 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, rains.

Rainfall records in 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 43 typifies this locally intense rainfall 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). Intensity of rainfall has been related directly (correlation coefficient 0.96 to 0.93) to soil loss over a 10-year period (Wischmeier and Smith, 1958). Locally intense rains such as those in the Texas Panhandle also tend to have larger 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 severely restrict raindrop impact and surface flow. Also, cultivation and grazing further reduce or stress the vegetation cover.

Field evidence suggests that surface sediment is temporarily stored within larger 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 Little Red River to export efficiently sediment eroded from the Caprock Escarpment area, as well as continue downcutting along their channel. 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 results from 25.4 to 35.6 cm/year (10 to 14 inches/year) of effective precipitation at a reference annual temperature of 50°F. Because mean annual temperatures in the Texas Panhandle range from 59.7°F (15.4°C) at Lubbock to 57.4°F (14.1°C) 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 measured precipitation 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. 40) 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. Sediment removal from the High Plains surface, however, is limited because of low surface slope gradients, nonintegrated drainage, and alteration by man.

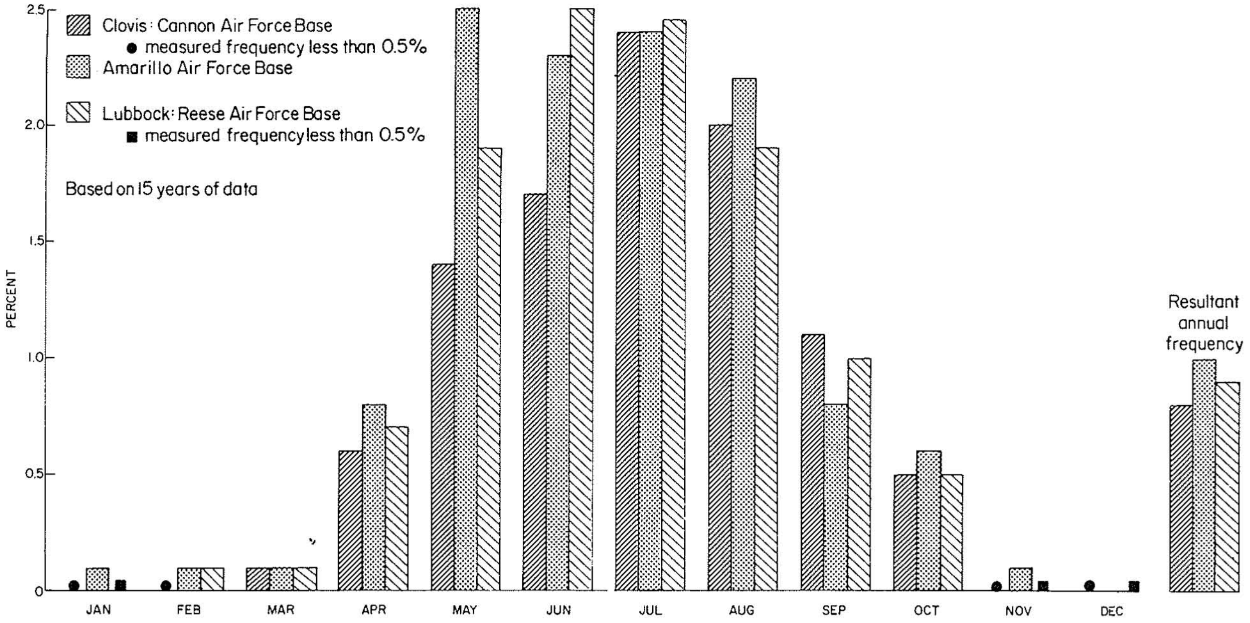

Figure 41. Percentage frequency of thunderstorms in the region of the Palo Duro Basin based on hourly observations (compiled from Orton, 1964).

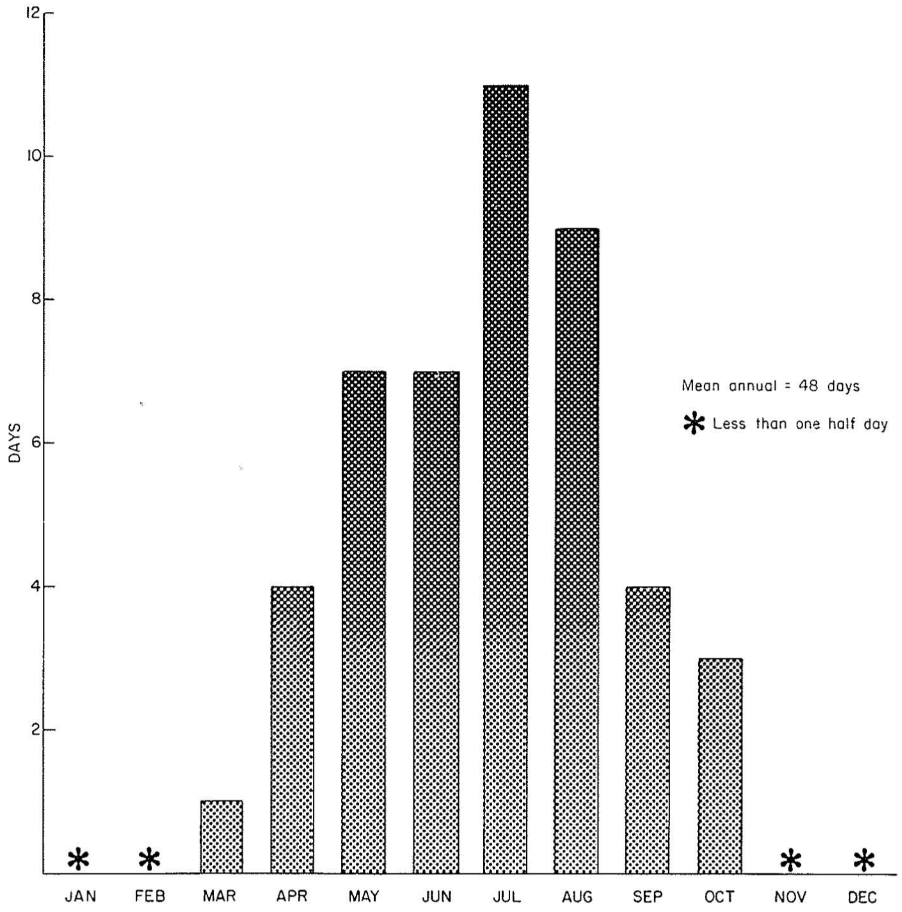

Figure 42. Thunderstorm days per month, Amarillo, Texas (data from Orton, 1964).

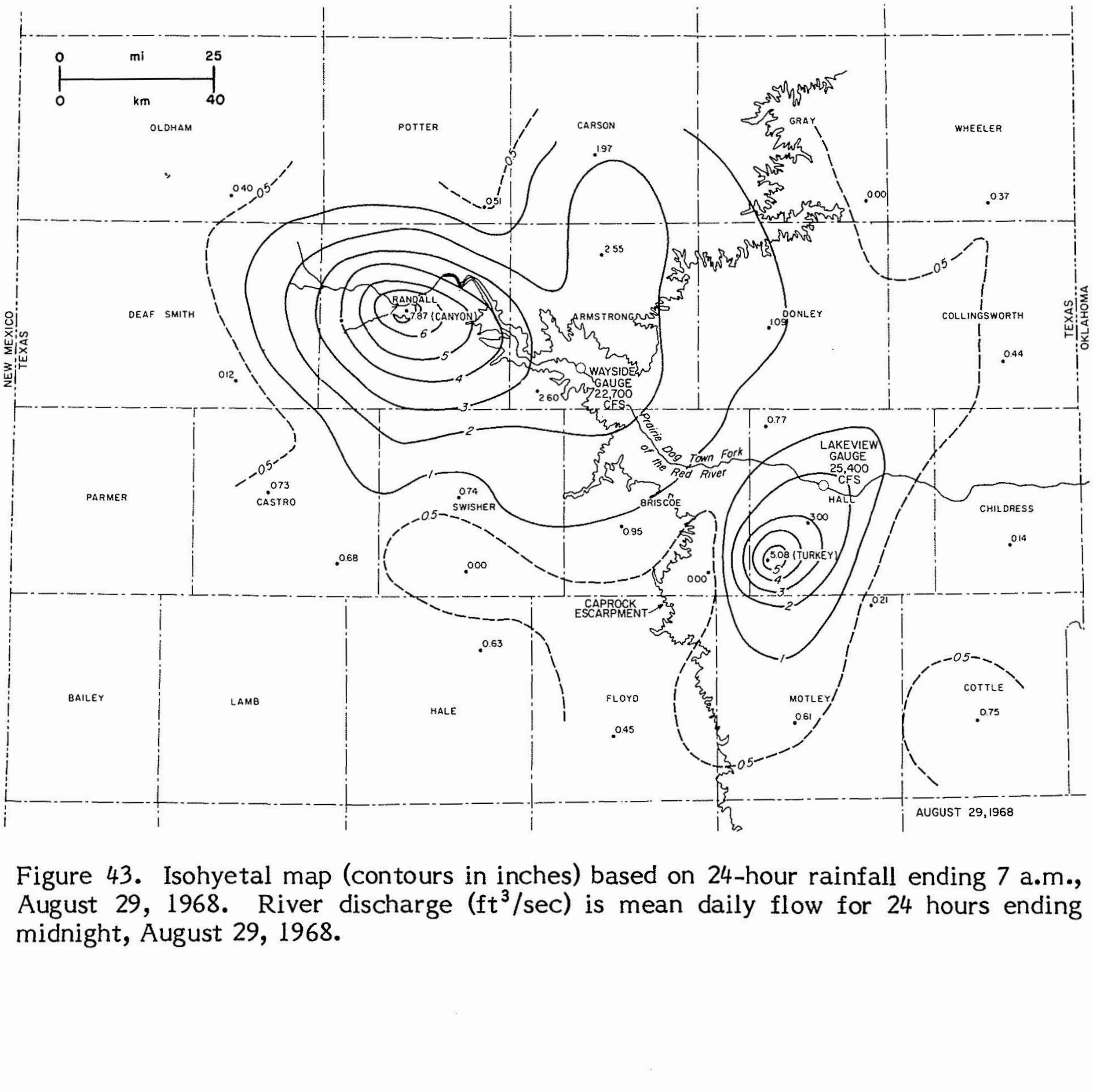

Figure 43. Isohyetal map (contours in inches) based on 24-hour rainfall ending 7 a.m., August 29, 1968. River discharge (ft^3/sec) is mean daily flow for 24 hours ending midnight, August 29, 1968.

RUNOFF CHARACTERISTICS AND A FLOOD IN THE TEXAS PANHANDLE

Robert J. Finley

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 flood on May 27, 1978 (fig. 44) shows the flashy intermittent flow characteristic of the Prairie Dog Town Fork. Occurrence of such high peak discharges during a relatively short period of record affects the shape of the flood return frequency plots (figs. 45 and 46) 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.

Assuming the May 27, 1978 event is typical of high discharge events in this region, their occurrence is a significant factor in sediment export from the Southern High Plains. 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 addresses the rate of westward retreat of the Caprock Escarpment.

On May 26, 1978, heavy rains from thunderstorms fell in northwest Randall County in the upstream reaches of Palo Duro Creek. Rainfall distribution of this storm (fig. 47) shows a peak of 13 cm (5.1 inches) at Canyon, Texas and 7.1 cm (2.80 inches) 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 approximately 6.4 cm/hour (2.5 inches/hour) (fig. 48).

Published return frequencies for rainfall (table 4) show that precipitation at Buffalo Lake has a return period just less than 10 years for an event lasting 3 hours. The 24-hour rainfall total of 13 cm at Canyon, Texas, has a return period just under 25 years (table 4). However, calculations for this study of return frequencies for 24-hour rainfall totals at Canyon (55-year period of record) suggest that Hershfield's (1961) data (table 4) are somewhat low. For example, 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, significant erosion and sediment transport occurred 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 5). 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 headward up to 12 m (39.4 feet), and large volumes of caliche rubble were carried down the canyon. Largest blocks moved were approximately 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 from past repetitive events with high capacity for sediment transport.

A stream bar consisting predominantly of gravel-sized caliche fragments (fig. 49) 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 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 in some areas by overbank flow. 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 at lower flow stages. Study of overbank deposits will aid 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 4. 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 5. 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	Maximum	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

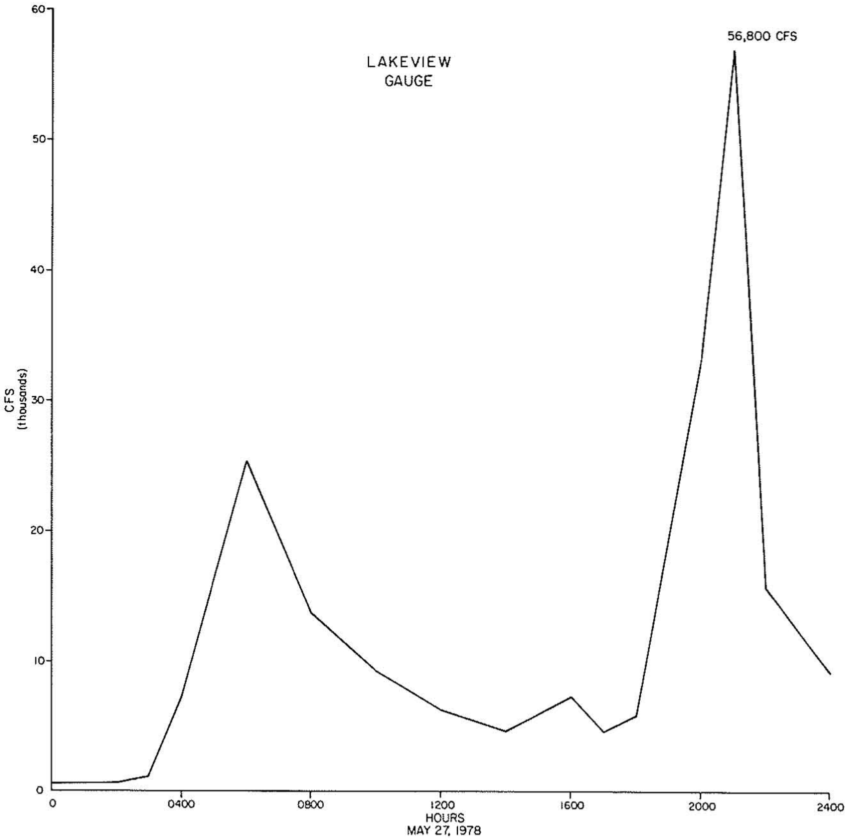

Figure 44. Instantaneous discharge based on hourly computations, Lakeview gauge, Prairie Dog Town Fork of the Red River.

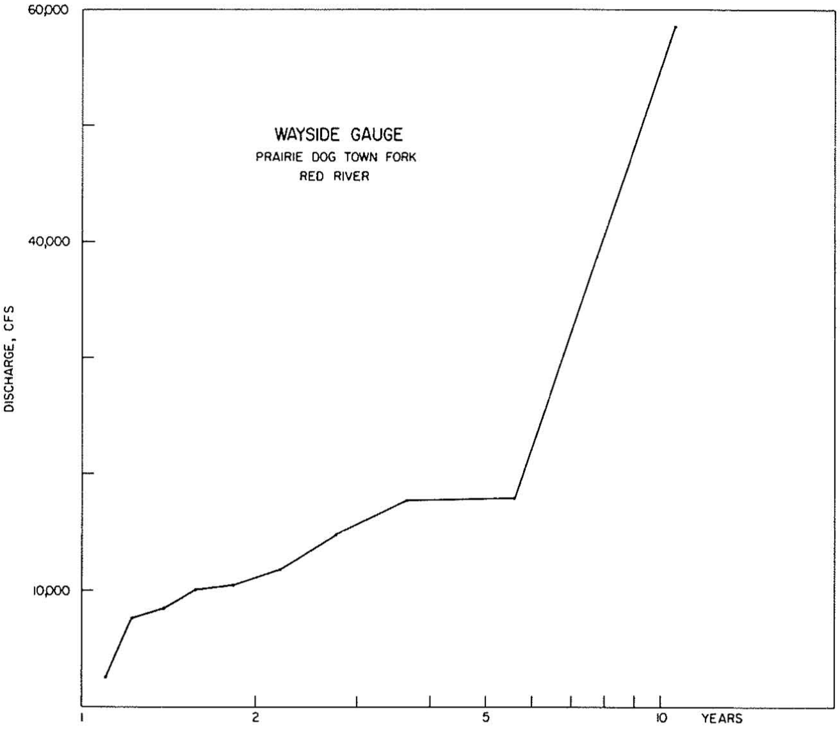

Figure 45. Return interval of annual peak discharge based on 1968-1976 water years.

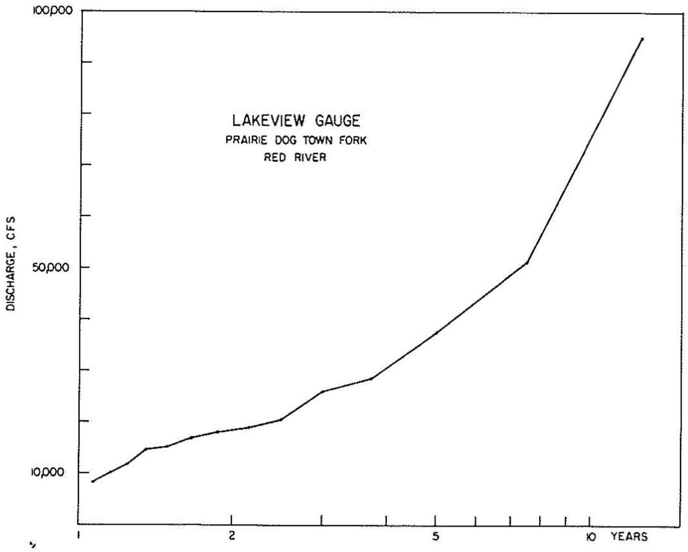

Figure 46. Return interval of annual peak discharge based on 1964-1976 water years.

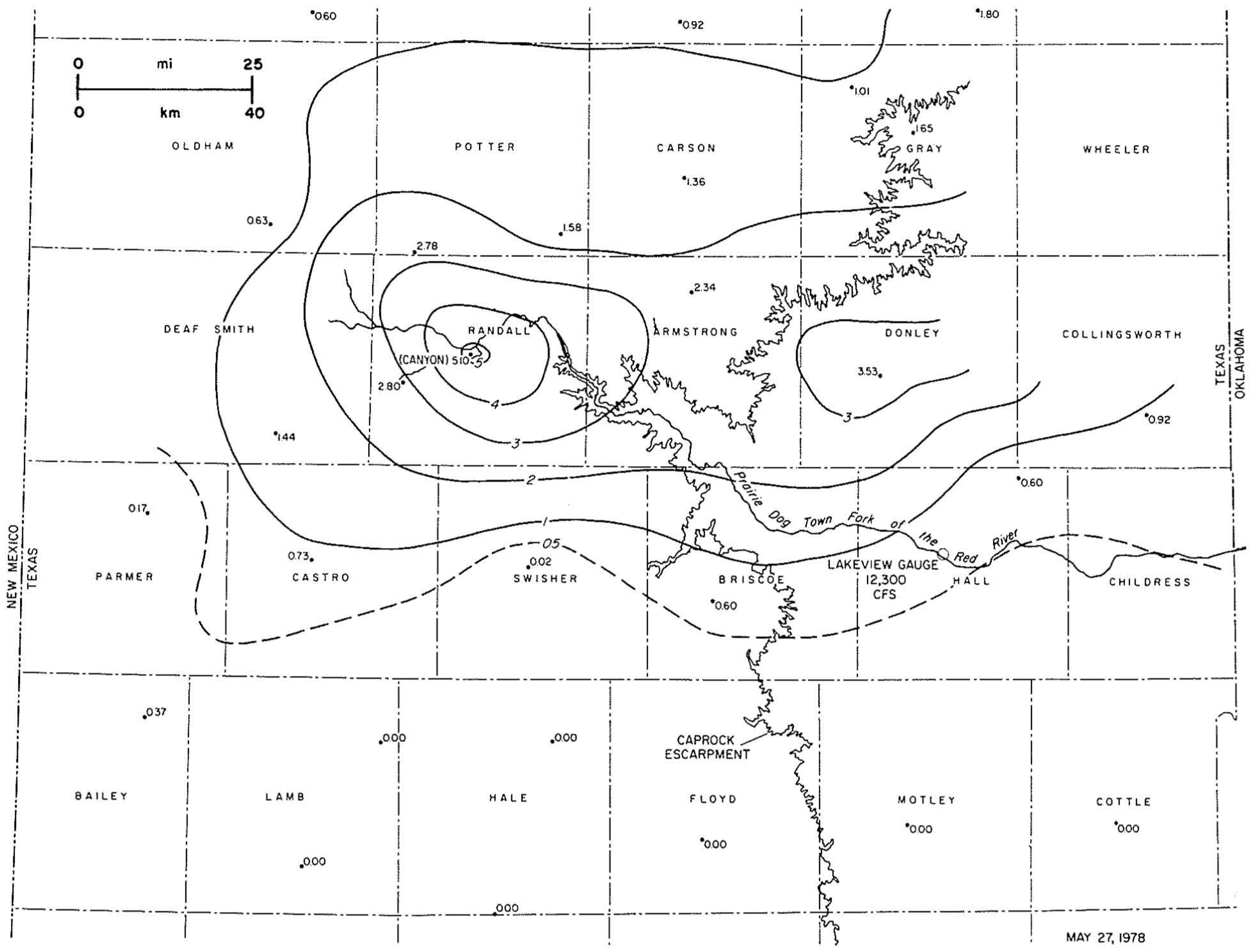

Figure 47. Isohyetal map (contours in inches) based on 24-hour rainfall ending 7 a.m., May 27, 1978. River discharge (ft^3/sec) is mean daily flow for 24 hours ending midnight, May 27, 1978.

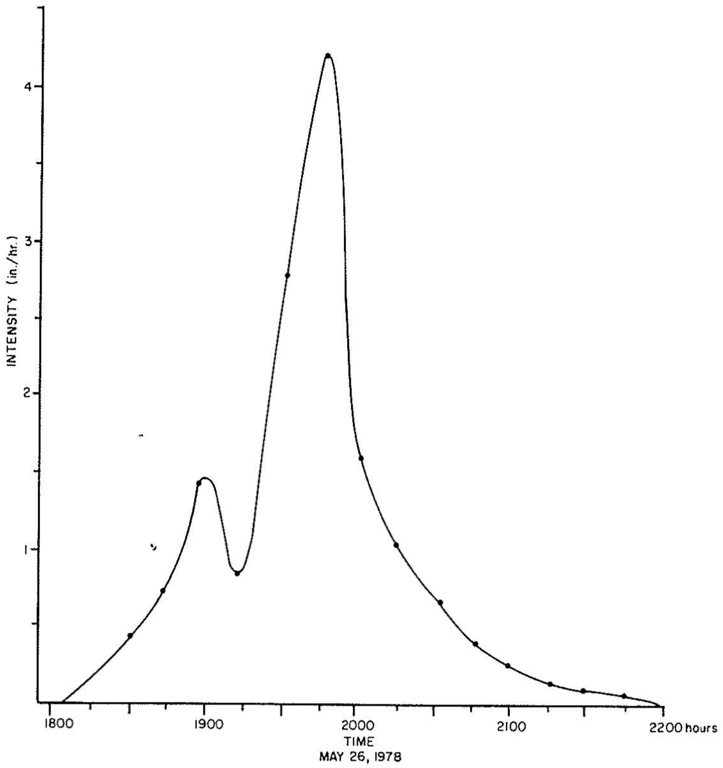

Figure 48. Rainfall intensity curve from Buffalo Lake erosion monitoring location.

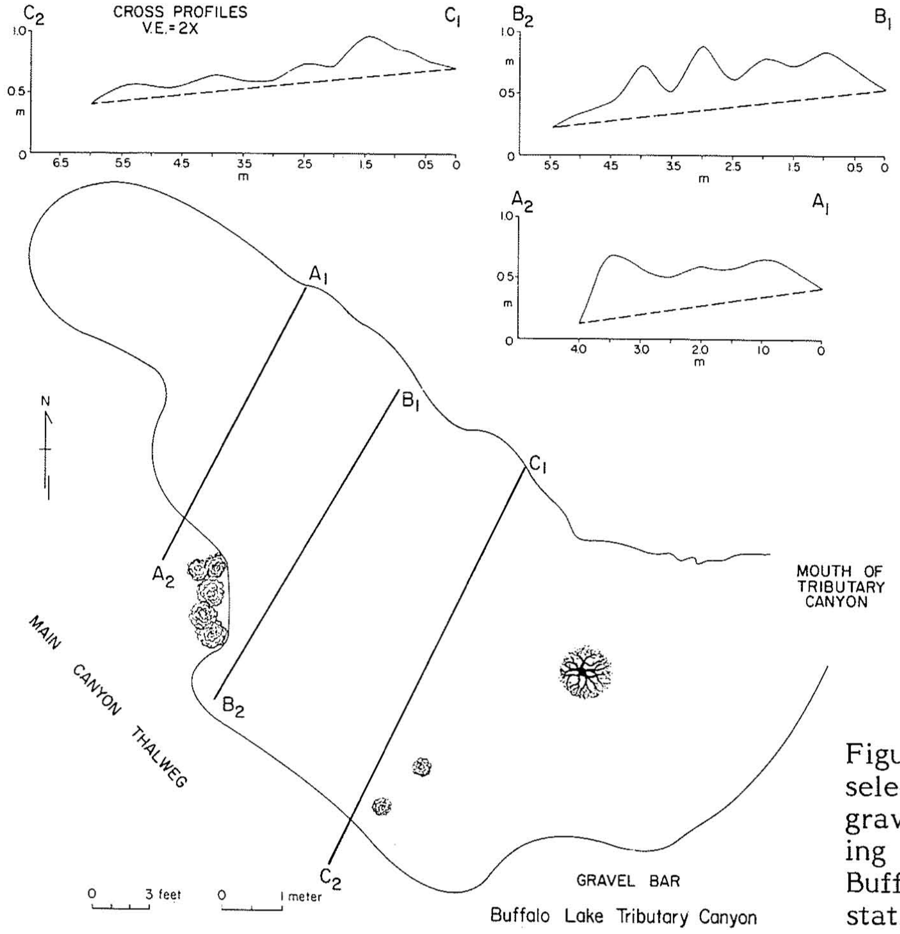

Figure 49. Plan view and selected cross profiles for gravel bar deposited during May 27, 1978 storm, Buffalo Lake monitoring station.

GEOMORPHIC MAPPING

Thomas C. Gustavson and Robert J. Finley

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 is the role of playas in development of High Plains drainage.[1]

Based on the analyses of 1:24,000 topographic maps, black-and-white controlled aerial photomosaics (1:24,000) of various vintages, and color-infrared aerial photographs (1:80,000; 1977), geomorphic map units for the High Plains were defined using unique combinations of geologic substrate and soil, landform morphology and topography, geologic process, and biota (Woodruff and others, in press; 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), and 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 High Plains are illustrated in figure 50.

1. Playa bottoms include either dry or water-filled ephemeral ponds that cover from 1 to 15 ha (2.5 to 38 ac) and are commonly up to 10 m (33 feet) deep.
2. Playa sides are the catchment area for deeper (greater than 5 m (16 feet) deep) playas.
3. Lee dunes are low topographic rises (commonly only about 3 m (10 feet) 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.

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[1] Geomorphic mapping developed in conjunction with C. M. Woodruff, Bureau of Economic Geology, The University of Texas at Austin.

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

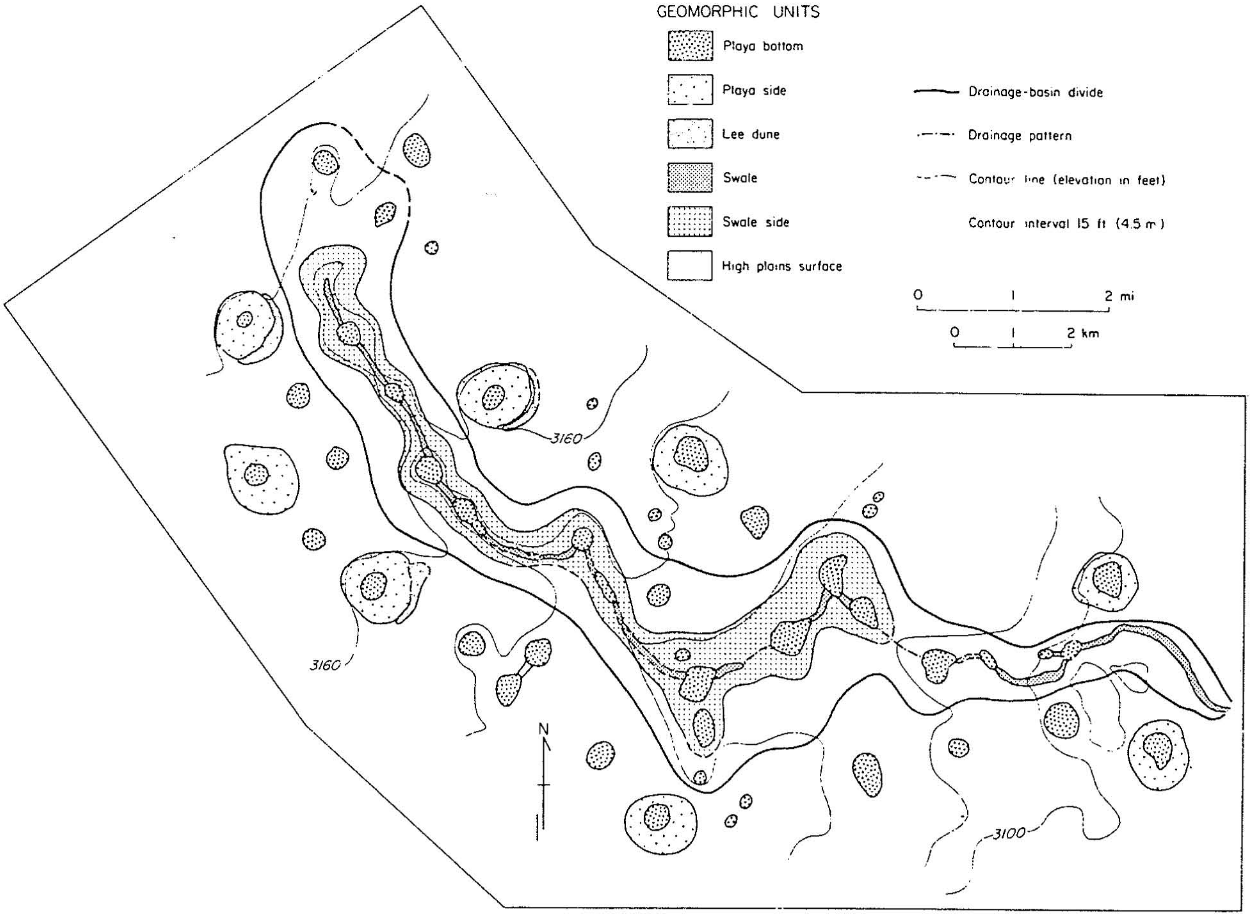

Figure 50. Geomorphic map of a small drainage basin approximately 50 km east-northeast of Lubbock.

ANALYSES OF SURFACE LINEAR ELEMENTS AND JOINTING, TEXAS PANHANDLE

Robert J. Finley and Thomas C. Gustavson

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 200,000 km^2 area including the High Plains over the Palo Duro Basin (fig. 51). 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 relationships between these trends and geologic structure 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 some degree of structural control of surface morphology. 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 due to agricultural practices. Analysis of three Landsat scenes (blocks 3, 4, and 6, fig. 51) was completed on specially enhanced false-color composite imagery.

On block 3, covering the Amarillo-Plainview area (fig. 52), 1,286 lineaments were identified. 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. In the Rolling Plains physiographic province, tonal anomalies probably represent poorly developed drainage features and are much less frequent. 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. 52). Control of physiography is indicated by a joint pattern persistent over the area of a county and perhaps a region.

Lineament orientations--Azimuth frequency diagrams illustrate the orientation of lineaments derived from Landsat imagery (fig. 53). The High Plains data show a trend centered at 300° to 320° and a subordinate, orthogonal trend at 30° to 50° (fig. 53). Lineaments on the Caprock Escarpment, which have here been separated from the High Plains data, are derived from Landsat scenes 3, 4, 6, and 7 (fig. 51). 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. 40). These data define a predominant trend at 0° to 20° and subordinate trends at 60° to 70° and at 300° to 330°. Two types of drainage features are common: stream segments and drainage lines. Stream segments are relatively short, straight channel reaches that are normally connected at sharp, angular junctions suggesting joint intersections. These are 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. 52) 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--More than 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 orthogonal 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 avoided. Graphic plots of joint orientations (figs. 54 and 55) and joint plots on geologic maps (figs. 56 and 57) indicate that major joint trends vary geographically and are oriented westerly, northwesterly, northerly, and northeasterly. Major joint trends are parallel to (1) major basement structural trends (fig. 2); (2) stream and valley segments and escarpments; and (3) trends of playa alignments and draws on the Llano Estacado. Thus the 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 along joints in the Ogallala caliche caprock and by local, preferential solution of cements along joints in the Dockum Formation.

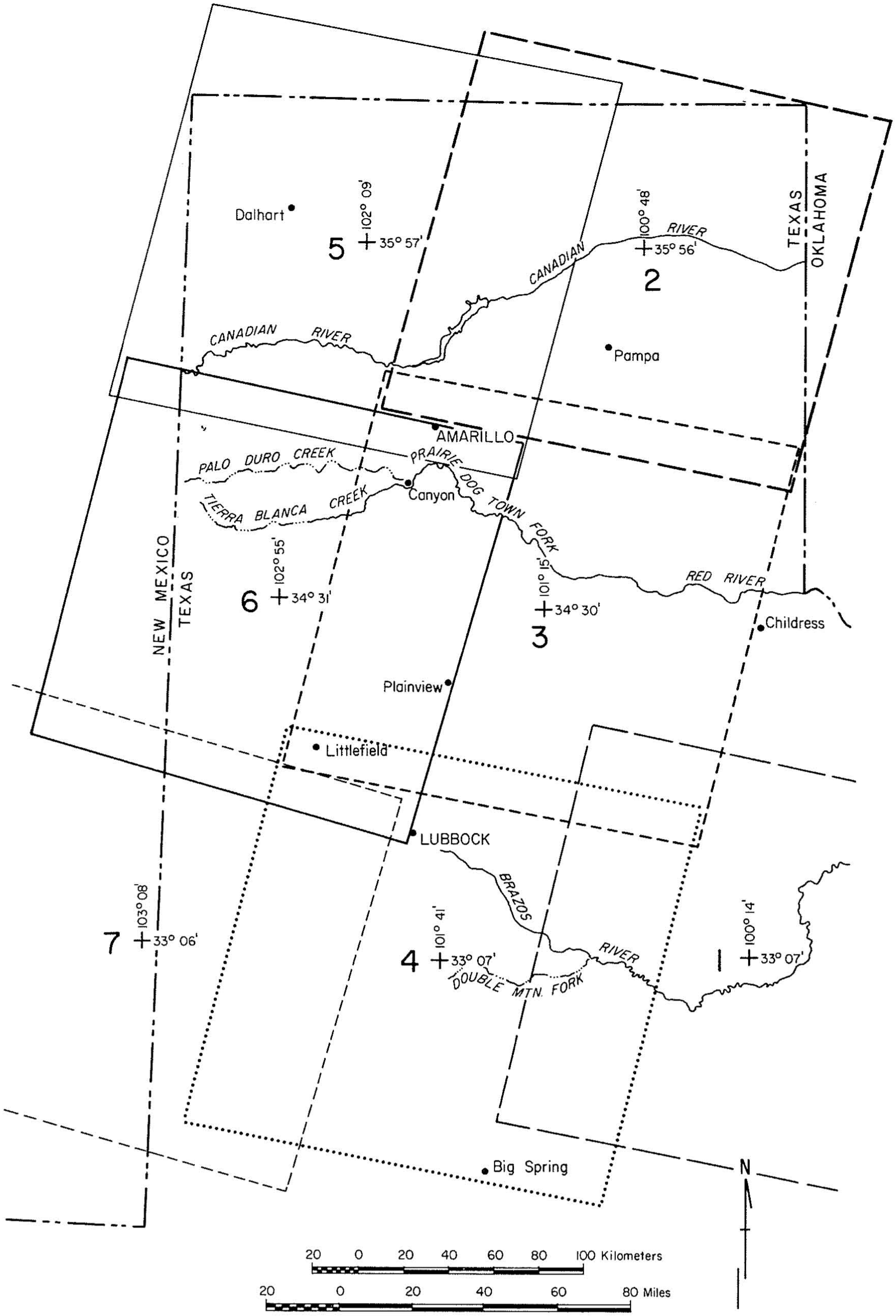

Figure 51. Generalized frame boundaries for Landsat coverage of the Texas Panhandle, numbered for reference to text discussion.

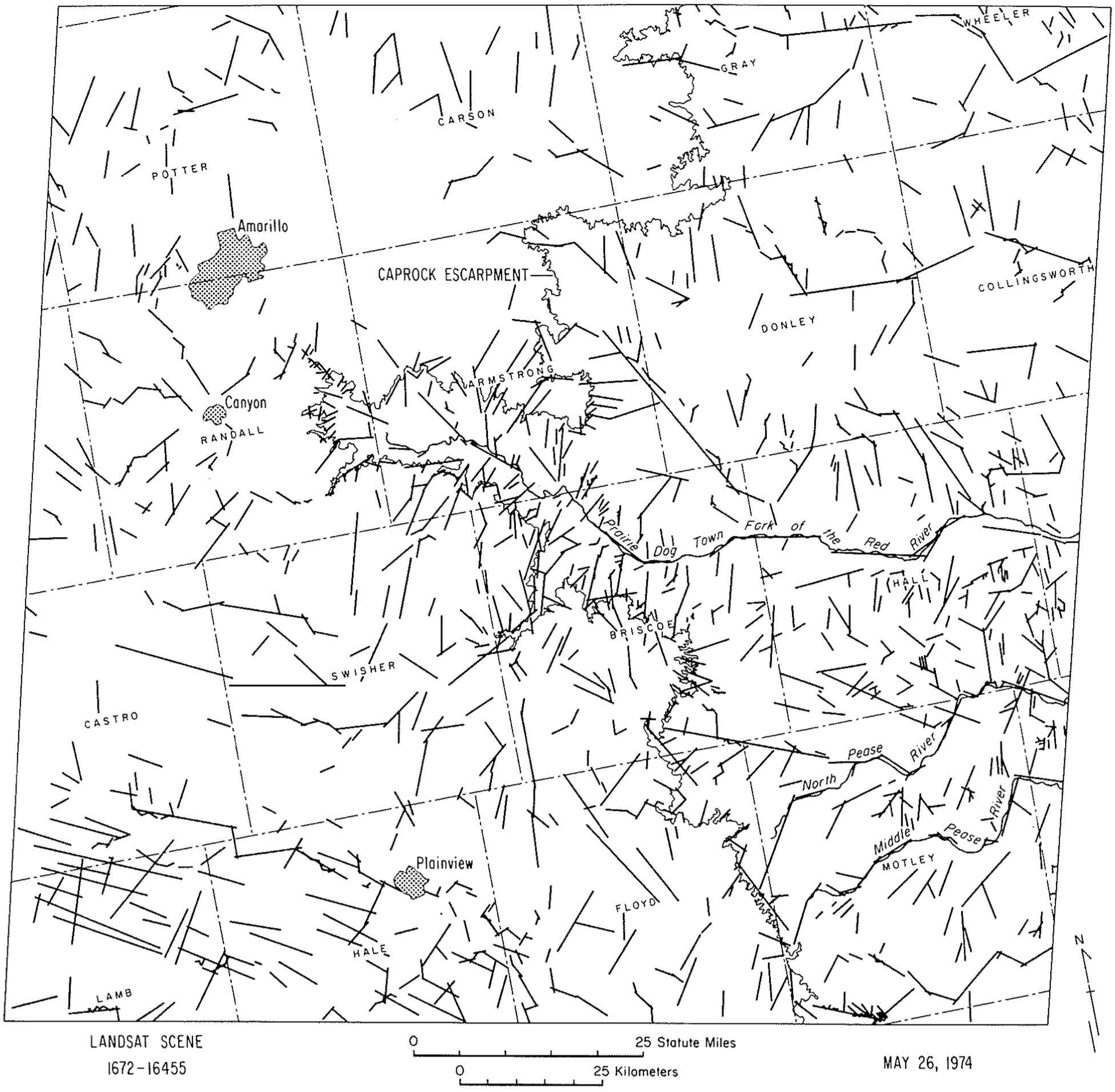

Figure 52. Lineaments derived from false-color composite Landsat imagery, Texas Panhandle region.

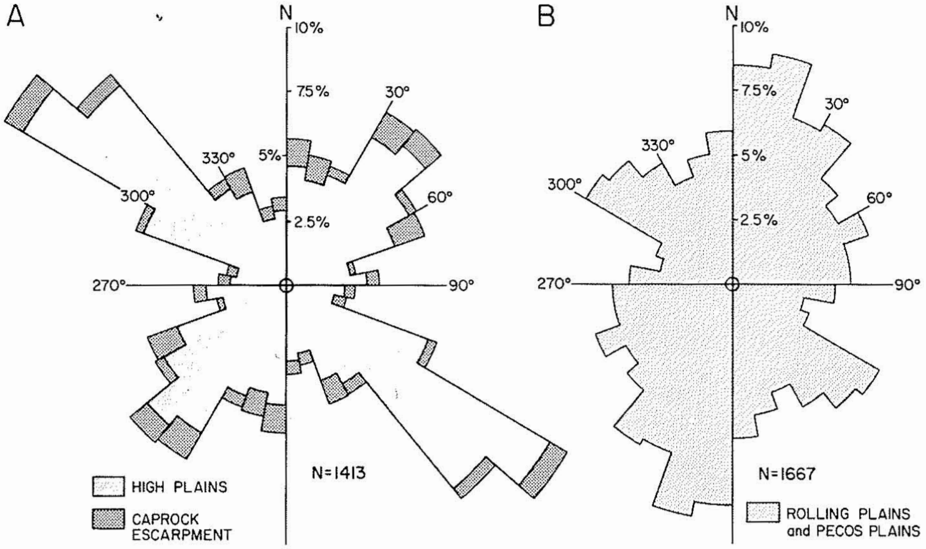

Figure 53. Lineament trends in the central Texas Panhandle and adjacent New Mexico.

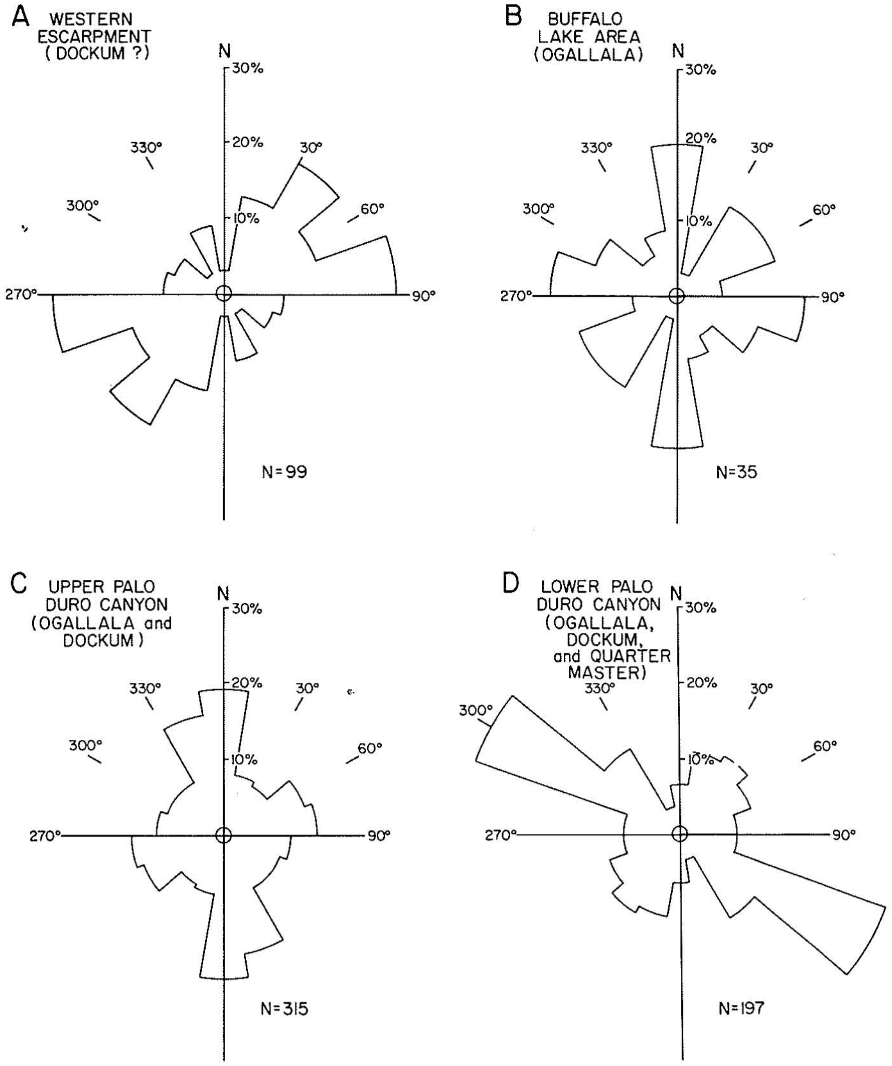

Figure 54. Summary of joint orientations grouped by locality, Texas Panhandle region.

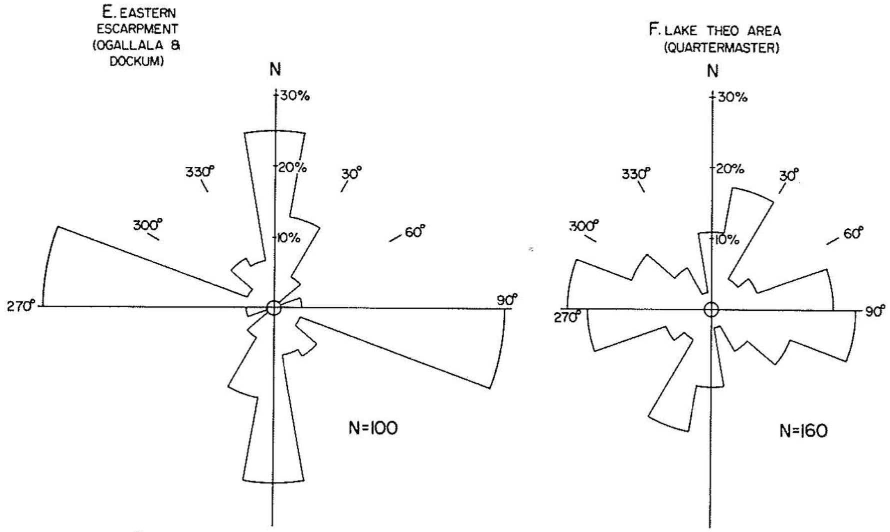

Figure 55. Summary of joint orientations grouped by locality, Texas Panhandle region.

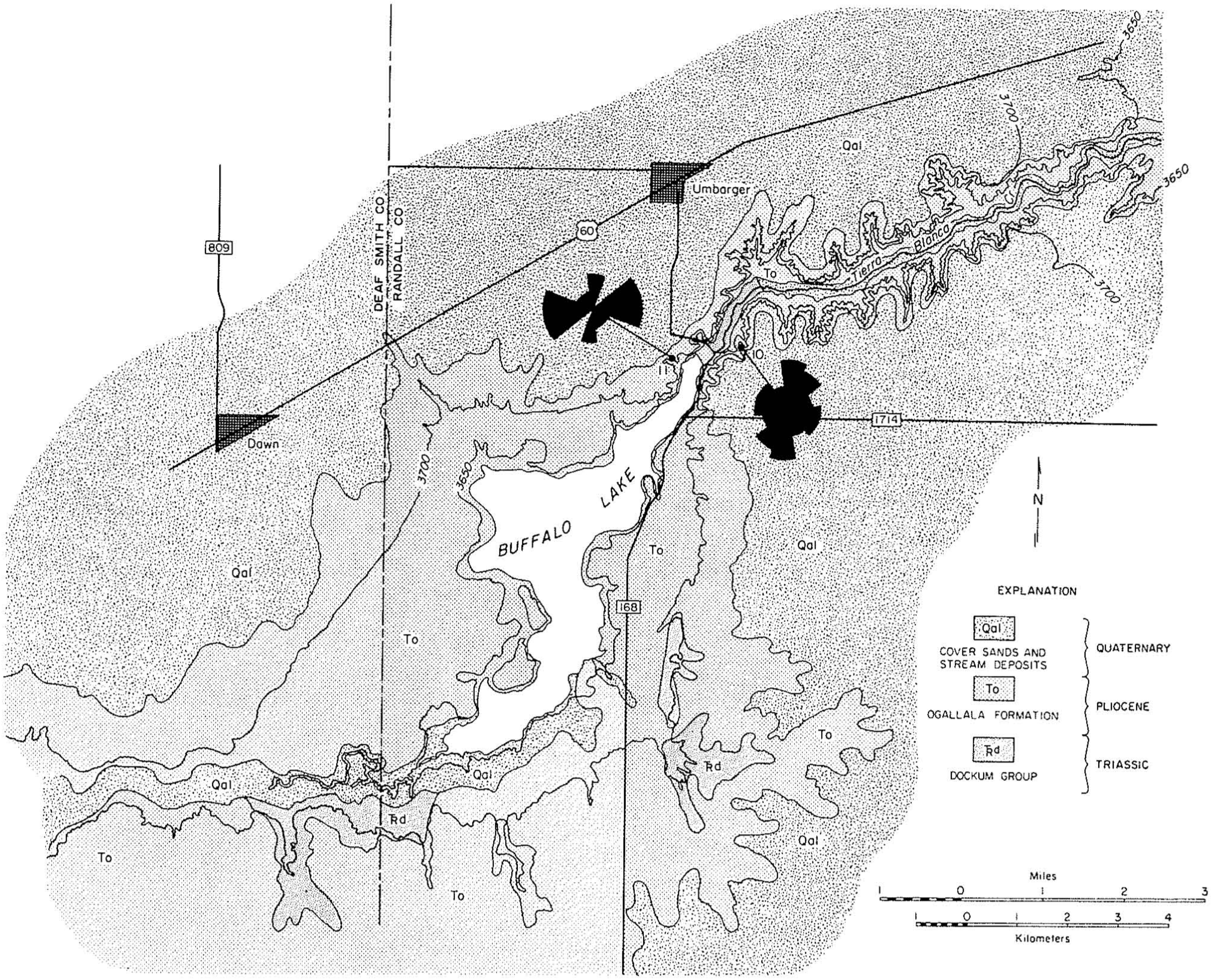

Figure 56. Geologic map and joint distribution, Buffalo Lake area, Texas Panhandle region.

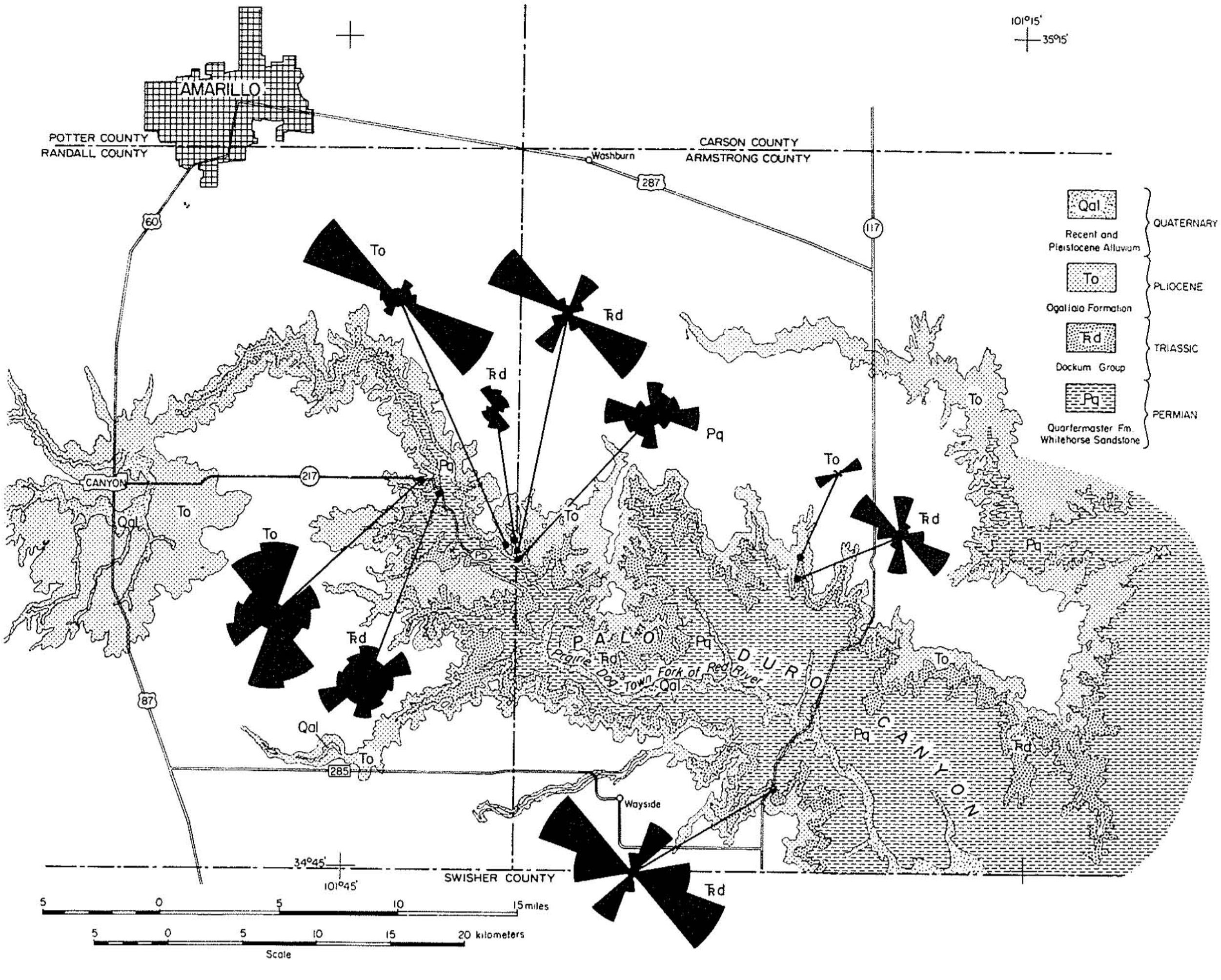

Figure 57. Joint orientations and geologic map, Palo Duro Canyon, Texas Panhandle region.

SALT DISSOLUTION

Thomas C. Gustavson

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 from 500 to 2,000 feet (150 to 600 m) deep (fig. 58). The coincidence of dissolution zones and major surface erosional features strongly suggests that there is a causal interrelationship between the 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.

To understand regional geologic structural changes that have occurred since the Permian Period, a structure contour map (sea level datum) on the top of the upper Permian Alibates Formation was prepared (fig. 59). The Alibates is a persistent marker unit which consists of one or more beds of dolomite and/or anhydrite (approximately 45 feet or 15 m thick). Its thin but widespread distribution suggests 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, thickness of the Alibates Formation would vary significantly over paleotopographic depressions or highs.

Major structural depressions are defined by elevations on the upper surface of the Alibates Formation in Oldham, Hartley, Moore, and Carson Counties. The depression in Oldham, Hartley, and Moore Counties was formed in part by salt dissolution and collapse/subsidence of the subjacent Permian evaporite sequence with subsequent infilling by Triassic and Tertiary sediments. The southern margin of the depression coincides with the trend of underlying dissolution zones (fig. 58). 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 second large depression exhibits approximately 300 feet (90 m) of relief and is filled with clastic sediments of the Ogallala Formation. This depression also lies within and to the north of the dissolution zone of the subjacent Permian salts, again suggesting a salt dissolution origin. Presence of thicker Ogallala deposits in the depression 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 Gray Counties, the dip of the Alibates Formation shifts from south to east, and a structural trough is defined by the 2,500-foot (750-m) contour in northeastern Briscoe County. 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.

Twenty-seven filled collapse chimneys were discovered in the Permian Whitehorse Formation during construction of the Sanford Dam on the Canadian River, 40 miles (64 km) northeast of Amarillo (fig. 60) (Eck and Redfield, 1963). The chimneys are circular to elliptical in cross section and are filled with slumped and brecciated sediments from the overlying Triassic Dockum Group and Tertiary Ogallala Formation. Chimneys apparently formed when Permian sediments collapsed into voids developed 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 on the Blaine Formation and a topographic map for an area including a large lake in Gray County shows that a structural depression of the Blaine Formation underlies the lake (fig. 61). In cross-sections the Blaine thins under the lake probably as a result of salt dissolution.

Topography on the Alibates Formation, as observed in the structure contour map in figure 59, the filled chimneys in the vicinity of Sanford Dam, and large lake depressions all illustrate that major structural collapses of as much as 300 feet (90 m) have occurred locally at the margin of the Palo Duro Basin as a direct result of salt dissolution.

Stream discharge of solution derived salts--The average annual solute load discharged from the Llano Estacado from 1969 to 1974 was 2,749,000 tons (approximately 2,493,000 m tons) of dissolved solids including 1,161,000 tons (approximately

1,053,000 m tons) of chloride and 507,900 tons (approximately 460,600 m tons) of sulfate (U. S. Geological Survey, 1970 to 1975). Nearly half of this dissolved load is transported by the Prairie Dog Town Fork of the Red River where the average load for the same period was 1,033,500 tons (937,384 m tons) dissolved solids including 425,300 tons (385,817 m tons) of chloride and 155,800 tons (141,310 m tons) of sulfate. The drainage basin of the Prairie Dog Town Fork of the Red River carries the largest solute load, and is the drainage system that has eroded the greatest distance westward into the High Plains. This further illustrates a close coincidence between active stream incision, scarp retreat, and the westward migration of subsurface salt dissolution zones.

Solute load is described in terms of sulfate (SO_4^{--}), chloride (Cl^-), and total dissolved solids (TDS) (fig. 62, table 6). 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 (rillenstein up to 1 cm across) 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, some are probably derived by subsurface dissolution of gypsum and anhydrite.

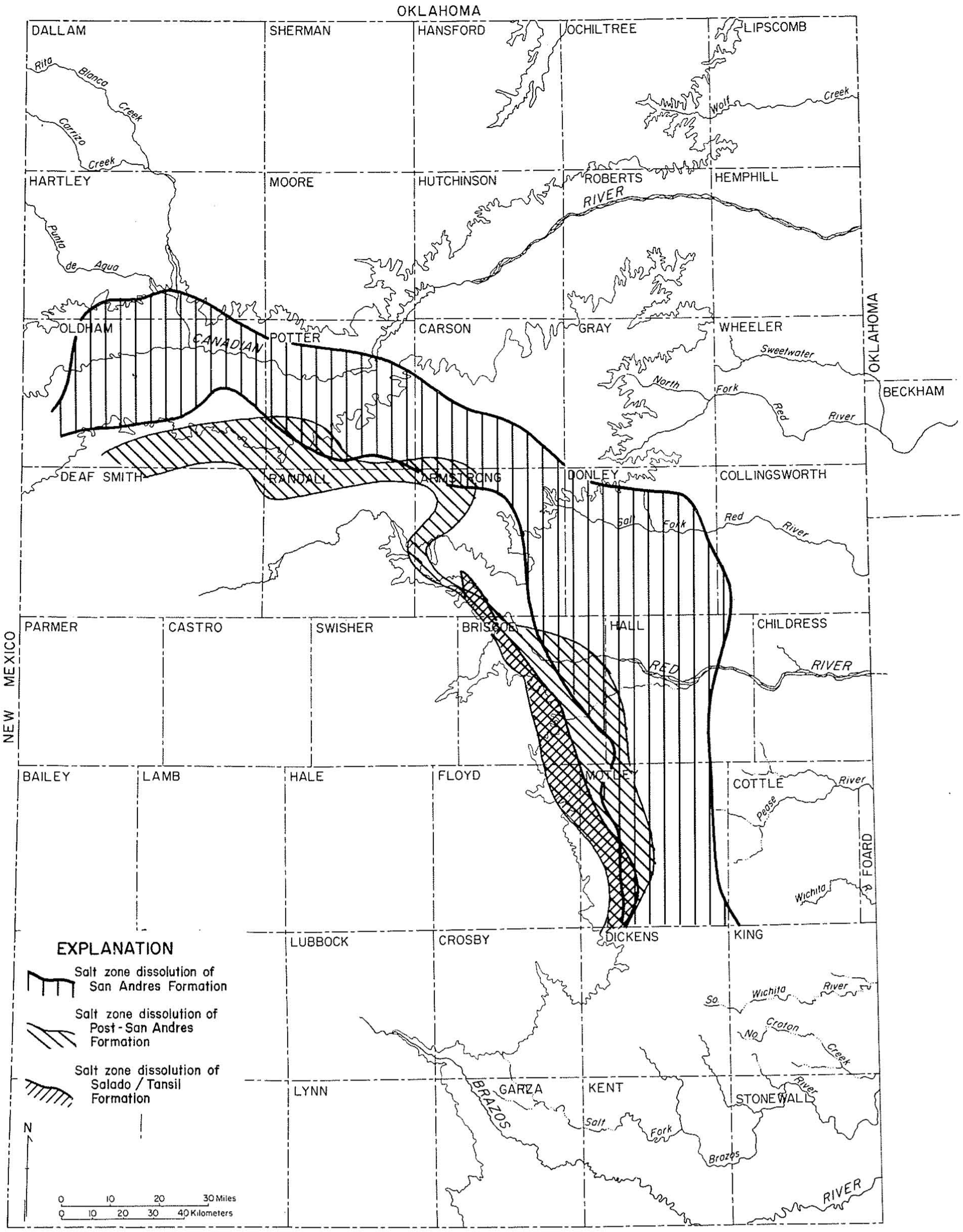

Figure 58. Salt dissolution zones, Texas Panhandle (also refer to figures 32 and 33).

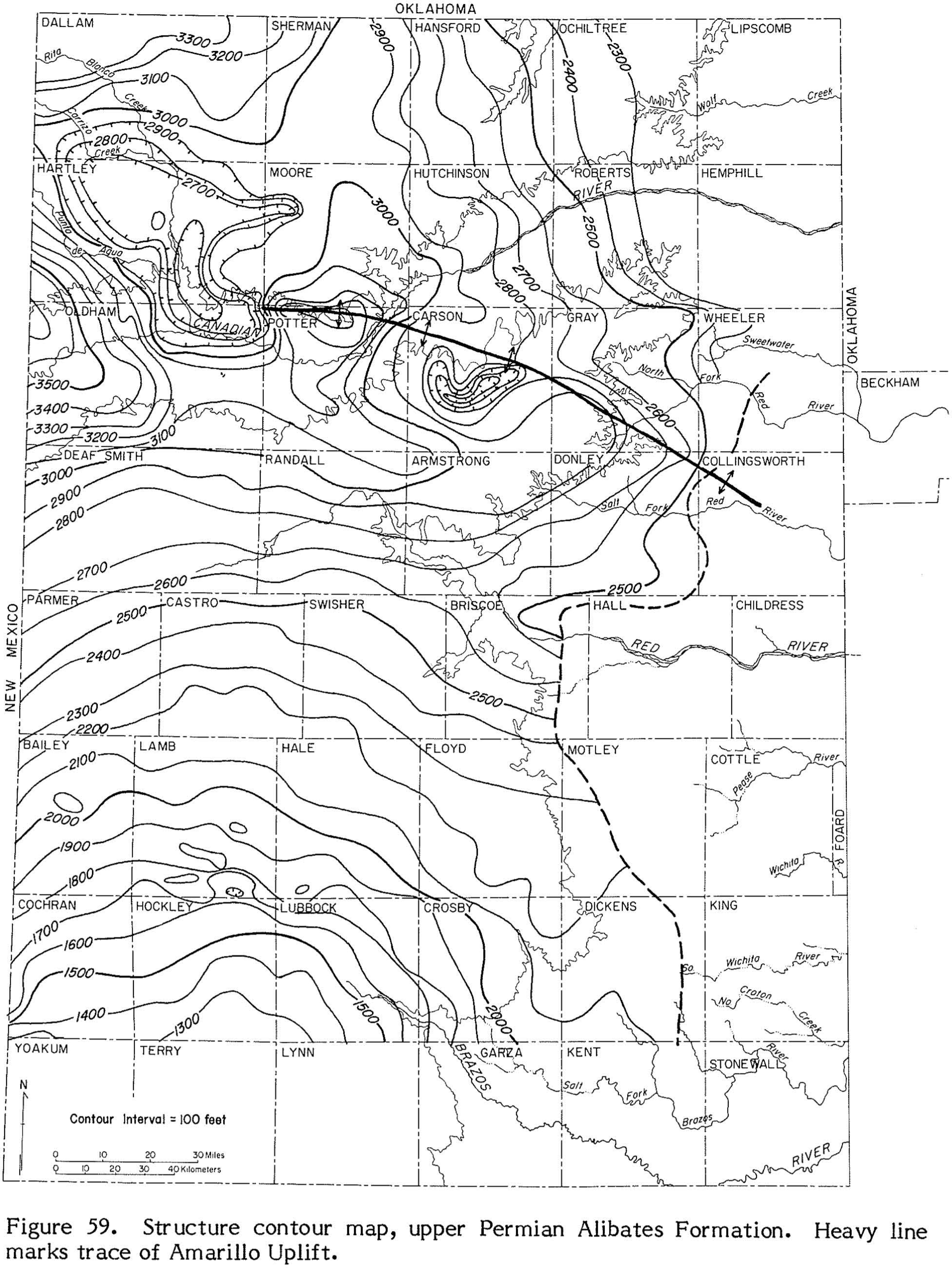

Figure 59. Structure contour map, upper Permian Alibates Formation. Heavy line marks trace of Amarillo Uplift.

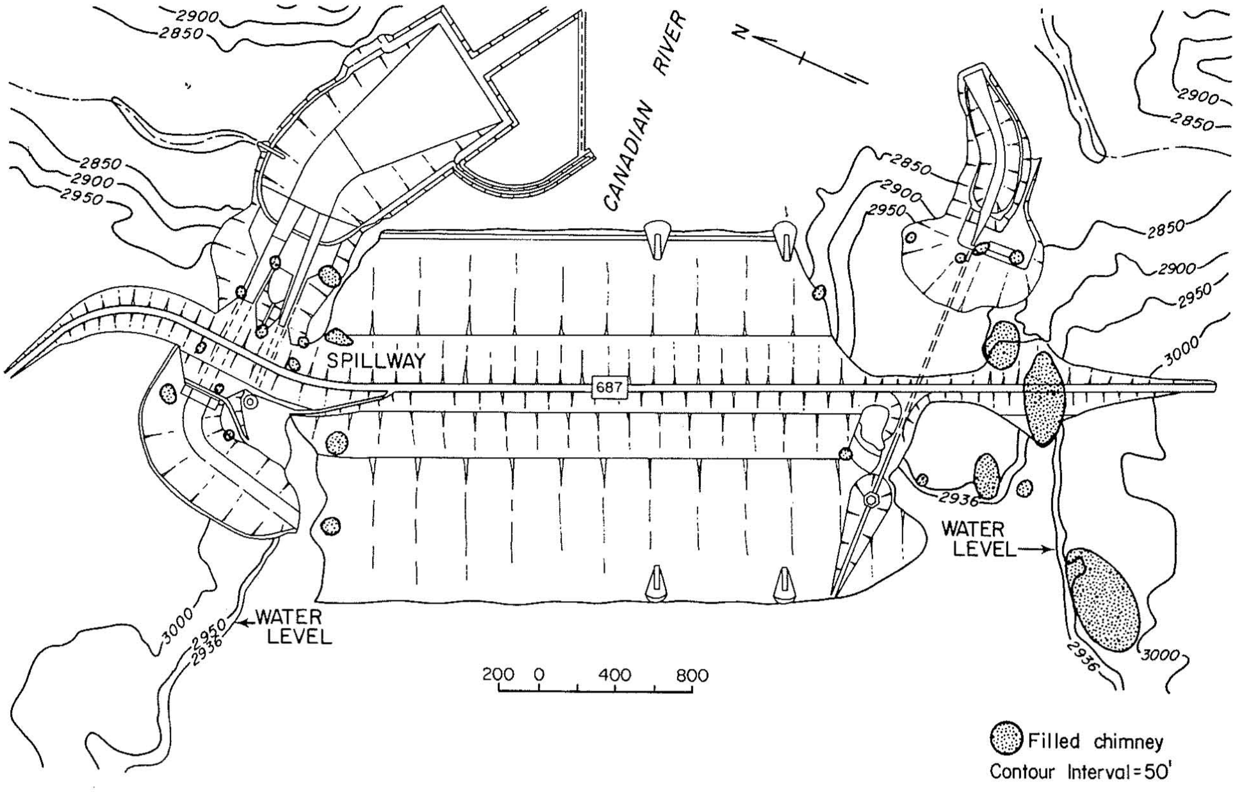

Figure 60. Filled collapse chimneys at Sanford Dam, Texas. Twenty-seven chimneys were discovered during construction of the dam (from Bock and Crane, 1963).

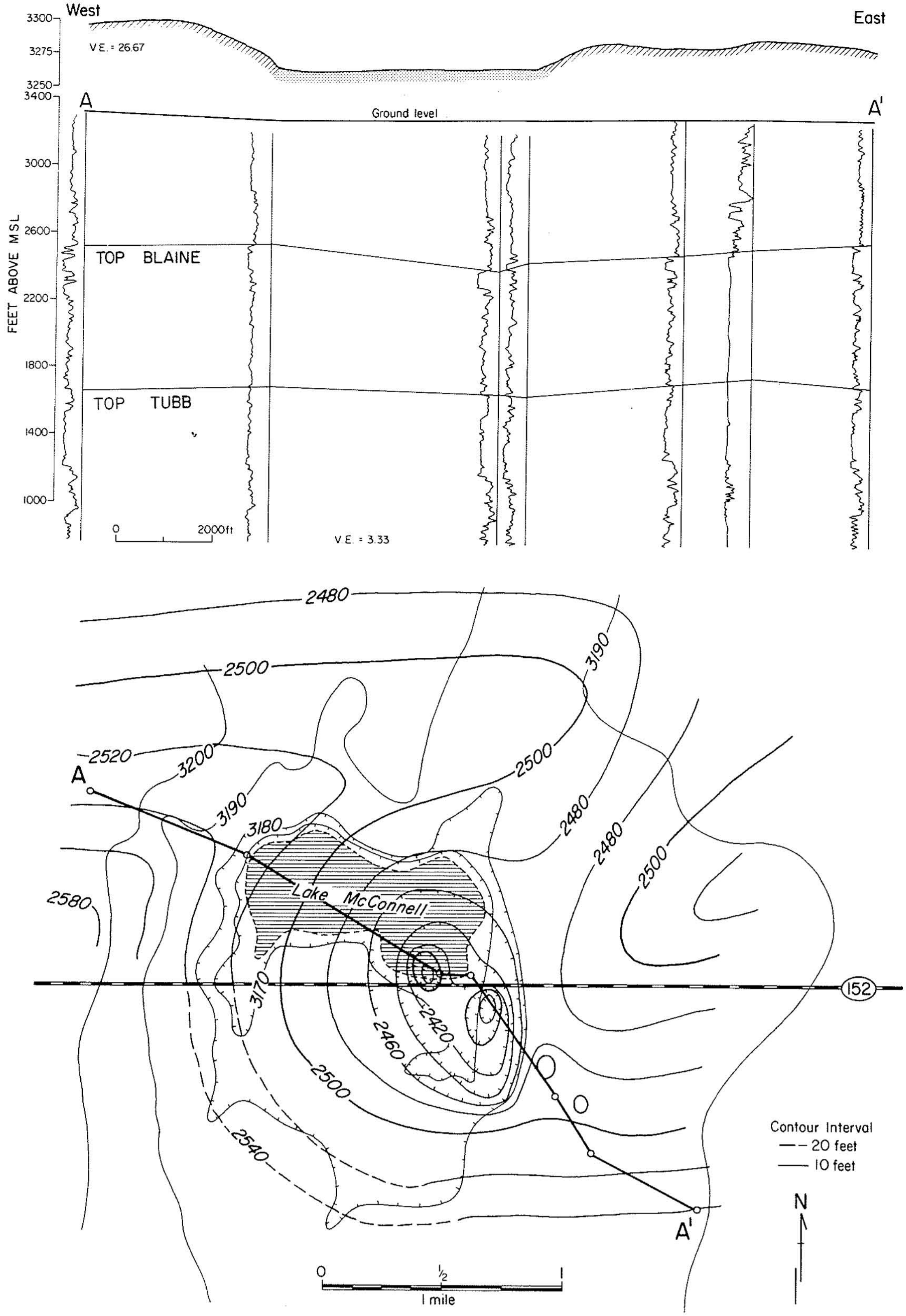

Figure 61. Superimposed topographic map of Lake McConnell and a structure contour map of a subsidence bowl on the top of the Blaine Formation. The cross section A-A^1 shows thinning of the Blaine Formation caused by salt solution.

Table 6. Water quality (6-year average) for streams draining the northern and eastern flanks of the Llano Estacado or Southern High Plains.

	10^3 tons per year		
Station	**Total Dissolved Solids**	**Chloride**	**Sulfate**
1 A	96.2	25.2	34.0
1 B	133.1	34.2	31.5
1 C[a]	67.3	26.0	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
4 C	1,033.5	425.3	155.8
5	129.4	58.6	22.8
7[b]	47.1	16.7	12.3
8[b]	7.5	1.8	2.8
9	336.0	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	600.0	299.7	72.8
18	138.3	35.0	49.3
TOTAL AVERAGE ANNUAL SOLUTE EXPORT			
	2,757.2	1,134.3	513.1

[a] Two-year average

[b] Three-year average

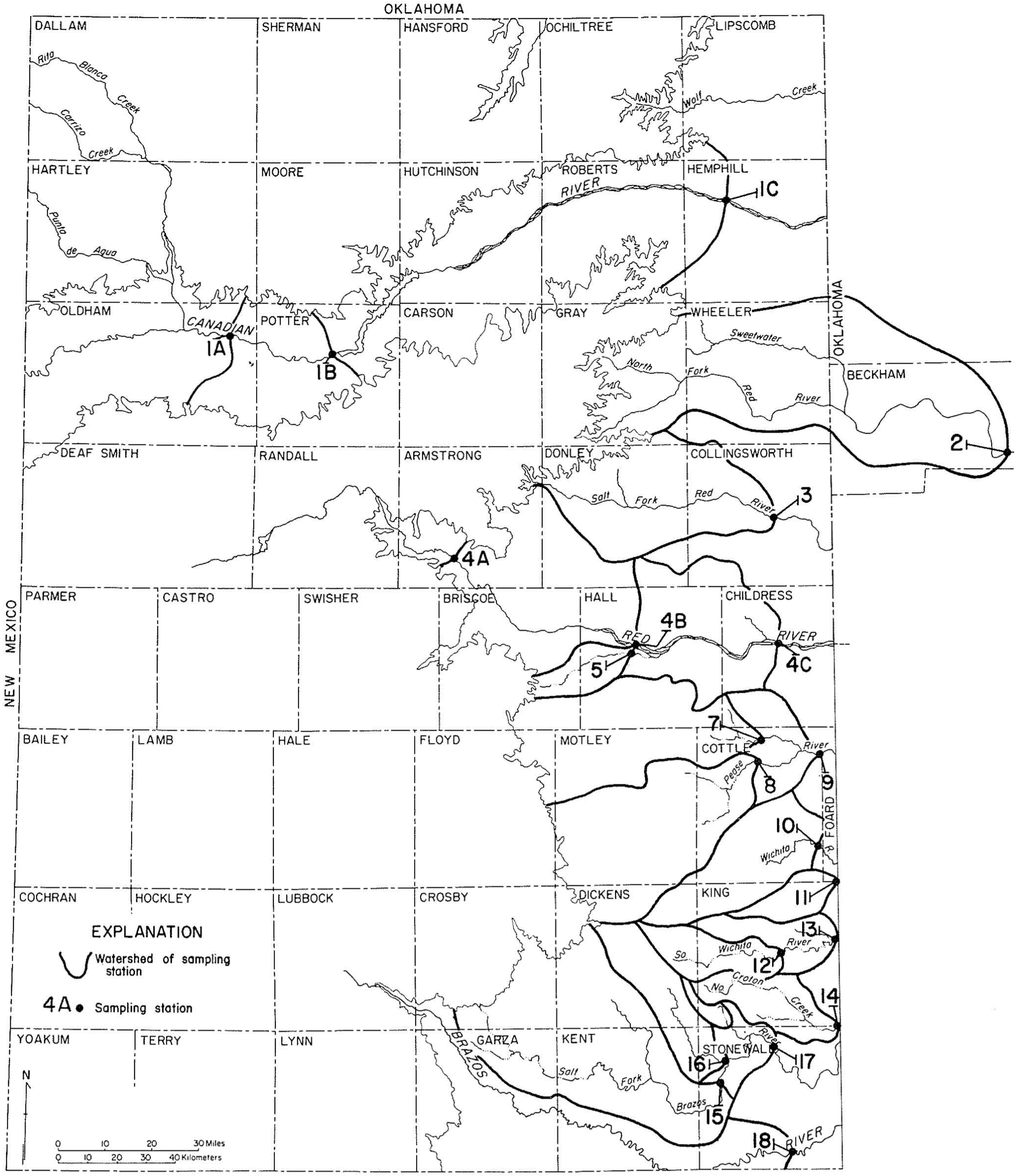

Figure 62. Drainage sub-basins and water-quality monitoring stations, Canadian River Valley and Rolling Plains (see table 6 for water quality data).

FUTURE RESEARCH GOALS

Research Staff

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

Research to determine if areas that are potentially suitable 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 U. S. 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, and 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 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 ensure 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, surface erosion, and sediment transport. These values will indicate if or how soon, even if considered in terms of hundreds 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-and-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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