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REGIONAL GEOLOGY OF THE LOW-PERMEABILITY, GAS-BEARING CLEVELAND FORMATION, WESTERN ANADARKO BASIN, TEXAS PANHANDLE: LITHOLOGIC AND DEPOSITIONAL FACIES, STRUCTURE, AND SEQUENCE STRATIGRAPHY

Topical Report

(January 1989 – December 1991)

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The Upper Pennsylvanian (lower Missourian) Cleveland Formation produces gas from low-permeability ("tight") sandstone reservoirs in the western Anadarko Basin of the northeastern Texas Panhandle. In this six-county region, these reservoirs had produced more than 412 Bcf of natural gas through December 31, 1989. Because of their typically low permeability, the Cleveland sandstones require acidizing and hydraulic fracture treatment to produce gas at economic rates.

Since 1982 the Gas Research Institute has supported geological investigations throughout the United States to develop the scientific and technological knowledge for producing from low-permeability, gas-bearing sandstones. As part of this program and the GRI Tight Gas Sands project, the Bureau of Economic Geology has been conducting research on low-permeability sandstones in the Cleveland Formation and on several other sandstone units of similar character in Texas and Wyoming. This effort is part of a broader program to increase the understanding and ultimate utilization of gas resources in these low-permeability formations through regional and field-specific geology, formation evaluation, and reservoir engineering.

This report summarizes findings on the regional geology, depositional setting, sequence stratigraphy, and petrology of the Cleveland Formation. Geological research on the Cleveland began with an effort to choose a formation in which to drill Staged Field Experiment (SFE) well number 4, the latest in a series of SFE wells drilled since 1986 to conduct geological and engineering research on low-permeability gas reservoirs. Although the Cleveland Formation was not chosen for SFE No. 4, investigation of this low-permeability, gas-bearing sandstone continued with the drilling of cooperative wells in the unit. Because the Cleveland Formation contains an estimated 38 Tcf of gas in place, development of advanced technology and understanding that can be applied to this and other tight gas formations will have a positive impact on gas supply by improving gas recovery and lowering completion costs.

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RESEARCH SUMMARY

Title	Regional Geology of the Low-Permeability, Gas-Bearing Cleveland Formation, Western Anadarko Basin, Texas Panhandle: Lithologic and Depositional Facies, Structure, and Sequence Stratigraphy
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Objectives	This report summarizes regional stratigraphic, structural, and paleoenvironmental studies and subregional petrographic and paleontological analyses of the Cleveland Formation in the western Anadarko Basin of the northeastern Texas Panhandle. Regional characterization of the Cleveland includes (1) lithostratigraphy and correlation of intraformational divisions and their component sandstones, (2) structural geology, including both present structure and syndepositional tectonics, (3) depositional facies and sandstone distribution, and (4) sequence stratigraphy of the Cleveland and adjacent stratigraphic units, which provides a basis for more accurate subregional and reservoir-scale geologic study of this gas-bearing formation.
Technical Perspective	Since 1982 the Gas Research Institute (GRI) Tight Gas Sands Project has supported geological investigations designed to develop knowledge necessary to efficiently produce from low-permeability, gas-bearing sandstones. As part of that program, the Bureau of Economic Geology has conducted research on low-permeability sandstone in the Upper Pennsylvanian (lower Missourian) Cleveland Formation in the northeastern part of the Texas Panhandle. Geologic research on the Cleveland Formation began in an effort to determine the suitability of the Cleveland as a candidate for the drilling of Staged Field Experiment (SFE) well number 4, the latest in a series of SFE wells drilled since 1986 to conduct geologic and engineering research on low-permeability gas reservoirs. Although the Cleveland Formation was not chosen for SFE No. 4, investigation of this low-permeability, gas-bearing sandstone continued with drilling of cooperative wells in the Cleveland.
Results	Although Cleveland low-permeability sandstone reservoirs in the western Anadarko Basin had produced over 412 Bcf of natural gas through December 31, 1989, little information was available on even the basic geology of the unit. In this study, characterization of the Cleveland Formation focused on five major areas: (1) stratigraphy, (2) structure, (3) petrology, (4) depositional environments, and (5) sequence stratigraphy. Regional correlation of the Cleveland Formation is based on the unpublished, petroleum-industry definition of the unit, which states that

the Cleveland is bounded by two thin (<10–28 ft), regionally correlative, high-gamma-ray marker beds composed of organic-rich black shale. Below the Cleveland is a siliciclastic interval of the Marmaton Group, and above the formation is the shale- and carbonate-bearing Kansas City Formation. The Cleveland ranges from 0 ft (absent) in parts of Hansford and Hutchinson Counties to a maximum of about 590 ft in southwestern Hemphill County. Depth to the top of the formation ranges from about 2,500 ft subsea in northern Hutchinson County to about 9,600 ft subsea in east-central Wheeler County. In Ochiltree and Lipscomb Counties, the major gas-producing area, subsea depth to the Cleveland is about 3,600 ft (west) to 5,400 ft (east); depth of the Cleveland below land surface in the two-county producing area is about 6,600 ft (west) to 8,000 ft (east).

The top of the Cleveland Formation in the study area composes a generally southeasterly dipping monocline interrupted by several prominent faults and locally by small folds. Dip progressively increases toward the southeast from 20–40 ft/mi to about 105 ft/mi. Dip direction ranges from S45°E to S25°E (135° to 155°) in most of the eastern part of the study area but is quite variable elsewhere, especially near faults and folds. Two distinct fault trends can be distinguished in the study area. The Lips fault zone, part of a regional trend of en echelon faults extending from the Amarillo Uplift, extends northwestward from eastern Wheeler County to its termination in southwestern Ochiltree County and has a maximum net vertical offset of 450–500 ft. Cleveland production along this probable moderate-angle reverse fault is restricted to its northwestern end in southwestern Ochiltree County. A shorter, subparallel fault zone, with a throw of no more than 100 ft, displaces the Cleveland in northern Hutchinson and southern Hansford Counties; folds associated with it form structural traps for Cleveland oil and gas. Other folds in the Cleveland occur sporadically as small (4 to 8 mi long), south- to southeast-plunging noses in Ochiltree and Lipscomb Counties. Reservoir-facies and porosity/permeability pinch-outs associated with these structures form the primary hydrocarbon traps.

Distinctive trends of Cleveland thickness variation record elements of the paleophysiography of the Cleveland depositional area and evidence of syndepositional faulting, flexure, and marked differential subsidence. Depositional patterns were controlled by (1) a paleohigh in the western part of the study area (eastern flank of Cimarron Arch) that separates siliciclastic facies from carbonate-dominated Cleveland of the Kansas Shelf, (2) subsidence of two subbasins within a northwest-trending half graben bounded by a syndepositional fault on its southern edge and a monoclinal flexure to the north, and (3) a two-tiered depositional shelf controlled by differential subsidence of an underlying Oswego Limestone buildup.

Petrographic examination of 24 Cleveland reservoir sandstone samples from 3 cores reveals characteristics that are probably generally shared throughout the gas-producing region of Ochiltree and Lipscomb Counties. All sandstone samples are either lithic arkoses or feldspathic litharenites and have an average composition of $Q_{59}F_{21}R_{20}$. Average grain size of the samples is 0.124 mm (very fine sand). The dominant cement is quartz (as overgrowths), with an average of 7.3 percent. Total-carbonate (calcite, Fe-rich calcite, ankerite, and siderite) cement averages 6.2 percent, and the average of total-clay (chlorite, illite, and kaolinite) cement is 3.0 percent. Average in situ permeability of Cleveland reservoir facies is 0.140 md, and average reservoir porosity ranges from 10 to 14 percent (porosimeter porosity). Average porosity (primary and secondary) for the nonproductive sandstones from the three cores is 2.8 percent (thin-section porosity).

The siliciclastic parts of the Cleveland Formation and underlying Marmaton Group (undivided) comprise mostly stacked, progradational marine successions containing deltaic facies (in ascending order within each cycle): (1) prodelta, (2) distal delta front, and (3) proximal delta front. An upward-fining fluvial sandstone with a markedly erosional base occurs in one stratigraphic zone in the middle Cleveland in most of the study area. Predominantly shale intervals record sedimentation in prodelta and distal shelf environments. Cleveland hydrocarbons are trapped primarily in proximal delta-front sandstones and in the fluvial channel fill. Regional cross sections and net-sandstone patterns indicate four dominant sandstone trends in the study area: three north-south-oriented, arcuate thicks composed of stacked delta-front facies at inferred stabilized shoreline positions and one east-west trend representing superimposed fluvial-channel incision after a drop in regional base level.

The lithostratigraphic interval that includes the Oswego Limestone, Marmaton Group (undivided), Cleveland Formation, and Kansas City Formation was examined in the context of its sequence stratigraphic framework. Parasequences (upward-coarsening and -fining genetic depositional cycles) of the component systems tracts were correlated only for the Marmaton Group (undivided) and the Cleveland Formation. This mostly siliciclastic interval can be subdivided into three sequences, at least one of which composing the Marmaton Group (undivided) and the lower part of the Cleveland Formation is bounded by type 1 sequence boundaries, or regional unconformities formed by lowstands of relative sea level. The Cleveland contains 10 parasequences (P) in the study area: (1) P1–P3 compose a progradational parasequence set deposited during a highstand of relative sea level, (2) P4, the middle Cleveland fluvial deposit, is an incised-valley fill underlain by an erosional surface formed during a sudden fall in relative sea level; channel aggradation occurred during subsequent sea level stabilization and early transgression, (3) P5 and P6 comprise deltaic facies of a transgressive systems tract, and (4) P7–P10 consist of several relatively poorly defined systems tracts. Source areas for Cleveland P1–P6 were to the west or southwest, whereas those of the thin, upper Cleveland parasequences were more distant to the east or southeast.

Technical Approach

The data base used in this study comprises (1) well-log suites for 863 wells evenly distributed throughout the 5,100-mi^2, 7-county study area, with an approximate well spacing of 3 mi, (2) lithologic sample logs for about 10 percent of these well logs, and (3) three cores (total of 263 ft) of sandstone-bearing portions of the Cleveland Formation from major gas-producing areas. Precise regional stratigraphic correlation and lithologic identification were possible because of the excellent well control and sufficient scatter of sample logs. These factors and the presence of distinctive formation boundary markers enabled construction of precise isopach, structure-contour, net sandstone, percent-sandstone, and cross sections of the Cleveland. Cores provided lithologic and sedimentologic data that were valuable for well-log calibrations and interpretations of depositional environments. Composition of shales and reservoir sandstones was determined by standard thin-section petrography, scanning electron microscopy, and X-ray diffraction. Total organic carbon content of Cleveland and Marmaton shales was calculated by standard coulometric techniques.

Project Implications

The importance of detailed resource characterizations in tight gas sandstone formations has been realized for many years by GRI. Through GRI-funded research, the understanding of the geologic processes affecting the source, distribution, and recovery of gas from these reservoirs has been greatly enhanced. This report serves as a reference that will aid tight gas sand development in the Cleveland Formation.

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INTRODUCTION

The Upper Pennsylvanian (lower Missourian) Cleveland Formation produces gas from low-permeability ("tight") sandstone reservoirs in the western Anadarko Basin of the northeastern Texas Panhandle. In this six-county region, these reservoirs had produced more than 412 Bcf of natural gas through December 31, 1989 (Railroad Commission of Texas, 1989). Because of their typically low permeability, the Cleveland sandstones require acidizing and hydraulic fracture treatment to produce gas at economic rates.

Since 1982 the Gas Research Institute (GRI) has supported geological investigations throughout the United States designed to develop the scientific and technological knowledge necessary to efficiently produce from low-permeability, gas-bearing sandstones. As part of this program and the GRI Tight Gas Sands project, the Bureau of Economic Geology has been conducting research on low-permeability sandstones in the Cleveland Formation and on several other sandstone units of similar character in Texas and Wyoming. This effort is part of a broader program to increase the understanding and ultimate utilization of gas resources in these low-permeability formations through integration of regional and field-specific geology, formation evaluation, and reservoir engineering.

This report summarizes findings regarding the regional geology, depositional setting, sequence stratigraphy, and petrology of the Cleveland Formation. Geological research on the Cleveland began with an effort to choose a formation in which to drill Staged Field Experiment (SFE) well number 4, the latest in a series of SFE wells drilled since 1986 to conduct geological and engineering research on low-permeability gas reservoirs. Although the Cleveland Formation was not chosen for SFE No. 4, investigation of this low-permeability, gas-bearing sandstone continued with the drilling of cooperative wells in the unit. Cooperative wells are gas wells in which operating companies allow GRI contractors to collect data necessary for integrated geological and engineering evaluation. Because the Cleveland Formation contains an estimated 38 Tcf of gas in place (Haas and others, 1988), development of advanced technology and understanding that can be applied to this and other tight gas formations will have a positive impact on gas supply by improving gas recovery and lowering completion costs.

Regional Tectonic and Paleogeographic Setting

The Anadarko Basin (fig. 1) of the Southern Midcontinent is the deepest Phanerozoic sedimentary basin within the North American craton. Locally along its southern margin against the Wichita Uplift in southwestern Oklahoma, the axially asymmetric, southeast-northwest elongate basin contains more than 40,000 ft of Cambrian through Permian sedimentary rocks (Ham and Wilson, 1967). In the western part of the Anadarko Basin the Paleozoic strata are as much as 13,000 to 16,000 ft thick. The broad shelf bordering the basin to the north, variously termed the Kansas Shelf or Northern Shelf, is thinner still, attaining thicknesses of 6,500 to 9,800 ft. Division between the "deep Anadarko Basin" and the adjacent shallower basin and shelf areas (fig. 1) has arbitrarily been established at the –15,000-ft basement depth contour (Petroleum Information Corporation, 1982). The Kansas Shelf is distinguished from the main basin by a hinge zone separating the area of steeper dips in the inner basin (90 to 140 ft/mi) from that of more gentle dips on the shelf (50 to 80 ft/mi) (Rascoe, 1962).

The Pennsylvanian orogenic episode of the greater Anadarko Basin area (Ham and Wilson, 1967) significantly influenced deposition of the lower Missourian Cleveland Formation. During this period the active Wichita and Amarillo Uplifts were separated from the Anadarko Basin by a series of large-displacement, moderate- to high-angle reverse faults. The adjacent basin subsided markedly; large volumes of coarse arkosic

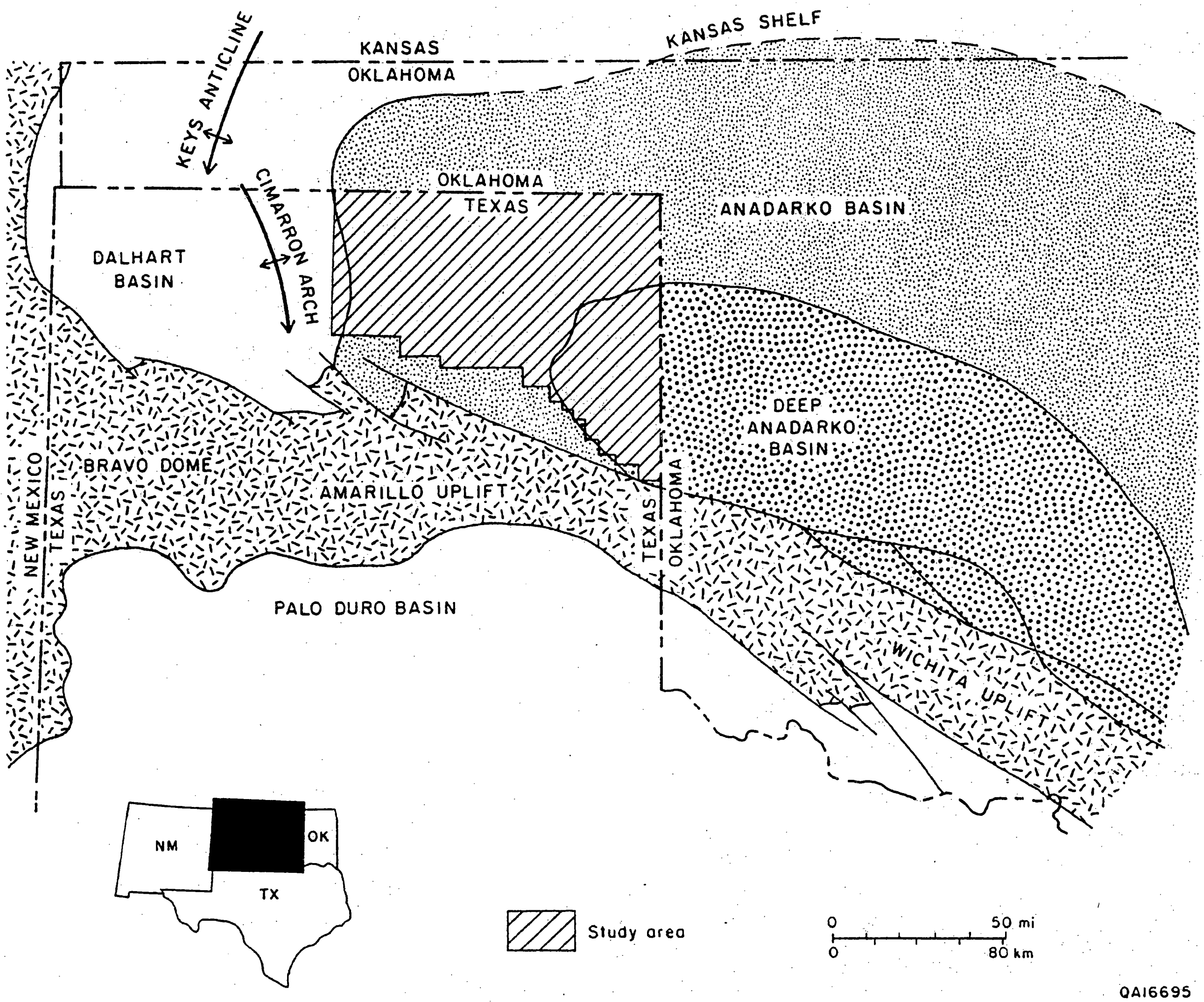

Figure 1. Regional geologic setting of the Cleveland Formation study area, western Anadarko Basin.

sediment ("grainte wash") were deposited along the southern margin of the rapidly subsiding Anadarko Basin adjacent to the uplifts. Other contemporaneous orogenic events resulted mainly in block faulting and folding along the margins of the basin. The Cimarron Arch (fig. 1) formed during the same tectonic episode as that of the Wichita and Amarillo Uplifts (Johnson and others, 1988). The locus of maximum sediment accumulation was the center of the Anadarko Basin during Early Pennsylvanian (Morrowan) time, and it migrated southeastward until the Late Pennsylvanian (Missourian), suggesting that Late Pennsylvanian uplift was greatest at the southeastern end of the basin (McConnell and others, 1990). The prominent Arbuckle Uplift and Ouachita foldbelt at the southeastern end of the Anadarko Basin were significant Missourian siliciclastic sediment sources of the basin (Visher and others, 1971; Moore, 1979; Rascoe and Adler, 1983).

The boundaries of the study area (figs. 1 and 2) coincide with those of the Cleveland tight-gas-sandstone area delineated in a petition to the Railroad Commission of Texas (1981) by Diamond Shamrock Corporation for formal tight-gas-sandstone designation. Maxus Exploration Company is currently one of the major Cleveland gas producers. The 5,100-mi^2 area includes all of Hansford, Lipscomb, and Ochiltree Counties, most of Hemphill County, and the northern parts of Hutchinson, Roberts, and Wheeler Counties. The Texas/Oklahoma state boundary marks the northern and eastern borders of the study area; the western edge of the study area is the approximate western extent of the Anadarko Basin. The irregular northwest-trending southern border defines the area of lateral stratigraphic gradation between the Cleveland Formation and granite wash deposited very locally along the northern flank of the northwest-trending Amarillo Uplift.

In the study area, the Anadarko Basin is bounded on the south by the Amarillo Uplift and on the west by the Cimarron Arch (fig. 1). The Cleveland Formation and other siliciclastic strata examined for this study thin toward, and interfinger northward

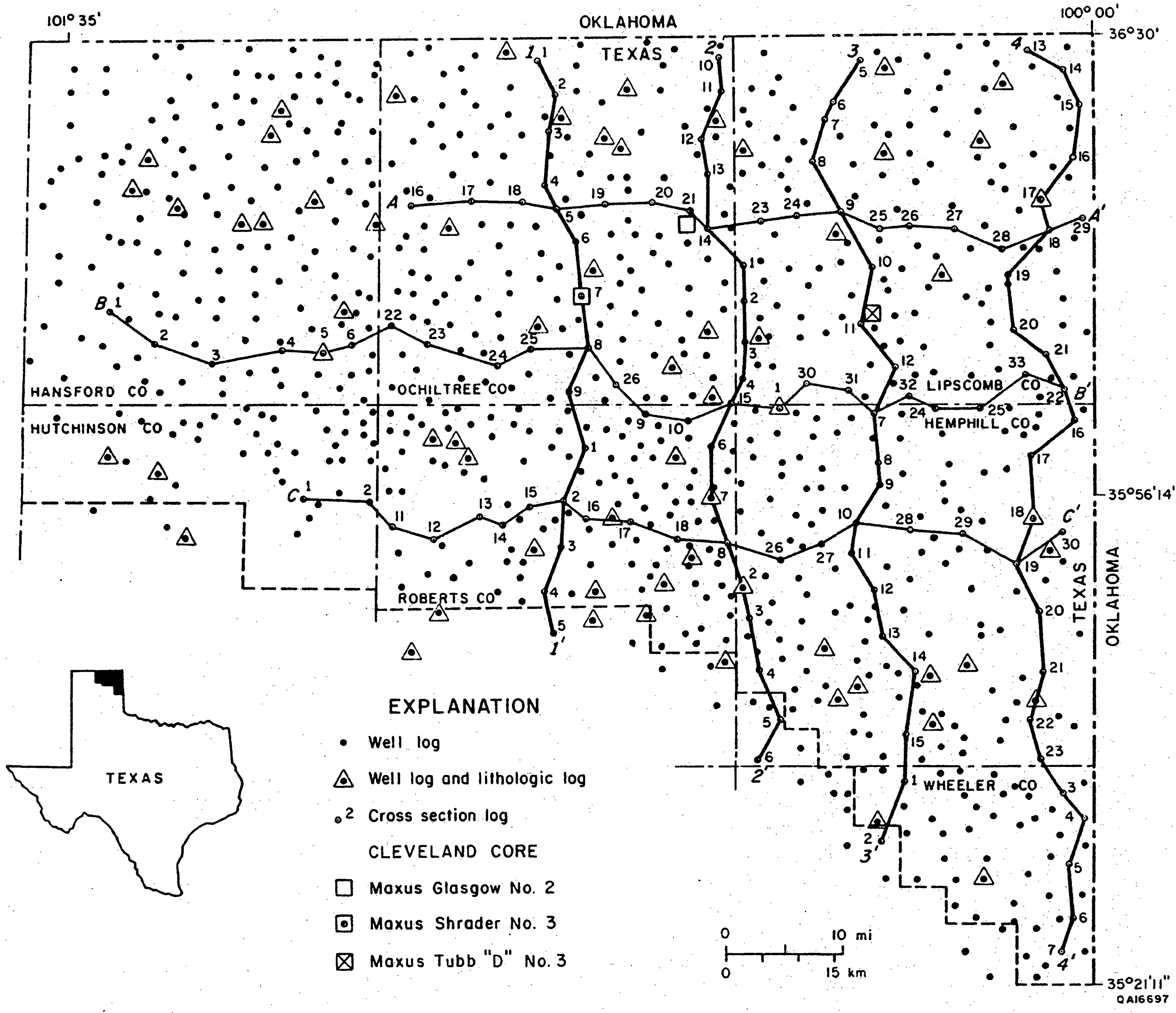

Figure 2. Map of study area showing well control (average of about 3-mi well spacing), cross-section lines, and Cleveland core locations. Refer to Appendix for names of cross-section wells.

with, carbonate-dominated shelf facies of the Kansas Shelf just south of the northern border of the study area. At the southern border of the study area these strata abruptly grade southward toward the Amarillo Uplift into a succession composed almost entirely of granite wash. The Cleveland thickens southeastward into the deep Anadarko Basin and thins westward to a feather edge.

Stratigraphic Nomenclature

The Pennsylvanian System of the Texas Panhandle and Oklahoma is divided into two formal lithostratigraphic schemes, one applying to the Anadarko Basin and the other to the adjacent Northern (Kansas) Shelf (Hills and Kottlowski, 1983; Johnson and others, 1988). Within the study area the largely siliciclastic facies of the Cleveland Formation are restricted to the basin proper, and thus the stratigraphic nomenclature of the Anadarko Basin is used in this report (fig. 3).

The succession examined in this study (Oswego Limestone to Kansas City Formation) comprises Middle and Upper Pennsylvanian (upper Desmoinesian to lower and middle Missourian) rocks. The Cleveland Formation is the lowest unit of the Skiatook Group, which also includes the Kansas City Formation. The underlying Marmaton Group consists of the Oswego Limestone at the base and undivided Marmaton Group at the top. The Cleveland and the Marmaton (undivided) are predominantly siliciclastic, sandstone-prone intervals between the mostly carbonate- and shale-bearing Oswego and Kansas City (fig. 4). Regional lateral lithologic variations evident within these formations in figure 4 are discussed in subsequent sections.

The Cleveland Formation is named for the townsite of Cleveland about 25 miles northwest of Tulsa, Oklahoma, where sandstone reservoirs first produced oil and gas at shallow depths (1,600 ft) in 1905 (Krumme, 1981). Extensive outcrops of the Cleveland occur in the vicinity of Tulsa, where the unit consists of several thick (as much as 200 ft)

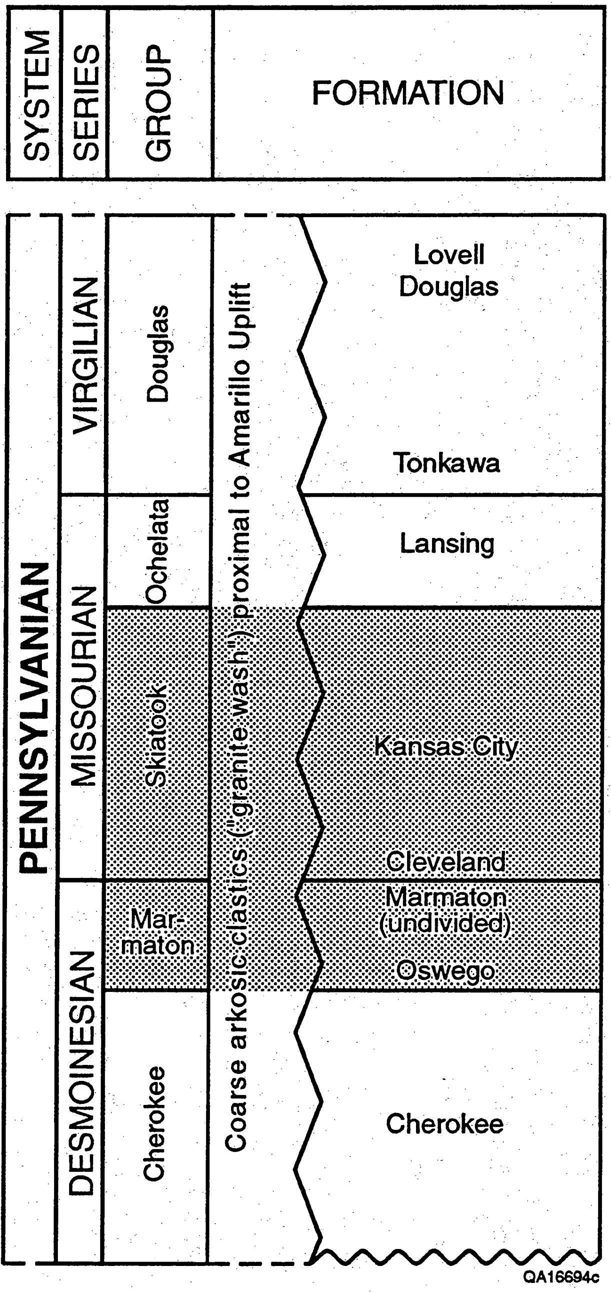

Figure 3. Middle and Upper Pennsylvanian stratigraphy of the Anadarko Basin. Patterning highlights study interval.

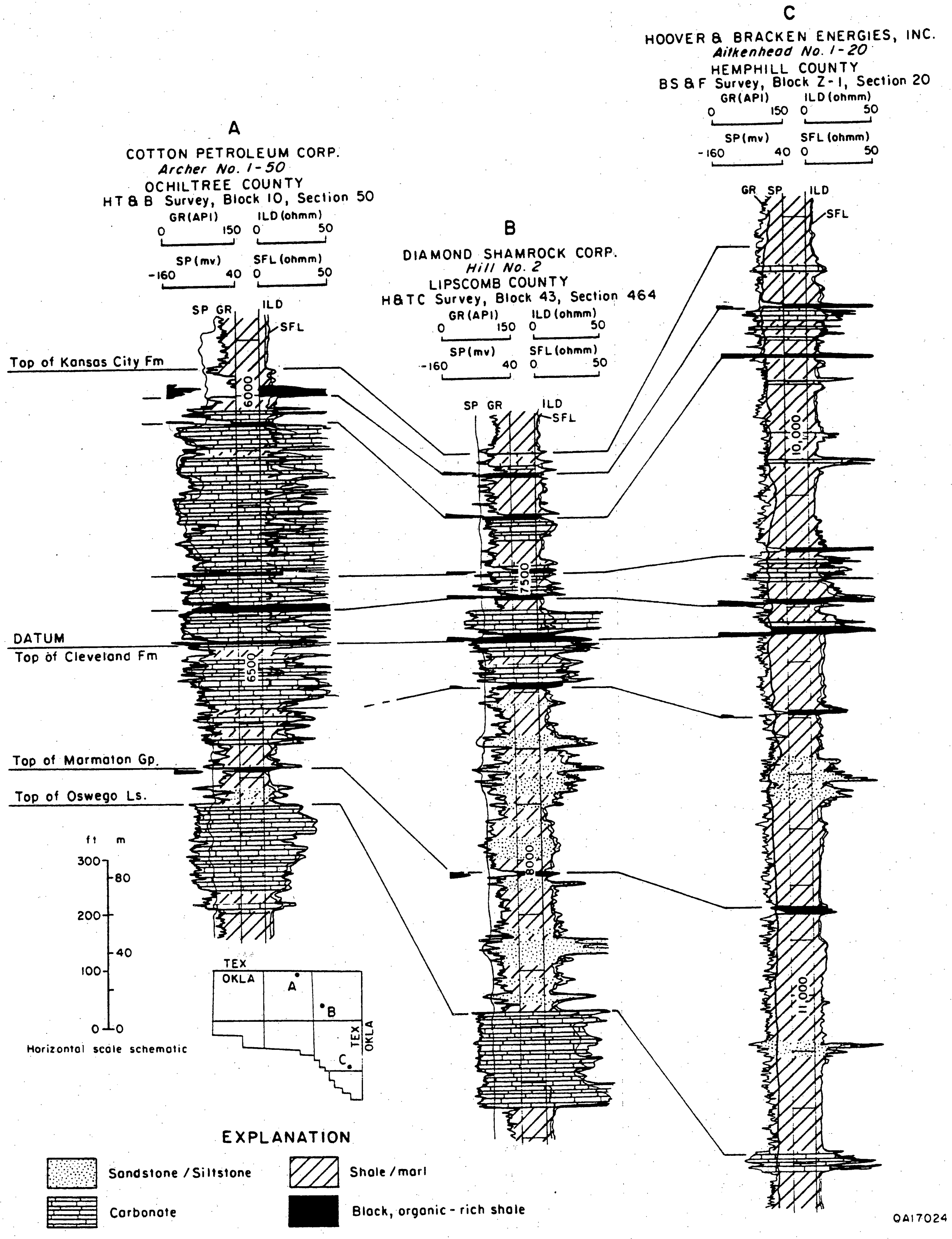

Figure 4. Representative shelf-to-basin cross section of the Oswego Limestone, Marmaton Group (undivided), Cleveland Formation, and Kansas City Formation. Regional lithostratigraphic and sequence stratigraphic correlations presented in this report emphasize the dominantly siliciclastic section comprising the Cleveland and Marmaton (undivided) intervals shown in well logs B and C.

channel-fill sandstones interstratified with shale, coal, and thin limestone beds (Bennison and Chenoweth, 1968; Krumme, 1981). Early stratigraphers interpreted the channelized base of the Cleveland sandstones in the Tulsa area as representing a regional unconformity that coincided with the boundary between the Desmoinesian and Missourian Series (Moore and others, 1937). However, Krumme (1981) concluded that these sandstones are regionally conformable and exhibit only local channel scouring; he thus cast some doubt on the validity of the placement of the series boundary. Although most existing stratigraphic schemes of the western Anadarko Basin also place the Cleveland at the base of the Missourian Series, no published documentation of the biostratigraphic basis for this placement in that area has yet been found. The original designation of an early Missourian age for the Cleveland is therefore presumed to be an extrapolation from the series-boundary designation in northeastern Oklahoma. Paleontological analyses of core samples from the uppermost Marmaton Group (undivided) in the study area confirm this age designation (see "Paleontology and Age of Cleveland Formation").

Previous Work

No regional stratigraphic or sedimentological studies of the Cleveland Formation in the Texas Panhandle exist. Most accounts are field descriptions presented in a volume on the oil and gas fields of the Oklahoma and Texas Panhandles published by the Panhandle Geological Society (Best, 1961; Brashear, 1961; Britt, 1961; Eckstrom, 1961; Ridgell, 1961). Stevens and Stevens (1960) and the National Petroleum Bibliography (1965) contain numerous field maps (structure-contour, isopach, net sand) of the Cleveland from major producing areas of the Texas Panhandle. Kousparis (1978) described geophysical aspects of a Cleveland reservoir in central Oklahoma. These studies are valuable because they provide specific data on Cleveland reservoir conditions. Finley (1984) summarized existing generalized geologic, engineering, and economic information on the formation. Kosters and others (1989) described Cleveland fields of the Texas Panhandle from which greater than 10 Bcf of gas had been produced; details of the field descriptions are mostly from the older published sources listed previously. Handford and others (1981) constructed regional cross sections of the entire Paleozoic section of the Texas Panhandle in which they define regional depositional systems, delineate series boundaries, and correlate major lithofacies. Although no lithostratigraphic units are differentiated on the cross sections, they provide a good regional perspective of the Pennsylvanian System in the western Anadarko Basin.

Kumar and Slatt (1984) studied Cleveland sandstones in the deep Anadarko Basin about 75 mi east of the eastern border of the Texas Panhandle in west-central Oklahoma by integrating well-log and seismic data. However, they did not correlate the deep Anadarko Cleveland facies with the formation in Texas.

Objectives

This report summarizes regional stratigraphic, structural, and paleoenvironmental studies, and subregional petrographic analysis of the Cleveland Formation in the western Anadarko Basin. Regional characterization of the formation was divided into four major areas: (1) lithostratigraphy and regional correlation of intraformational divisions and their component sandstones, (2) structural geology, including both present structural expression of the formation and syndepositional tectonics that markedly affected formation thickness and sandstone occurrence, (3) depositional facies and regional sandstone distribution, and (4) sequence stratigraphy of the Cleveland Formation and its adjacent stratigraphic units (underlying Maramaton Group and overlying Kansas City Formation [fig. 3]). Petrographic study of Cleveland sandstones from available cores (see "Data Base and Methods") includes documentation of grain size, grain lithology, cement mineralogy, and primary and secondary porosity. Analysis of fossils from the upper Marmaton Group (undivided) and the lower and middle Cleveland Formation enabled precise age determination of these strata in the western Anadarko Basin and provided data on paleobathymetric conditions of deposition.

Sequence stratigraphy is an evolving geologic concept that enables regional study of genetically related depositional facies. Using a sufficient density of well control supplemented by core data, sequence stratigraphic analysis yields a high-resolution chronostratigraphic framework for subsurface correlation of these facies (Van Wagoner and others, 1990). The resulting analysis provides a powerful predictive model for the vertical and areal occurrence of potential reservoirs, sealing strata, and source rocks within the stratigraphic interval studied. The sequence stratigraphic model was applied not only to the Cleveland Formation but also to underlying (Oswego Limestone, Marmaton Group [undivided]) and overlying (Kansas City Formation) successions to more accurately define the position of the Cleveland in the regional sequence framework of the western Anadarko Basin. Although beyond the scope of this study, such analysis of the Cleveland and adjacent formations may provide a basis for more accurate subregional and reservoir-scale geological studies of Cleveland gas-bearing sandstones.

Data Base and Methods

The data base used in this study comprises (1) well-log suites for 863 wells evenly distributed throughout the 5,100-mi^2 study area, with an approximate average well spacing of 3 mi, (2) accompanying lithologic sample logs for about 7 percent of these well logs, and (3) three cores of sandstone-bearing portions of the Cleveland Formation from major gas-producing areas (fig. 2). Thin sections and chips from 24 sandstone and 2 shale samples were cut from the 3 cores for petrographic and X-ray diffraction (XRD) analysis; 11 additional shale samples were cut for XRD and total organic carbon (TOC) analysis. Marine microfossils were separated from 17 shale samples of approximately 1 kg each from the 3 cores to determine the age of the upper Marmaton Group (undivided) and the Cleveland Formation. Two sidewall cores of the basal Cleveland shale marker bed were provided by Maxus Exploration Company from the Maxus Littau No. 3 well in east-central Ochiltree County (H&TC Survey, Block 43, Section 665).

Well-log suites consist of various combinations of spontaneous-potential (SP), resistivity, gamma-ray, sonic, neutron porosity, density, and caliper logs; however, most suites include SP, resistivity, gamma-ray, and sonic curves. Of these, gamma-ray and resistivity logs are the most effective ones for accurate correlation of the Cleveland section; reasons for this are discussed in the following section (see "Lithostratigraphy"). Identification of lithology from sonic, porosity, and density logs was only occasionally necessary because of the fairly even distribution of lithologic sample logs within the study area (fig. 2). Well logs were selectively chosen from large collections housed at the Bureau of Economic Geology to provide an even regional distribution of well control. Gaps of data in the otherwise even distribution are primarily due to either the absence of wells in certain areas or to the presence of wells that are too shallow to have penetrated the Cleveland. A limited number of well logs from south of the southern border of the study area were studied to better document the lateral facies relations between the Cleveland sandstones and the granite wash.

To construct net- and percent-sandstone maps of the Cleveland Formation, sandstone-interval thicknesses were measured on well logs by using (1) a minimum cutoff of 15 to 20 ohm-m on the deep induction log and/or (2) a decrease greater than 6 to 10 API units in the gamma-ray response from the shale base line. Because the Cleveland is a tight formation, the SP log did not accurately record sandstone intervals. Resistivity log cutoffs were adjusted in local areas to account primarily for increased calcite content in sandstones.

Lithologic sample logs provided good control on the identification of lithology throughout the study area. Major changes in Cleveland lithology occur at the subregional scale, and thus the distribution of lithologic sample logs was adequate. A few lithologic logs for wells not indicated on figure 2 were also utilized in the study.

Internal sedimentary features, textures, and rock compositions identified from the three cores (Maxus Shrader No. 3, Maxus Tubb "D" No. 3, Maxus Glasgow No. 2; fig. 2) were used to substantiate interpretations of depositional environments and facies boundaries deduced from well-log signatures and correlation.

LITHOSTRATIGRAPHY

Cleveland Formation

Formation Boundaries

No published formal or informal definition of the Cleveland Formation in the subsurface Anadarko Basin exists in the literature. Best (1961), Brashear (1961), Ridgell (1961), and the Railroad Commission of Texas (1981) illustrated SP/resistivity logs of parts of the Cleveland Formation, primarily the productive sandstones in the middle of the formation, but not the entire unit. Britt (1961) presented an SP/resistivity log of what is probably the complete Cleveland section in the Ellis Ranch field in eastern Ochiltree County; however, because of local lithologic and thickness changes and variation in electric-log signature of the Cleveland, correlation with even surrounding Ellis Ranch wells proved to be imprecise at best. As is discussed below, accurate regional and subregional correlation of the formation's boundaries requires gamma-ray logs.

The stratigraphic boundaries of the Cleveland Formation used in this study are those typically used by the petroleum industry (Maxus Exploration Company, unpublished cross sections; Mike Brenner, personal communication, 1990). Elevations of the top of the Cleveland given on oil- and gas-well completion cards commonly record only the top of the major producing sandstone within the medial part of the formation.

Base of Cleveland

The base of the Cleveland Formation is defined as the top of a regionally continuous high-gamma-ray shale marker bed of the uppermost Marmaton Group (undivided) (fig. 4) that is typically about 10 ft thick but ranges from less than 10 to about 28 ft thick. The marker bed extends areally throughout Lipscomb, Hemphill, and northern Wheeler Counties, includes all of Ochiltree and most of Roberts Counties except locally in their southernmost and northernmost parts, respectively, and extends to northern and (only locally) southeastern Hansford County and northeastern Hutchinson County. Beyond the eastern border of the study area, the marker bed can be correlated as a continuous unit at least as far east as west-central Oklahoma (Oryx Energy Company, unpublished cross sections). It continues northward into the carbonate-dominated section of the distal Kansas Shelf facies and southward, where the marker bed commonly interfingers with distal granite wash facies of the Amarillo Uplift (see fig. 24, below). The marker bed is not present where the Cleveland Formation is very thin or absent in western and central Hansford and western Hutchinson Counties. Where only locally preserved, the marker bed is either erosionally truncated, changes texturally and/or in content within major axes of Cleveland siliciclastic deposition (that is, "diluted" by siliciclastic influx, thereby decreasing the gamma-ray response to match that of the adjacent shales), or pinches out. In these areas the formation base is correlated by resistivity markers between wells that record the locally preserved high-gamma-ray shale marker beds.

Whole core and sidewall cores of the basal marker bed provided by Maxus Exploration Company from the Maxus Glasgow No. 2 (fig. 2 and fig. 6, below) and Maxus Littau No. 3 wells, respectively, in east-central Ochiltree County, show that the bed is a dark-gray (N3) (Goddard and others, 1979) to black (N1), organic-rich, pyritic, fossiliferous clay shale. On gamma-ray logs from these and other wells, this bed exhibits a distinctive, off-scale, high-gamma-ray response of as much as 190 to 260 API units (fig. 4). Locally, in central Ochiltree County and other limited areas, the marker bed comprises two high-gamma-ray shale units separated by a shale bed that is approximately 8 ft thick and of significantly lower response. In these areas the base of the Cleveland was placed at the top of the upper unit. The corresponding resistivity log response is typically one of moderate increase relative to that of adjacent shale intervals (fig. 4). Subregionally, this resistivity response is distinctive and is readily traceable among wells for which gamma-ray logs are not available.

Both the higher resistivity signature and the markedly higher gamma-ray response than those of adjacent shales is due primarily to the high concentration of organic matter in the clay shale. TOC values of samples from the high-gamma-ray marker bed in the Maxus Glasgow No. 2. and Maxus Littau No. 3 wells range from 1.9 to 5.7 weight percent; the average value for four samples (two from each well) is 3.4 weight percent. In contrast, TOC values for other dark-gray shales from throughout the three cores average 0.8 weight percent (seven samples; range of 0.5 to 1.1 weight percent). TOC values greater than 0.5 weight percent are generally accepted as indicators of potential hydrocarbon source rock, and rocks with values above 1.0 weight percent are considered good source rocks (Tissot and Welte, 1978). The spectral log from the Maxus Glasgow No. 2 well, the only one of the three Cleveland cores that sampled the black shale marker bed, indicates that uranium is the source of the high-gamma-ray values of the basal Cleveland black shale; thorium and potassium values exhibit little to no variation across the marker bed. Uranium concentration in the Glasgow marker bed is about

16 ppm. Adsorption of uranium ions onto concentrated organic matter is the cause of the high radioactive log response (Swanson, 1960, 1961; Leventhal, 1981).

The mineralogy of the basal black shale samples determined by XRD is consistently (in general order of abundance) quartz, calcite, dolomite, albite, kaolinite, and siderite. Illite is present in two of the four samples. Other Cleveland shales in the cored sections are composed of quartz, kaolinite, illite, albite, and siderite. Malachite and calcite are present in some of the samples. Relative mineral abundances among the samples vary slightly. The primary mineralogical difference between the high-gamma-ray marker shales and the other Cleveland shales is the presence of dolomite in the marker shales.

Top of Cleveland

Industry defines the top of the Cleveland Formation as the base of the lowest of five thin high-gamma-ray shale marker beds that can be correlated regionally within the carbonate-and-shale succession of the Kansas City Formation (fig. 4). Although no cores from this interval are available, the lithology and organic content of the Kansas City marker beds are probably similar to those of the clay shale marker bed at the base of the Cleveland Formation. Lithologic sample logs consistently describe the five thin units as black shales within intervals of limestone/dolostone and gray shale. Thickness of the upper Cleveland marker bed is generally no more than 10 ft. Its gamma-ray responses are commonly as much as 340 API units in the eastern part of the study area, but they gradually decrease toward the west, probably recording increasing proximity to minor diluting siliciclastic sources at the Anadarko Basin's western edge. The marker bed's resistivity response is typically much greater than that of the formation's basal marker (fig. 4).

As both the Cleveland and overlying Kansas City Formations thin toward the western margin of the Anadarko Basin, the intervals between the five Kansas City high-gamma-ray marker beds also thin to the point where the upper Cleveland marker bed consolidates with the next younger Kansas City black shale marker. In the west-central part of the study area, a general trend of progressive upsection and westward consolidation and possibly pinch-out of successive, overlying shale marker beds within the Kansas City is evident. Locally over the crest of a paleohigh in the western part of the study area (see "Thickness"), several or all of the five high-gamma-ray shales in the Kansas City have consolidated into one or two units. Consolidation/pinch-out north of this paleohigh in northern Hansford County only occurs immediately adjacent to the paleohigh; the five Kansas City marker shales are well defined in the northwestern and north-central part of the study area. In the western part of the study area the top of the Cleveland is placed at the base of the lowest gamma-ray marker bed in the Kansas City Formation. Several of the regional dip sections presented later in this report illustrate this phenomenon (see "Sequence Stratigraphy").

Thickness

Because of the distinctive and readily identifiable log response of the regionally correlative Cleveland Formation boundary shales (fig. 4), variation in thickness of the formation within the study area can be mapped with great precision. Calculation of formation thickness, not corrected for the minimal regional dip (see "Present Structure"), is accurate to within 2 ft when measured on the expanded gamma-ray and resistivity logs that accompanied most well logs used in the study.

The principal regional trend of thickness variation within the formation is one of increasing thickness toward the southeast into the deep Anadarko Basin along the basin's structural axis. However, subregionally the Cleveland also thickens markedly (1) toward the north-northeast off the northern flank of the Amarillo Uplift at the southern border of the study area, (2) toward the south and especially the north from the western paleohigh, and (3) toward the southwest in northeastern Lipscomb County (fig. 5).

The unit ranges in thickness from 0 ft in parts of Hansford and Hutchinson Counties to a maximum of about 590 ft in southwestern Hemphill County (fig. 5). Thinnest Cleveland (0 to about 50 ft range defining western paleohigh on inset in fig. 5) is restricted to central Hansford, west-central Ochiltree, and western Hutchinson Counties. However, note that this area of relatively widely separated contours continues toward the east into Ochiltree and northeasternmost Roberts Counties. Regions of thickest Cleveland (>300 ft) are the southern two-thirds of Lipscomb, most of Hemphill, and northern Wheeler Counties. A prominent, northwest-trending linear trough of thickest Cleveland also extends from southwestern Hemphill County into north-central Roberts County. The northwestward continuation of this trough exists primarily as aligned, discontinuous local thicks in southwestern Ochiltree and southeastern Hansford Counties.

As a generalization, regions of principal Cleveland sediment accumulation existed in the northern and southern parts and eastern third of the study area; the northern and southern areas were separated by an east-trending depositional barrier (paleohigh) in the study area's central portion.

Lithology

The Cleveland Formation is mostly sandstone, siltstone, and shale throughout the eastern, central, and southern parts of the study area, whereas carbonates (limestone, minor dolostone, and minor marl) and shale dominate the formation in the northwestern and north-central regions (fig. 4). Arkosic granite wash is common in the Cleveland section in the southernmost part of the study area. Because the Cleveland sandstones are the reservoir lithology, discussion of their composition, petrophysical

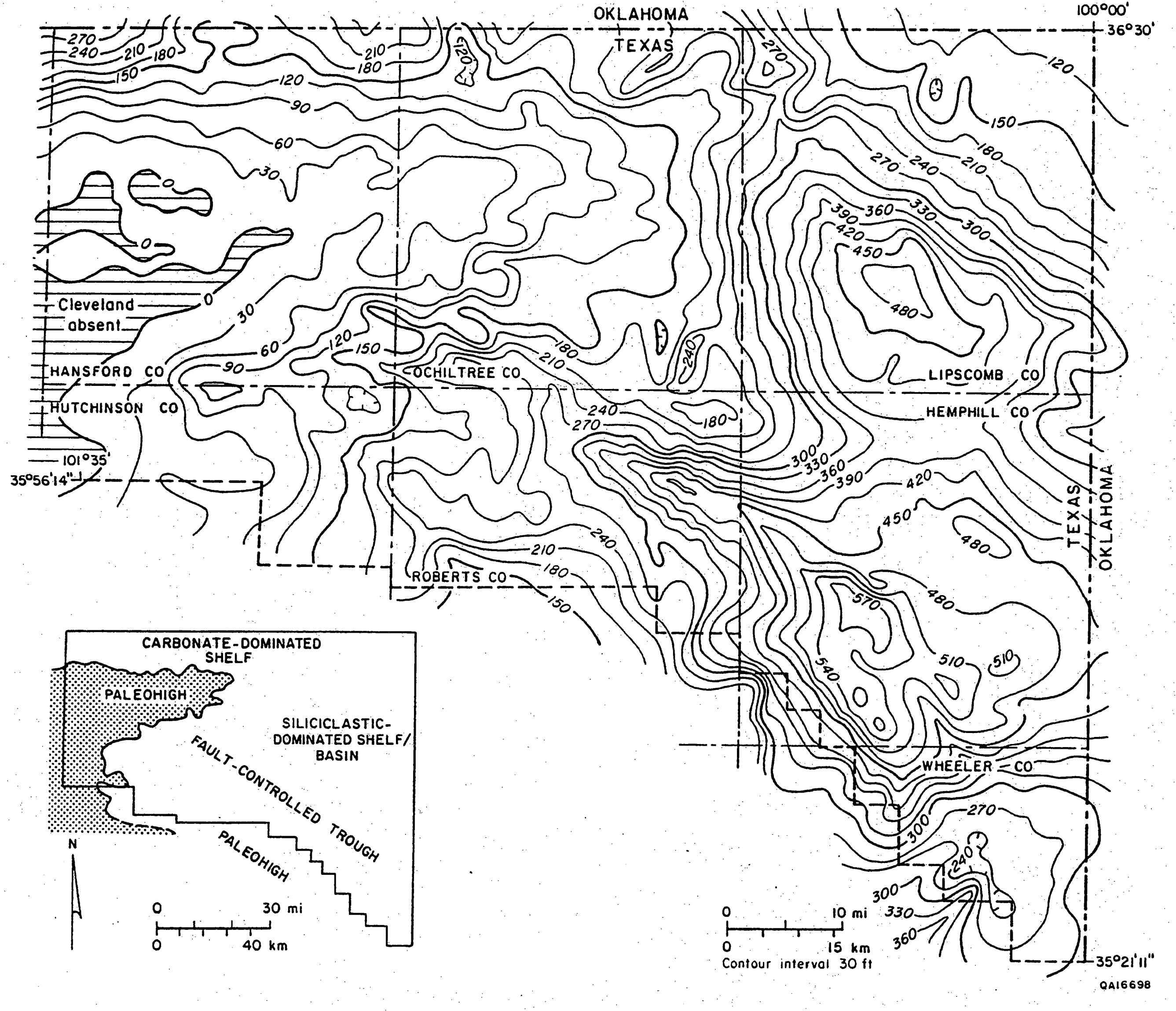

Figure 5. Isopach map of the Cleveland Formation and generalized paleogeography during Cleveland deposition. Areal limit of paleohigh in western part of study area (inset map) arbitrarily defined by 50-ft contour line.

characteristics, and regional distribution is emphasized. Sandstone and shale depositional facies and regional genetic stratal patterns are discussed in subsequent sections ("Depositional Facies" and "Sequence Stratigraphy," respectively). General descriptions of component Cleveland lithologies obtained from lithologic sample logs are summarized in table 1.

Sandstone

Stratigraphic Distribution

Cleveland sandstones are typically best developed in the middle part of the formation, although thinner and siltier sandstones can occur throughout the Cleveland (fig. 4). Sandstone thickness ranges from thin beds to sand-dominated intervals as much as 80 ft thick. The formation consists primarily of stacked, upward-coarsening units of (in ascending order) silty shale, interbedded siltstone/sandstone, and sandstone. A single, thick (20 to 65 ft) upward-fining sandstone unit is a common feature of the formation in most of the southern and central parts of the study area.

Color and Texture

Within the study area there is generally little variation in the color, texture, and gross composition of Cleveland sandstones, especially in the major gas-producing regions of Ochiltree and Lipscomb Counties. Where examined in core and described in lithologic sample logs throughout the study area, Cleveland sandstones are almost uniformly light gray (N7) (Goddard and others, 1979) to very light gray (N8, described as white on most sample logs). Sandstones are typically very fine to fine grained (locally coarsening to medium and coarse grained); are mostly well bedded, laminated, or cross-laminated; and contain abundant shale laminae, thin shale interbeds, and shale lenses

Table 1. Cleveland lithology from sample logs in the northern, central, and southern parts of the study area.

Lithology	Description
North	
Sandstone	White to gray, very fine to fine grained, angular to subangular grains, massive to slightly platy, slight porosity to tight, slightly calcareous, micaceous, commonly trace of oil stain
Shale	Medium dark gray, calcareous, laminated, micaceous, locally arenaceous
Carbonate*	Limestone, buff to brown, finely crystalline, tight, in part dolomitic, locally arenaceous, sparse glauconite, locally bearing chert, locally fossiliferous
	Marl, dark gray, tight, locally silty
Central	
Sandstone*	White to gray, very fine to fine grained, angular to subangular grains, massive to platy, mostly tight with some slight porosity, slightly calcareous, argillaceous, micaceous, commonly trace of oil stain, locally trace of pyrite
Shale*	Gray to black, laminated, micaceous, locally arenaceous; thin brown mudstone uncommon
Carbonate	Limestone, gray and brown, finely crystalline, tight, locally sparse pellets and fossils, locally oolitic and arenaceous
	Dolostone, brown, finely crystalline, less common than limestone in thin zones (<15 ft)
	Marl, gray, tight
Coal	Bedded, vitreous, in thin zones (<2 to 5 ft), only locally present
South	
Sandstone*	White to brownish-gray, very fine to coarse grained, subangular to subrounded grains, massive, mostly tight with some slight porosity, arkosic, argillaceous, micaceous
Shale*	Medium dark gray, calcareous, laminated, micaceous, locally arenaceous
Carbonate	Limestone, gray to brown, finely crystalline, tight, locally arenaceous and arkosic, slightly fossilferous, dolomitic
	Dolostone, gray to brown, finely crystalline, less common than limestone in thin zones (<15 ft)
	Marl, gray, tight, arenaceous
Granite wash*	Gray to brown, fine to very coarse grained, commonly conglomeratic, subrounded to rounded grains, arkosic, micaceous

*Dominant lithologies

(drapes) (figs. 6 through 8). As observed in the three cores from the gas-producing region, relatively little clay-free ("clean") sandstone is present (sporadically in the interval 7,197 to 7,206 ft of the Maxus Glasgow No. 2 of fig. 6; 7,021.5 to 7,025 ft of the Maxus Shrader No. 3 of fig. 7; and 8,063 to 8,075 ft of the Maxus Tubb "D" No. 3 of fig. 8). However, sandstone intervals with visually estimated sand contents of 60 to 80 percent are common. Sedimentary structures within sandstones and siltstones are generally small scale, ripple trough lamination with shale drapes (flasers) being by far the most common type. In descending order, horizontal lamination, massive (structureless) thin to medium beds, normally graded thin beds, and medium- to large-scale crossbeds follow in relative abundance. Cleveland sandstones gradationally become coarser grained (medium to very coarse sand) and arkosic toward the far southern part of the study area, in proximity to the granite wash deposits along the Amarillo Uplift.

Composition

Regional data on Cleveland sandstone composition are unavailable. However, petrographic examination of 24 Cleveland sandstone samples from the 3 cores reveals characteristics that are probably shared throughout at least the gas-producing region of Ochiltree and Lipscomb Counties (tables 2 through 4). The sandstone samples used for petrographic analysis in this study are not representative of the Cleveland Formation as a whole, but they are representative of the Cleveland reservoir sandstones.

All Cleveland sandstones examined are classified as either lithic arkoses or feldspathic litharenites (Folk, 1974) (fig. 9). Except for one sample from the Maxus Tubb "D" No. 3 well (sample depth 8,109.7 ft), the sandstones are quartz-grain dominated (Dutton and Hentz, 1991). The average Cleveland sandstone composition derived from all 24 core samples is $Q_{59}F_{21}R_{20}$ (S. P. Dutton, personal communication, 1991). Average composition among the three wells is remarkably consistent, with the

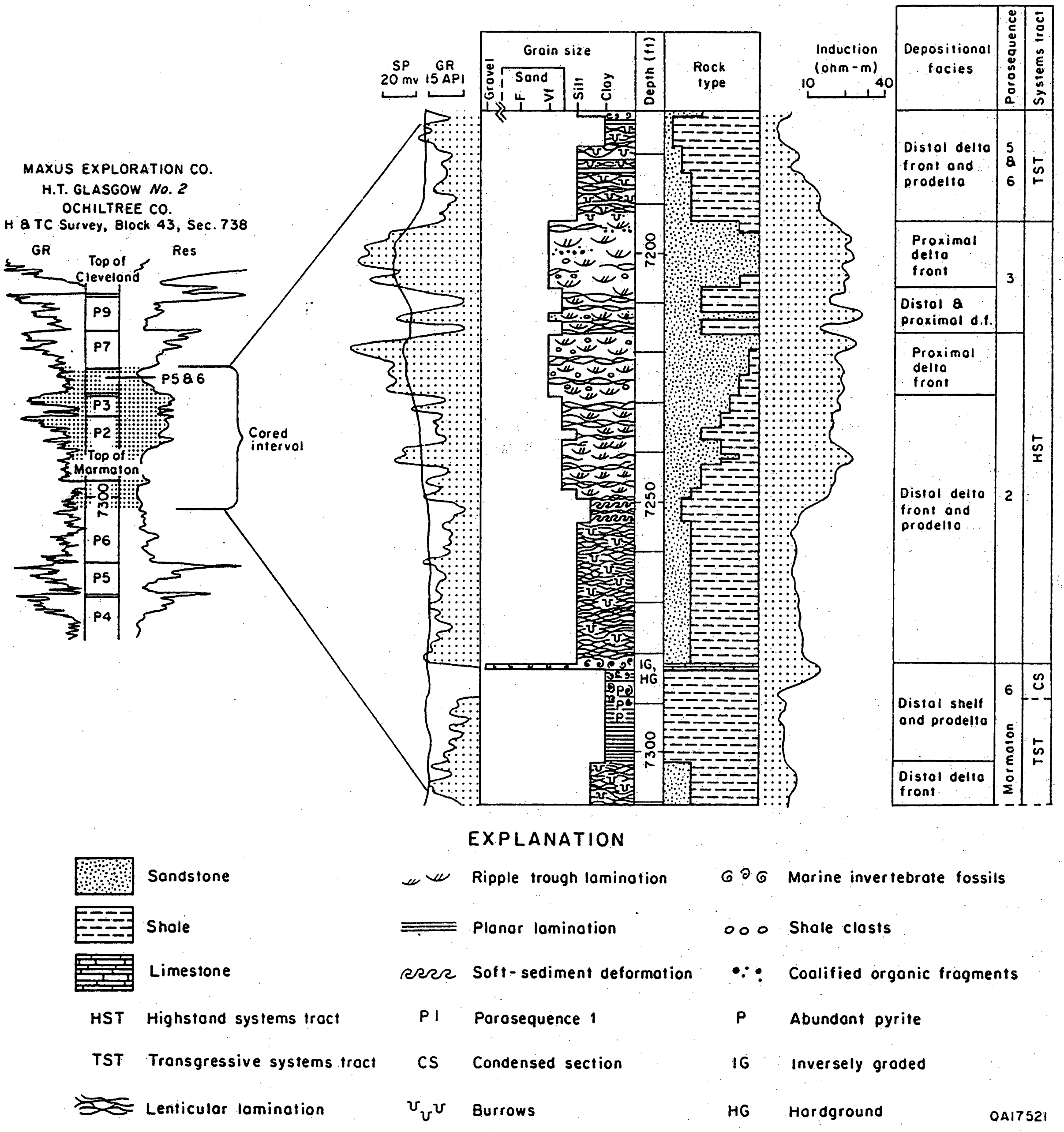

Figure 6. Core log of the upper Marmaton Group (undivided) and lower and middle Cleveland Formation from the Maxus Glasgow No. 2 well in east-central Ochiltree County. Log depths are given; to locate sandstone samples used in petrographic analysis, which are identified by core depth (table 2), the core-to-log correction factor is log depth + 9 ft = core depth. See figure 2 for location of well.

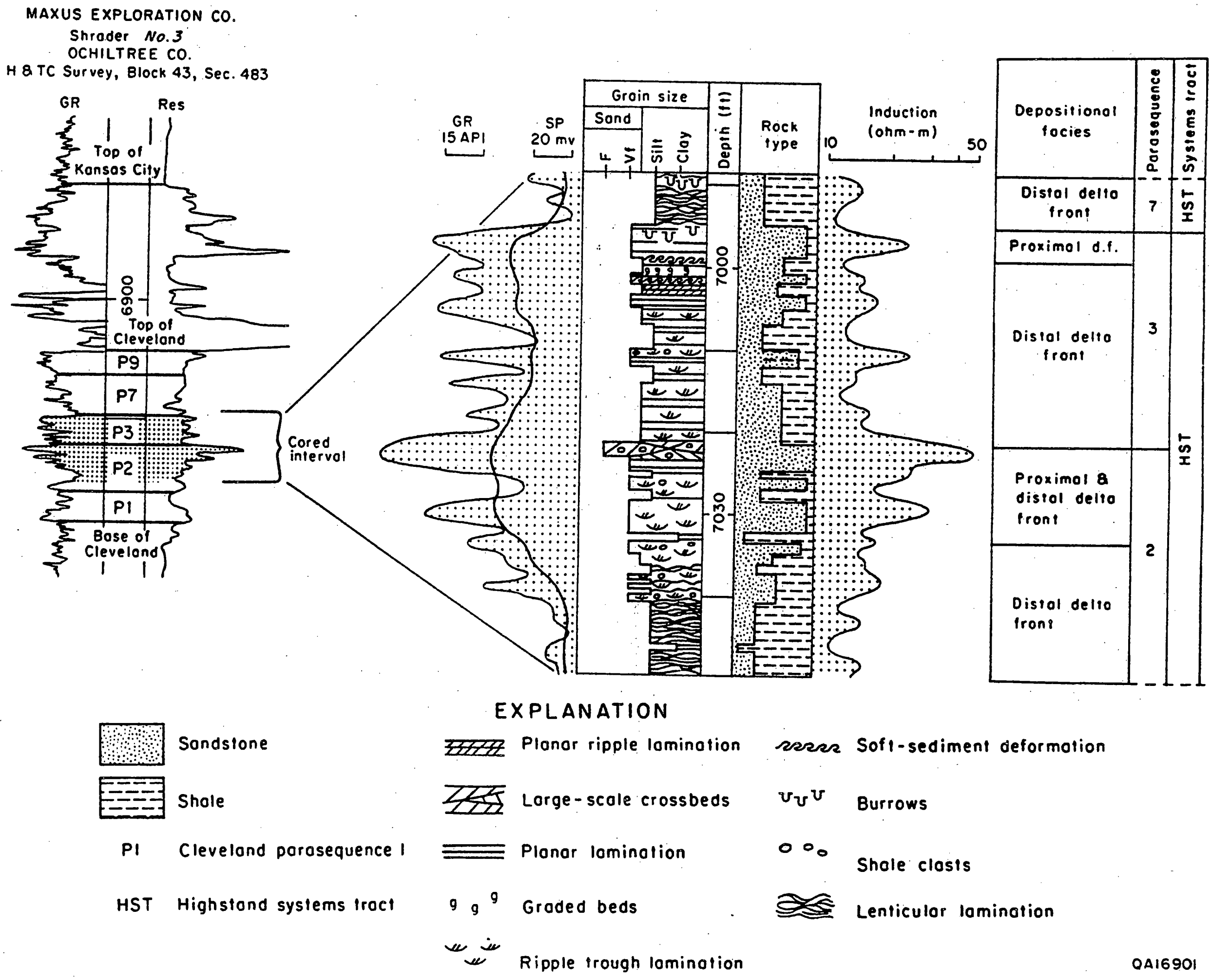

Figure 7. Core log of the middle Cleveland Formation from the Maxus Shrader No. 3 well in south-central Ochiltree County. Log depths are given; to locate sandstone samples used in petrographic analysis, which are identified by core depth (table 3), the core-to-log correction factor is log depth + 2 ft = core depth. See figure 2 for location of well.

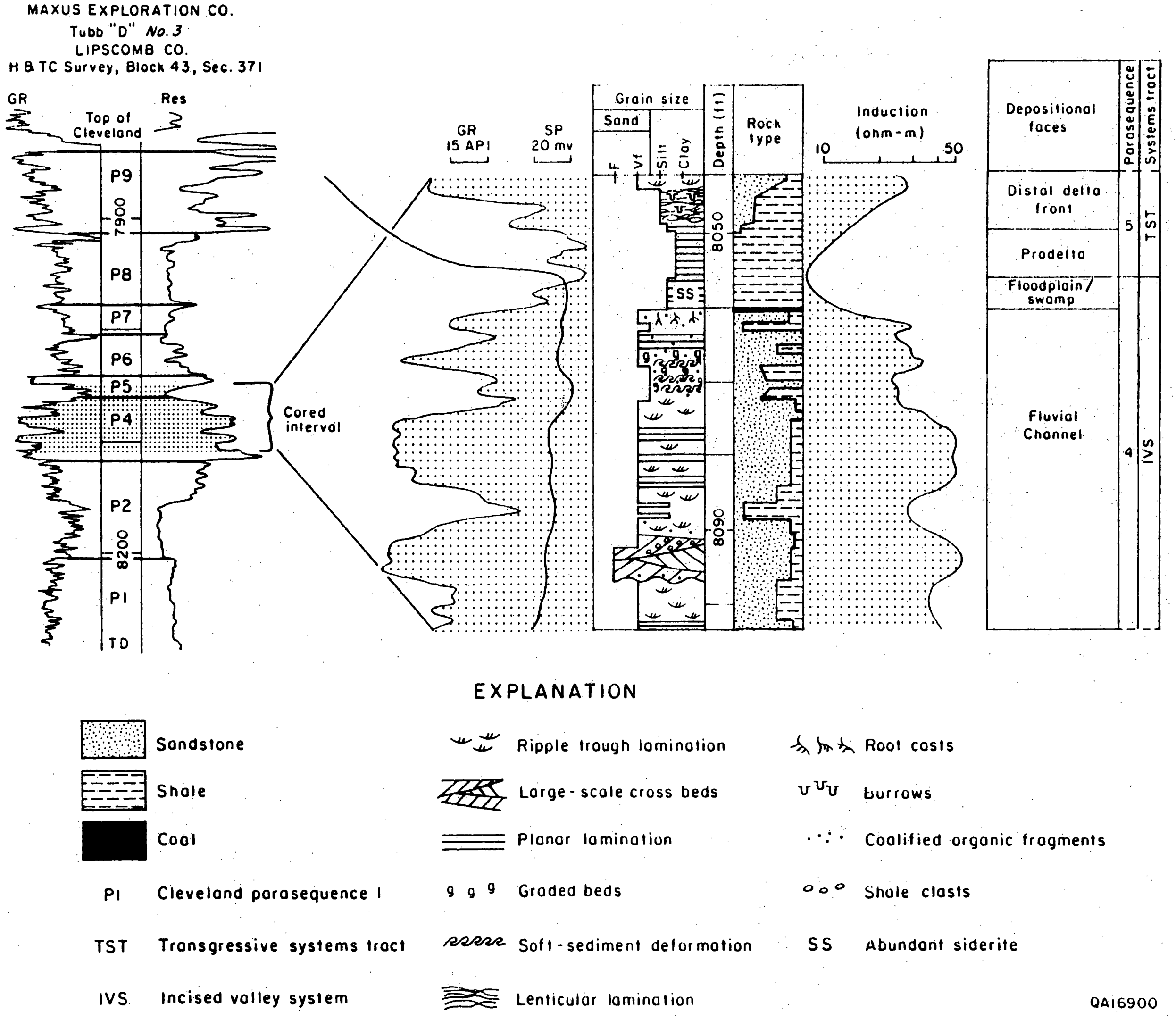

Figure 8. Core log of the middle Cleveland Formation from the Maxus Tubb "D" No. 3 well in south-central Lipscomb County. Log depths are given; to locate sandstone samples used in petrographic analysis, which are identified by core depth (table 4), the core-to-log correction factor is log depth + 14 ft = core depth. See figure 2 for location of well.

Table 2. Petrographic analyses of Maxus Glasgow No. 2 Cleveland Formation samples.

Core depth (ft)	Framework grains (%)									Matrix (%)
	Quartz	Plag.[1]	K-spar[2]	PRF[3]	MRF[4]	Chert	Ss[5]/Clay[6]	Muscovite	Other	Clay-sized fines
7,204.2	37.0	14.5	0.5	4.5	16.0	0	1.5 / 0	3.0	5.0[7,8,9]	1.5
7,206.1	47.0	13.5	0	4.5	12.0	0	0.5 / 1.0	2.5	1.0[7,9]	0
7,210.3	40.5	13.5	0	2.5	8.0	0	0 / 0	1.0	1.0[7,10]	0
7,214.6	48.0	14.5	0.5	2.5	14.5	0.5	0 / 0	0	1.5[8,9,10]	0
7,216.3	39.5	18.5	2.0	4.0	12.0	0	0 / 0	0	1.5[7,9,11]	0
7,223.2	47.5	7.5	0.5	1.5	14.5	0	0 / 0	2.0	3.5[8,9]	0
7,228.4	50.5	15.5	0	1.0	11.5	0	1.5 / 0	3.0	2.0[7,9]	0
7,233.3	46.5	16.0	0.5	4.0	11.0	0.5	1.0 / 0	1.0	0.5[10]	0
7,237.5	44.5	14.5	1.5	6.0	11.0	0.5	2.5 / 0	1.5	3.5[7,9,10]	0
7,243.7	53.5	7.0	1.0	2.0	11.0	0.5	0.5 / 0	1.5	0	0.5

Core depth (ft)	Cements (%)							Porosity (%)		Grain size (mm)
	Quartz	Calcite	Ankerite	Siderite	Illite	Chlorite	Other	Primary	Secondary	
7,204.2	6.0	1.5	0	0.5	2.0	3.0	0	2.0	1.5	0.075
7,206.1	5.0	2.5	0	1.0	1.0	4.0	0	1.0	3.0	0.075
7,210.3	1.0	22.5	10.0	0	0	0	0	0	0	0.120
7,214.6	4.5	0	2.0	0.5	1.5	2.0	0	2.5	4.5	0.113
7,216.3	8.0	2.0	0	0.5	2.0	3.5	0.5[12]	3.0	3.0	0.120
7,223.2	6.5	14.0	0	0	0.5	1.5	0	0	0.5	0.113
7,228.4	4.0	0	0	2.0	1.5	2.0	0.5[12]	0.5	4.5	0.098
7,233.3	9.0	2.5	0	0.5	1.0	1.0	0	2.0	3.0	0.098
7,237.5	8.0	1.5	0	0.5	1.5	1.5	0	0.5	1.0	0.090
7,243.7	4.0	14.0	0	2.5	1.0	1.0	0	0	0	0.075

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[1] Plagioclase; [2] potassium feldspar; [3] plutonic rock fragments, mainly quartz diorite; [4] metamorphic rock fragments, mainly muscovite-rich phyllite and schist; [5] sandstone fragment; [6] clay clast; [7] chlorite; [8] organics; [9] biotite; [10] zircon; [11] tourmaline; and [12] feldspar overgrowth, probably albite.

Table 3. Petrographic analyses of Maxus Shrader No. 3 Cleveland Formation samples.

Core depth (ft)	Framework grains (%)									Matrix (%)
	Quartz	Plag.[1]	K-spar[2]	PRF[3]	MRF[4]	Chert	Ss[5]/Clay[6]	Muscovite	Other	Clay-sized fines
7,003.0	48.5	6.5	1.5	1.0	15.0	1.5	1.5 / 1.5	3.5	1.0[7,8]	0
7,012.9	48.5	12.5	0.5	2.5	10.5	0.5	1.5 / 0.5	0	1.0[7]	1.0
7,024.9	40.5	14.0	0	3.5	11.5	0	2.5 / 1.5	0.5	1.5[9,10]	0
7,026.6	50.0	11.5	1.0	5.0	6.0	0	1.5 / 0	0	1.0[9]	0
7,032.7	46.0	10.5	0	5.5	13.0	0	2.5 / 0.5	0.5	1.0[11]	0
7,041.4	47.5	11.0	1.5	3.5	8.5	2.5	2.5 / 0.5	3.5	1.5[7,8,10]	0.5

Core depth (ft)	Cements (%)							Porosity (%)		Grain size (mm)
	Quartz	Ankerite	Kaolinite	Illite	Chlorite	Siderite	Other	Primary	Secondary	
7,003.0	7.0	2.0	0	0.5	1.5	3.0	0	1.0	3.5	0.090
7,012.9	10.0	4.5	0.5	0.5	3.0	1.5	0	0	1.0	0.150
7,024.9	8.0	7.5	3.0	1.5	1.0	0.5	0.5[12]	0.5	2.0	0.188
7,026.6	10.0	5.5	0.5	1.0	2.0	0	0	2.0	3.0	0.165
7,032.7	6.0	5.0	0	1.0	1.0	0.5	0	4.5	2.5	0.128
7,041.4	12.0	1.5	0.5	0	1.0	1.5	0	0	0	0.113

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[1] Plagioclase; [2] potassium feldspar; [3] plutonic rock fragments, mainly quartz diorite; [4] metamorphic rock fragments, mainly muscovite-rich phyllite and schist; [5] sandstone fragment; [6] clay clast; [7] chlorite; [8] organics; [9] biotite; [10] zircon; [11] tourmaline; and [12] feldspar overgrowth, probably albite.

Table 4. Petrographic analyses of Maxus Tubb "D" No. 3 Cleveland Formation samples.

Core	Framework grains (%)									Matrix (%)
depth (ft)	Quartz	Plag.[1]	K-spar[2]	PRF[3]	MRF[4]	Chert	Ss[5]/Clay[6]	Muscovite	Other	Clay-sized fines
8,056.2	52.0	7.0	0.5	0	13.5	0	1.0 / 0.5	4.0	0.5[7]	6.0
8,064.8	5.5	0	0	0	0	0	0 / 0	4.0	5.5[8]	85.0
8,072.7	21.5	0	0	0	0	0	0 / 0	4.0	9.0[8]	64.5
8,079.7	48.5	11.5	0	2.0	14.0	0	1.5 / 0	1.0	0	0
8,088.5	50.5	11.5	0	1.5	13.0	0.5	2.5 / 0.5	0	0	0
8,096.1	41.5	12.0	0	3.0	16.5	1.5	0 / 2.0	0	0.5[9]	0
8,101.9	41.5	13.5	0	2.5	19.0	0.5	6.5 / 1.0	1.5	1.0[10]	0
8,107.4	43.0	12.0	0	3.5	13.5	0	1.5 / 2.0	0.5[5]	1.5[8,9,10]	0
8,109.7	27.0	22.5	0	3.5	24.0	0.5	2.0 / 4.0	0	0.5[9]	0
8,116.4	44.5	16.5	0	4.5	15.5	1.0	3.0 / 1.0	0.5	1.0[8,11]	0

Core	Cements (%)							Porosity (%)		Grain size
depth (ft)	Quartz	Fe-Calcite	Ankerite	Illite	Chlorite	Siderite	Other	Primary	Secondary	(mm)
8,056.2	9.5	2.0	0	1.5	1.5	0.5	0	0	0	0.090
8,064.8	0	0	0	0	0	0	0	0	0	0.004
8,072.7	0	0	0	0	0	1.0	0	0	0	0.004
8,079.7	8.0	4.0	3.5	1.0	1.5	0	0	0.5	1.5	0.135
8,088.5	10.5	0	0.5	1.0	2.0	1.5	0	2.5	2.0	0.150
8,096.1	9.0	7.0	0.5	0.5	2.0	1.0	0	1.5	1.5	0.120
8,101.9	9.5	0	0	0	2.5	0	0	0	0.5	0.165
8,107.4	5.5	14.5	0.5	0.5	1.0	0	0	0	0.5	0.150
8,109.7	8.0	0	0	1.0	2.5	0.5	1.5[12]	0.5	1.0	0.180
8,116.4	6.0	0	0	1.0	3.5	0	0	0.5	1.5	0.173

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[1] Plagioclase; [2] potassium feldspar; [3] plutonic rock fragments, mainly quartz diorite; [4] metamorphic rock fragments, mainly muscovite-rich phyllite and schist; [5] sandstone fragment; [6] clay clast; [7] chlorite; [8] organics; [9] biotite; [10] zircon; [11] tourmaline; and [12] feldspar overgrowth, probably albite.

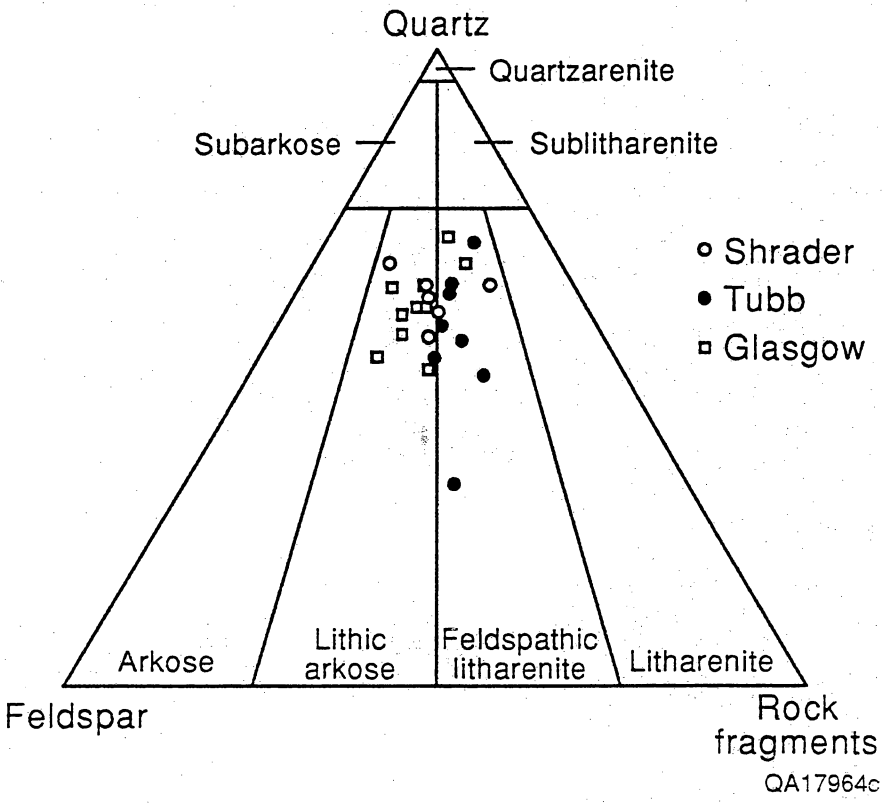


Figure 9. QFR (quartz:feldspar:rock fragments) ternary diagram illustrating detrital components of Cleveland sandstone samples from the Maxus Shrader No. 3, Maxus Tubb "D" No. 3, and Maxus Glasgow No. 2 wells.

Maxus Glasgow No. 2 well containing $Q_{60}F_{23}R_{17}$, the Maxus Shrader No. 3 well containing $Q_{61}F_{20}R_{19}$, and the Tubb containing $Q_{55}F_{20}R_{25}$. Preserved feldspar grains are mostly plagioclase; potassium feldspar is either absent or a minor constituent in samples (tables 2 through 4). Rock fragments comprise low-rank metamorphic (muscovite-rich phyllite and schist) and plutonic (quartz diorite) lithologies. Chert fragments are absent or minor constituents. There is generally little or no clay-sized matrix in the 24 samples; however, the visually cleanest (reservoir-quality) samples were purposely selected for petrographic inspection. Average grain size of all samples is 0.124 mm (core averages: Glasgow 0.098 mm, Shrader 0.139 mm, Tubb 0.145 mm), placing the average grain size in the very fine sand category but close to the very fine/fine sand limit (0.125 mm). Grain size range is 0.075 to 0.188 mm.

The dominant cement (tables 2 through 4) in the 24 sandstone samples is quartz (as overgrowths), with an average of 7.3 percent of the whole rock volume for all samples (Dutton and Hentz, 1991). Total-carbonate cement averages 6.2 percent of the whole rock volume for all samples; the carbonate cements encountered include calcite, Fe-rich calcite, ankerite, and siderite. The average of total-clay (chlorite, illite, and kaolinite) cement for all samples is 3.0 percent of the whole rock volume, with chlorite being the most dominant of the authigenic clay minerals at 1.9 percent. Feldspar overgrowths, probably albite, occur in 4 of the 24 sandstone samples.

Permeability and Porosity

As a formally designated low-permeability ("tight") gas formation, the Cleveland contains reservoir sandstones that typically have permeabilities of less than or equal to 0.10 md. The arithmetic average in situ permeability for Cleveland sandstones in 501 wells in the main gas-producing region of Ochiltree and Lipscomb Counties is 0.140 md (Railroad Commission of Texas, 1981), ranging from a high of 19.55 md to a low of

<0.001 md. The few large maximum readings recorded may be due to natural fractures within the reservoir. In the Ellis Ranch field of eastern Ochiltree County, the premier Cleveland gas-producing field, typical permeability is 0.4 md (Britt, 1961).

Average porosity observed in thin section (primary and secondary) for all sandstone samples from the three cores examined in this study (tables 2 through 4) is 2.8 percent, primary porosity averaging 1.0 percent and secondary porosity averaging 1.7 percent (Dutton and Hentz, 1991). The wells from which the samples were taken are nonproductive in the Cleveland interval.

Limited published data on the porosity of Cleveland reservoirs are available. However, those that exist suggest a remarkably uniform character within the producing reservoirs in Ochiltree and Lipscomb Counties. In the Ellis Ranch field typical porosity measured from core is about 14 percent (Britt, 1961); although not specified, this value is probably porosimeter porosity. Analyses from four other cores throughout the two-county area show average porosities ranging from 10 to 14 percent (Maxus Exploration Company, unpublished data). The significant porosity difference between Cleveland reservoir and nonreservoir rocks may be misleading because the two data sets probably resulted from two different porosity-measuring techniques. Because porosimeter porosity is typically 5 to 6 percent higher than porosity measured in the same sample by observation in thin section, most of the porosity difference can be accounted for by differing methods of measuring porosity. Regionally, typical Cleveland reservoir (pay zone) characteristics are (1) porosities ranging from 10 to 15 percent, (2) permeabilities ranging from 0.1 to 141 md, (3) water saturation ranging from 30 to 40 percent, (4) initial reservoir temperature ranging from 140° to 182°F, and (5) initial reservoir pressure ranging from 1,750 to 3,560 psi (Kosters and others, 1989).

Regional Distribution

Net- and percent-sandstone maps of the Cleveland Formation record distinct areal sandstone distribution patterns within the unit (figs. 10 and 11). Thickest (80 to >160 ft) net sandstone occurs primarily in two parallel, arcuate, north-south-trending belts extending from (1) east-central Ochiltree through southwestern Lipscomb and northwestern Hemphill Counties into east-central Roberts County (*western trend*) and (2) northwestern Lipscomb County through central Lipscomb and Hemphill Counties to southwestern Hemphill County (*central trend*) (fig. 10). The central trend also includes the shorter but distinct northwest-elongate sandstone thick in southern Hemphill and northern Wheeler Counties. A third, less pronounced, parallel trend of aligned sandstone thicks is suggested in east-central Lipscomb County (*eastern trend*). The central trend is the most prominent of the three and contains the maximum net-sandstone reading of 215 ft in south-central Lipscomb County. Other areas of thick net sandstone exist (1) within an elongate east to east-southeast trend extending from southeastern Hansford and northern Hutchinson Counties to the east-central edge of the study area and (2) in central Wheeler County, an area of localized accumulation of coarse arkosic sandstone locally derived from the Amarillo Uplift.

Comparison of the Cleveland isopach map (fig. 5) and net-sandstone map (fig. 10) indicates that areas of primary sand accumulation in the formation coincide with areas of greatest formation thickness. Note in particular the concurrence of (1) the prominent central sandstone trend in the eastern part of the study area with broad areas of thick Cleveland in Lipscomb and Hemphill Counties and (2) the elongate east-southeast sandstone trend in the western and central parts of the study area and the southern parts of the western and central sandstone trends with the linear formation thick (depotrough).

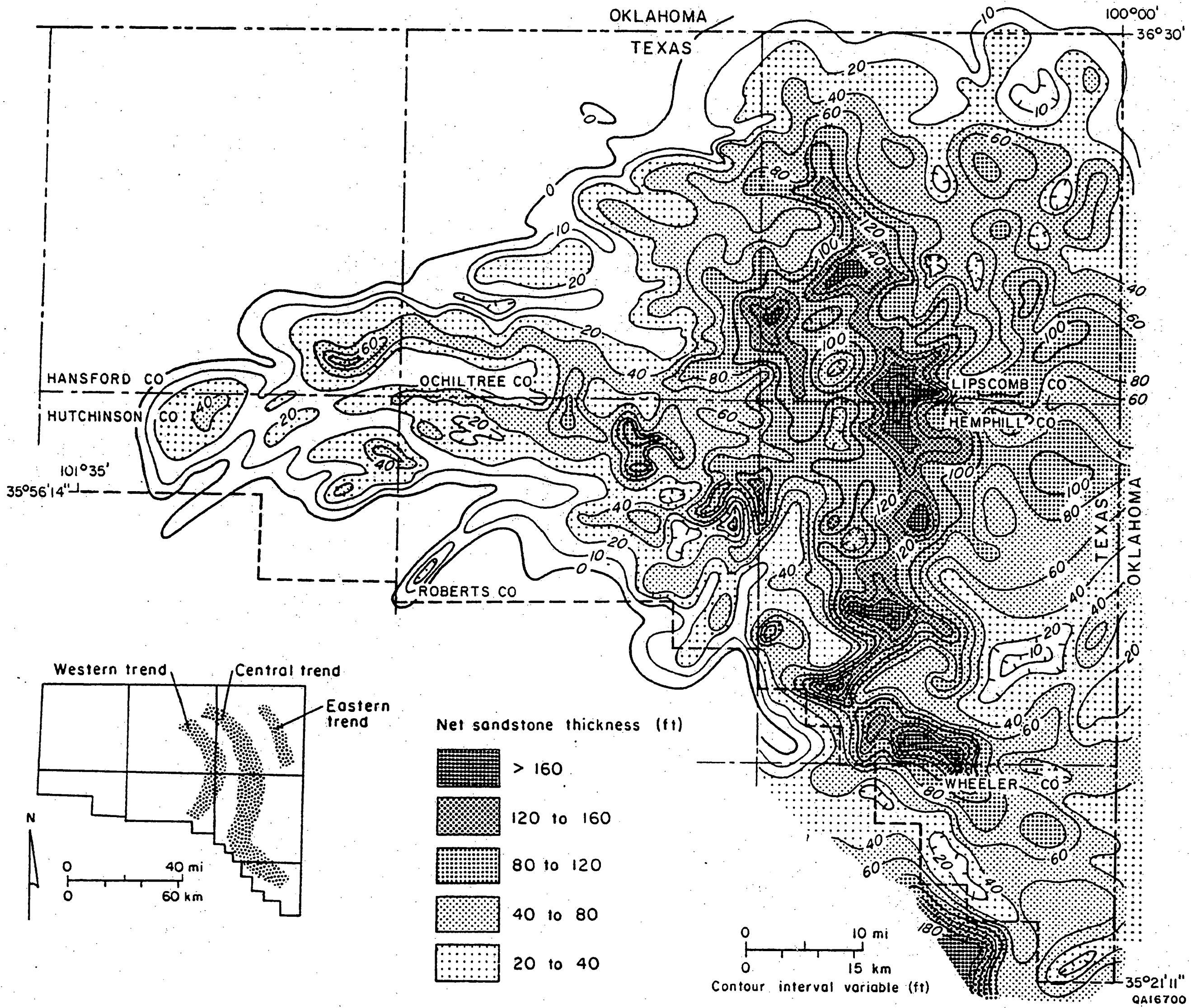


Figure 10. Net-sandstone map of the Cleveland Formation in the western Anadarko Basin. Inset map highlights primary trends of thickest net sandstone.

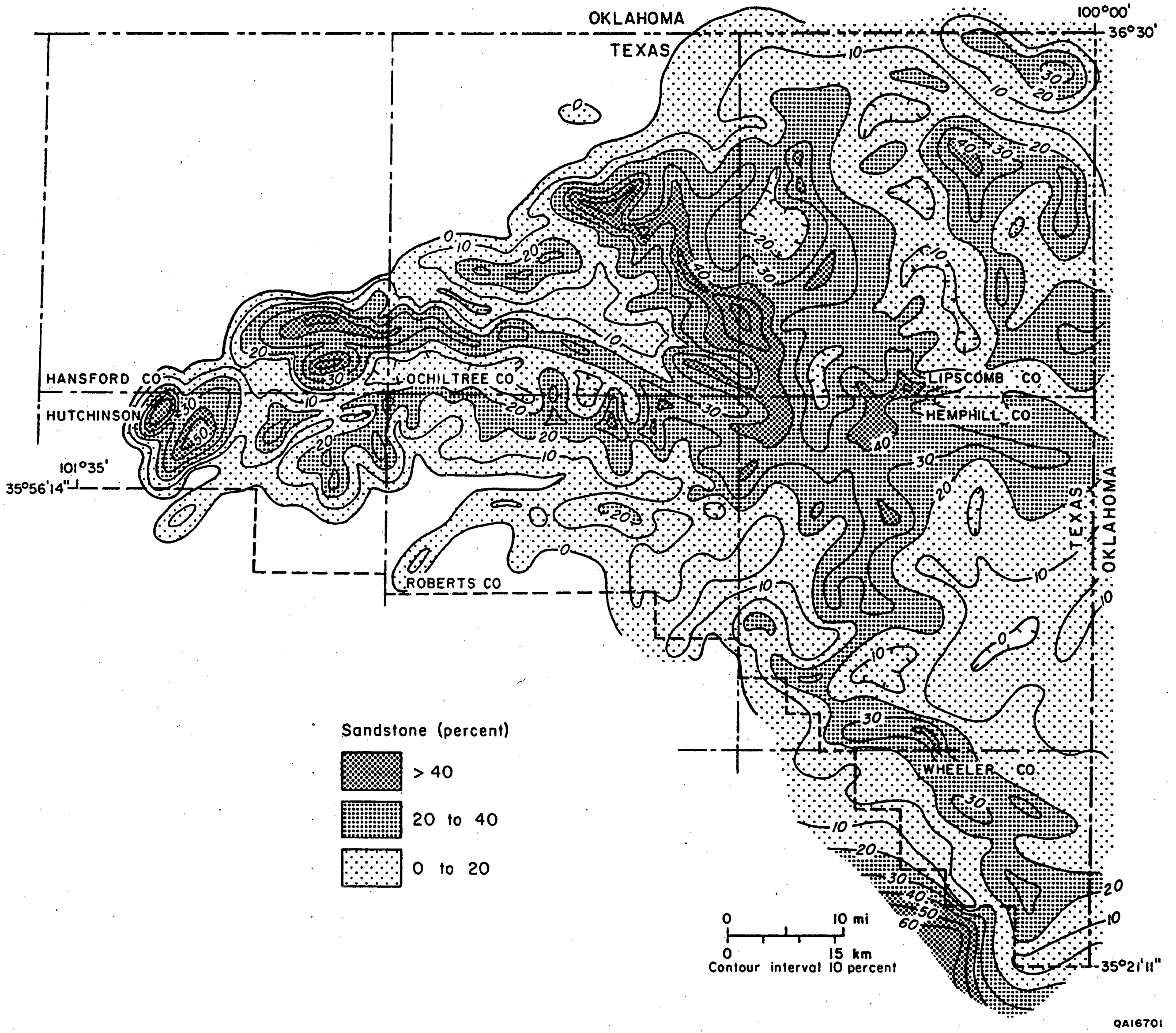


Figure 11. Percent-sandstone map of the Cleveland Formation in the western Anadarko Basin. Areas of thick sandstone occurrence where the Cleveland Formation is relatively thin are emphasized.

Percent-sandstone trends within the Cleveland Formation (fig. 11) generally mimic trends illustrated on the net-sandstone map (fig. 10), although they commonly emphasize areas of relatively thin but sandstone-rich Cleveland. Exceptions are evident in the eastern third of the study area where the Cleveland is quite thick. Principal areas of highest percent sandstone (30 to >50 percent) are found (1) sporadically aligned along the prominent central sandstone trend of figure 10, (2) within the northern part of the western sandstone trend of figure 10, (3) aligned along the elongate east-southeast sandstone trend of the western and central parts of the map area, and (4) in central Wheeler County where the formation abruptly thins against the northern flank of the Amarillo Uplift.

Carbonates

Carbonate lithologies, including limestone, dolostone, and marl (table 1), are restricted to the upper part of the Cleveland Formation throughout most of the sandstone-bearing parts of the study area (fig. 4). Except for a thin (4-inch) fossiliferous grainstone in the Maxus Glasgow core (fig. 6), no carbonate lithologies are present in cores examined for this study; therefore, rock descriptions other than those from lithologic sample logs (table 1) are not available.

Limestone and minor marl dominate the Cleveland section in the northwestern and north-central parts of the study area (figs. 4 and 12) where the siliciclastic Cleveland Formation grades into the thick carbonate and shale succession of the Kansas Shelf to the north of the study area. Carbonates here typically attain net thicknesses of as much as 190 ft (only limestone measured) and compose an estimated 90 percent or more of the entire Cleveland interval. This region of marked northward thickening of carbonates in the formation is restricted to the north of the Cleveland paleohigh (compare fig. 5 with fig. 12). To the south in central Wheeler County, limestones in the

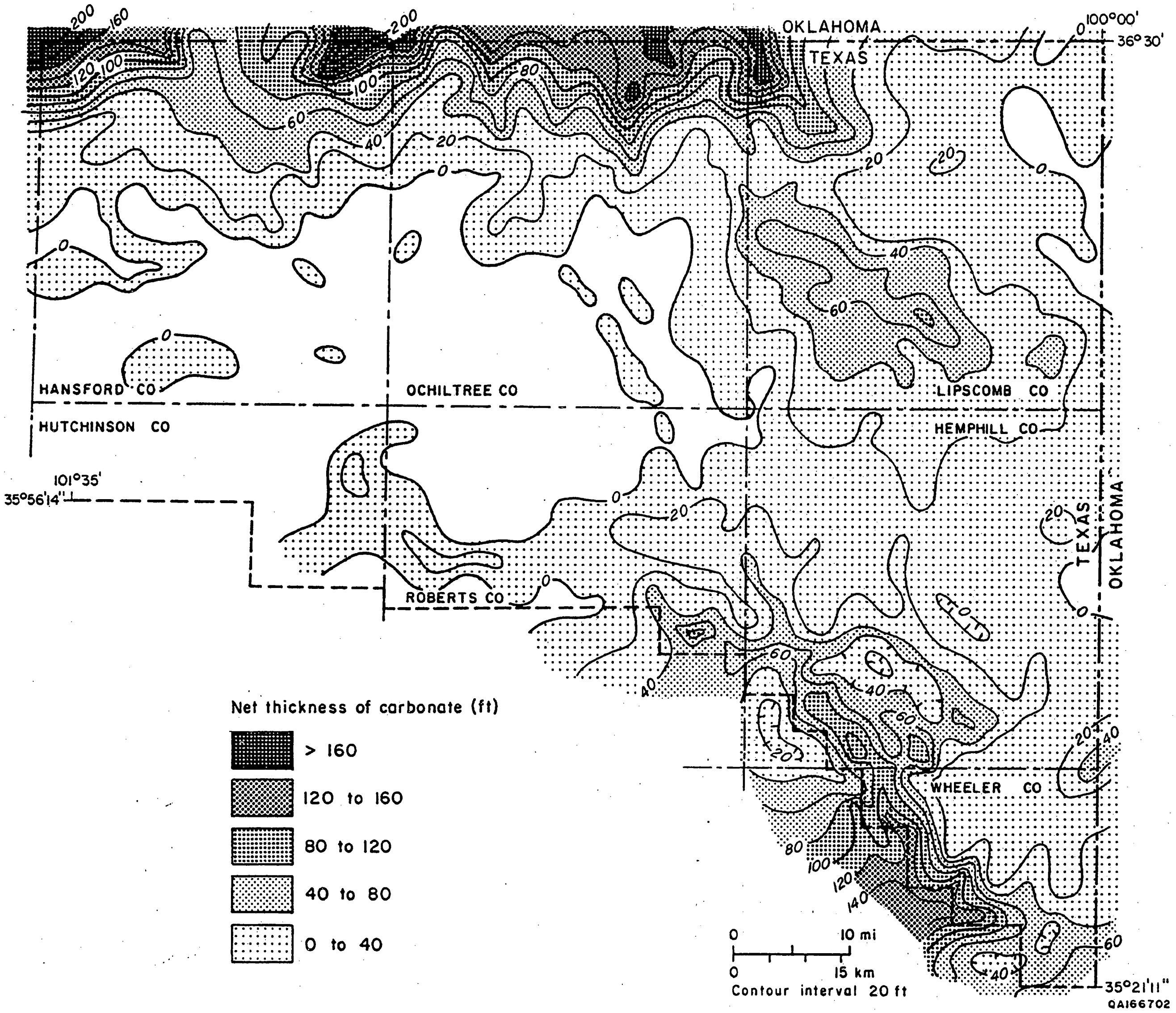


Figure 12. Net-carbonate map of the Cleveland Formation in the western Anadarko Basin. Only limestone and dolostone were measured for this map; marl was included as a shale lithology. Carbonates (primarily limestone) in the Cleveland are restricted to the upper part of the formation throughout most of the study area. However, carbonates compose most of the formation in the northern area where the siliciclastic facies of the Cleveland thin into the thick carbonate facies of the Kansas Shelf.

middle and upper Cleveland form prominent local buildups along the northern flank of the Amarillo Uplift (fig. 12), where locally they make up close to 60 percent of the formation. A moderate carbonate thick in southern Lipscomb County (fig. 12) coincides with an area of underlying primary sand accumulation (northern part of the central sandstone trend of fig. 10) and may have formed at least in part because of the presence of this relatively stable and less compactible substrate (forming a subtle topographic high during carbonate deposition). Throughout most of the study area, carbonates compose less than 10 to 15 percent of the Cleveland Formation.

No Cleveland carbonates exist in the west-central and central parts of the study area because (1) the formation is absent (fig. 5) and (2) the region was probably a primary terrigenous-sediment transport route (fig. 10) throughout most of Cleveland time, thus preventing extensive biologic production of carbonates.

The lateral stratigraphic transition from the thick Pennsylvanian shelf carbonate successions just north of the study area and the siliciclastics toward the south in the Anadarko Basin has not been well understood, in part because of the difficulty in carrying physical correlations across the zone of lithologic change. However, current thought is that the siliciclastics are coeval with shale units of the Kansas Shelf and were not deposited contemporaneously with the shelf carbonates (Johnson and others, 1988). Detailed correlations between the siliciclastic- and carbonate-dominated Cleveland sections (generalized in fig. 4, logs A and B) support this. The regional black shale marker beds at the base and top of the Cleveland and the subregional distribution of two similar black shale marker beds in the upper part of the formation (one of which is illustrated in fig. 4) enabled precise correlation within the transition zone. Most common at the top of the formation in the study area, carbonates become progressively more abundant downsection in the Cleveland toward the north. Cleveland sandstone and shale intervals grade northward into shales between thick carbonate beds of the shelf facies.

In most of the southern part of the study area, interfingering of upper Cleveland carbonates and granite-wash-bearing intervals is common. Basinward to the southeast, Cleveland carbonates gradually thin and pinch out within eastward-thickening shale successions (fig. 4).

Shale

Cleveland shales are generally most abundant in the southeastern part of the study area (fig. 4), where the formation comprises a higher percentage of basinal facies and major sandstone accumulations are not present (that is, away from major axes of sand deposition; figs. 10 and 11). The entire siliciclastic interval that includes the Cleveland and the underlying Marmaton Group (undivided) becomes progressively richer in shale toward the deep Anadarko Basin (fig. 1).

Inspection of the numerous lithologic sample logs and well logs from throughout the study area and of the Cleveland cores indicates that there are two general types of shale in the Cleveland section. Most of the shale (type 1) is medium-dark gray to dark gray (N4 to N3) (Goddard and others, 1979) and ranges widely in quartz-silt content from silt rich (verging on siltstone) to silt poor (clay shale). Darkest shales contain the least silt. Shales are commonly micaceous and laminated. Sample logs indicate that this type 1 Cleveland shale is calcareous in the northern and southern parts of the study area but is noncalcareous in the central region (table 1). Shales in the Cleveland core (Maxus Glasgow No. 2) from the northern region are shown to be noncalcareous to strongly calcareous by HCl acid testing; however, shales in the other two Cleveland cores (Maxus Shrader No. 3 and Maxus Tubb "D" No. 3) farther south are mostly noncalcareous. Bedding ranges from thick (about 100 ft) to thin as interlaminations and lenses/drapes with sandstone and siltstone. The second type of Cleveland shale (type 2) occurs as two thin (<10 ft) beds in the upper half of the formation primarily throughout the eastern half of the study area. Sample logs invariably identify them as black shales, and they have characteristically high gamma-ray responses. Figure 4 illustrates one of the beds (7,700 ft in log B; 10,500 ft in log C); figure 8 shows both of these thin radioactive shales at the tops of parasequences 6 and 8. No samples of type 2 Cleveland shales were cored, although these beds are probably similar to the formation's high-gamma-ray boundary marker beds described above (see "Base of Cleveland"). Collectively, these beds compose only a minor part of the Cleveland section but are regionally quite significant by enabling precise correlation within the formation in the area of thickest Cleveland.

Granite Wash

Granite wash, which was eroded from the mostly granitic Amarillo Uplift (fig. 1), is areally restricted to a narrow zone bordering the northern flank of the structure in southern Hutchinson and Roberts Counties and southwestern Hemphill and Wheeler Counties. These coarse siliciclastics extend through the Pennsylvanian section in the Anadarko Basin (fig. 3). Only a few wells south of the southern border of the study area, which approximately coincides with the northernmost edge of the Amarillo Uplift, were examined; therefore, granite-wash intervals were not traced far up the paleohigh. Nevertheless, correlation among these wells indicates that, within the Cleveland Formation, the distance between the distal (northernmost) parts of granite-wash tongues and equivalent updip sections to the south, which are composed entirely of granite wash, is typically no more than 10 to 15 mi. Thus, the gradation from the fine-grained siliciclastic Cleveland to its coarser arkosic equivalent is relatively abrupt.

No cored granite wash was examined for this study. Lithologic details come only from sample logs (table 1). However, granite wash is readily distinguished from other Cleveland lithologies by its much more pronounced SP and resistivity log responses. The

SP curve typically exhibits a negative deflection from the shale base line of as much as 140 mV; lateral separation of the deep induction log from the laterolog is commonly as much as 20 to 30 Ω•m. Both responses record the permeability of the coarse granite wash as being much higher than permeabilities of adjacent lithologies. The gamma-ray response of the granite wash is not diagnostic; it is typically slightly to moderately lower than that of Cleveland shale.

As recorded on lithologic sample logs from the southernmost part of the study area, arkosic sandstone in the Cleveland is common in this region. It is inferred that the granite wash served as a local, proximal sediment source to the much finer grained Cleveland sandstones.

Coal

The presence of thin (<2 to 5 ft) vitreous coal in the Cleveland Formation is documented from two areas in the western Anadarko Basin. Coal was recorded on a lithologic sample log and on surrounding well logs from southeastern Hemphill County. The 4-ft coal bed in this area coincides with a distinctive low-velocity, sonic-log signature of >100 µ/ft. With distance (>3 mi), the sonic logs of surrounding wells exhibit gradually decreasing travel time for this bed, suggesting local lateral gradation to carbonaceous shale. Furthermore, the core from the Maxus Tubb "D" No. 3 well in south-central Lipscomb County contains a thin (about 1 inch thick) coal bed sitting above a rooted zone (fig. 8). Because of its thinness, this coal cannot be detected on the accompanying sonic log; logs of surrounding wells similarly do not indicate the presence of coal at that horizon, probably for the same reason.

No comprehensive survey was conducted for coal in all the well logs used in this study. However, given (1) the limited thickness and probable discontinuity of the coal, and therefore difficulty in detection and (2) the apparent local distribution of the seams, it is probable that Cleveland coals are more widespread in the study area than the two documented occurrences would suggest and that they are beyond the limit of detection on most well logs.

Adjacent Formations

Oswego Limestone

The Oswego Limestone, the basal formation of the Marmaton Group (fig. 3), is distributed throughout the study area and provides a regionally correlative lithostratigraphic base to the overlying siliciclastic interval comprising the Marmaton Group (undivided) and the Cleveland Formation (fig. 4). In most of the western Anadarko Basin, the Oswego is composed of interstratified limestone and shale in beds 10 to 50 ft thick; the top of the formation is the top of the uppermost limestone bed. Oswego limestone beds become progressively less numerous and thinner toward the southeast into the deep Anadarko Basin, where they interfinger with thickening basinal shale facies. The base of the Oswego is poorly defined where it contains shale interbeds. Regional correlation of the formation's base is beyond the scope of this investigation, and no studies were found that provided consistency in the base's stratigraphic position.

In a north-south-trending zone approximately coinciding with the Cleveland Formation thick in south-central Lipscomb and north-central Hemphill Counties (fig. 5), the Oswego takes on a markedly different bedding character. Here, the formation is a single bed ranging from 100 to 250 ft thick and composed almost entirely of limestone (fig. 4, sections A and B). In this area the formation's base is easily identified. Log response is typically blocky, but the formation may also contain several upward-coarsening and upward-fining limestone units. The subregional areal extent of the thick-bedded Oswego facies and its coincidence with thickest Cleveland strongly suggest differential subsidence within the study area at least from Oswego through Cleveland time. A more complete discussion of possible structural effects on deposition is found in "Structural Framework." Also, for a more complete graphic perspective of the regional variation in the bedding character of the Oswego, refer to the cross sections presented in "Sequence Stratigraphy."

Marmaton Group (Undivided)

In regional thickness variation and in gross stratigraphic and lithologic character, the siliciclastic Marmaton Group (undivided) is generally similar to the overlying Cleveland Formation. The interval thickens from 0 ft over the same western paleohigh that affected Cleveland deposition (fig. 5) to a maximum of about 560 ft toward the southeast (fig. 4). The Marmaton (undivided) thins toward the north as it grades into shale intervals in Kansas Shelf carbonate facies and toward the south against the Amarillo Uplift.

Marmaton sandstones are thickest and best developed in the east-central part of the study area. Here in the lower part of the formation, they are generally thicker bedded (20 to 30 ft) and, based on their log response, more clay free than in the upper half. These lower Marmaton (undivided) sandstones cap several upward-coarsening intervals (fig. 4, section B). Mostly thinner bedded (<10 ft) shaly sandstones are interstratified with shales of similar thickness in the upper part of the formation. Elsewhere, Marmaton sandstones are generally thin and poorly to moderately developed (fig. 4, section C).

Kansas City Formation

The Kansas City Formation, the upper formation of the Skiatook Group (fig. 3), overlies the Cleveland Formation throughout the study area. The carbonate- and shale-bearing Kansas City forms the upper lithostratigraphic limit to the largely siliciclastic

Cleveland/Marmaton (undivided) section below. The Kansas City ranges in thickness from about 20 ft or less in the extreme western parts of Hutchinson and central Hansford Counties (probably absent locally) to about 1,190 ft in east-central Wheeler County in the extreme southeastern corner of the study area.

As with the Cleveland, limestone is the principal lithology of the Kansas City where the carbonate facies thicken toward the Kansas Shelf in the northwestern and north-central parts of the study area (northern Hansford and Ochiltree Counties). Shale of more basinal facies becomes increasingly more voluminous toward the south and southeast (fig. 4), where it composes most of the unit. Comparison of well logs and lithologic sample logs shows that the order of relative carbonate abundance is limestone, marl, and dolostone.

Shales are mostly gray, but several conspicuous thin (<10 ft) black shale beds with high, off-scale gamma-ray responses are fairly evenly distributed within the Kansas City. The lowest black shale forms the base of the formation. Five black shales can be correlated regionally in most of the study area and are excellent marker beds (fig. 4). As the Kansas City thins toward the west-central and southwestern parts of the study area, the number of black shales progressively decreases. For a graphic perspective of the regional distribution of the black shale marker beds and of the lithologic variation of the Kansas City, refer to the cross sections presented in "Sequence Stratigraphy."

PALEONTOLOGY AND AGE OF CLEVELAND FORMATION

Of the three cores from which rock samples were taken for paleontological analysis, only the Maxus Glasgow No. 2 core yielded abundant fossils. Poor recovery was due mostly to (1) the great difficulty in disaggregating the well-indurated, cemented, pyrite-rich shales and (2) the paucity or absence of fossils in deltaic shale facies (see "Deltaic Facies"). Most fossils from the Glasgow core came from the high-gamma-ray black clay shale and carbonate grainstone bed at the top of the Marmaton Group (undivided); the grainstone bed in particular contained numerous taxa (table 5). Fossils in these uppermost 5 ft of Marmaton strata (7,287.0 to 7,282.5 ft, fig. 6) increase in total number and diversity upward (table 6). Conodonts of several species occur throughout but generally decrease in number upward within the black clay shale; conodonts are common in the grainstone bed, but they are exclusively robust platform types. The absence of the more delicate ramiforms indicates that the conodonts in the grainstone were transported/reworked. Other shales in the Glasgow core either are barren or contain rare fossils (table 6).

The age of the uppermost Marmaton interval is latest Desmoinesian, as indicated primarily by the presence of several terminal species of the conodont *Neognathodus* and the terminal articulate brachiopod *Mesolobus* (D. R. Boardman II, personal communication, 1991). The distinctive faunal assemblage of the black clay shale/grainstone interval enables correlation with a bed of similar lithology throughout the North American Midcontinent (see "Cleveland Formation and Late Pennsylvanian Eustasy"). The lithostratigraphic position of the Desmoinesian/Missourian Series boundary cannot be determined with precision in the Maxus Glasgow No. 2 core because of the absence of diagnostic fossils above the carbonate grainstone bed at the top of the Marmaton Group. However, most, possibly all, of the Cleveland Formation is early Missourian in age. Elsewhere in the Midcontinent region, the series boundary typically occurs at stratal contacts where continental beds overlie marine strata, commonly unconformably (D. R. Boardman II, personal communication, 1991). The series boundary in the Cleveland study area may thus be tentatively placed at the base of the fluvial incised-valley fill and correlative horizon near the middle of the formation (see "Fluvial Facies"; "Sequence Stratigraphy, Incised-Valley System").

Table 5. Faunal content of limestone at the top of the Marmaton Group in the Maxus Glasgow No. 2 well (at depth of 7,282.5 ft, figs. 6 and 18). Fossils are presented in approximate order of abundance by major fossil group.

- Mollusks
  - Pelecypods
    - *Paralledon*
    - *Schizodus*
    - *Anthraconeilo*
    - Unidentifiable nuculoids
  - Gastropods
    - *Euphemites*
    - *Bellerophon*
    - *Sinuitina*
    - *Glabrocingulum*
    - *Trepospira*
    - *Donaldina*
    - *Plocezyga*
    - *Meekospira*
    - *Soleniscus*
  - Nautiloids
    - *Pseudorthoceras*
  - Ammonites
    - *Trochilioceras prone*
- Crinoid stems, unidentifiable
- Brachiopods
  - Inarticulate
    - *Orbiculoidea*
  - Articulate
    - *Leorhynchoidea*
    - *Mesolobus*
    - *Hustedia*
    - Productid spines
- Conodonts
    - *Neognathodus medexultumus*
    - *Neognathodus* (several terminal species)
    - *Idiognathodus nodocarinatus**
    - *Idiognathodus expansus*
    - *Idioprioniodus* sp.
    - *Gondolella* sp.
    - *Adetognathus lautus*
- Ostracods
    - *Cavellina*
    - *Healdia*
    - *Hollinella*
- Corals
  - Tabulate
    - *Michelinia*
    - *Thamnoporella*

*=I. *cf. concinnus*, I. sp. 6, and I. *aff. excelsus*

Table 6. Vertical succession of faunal assemblages in the Maxus Glasgow No. 2 core (fig. 6).

Log depth (ft)	Fossils	Environmental conditions
7,172.0	Pelecypods (*Dunbarella*), bryozoan fragments, and rare ostracods	Shallow marine
7,252.2	Barren	Marginal marine
7,254.0	Barren	Marginal marine
7,282.5	Abundant macrofossils (see table 5)	Deep marine, condensed sedimentation, aerobic
7,283.1	Abundant macrofossils including brachiopods (*Leiorthynchoidea*), nuculoid pelecypods, nautiloids (*Pseudorthoceras*), crinoid stems; rare conodonts (ramiforms), rare ostracods (*Cavellina, Hollinella*), rare small calcareous foraminifera	Deep marine, condensed sedimentation, slightly dysaerobic
7,285.0	Rare macrofossils including inarticulate brachiopods (*Orbiculoidea*); moderately abundant conodonts (mostly ramiforms, also platforms including *Idiognathodus*), rare ostracods (*Cavellina*)	Deep marine, condensed sedimentation, moderately dysaerobic
7,287.0	Abundant conodonts (mostly ramiforms, also platforms including *Idiognathodus expansus*, *Neognathodus*)	Deep marine, maximum sediment condensation, highly dysaerobic
7,290.2	Rare ostracods (*Cavellina*), rare bryozoan fragments	Shallow to marginal marine
7,293.5	Rare ostracods (*Cavellina*), rare bryozoan fragments	Shallow to marginal marine
7,297.3	Rare ostracods (*Cavellina*)	Marginal marine
7,300.2	Barren	Marginal marine to nonmarine
7,303.5	Barren	Marginal marine to nonmarine

STRUCTURAL FRAMEWORK

Present Structure

Regional Perspective

At the western end of the Anadarko Basin, the top of the Cleveland Formation composes a generally southeasterly dipping monocline interrupted by several prominent faults and locally by small folds (fig. 13). Dip progressively increases toward the southeast into the deep Anadarko Basin. Dip varies from a minimum of 20 to 40 ft/mi in the western part of the study area (Hansford County) to about 70 ft/mi in most of the central and eastern parts (Ochiltree, Lipscomb, Hemphill, and northeastern Roberts Counties) to a maximum of about 105 ft/mi in the extreme southeastern part (east-central Wheeler County). Dip direction at the top of the Cleveland Formation ranges from about S45°E to S25°E (135° to 155°) throughout most of the eastern part of the study area, but it shifts locally to S75°E (105°) in northwestern Roberts County on the southwestern side of the major fault zone and to variable dip directions within the fault zone itself (fig. 13). The radial arrangement of dip directions in the west reflects the geometry of the western terminus of the Anadarko Basin. These dip patterns within the seven-county Cleveland study area closely approximate those of the tops of the underlying Mississippian System (Totten, 1956, his fig. 4; Swanson, 1979, his fig. 3; Ruppel, 1985, his fig. 4) and Lower Ordovician Ellenburger Group (Ruppel, 1985, his fig. 3) within the same area.

Faults

Two distinct fault trends can be distinguished in the study area (fig. 13). These northwest-trending fault zones are the easternmost of several en echelon fault zones that extend as much as 70 mi northwestward from the Amarillo Uplift in the northern

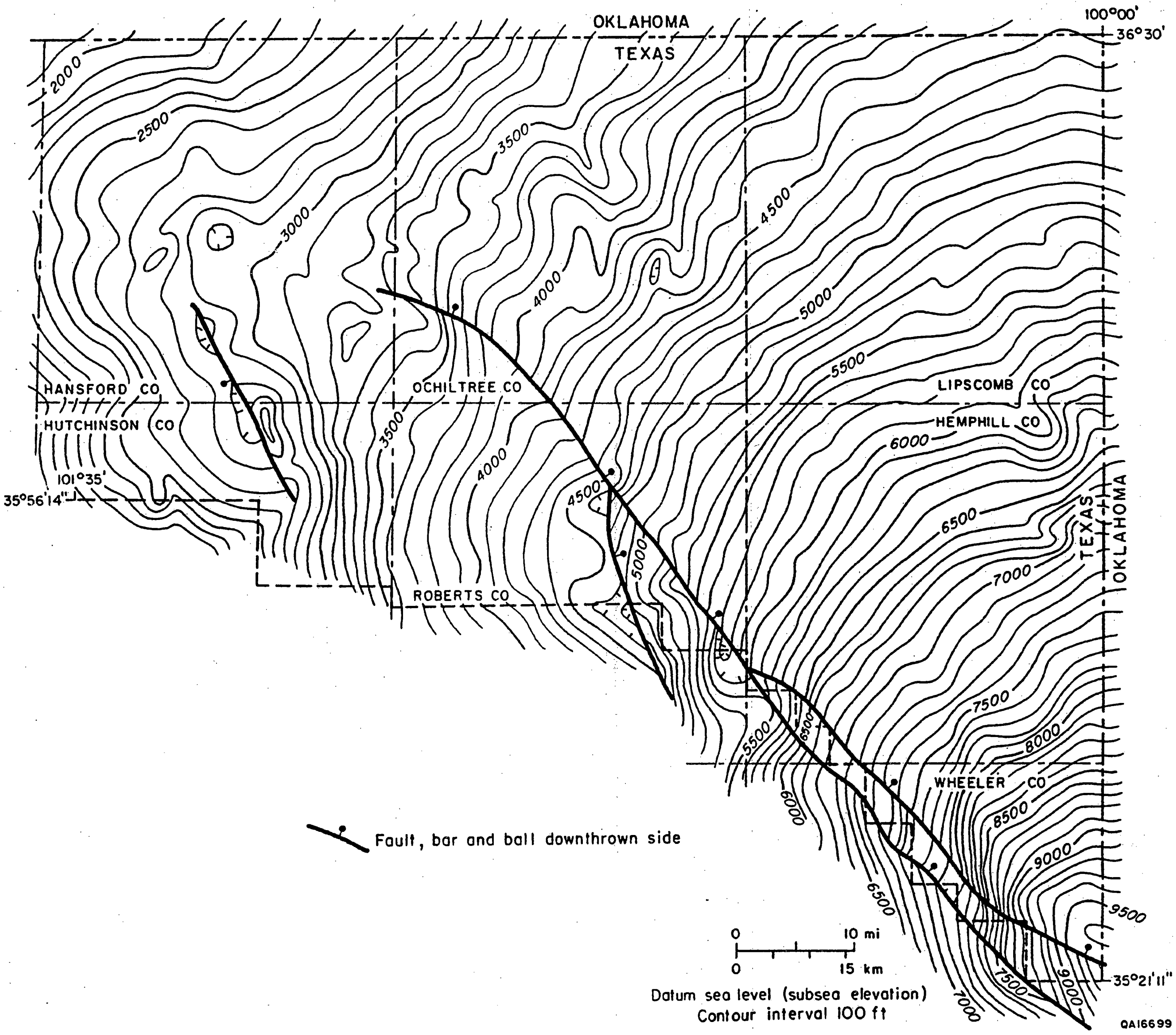


Figure 13. Structure map contoured on top of the Cleveland Formation in the western Anadarko Basin. Prominent structures are the Lips fault (longest fault zone), the Camrick–Perryton Arch (southeast-plunging fold in northeastern Ochiltree County), and the Central Lipscomb–Feldman structure (southeast-plunging fold in northeastern Hemphill County). Although the Cleveland is absent in parts of Hansford and Hutchinson Counties (fig. 5), the top-of-Cleveland correlation maker extends into these areas.

Texas Panhandle (highly generalized in fig. 1). These zones, including those mapped in this study, displace several stratigraphic levels above and below the Cleveland Formation within the western Anadarko Basin: top of the Lower Ordovician Ellenburger Group (Ruppel, 1985, his fig. 3), top of the Mississippian System (Ruppel, 1985, his fig. 4; Swanson, 1979, his fig. 3), and the top of the Pennsylvanian System (Dutton and others, 1982, their fig. 15). The longer of the two fault zones mapped in this study is also present at the top of the crystalline basement (Dutton and others, 1982, their pl. 5).

The principal fault zone cutting the Cleveland, termed the Lips fault (Evans, 1979), strikes about N40°W (320°) and exhibits a decreasing amount of throw toward its termination in the northwest. Net vertical offset ranges from about 450 to 500 ft in east-central Wheeler County to 200 ft or less in southwestern Ochiltree County. The zone is interpreted as being composed of at least three major fault segments in the study area, two of which merge toward and connect with a central fault (fig. 13). Dutton and others (1982) and Ruppel (1985) mapped this zone as a single fault and a group of parallel nonjoining faults, respectively, although their studies were more regional in scope and therefore employed considerably sparser well control than this investigation. The net displacement is dip slip, the relative downthrown sides of the individual fault blocks consistently on the northeast sides. The dip directions and angles of the fault planes cannot be determined with the study's data set; however, the faults are probably either moderate- to high-angle normal or reverse faults. Harlton (1963) and Ham and others (1964) described the faults composing the southern edge of the Anadarko Basin in southwestern Oklahoma as steeply dipping to vertical, and Evans (1979) interpreted the Lips fault as a high-angle reverse fault. However, seismic profiling of similarly northwest-trending faults separating the Wichita Uplift from the Anadarko Basin in southwestern Oklahoma indicates that these nearby faults are moderate-angle (averaging 30° to 40°), southwesterly dipping reverse faults along which crystalline rocks of the

Wichita Uplift were thrust over sedimentary rocks of the basin during Pennsylvanian time (Brewer and others, 1983). Significant regional crustal shortening (compression) occurred in the Anadarko Basin during the Late Pennsylvanian (Ham and others, 1964), the final stage of the basin's long tectonic evolution. The faults in the study area probably also record this deformation episode and are reverse in nature.

A shorter fault or a fault zone at least 18 mi long and striking N25°W (335°) displaces Cleveland rocks in northern Hutchinson and southern Hansford Counties (fig. 13). Maximum throw along this fault is probably not much more than 100 ft, and net displacement is down to the southwest. The same fault has also been mapped at the top of the Mississippian System (Totten and Horn, 1968, their fig. 3; Swanson, 1979, his fig. 3). The fault is associated with two structural highs on the northeastern side of the fault and a low on the downthrown side. Ridgell (1961) also mapped the more prominent of the two highs on the top of the Oswego Limestone in the North Hutchinson field.

Folds

There are three principal areas of folded Cleveland in the study area: (1) sporadically throughout most of Ochiltree and Lipscomb Counties, (2) in northeastern Hemphill County, and (3) along the southwestern side of the principal fault zone in Wheeler, Hemphill, and Roberts Counties (fig. 13). In areas (1) and (2), folds generally plunge toward the south to southeast and have axial traces that are less than 4 to about 8 mi long. Most of the smallest folds could be classified as structural noses. These smallest folds in Lipscomb County are not well expressed in figure 13 because of the small scale of the map. However, Best (1961), Brashear (1961), and the National Petroleum Bibliography (1965) presented larger scale maps of several fields in area (1) that delineate the smaller, primarily southeast-plunging folds. Two regional-scale, southeast-plunging anticlines in northeastern Ochiltree County and northeastern

Hemphill County (fig. 13) are termed the Camrick–Perryton Arch and Central Lipscomb–Feldman structure, respectively (Eddleman, 1961).

In Situ Stress and Neotectonics

The northern Texas Panhandle was initially designated as being in the Midcontinent stress province by Zoback and Zoback (1980), who in a subsequent work (1989) placed it in a "mid-plate" stress province. By either designation, this stress province is a large, relatively tectonically quiescent region characterized by nearly uniform northeast- to east-northeast-striking maximum horizontal compressive stress produced either directly or indirectly by plate-tectonic processes. The northeast-southwest compressive stress here has been defined by hydraulic fracture measurements (Haimson, 1977) and by earthquake focal mechanisms (Herrmann, 1979). In the Texas and Oklahoma Panhandles, stress-induced well-bore breakouts and hydraulic fracture measurements also generally indicate northeast-oriented compressive stress (Dart, 1989). The orientation of least principal horizontal stress indicated by hydraulic fracture treatment in the Anadarko Basin is N25°W (von Schonfeldt and others, 1973).

Locally, in situ stress at the Maxus Glasgow No. 2 well (fig. 2) was determined using several methods of analysis: Formation Microscanner highlight imagery, core fracture analysis, velocity anisotropy analysis, and borehole breakout analysis (Hill, 1991). The data gathered indicate a maximum horizontal compressive stress direction between 95° and 105°, an east-southeast stress direction that deviates only slightly from the much more generalized and regional data sets described above. The few near-vertical natural fractures observed in the Glasgow well have a strike range of 120° to 130°.

One of the most prominent young tectonic features in the Midcontinent stress province is the northwest-trending Meers fault along the northern edge of the Amarillo–Wichita Uplift in southwestern Oklahoma. The fault is coincident with a pre-

Permian fault, but scarps in alluvium indicate the fault is Quaternary in age (Gilbert, 1983; Luza, 1989). The fault displays reverse sense of motion and a component of left-lateral slip (Ramelli and Slemmons, 1986; Myers and others, 1987). Recent studies indicate that movement occurred on the Meers fault during late Holocene time (Madole, 1988; Luza, 1989). Movement on the Meers fault suggests that significant east-northeast-directed tectonic compressive stress may exist in the nearby Cleveland study area.

More than 370 locatable earthquake events have taken place in the Anadarko Basin since 1897 (Luza, 1989). However, only a few earthquakes have occurred in the shelf region and deep parts of the basin. The Amarillo–Wichita Uplift and its associated fault zones, including those in the Cleveland study area (fig. 13), are seismically quiet relative to the extreme eastern end of the Anadarko Basin where most earthquakes have occurred. However, notable seismic events with Richter magnitudes of as much as 4.8 have been recorded in the northern Texas Panhandle and northeastern New Mexico (Northrup and Sanford, 1972).

Syndepositional Tectonics and Paleophysiography

Regional Perspective

The active period of tectonism in the Anadarko Basin during the late Paleozoic had a profound effect on sediment accumulation in the basin. Actively subsiding throughout the Pennsylvanian orogenic activity, the Anadarko Basin received as much as 18,000 ft of Pennsylvanian siliciclastics and carbonates (Johnson, 1989); a maximum of about 9,000 to 10,000 ft accumulated in the study area (Nicholson, 1960, his fig. 47). Major positive tectonic elements that are associated with, and that contributed detritus to, the basin during the Middle to Late Pennsylvanian were the Arbuckle Uplift and Ouachita foldbelt at the southeastern margin of the basin, the Wichita–Amarillo Uplift defining the southern flank of the basin, and the Ozark Uplift to the northeast (Frezon and Dixon, 1975; Moore, 1979: Rascoe and Adler, 1983). The Cimarron Arch, which forms the western terminus of the Anadarko Basin (fig. 1), was probably active during the end of tectonic activity that created the Wichita–Amarillo Uplift (Johnson, 1989). Farther west, active tectonic elements of the front range of the Ancestral Rocky Mountains (Sierra Grande and Apishapa Uplifts) and the Bravo Dome (fig. 1) shed siliciclastic detritus into the western Anadarko Basin in the Late Pennsylvanian (Hills, 1963).

Emergent Areas and Paleohighs

Two regional structures were emergent peripheral to the western part of the Anadarko Basin during deposition of the Cleveland Formation: the Amarillo Uplift and the Cimarron Arch. Emergence of the Amarillo Uplift during most of the Pennsylvanian Period and specifically during Late Pennsylvanian (Missourian) time is well documented (for example, Totten, 1956; Frezon and Dixon, 1975; Dutton, 1982). Regional isopachous mapping (fig. 5) and correlation (fig. 21, below) of the Cleveland Formation in the western Anadarko Basin reveals that the formation is absent and very thin throughout most of Hansford and western Hutchinson Counties. This area coincides with the eastern margin of the Cimarron Arch. Of the lithostratigraphic units examined for this study (figs. 3 and 4), both the Marmaton Group (undivided) and the Cleveland Formation gradually pinch out toward the Cimarron Arch and are absent over it. The Kansas City section also thins toward but also over the uplift to a minimum thickness of 30 ft or less. The Oswego Limestone occurs throughout the uplift region in the study area; however, thickness variation, if any, of this unit over the uplift could not be determined because the base of the Oswego is poorly defined there.

These thickness trends indicate that the Cimarron Arch was emergent (but with low relief) during Marmaton and Cleveland siliciclastic deposition (fig. 14) and was still a

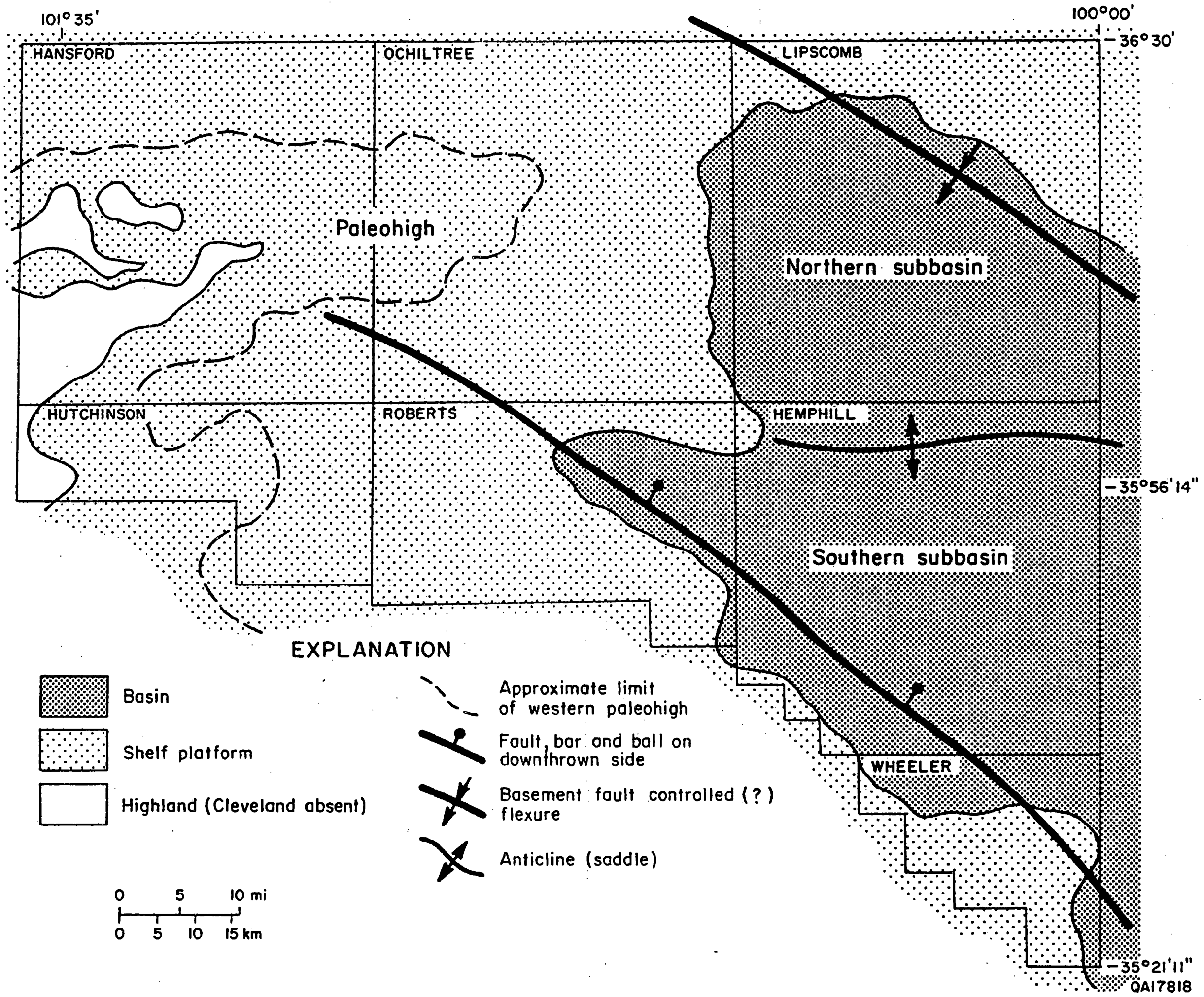


Figure 14. Paleophysiographic/paleotectonic map of the Cleveland Formation. Physiographic boundaries are based on regional thickness patterns of the entire formation (compare with fig. 5). See text for discussion of relationship between tectonics and sedimentation.

significant topographic high (but not emergent) during subsequent Kansas City time. The thick-bedded limestones of the Oswego interval formed the resistant substrate of the exposed Cimarron landmass in the western part of the study area.

Generally east-west-trending areas of widely spaced isopach contours of relatively thin Cleveland in eastern Hansford County, most of Ochiltree County, northern Hutchinson County, and western Roberts County (fig. 5) define a physiographic paleohigh/shelf-platform region peripheral to the Marmaton/Cleveland highland, which composes the eastern flank of the Cimarron Arch (fig. 14). During deposition of the Cleveland Formation, this paleohigh and the adjacent stable shelf platform in most of Hansford and Ochiltree Counties collectively served as an effective partition separating carbonate-shelf deposition to the north (fig. 12) from siliciclastic-dominated shelf and basin deposition to the south (figs. 10 and 11).

Physiographic Shelf Platform and Basin

Isopach patterns also clearly differentiate distinctive shelf-platform and basin regions separated by a narrow zone coinciding with a steep formation-thickness gradient extending along the Ochiltree/Lipscomb county line through eastern Roberts County and into southwestern Hemphill and northern Wheeler Counties (compare fig. 5 with fig. 14). The shelf-platform physiographic region, which actually encompasses only part of the entire Cleveland shelf depositional setting (see "Cleveland Formation, Highstand Systems Tract"), is interpreted to have been a relatively tectonically quiescent, gently sloping part of the study area during Cleveland time, having experienced minimal subsidence and sediment accumulation. In contrast, the Cleveland physiographic basin region, which extends southeastward beyond the study area, underwent marked subsidence. Regional cross sections (fig. 4; figs. 20, 21, 22, 25, and 26, below) show generally progressive basinward thickening of all correlation subdivisions of the

Cleveland Formation, Marmaton Group (undivided), Oswego Limestone, and Kansas City Formation. Moreover, several subdivisions of the Marmaton (undivided) and Cleveland pinch out at the basin/shelf-platform boundary (at Ochiltree wells 21 and 14 on fig. 20, below, and at Hemphill well 1 on fig. 21, below), indicating that a physiographic break existed at this position during deposition and acted as a depositional barrier for parts of the siliciclastic interval. It is emphasized that the above-described shelf platform and basin are physiographic regions; compelling evidence suggests that much of the physiographic basin in the study area was actually part of an irregular Cleveland depositional shelf that underwent marked differential subsidence (see "Cleveland Formation, Highstand Systems Tract").

Effects of Faulting and Differential Subsidence on Deposition

The Cleveland basin in the study area is bounded in the south by a prominent, northwest-trending linear zone of thick Cleveland (fig. 5), which is interpreted to have been a fault-controlled trough that was actively subsiding during Cleveland deposition (fig. 14). This same zone also exists as a linear thick in the Lower Pennsylvanian Morrowan Series (Eddleman, 1961, his fig. 2) and was therefore probably a site of continuous differential subsidence throughout most of the Pennsylvanian Period. Faults composing this zone (Lips fault) currently displace the formation (fig. 13). The northern border of the Cleveland basin is marked by a parallel (northwest-trending) monoclinal flexure that marks an abrupt change in Cleveland thickness in northeastern Lipscomb County (compare fig. 5 with fig. 14). Because these parallel structures are elements of the regional tectonic fabric of northwest-trending, en echelon fault zones described above (see "Structural Framework, Faults"), downwarping on the southern limb of the flexure was probably controlled by movement (drape folding) on a basement fault that was parallel to the southern fault but did not extend upward into the Cleveland section.

The syndepositional fault and flexure form a possible half graben in the eastern part of the study area, which during Cleveland time contained two structural subbasins (figs. 5 and 14). Subsidence of the southern subbasin was probably primarily controlled by down-to-the-north displacement along the fault zone, whereas down-to-the-south faulting along a buried fault probably sustained downwarping south of the flexure in the northern subbasin. It cannot be determined whether these parallel structures were moderate- or high-angle reverse faults (thus not forming a true graben), normal faults, or one of each during deposition of the Cleveland Formation, but the relative displacement along the structures is clear. The subbasins are separated by an east-west-trending linear zone of relatively less subsidence (thinner Cleveland) than that in the adjacent subbasins; this zone forms a structural saddle extending just south of and along the Lipscomb/Hemphill county line (figs. 5 and 14 and figs. 24 through 26, below). The saddle is a hinge zone separating two areas of more pronounced subsidence.

The half graben influenced regional sedimentation patterns from at least Oswego through Kansas City time. The northern and southern boundaries of the zone of Oswego Limestone buildup in the eastern part of the study area (see "Oswego Limestone") coincide closely with the mapped flexure-hinge and fault-trace locations, respectively (compare fig. 14 with fig. 27, below). The western border of the subbasins and of the Oswego Limestone buildup also nearly coincide, indicating a sustained, higher rate of subsidence east of this location from Oswego through at least Cleveland time. Primary Cleveland sandstone accumulations are located mostly between the two graben-bounding structures (figs. 10 and 11). Moreover, Cleveland net-carbonate distribution patterns in the eastern third of the study area show general northwest orientations (fig. 12) parallel to the structures.

DEPOSITIONAL FACIES

The siliciclastic parts of the Cleveland Formation and Marmaton Group (undivided) comprise mostly stacked, upward-coarsening depositional cycles (figs. 4, 6, and 7) that are interpreted to be progradational marine successions composed primarily of deltaic facies (in ascending order within each cycle: prodelta, distal delta front, and proximal delta front). Upward-coarsening progradational interdeltaic (shoreface) deposits possibly exist in the siliciclastic interval, but without the benefit of more cores they are difficult to distinguish from deltaic facies solely on the basis of log expression. However, assemblages of sedimentary features in sufficiently thick core sections can be used to confidently distinguish deltaic from shoreface deposits (Moslow and Pemberton, 1988). All progradational successions in the three Cleveland cores examined for this study are interpreted to be deltaic.

An upward-fining sandstone (ranging from about 20 to 65 ft thick), interpreted to record fluvial sedimentation, occurs in one stratigraphic zone in the middle part of the Cleveland throughout most of the eastern part of the study area and locally in the west. The Maxus Tubb "D" No. 3 core is the only one of the three cores that contains this aggradational deposit.

The high-gamma-ray, organic-rich black clay shale and immediately adjacent shales in the Maxus Glasgow No. 2, and the equivalent interval that is regionally distributed in the study area, are interpreted to represent distal shelf sedimentation.

Interpretations of depositional environments in the Cleveland study area are based on (1) regional well-log expression, (2) lateral and vertical associations of depositional cycles, (3) lithological and sedimentological characteristics in core, and (4) areal depositional patterns determined by net- and percent-sandstone mapping.

Inferred source areas and paleotransport directions for sediments in the siliciclastic Cleveland Formation and Marmaton Group (undivided) are discussed in "Source Areas of

Systems Tracts." However, in summary, most of the Cleveland Formation was derived from highland sources to the southwest, whereas adjacent intervals had more distant easterly sources.

Deltaic Facies

Prodelta

Prodelta facies in the Cleveland Formation occurs in the lower part of the upward-coarsening progradational successions (figs. 6 and 8). In the three Cleveland cores examined, this facies is either thin, exceeding no more than 5 ft in thickness and commonly interbedded with distal delta-front sandy shales, or absent (fig. 7) at the base of deltaic cycles. The facies comprises dark-gray (N3) laminated shale with sparsely distributed thin streaks and lenses of siltstone no more than 0.5 inch long. No macrofossils or burrows were observed in these deposits.

Having been deposited in the most basinward, or distal, of deltaic subenvironments (transitional with shelf deposits), prodelta deposits in modern settings are characteristically very fine grained and display low lithologic variation (for example, Kanes, 1970; Maldonado, 1975; Coleman, 1982). Because deposition is entirely from suspension, parallel laminae are by far the most common primary sedimentary structure. Because of the high rates of deposition associated with prodelta deposits, these deposits typically escape intense burrowing. Siltstone streaks and lenses probably record storm-induced current activity at the most basinward part of the delta systems.

Distal Delta Front

The most abundant of the delta deposits, the distal delta front composes the thickest facies interval in the individual deltaic cycles in the Cleveland cores (for example, 7,280 to 7,230 ft, fig. 6). Because it occurs higher in the upward-coarsening deltaic successions than the underlying prodelta deposits, this facies is characteristically sandier than the prodelta deposits. The distal delta-front intervals coarsen upward gradationally (figs. 6 and 7) from a typically burrowed to laminated dark-gray (N3) shale containing streaks and thin lenses of siltstone (fig. 15a and b) to a nonburrowed lenticular laminated to thin-bedded light-gray (N7), very fine sandstone and medium-dark-gray (N4), planar- to wavy-laminated shale. The dominant sedimentary structures in upper distal delta-front facies are lenticular thin beds and laminae of ripple cross-lamination (commonly asymmetrical wave-ripple cross-lamination) and planar to slightly wavy fine lamination (figs. 6 through 8 and fig. 16). Planar-tabular cross-lamination, normally graded thin beds, and soft-sediment-deformed beds occur less commonly (figs. 6 and 7). Shale laminae and thin interbeds become thinner, less abundant, and more lenticular upward.

Because distal delta-front deposits record more shoreward deposition than the prodelta deposits, sedimentary features are more varied and of a larger scale than those of the prodelta facies. Modern distal delta-front deposits (also termed distal bar deposits) exhibit an assemblage of sedimentary features similar to those in the three Cleveland cores and were deposited on the seaward-sloping margin of an advancing delta-front complex (for example, Coleman and Gagliano, 1964, 1965; Donaldson and others, 1970; Manka and Steinmetz, 1971; Oomkens, 1974). Wave-ripple cross-laminations with diagnostic irregular lower bounding surfaces, bundle-wise arrangement of foreset laminae, and foreset laminae with offshoots (De Raaf and others, 1977), commonly observed in the upper parts of the distal delta-front intervals in the Cleveland cores (fig. 16), indicate sand transport/reworking on the subaqueous delta plain by wave activity.

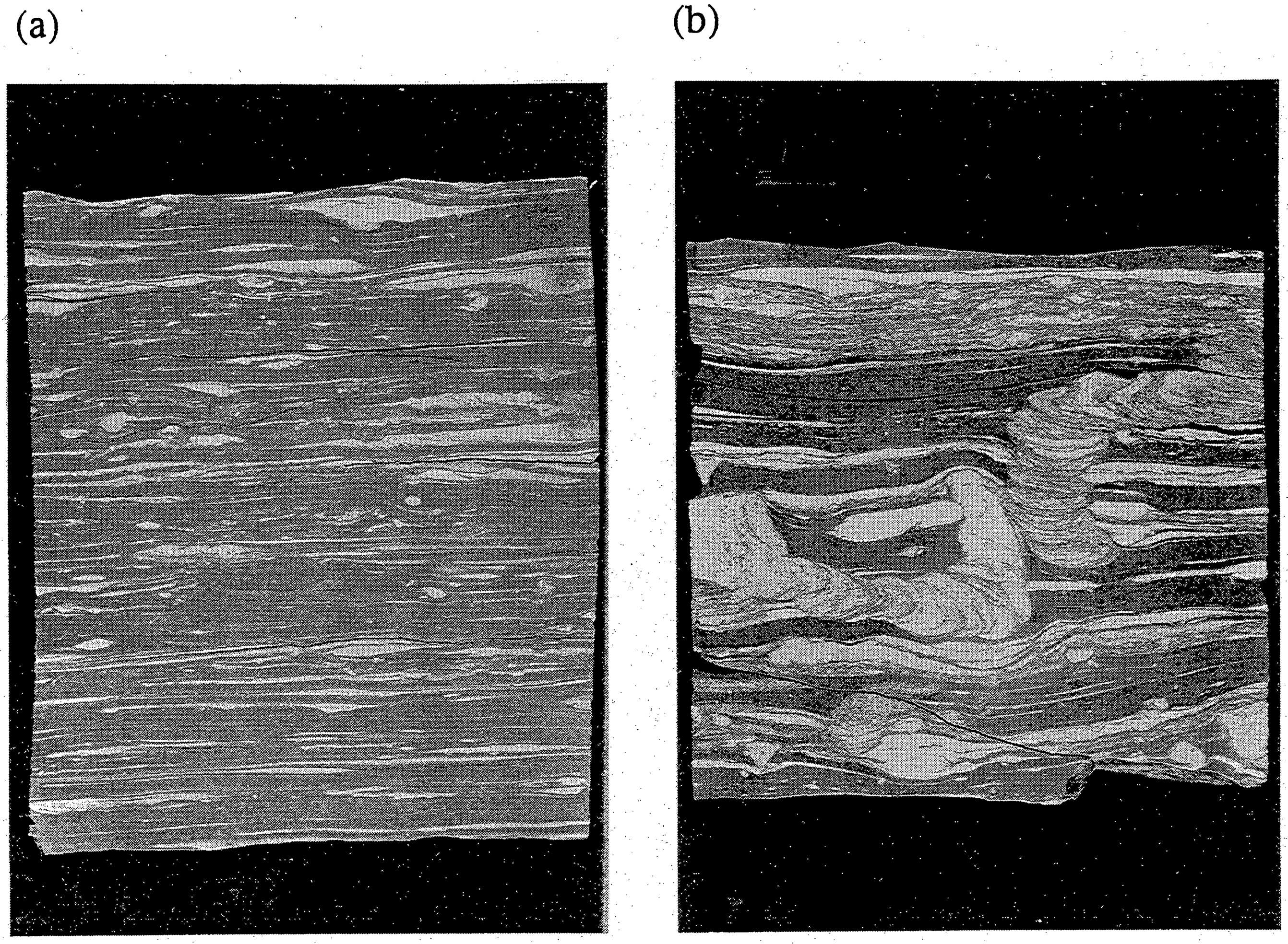


Figure 15. Core photographs of lower distal delta-front facies. Core slabs are 3.5 inches wide. (a) Sparsely burrowed (horizontal burrows as siltstone-filled pods) dark-gray shale with thin lenses and laminae of siltstone and very fine sandstone typical of the thickest deltaic successions in the Cleveland cores. From Maxus Glasgow No. 2 at 7,273 ft (log depth). (b) Heavily burrowed (vertical and horizontal burrows) dark gray shale and siltstone/very fine sandstone that occur in the thinnest deltaic successions. From Maxus Glasgow No. 2 at 7,184 ft (log depth).

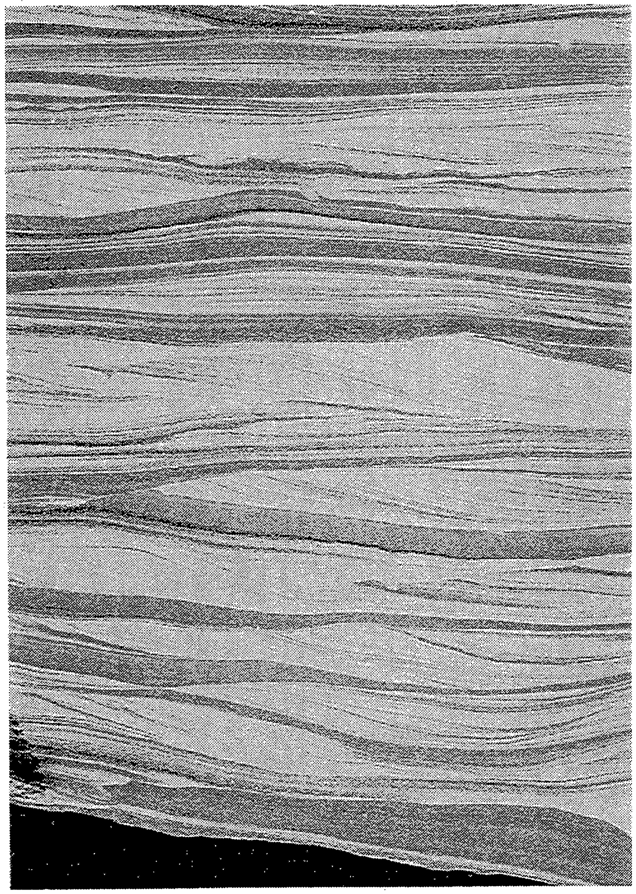


Figure 16. Core photograph of upper distal delta-front facies. Core slab is 3.5 inches wide. Ripple cross-laminated and lenticular laminated very fine sandstone in dark-gray shale typify these rocks. Note asymmetrical wave ripples throughout most of core section. Absence of burrows in this facies is attributed to more rapid sediment influx and higher energy conditions of sedimentation (wave modification) relative to the lower distal delta-front facies. Burrowed (fig. 15) and nonburrowed variations of the distal delta-front facies compose the major part of deltaic successions in the Cleveland Formation. From Maxus Glasgow No. 2 at 7,243 ft (log depth).

Proximal Delta Front

Proximal delta-front facies are differentiated from underlying distal delta-front deposits primarily by the occurrence of coarser light-gray (N7) sandstone (to fine-grained sandstone), the near absence of shale (thin shale beds and laminae occur but are rare), and the presence of other sedimentary features that are indicative of higher energy, more nearshore conditions of deposition relative to those of the underlying facies. The thickest and cleanest sandstones from the cored deltaic intervals come mostly from the proximal delta-front facies (table 2: all samples except last one listed; table 3: most of the samples). Proximal delta-front and upper distal delta-front sandstones within individual deltaic sections range from 10 to 60 ft thick. Where such facies of two deltaic cycles are superimposed, total continuous sandstone thickness is as much as 90 to 100 ft. These accumulations compose the primary reservoir rocks in the Cleveland Formation.

The most common sedimentary structure of this facies is ripple cross-lamination (and sparser wave-ripple cross-lamination) with thin shale drapes (flasers) (fig. 17a and b). The abundance of rounded and angular shale intraclasts (isolated, as local concentrations, and aligned along foresets), the presence of coaly organic fragments (fig. 17b), and the occurrence of large-scale crossbeds (fig. 7) are unique to this deltaic facies in the Cleveland cores.

This deltaic facies represents deposition in the shallowest water on the subaqueous Cleveland delta plains and was deposited mostly as distributary mouth bars in areas of shoaling associated with the seaward terminations of distributary channels. In modern deltas, these bar sediments are subjected to constant reworking by distributary currents and by waves generated in open water beyond the channel mouth; high-energy currents and proximity to distributary feeders produce well-winnowed sands with

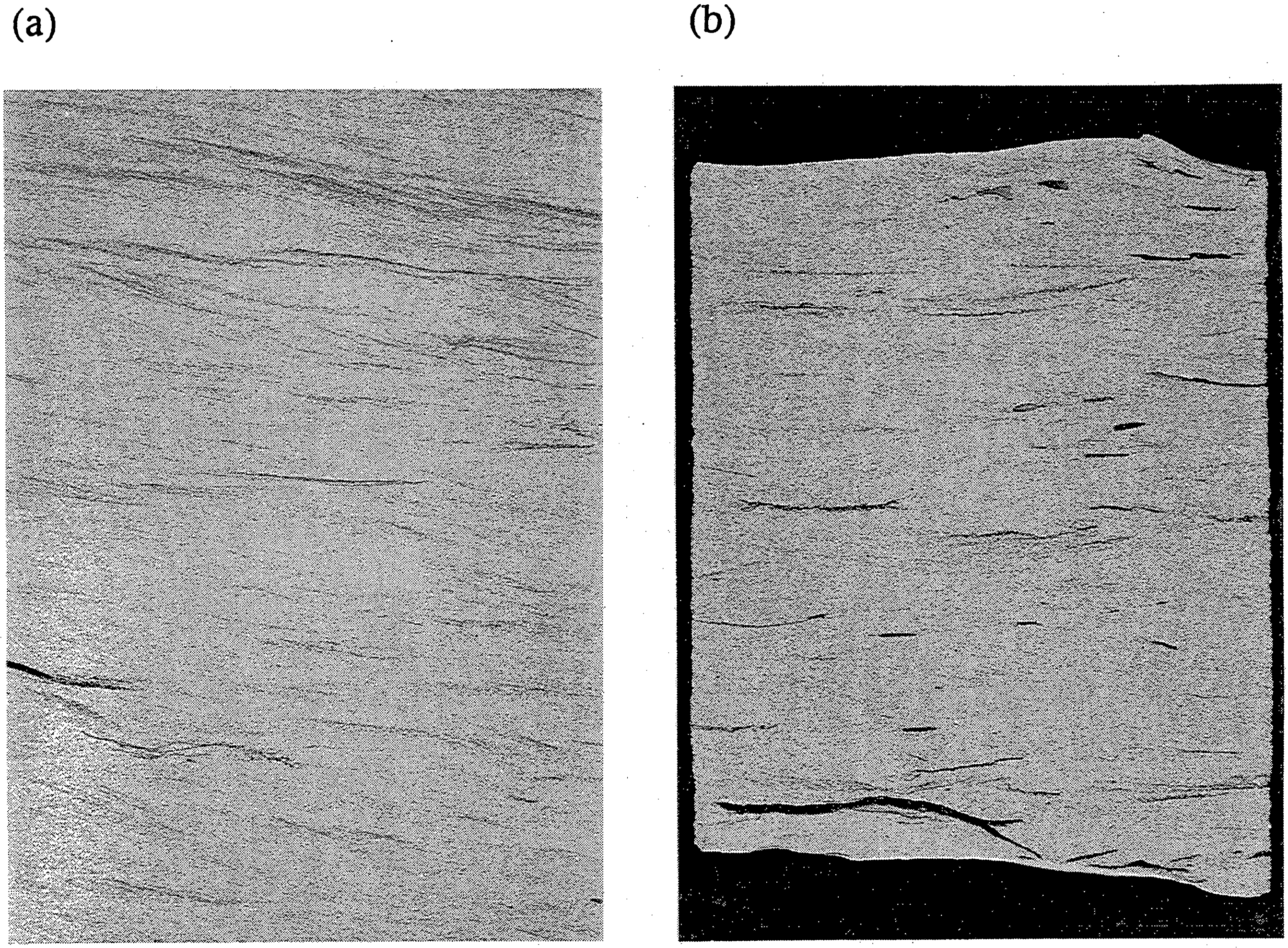


Figure 17. Core photographs of proximal delta-front facies. Core slabs are 3.5 inches wide. (a) Ripple cross-laminated very fine sandstone with evenly distributed shale drapes (flasers) and coaly organic laminae on tops of ripple forms. From Maxus Glasgow No. 2 at 7,201 ft (log depth). (b) Ripple cross-laminated very fine sandstone containing shale intraclasts, thin shale drapes (flasers), and organic material. Presence of shale intraclasts as long as 1 inch and organic debris is a common and unique feature of the proximal delta-front intervals. From Maxus Glasgow No. 2 at 7,217.5 ft (log depth).

intraclasts and accumulations of organic debris (Coleman and Gagliano, 1965; Coleman and Prior, 1982).

The elongate, north-south-oriented net- and percent-sandstone thicks of the western, central, and possibly the eastern sandstone trends (figs. 10 and 11) are composed mostly of the well-developed delta-front sandstones at the tops of the stacked Cleveland deltaic successions. Proximal delta-front sands prograded no farther east than about the central to eastern parts of Lipscomb and Hemphill Counties. The crescentic, strike-elongate sandstone trends probably represent positions of shoreline stabilization and enduring sand depocenters during eastward progradation of the Cleveland deltas. The western and central sandstone trends coincide closely with the region of pronounced syndepositional subsidence shown on the Cleveland isopach map (fig. 5) and more precisely with the limits of the Oswego Limestone buildup (compare fig. 10 with fig. 27, below). Although superficially resembling elongate distributary lobes, the dip-oriented sandstone trends extending eastward from the central trend near the Lipscomb/Hemphill county line are composed mostly of a single fluvial channel fill that overlies the superimposed deltaic cycles (see "Fluvial Facies" and "Sequence Stratigraphy, Incised-Valley Fill System"). No distributary channel-fill deposits were encountered in the cores. Because the sandstone-distribution maps (figs. 10 and 11) record the cumulative sandstone pattern of the entire Cleveland Formation and not of any individual delta system, locally occurring distributary channels are poorly defined, if at all. However, the overall broadly lobate areal sandstone pattern most closely resembles that of modern wave-dominated deltas with steep offshore slopes (Coleman and Wright, 1975), such as probably existed at the western end of the Anadarko Basin during Cleveland time.

Fan-Delta Facies

No data gathered for this study conclusively demonstrate the existence of Cleveland fan delta facies, although such coarse, arkosic facies occur in a narrow zone adjacent to the northern flank of the tectonically active Amarillo Uplift probably throughout the Pennsylvanian System. Dutton (1982) described Missourian fan-delta deposits composed of granite wash in Mobeetie field in northwestern Wheeler County, Texas. The (1) abundance of arkosic sediments in the Cleveland Formation in the southernmost part of the study area (table 1) and (2) presence of a lobate thick of arkosic sandstone trending parallel to the Amarillo Uplift in central Wheeler County (fig. 10) suggest synorogenic fan-delta sediment transport off the Amarillo highlands during Cleveland time. Tongues of granite wash, primarily in the Marmaton Group (undivided) and the Kansas City Formation, extend into the southern part of the study area and also probably represent fan-delta deposits (figs. 23 through 26, below).

Fluvial Facies

Throughout most of the study area, a single, generally continuous, uniformly upward-fining sandstone interval occurs near the middle (eastern part of study area) and upper (western part of study area) parts of the Cleveland Formation (cored interval in fig. 8; parasequence 4 in fig. 19, below; incised-valley fill in figs. 21 and 22, below; and fig. 29, below). The interval is a single, regionally correlative stratigraphic zone that ranges from about 20 to 65 ft thick. It exhibits a sharp, regionally erosional base. Where thickest in the central and eastern parts of the study area, this sandstone unit (parasequence 4 in fig. 19, below) incises the uppermost of three underlying deltaic intervals (Cleveland parasequence 3, see "Sequence Stratigraphy"), locally completely removing this interval and cutting into the next older deltaic cycle (parasequence 2). In the western part of the study area the upward-fining unit is the primary sandstone interval in the formation (incised-valley fill in fig. 21, below) and occurs in narrow, strongly east-west-aligned sandstone belts (figs. 10 and 11). Degree of incision by the sandstone in this area is difficult to determine because the interval below the sandstone is shaly and has few marker beds. The east-west trend of this unit continues into the eastern part of the study area but is largely obscured on the net- and percent-sandstone maps of the Cleveland (figs. 10 and 11) because thicknesses of all Cleveland sandstone units were mapped. Primarily on the basis of (1) its regional erosional relation with underlying units, (2) the uniformly aggradational nature of its log expression, and (3) its linear areal configuration, this unit is inferred to be a channel-fill deposit.

The cored interval from the Maxus Tubb "D" No. 3 well in south-central Lipscomb County (fig. 2) comprises most of this upward-fining sandstone interval; only the very basal part of the deposit is not represented (fig. 8). The aggradational deposit in the Tubb well probably includes two channel-fill successions at (1) 8,120 to 8,096.5 ft and (2) 8,096.5 to 8,056 ft. The core consists of the upper part of interval 1 and all of interval 2. In addition to fining upward in grain size (8,096.5 to 8,056 ft; fine sand to silty shale), the Cleveland channel fill generally fines upward in the scale of primary sedimentary structures (fig. 8). The base of channel fill 2 (at 8,096.5 ft, fig. 8) exhibits a sharp contact with underlying rocks and is probably erosional. Large-scale crossbeds containing coaly organic fragments and shale intraclasts aligned along the foresets compose the basal sandy part of the channel fill. The middle sandy channel-fill deposits are mostly thin interbeds of ripple-laminated units and planar lamination; shale drapes (flasers) on ripple forms are common. The upper sandy channel fill comprises a more diverse assemblage of sedimentary features, including cross-lamination, planar lamination, normal grading, soft-sediment deformation, thin shale interbeds, and coaly organic fragments. A thin coal bed and carbonaceous shale bearing coarse plant fossils (4 inches thick), underlain by a moderately bioturbated (rooted) zone, cap the entire sandy channel fill. The remainder of the channel fill in the Tubb core (8,060 to 8,056 ft, fig. 8) consists of richly sideritic (as high as 60 percent), finely laminated, dark-gray silty shale containing silty nodules up to 2 inches thick.

The upward-fining interval is interpreted to have been deposited by a regional fluvial system developed during or after a pronounced drop in the regional base level during Cleveland time (see "Cleveland Formation, Incised-Valley System"). Although on any one well log the succession of several upward-coarsening deltaic cycles overlain by this channel-fill interval resembles that of a delta distributary channel incising delta-front and prodelta deposits (for example, fig. 19, below), this is clearly not the true facies relation for several reasons. The channel fill is regionally distributed (its distribution would be highly localized if it were a delta distributary channel). Moreover, the channel fill occurs in a single stratigraphic zone and consistently overlies the interval of the three stacked deltaic cycles composing the lower Cleveland section (multiple delta distributary channel fills would occur locally and sporadically above any or all of the individual deltaic cycles at or near delta depocenters). The channel-fill facies succession in the Maxus Tubb core (fig. 8) most closely resembles that of a sandy meandering river system (Walker and Cant, 1984). The primary evidence of this interpretation is (1) upward-fining trends in sand grain size and sedimentary structures, (2) concentration of intraclasts and organic material above an erosional base, (3) soft-sediment-deformed and thin graded beds, probably recording oversteepening and resedimentation (by slumping and minor sediment gravity flows) of upper point-bar deposits, and (4) occurrence of a rooted zone and coal bed that grades upward to 3 inches of plant-fragment-rich dark-gray shale at the top of the fluvial sandstone. The coal, plant-bearing shale, and laminated sideritic shale above the sandy channel facies represent deposition under oxygen-poor conditions (floodplain swamp or lake) in the abandoned channel.

Distal Shelf Facies

A lithofacies that displays evidence of having been deposited in an offshore marine environment that was not influenced by significant siliciclastic influx (that is, away from deltaic depocenters) occurs in the Maxus Glasgow No. 2 core at about 7,290 to 7,282.5 ft (fig. 6). This interval corresponds to the regionally distributed high-gamma-ray black clay shale that defines the lithostratigraphic boundary between the Marmaton Group and the Cleveland Formation (see "Base of Cleveland" for details of its distribution, well-log character, and mineralogy). The facies is a finely laminated to structureless, generally black (N1), organic-rich, fossiliferous clay shale. Finely disseminated pyrite is pervasive throughout the facies, and the clay shale is more calcareous upward. Calcium phosphate nodules are sparse in the deposit. TOC of this facies ranges from 1.9 to 5.7 weight percent, which contrasts sharply with the TOC range of 0.5 to 1.1 weight percent for prodelta and distal delta-front shales.

Most fossils from the black clay shale include generally small (<2 cm) mollusk remains and abundant microfossils (table 6). Mollusks are generally fragmental, probably in part allochthonous, and gradually increase in abundance upward in the clay shale. The uppermost 4 inches of this facies comprises a fossiliferous carbonate grainstone resting on a sharp, probably erosional base (fig. 18). Abruptly above this interval lies nonfossiliferous lower distal delta-front and prodelta facies of the Cleveland Formation. The grainstone contains a diverse assemblage of fauna (table 5) and carbonate grains (<1 to 5 mm), including (in approximate order of abundance) coated grains, pelecypods, gastropods, crinoids, encrusting algae, oncolitic coatings, crinoid-grainstone lithoclasts, and tabulate corals. Pelecypods and gastropods compose the bulk of the faunal component. At least one hardground underlain by a few bored pelecypod fragments occurs within the grainstone bed. A similar, abundantly fossiliferous bed capping a transgressive interval occurs at the top of the Glasgow core (fig. 6).

Figure 18. Core photograph of carbonate grainstone in uppermost part of the distal shelf facies. Core slab is 3.5 inches wide. This highly fossiliferous deposit (table 5) is interpreted to represent current-concentrated fossil material that accumulated in an area of sediment starvation on the Cleveland shelf. Note the thin, uneven, nonfossiliferous hardground abruptly truncating the fossil bed about 3 inches above its base. Several bored pelecypod fragments lie below the hardground; a more mud-rich but less fossiliferous thin bed overlies it. Black, organic-rich, fossiliferous clay shale directly underlies the grainstone. Lenticular laminated siltstone and shale of lower distal delta-front and prodelta facies of the lower Cleveland Formation directly overlie the grainstone. From Maxus Glasgow No. 2 at 7,282.5 ft (log depth).

This facies is interpreted to record distal shelf deposition of pelagic or hemipelagic sediments that were deposited under very low sedimentation rates (see "Sequence Stratigraphy, Condensed Section"). The primary evidence for this interpretation includes (1) sedimentary structure in the shaly facies indicative of sedimentation from supension, (2) concentrated organic material (high TOC), (3) abundance of pyrite, (4) occurrence of phosphate nodules, (5) existence of a hardground, (6) presence of offshore (deep-water) pelagic fauna, including varieties of conodonts within the black clay shale (see "Paleontology and Age of Cleveland Formation"), and (7) the facies' regional areal distribution and facies relations with underlying transgressive deposits. Where this facies occurs in the study area, it consistently rests gradationally above a much thicker, shale-rich transgressive interval and thus represents the culmination of relative sea-level rise during late Marmaton time. Further details of this interpretation (item 7) are discussed in "Sequence Stratigraphy, Marmaton Group (Undivided)." Items 2, 3, and 4 demonstrate that anaerobic to largely dysaerobic sediment conditions existed during deposition of this facies; paleontological data indicate that variably highly dysaerobic to aerobic bottom-water conditions influenced the biological environment (table 6). The fossil assemblage of the carbonate grainstone bed is a well-developed *Trepospira*-Ammonoid Community (D. R. Boardman II, personal communication, 1991; table 5), one of the deepest water communities found in Pennsylvanian Midcontinent cyclothems (Boardman and others, 1984). The hardground (item 4) in the grainstone bed represents a readily identifiable hiatus in sedimentation.

SEQUENCE STRATIGRAPHY

The terms associated with the evolving geologic concept of sequence stratigraphy are many and varied, but they are well described in several sources (for example, Van Wagoner and others, 1987, 1990). A brief summary of key terms used in this report is presented below, but the reader may wish to consult the citations listed above and below for more in-depth treatment of the sequence stratigraphic model. The fundamental unit of sequence stratigraphy is the *sequence*, a lithogenetic unit bounded by regional unconformities and their correlative conformities and composed of systems tracts. *Systems tracts* are contemporaneous depositional systems (three-dimensional assemblages of genetically related facies) that are genetically linked (Brown and Fisher, 1977). More recently, the concept of systems tracts has been applied to depositional and erosional processes associated with *lowstand*, *transgressive*, and *highstand* phases of eustatic (global sea level) fluctuations (Posamentier and others, 1988). Systems tracts are defined by their position within the sequence and by the stacking patterns of parasequence sets. A *parasequence* is a conformable, typically progradational (upward-coarsening) succession of genetically related strata bounded by marine-flooding or equivalent surfaces. The interplay between rates of *accommodation* (volume of space available for potential sediment accumulation) change and sediment supply determines stacking patterns exhibited by genetically related parasequences, or *parasequence sets*. *Relative sea level* change determines whether accommodation is increasing or decreasing and involves the interplay between eustasy, subsidence/uplift, and sediment supply. *Lowstand* and *highstand systems tracts* consist of progradational (seaward-stepping) parasequence sets; lowstand systems tracts are deposited during rapid fall of relative sea level below the depositional shoreline break and commonly below shelf edges, and highstand systems tracts form when relative sea level is at a maximum. *Incised-valley systems* are entrenched fluvial systems that have extended their channels basinward and have eroded into underlying strata in response to a fall in relative sea level. The *transgressive systems tract* comprises a retrogradational (landward-stepping) parasequence set deposited during rise of relative sea level. *Maximum flooding surfaces* mark extended periods of sediment starvation that terminate transgressive deposition. These surfaces constitute important regional nondepositional lithogenetic boundaries that separate transgressive from highstand systems tracts. The *condensed section* is a facies consisting of thin marine beds of pelagic or hemipelagic origin that are deposited at very low sedimentation rates and are most extensive at the time of maximum regional transgression of the shoreline (Loutit and others, 1988).

For this study, the sequence stratigraphic model has been applied primarily to the siliciclastic interval consisting of the Marmaton Group (undivided) and the Cleveland Formation. However, the carbonate-bearing, sandstone-poor Oswego Limestone and Kansas City Formation are also discussed to more fully define the position of the Cleveland in the regional sequence framework of the western Anadarko Basin.

Systems Tracts and Sequence Boundaries

Marmaton Group

Oswego Limestone

Only the upper part of the Oswego Limestone (fig. 3), particularly the upper contact, was correlated for this sequence stratigraphic analysis. This horizon is inferred to be a sequence boundary, probably a type 1 sequence boundary (an unconformity that extends across the shelf and into the basin as a result of a rapid eustatic fall at a rate greater than that of subsidence at the shelf area), resting above Oswego highstand carbonate facies. Designation of the top of the Oswego as a sequence boundary is based primarily on (1) the regional relation of the formation with overlying siliciclastic systems tracts and (2) sedimentary aspects of the formation where it is exposed in Oklahoma, Kansas, and Missouri.

Where the base of the Oswego Limestone is clearly defined in the eastern part of the study area, the uniform, generally blocky log expression of the unit suggests that it is part of, or wholly composes, a single depositional systems tract. Elsewhere, where the base of the Oswego is not clearly defined, a similar evaluation of the unit cannot be made, and it may be found that the Oswego interval comprises several systems tracts. In regional cross sections (figs. 20 through 26, below), the base of the Oswego is correlated, but this correlation is purely lithostratigraphic. Local, detailed well-log correlation in basinward areas where the Oswego limestone facies thins toward the southeast (fig. 4 and figs. 20 through 22, below) indicates that the thick Oswego buildup is actually equivalent to a southeastward-thickening, predominantly shale succession. The blocky, buildup facies described herein may be just the uppermost of several systems tracts. However, throughout most of the study area the Oswego is overlain by a regionally correlative progradational parasequence, set in the lower part of the Marmaton siliciclastic interval (fig. 19), that exhibits unequivocal evidence of deposition during a relative sea-level lowstand (see "Marmaton Group [Undivided], Lowstand Systems Tract"). The thick (100 to 250 ft), blocky aggradational interval that composes the Oswego in most of the eastern part of the study area (fig. 4) is probably a highstand systems tract, given that the Oswego (1) is regionally distributed throughout at least all of the western Anadarko Basin, (2) has considerable thickness in many areas, and (3) is subregionally underlain by a retrogradational parasequence set composing a transgressive systems tract. These are characteristic features of highstand carbonate systems tracts, particularly "keep-up" carbonate systems (carbonate accumulation is maintained within the photic zone near sea level) described by Sarg (1988). By this line of reasoning, the top of the Oswego, which lies below an inferred lowstand systems tract, is thus indirectly interpreted to be a sequence boundary. Derstine (1989) proposed that a sequence boundary occurs near the top of the Oswego in west-central Oklahoma; however, he also concluded that the Oswego is composed of three sequences and several systems tracts representing several eustatic cycles. Such may be the case in the study area, but only detailed correlation from the Texas Panhandle to Oklahoma will help resolve the regional character of the complete Oswego interval.

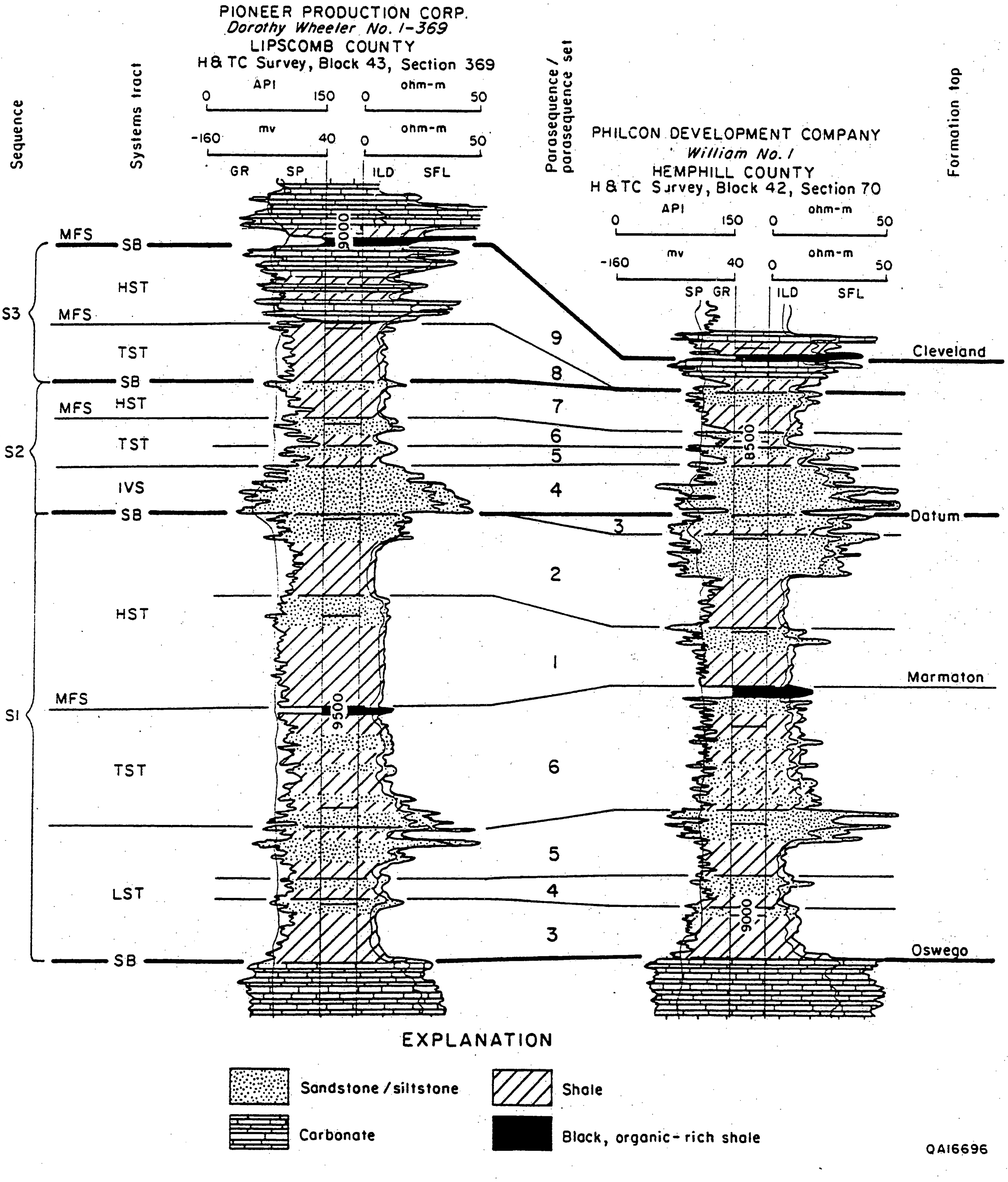


Figure 19. Representative well logs of the siliciclastic Marmaton Group (undivided) and Cleveland Formation, showing log expression of the component sequences, systems tracts, and parasequences. Wells are located about 10 mi apart in south-central Lipscomb County (Pioneer Wheeler No. 1-369) and northwestern Hemphill County (Philcon William No. 1). Note that parasequences are numbered independently within each formation. Parasequences 1 and 2 of the lower Marmaton siliciclastic interval and parasequence 10 of the upper Cleveland Formation are absent in the region of these wells. S1, S2, and S3 are sequences 1, 2, and 3. MFS = maximum flooding surface (coincides with top of thin, high-gamma-ray, black shale intervals interpreted as marine-condensed sections); SB = sequence boundary; LST = lowstand systems tract; TST = transgressive systems tract; HST = highstand systems tract; and IVS = incised-valley system.

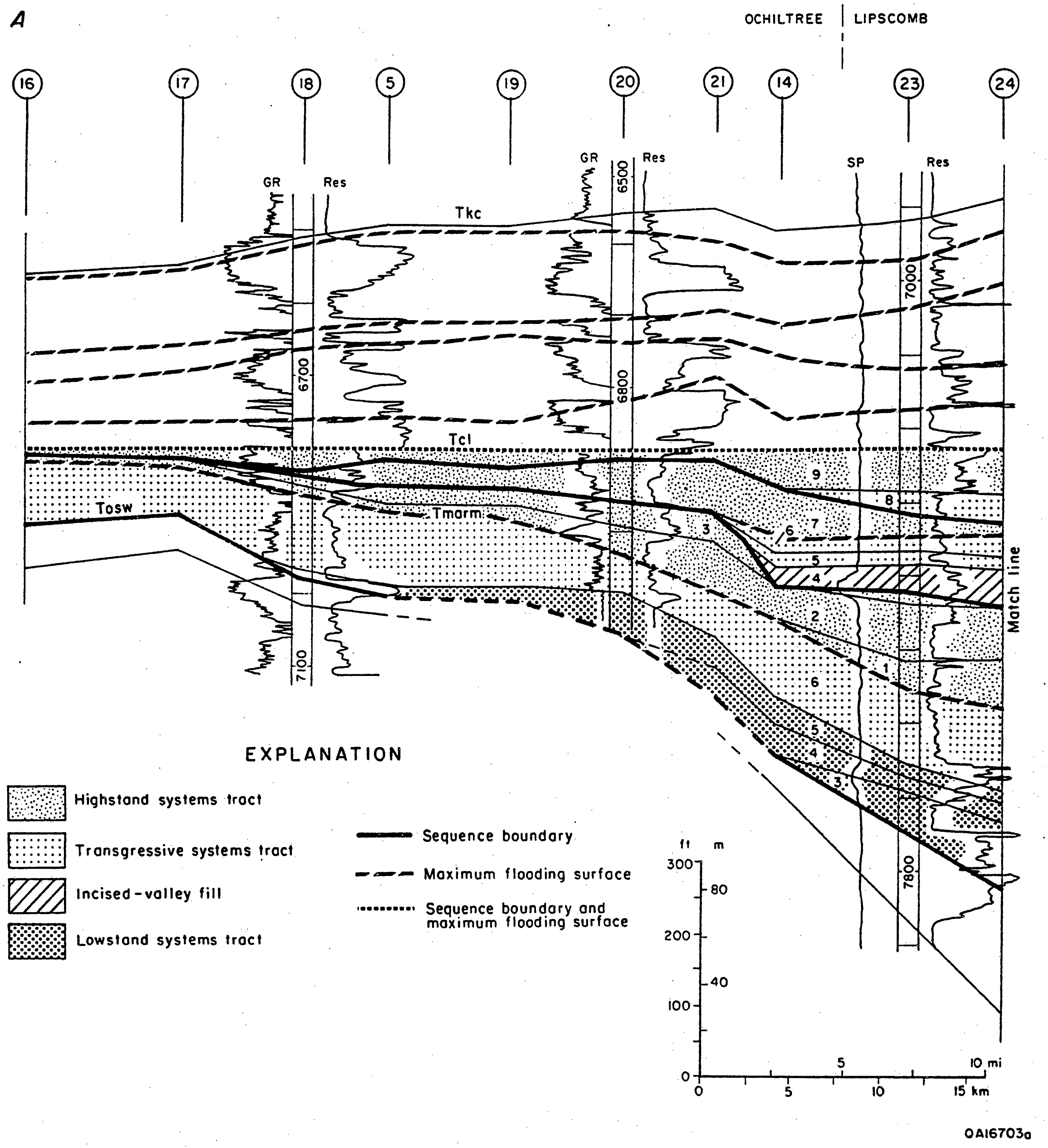


Figure 20. Regional dip-oriented cross section A–A′ of the northern part of the study area. That part of section between well 14 (Ochiltree County) and well 18 (Lipscomb County) coincides with the northern subbasin of the Cleveland Formation (fig. 14). Two interpreted Oswego shelf-platform steps (slope breaks) that affected Marmaton and Cleveland siliciclastic sedimentation occur at well 25 (Lipscomb County) and well 20 (Ochiltree County). Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

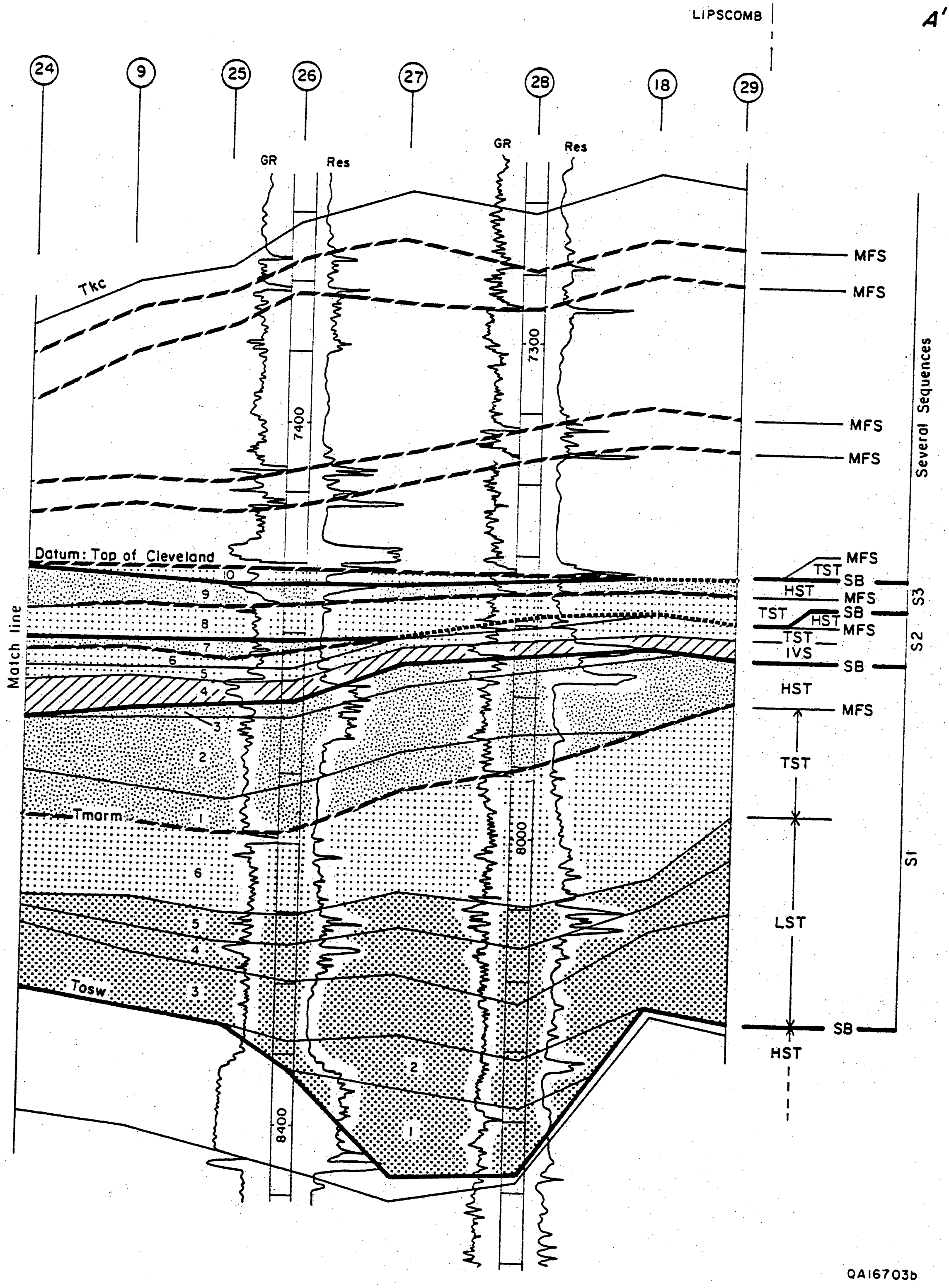

LIPSCOMB
A'
24
9
25
26
27
28
18
29
GR
Res
GR
Res
Tkc
7300
7400
8000
8400
MFS
MFS
MFS
MFS
Several Sequences
Datum: Top of Cleveland
Match line
10
9
8
7
6
5
4
3
2
1
Tmarm
6
5
4
3
2
1
Tosw
MFS
TST
SB
HST
MFS
TST
SB
HST
MFS
TST
IVS
SB
HST
MFS
TST
LST
SB
HST
S3
S2
S1
QA16703b

fig. 20 (cont.)

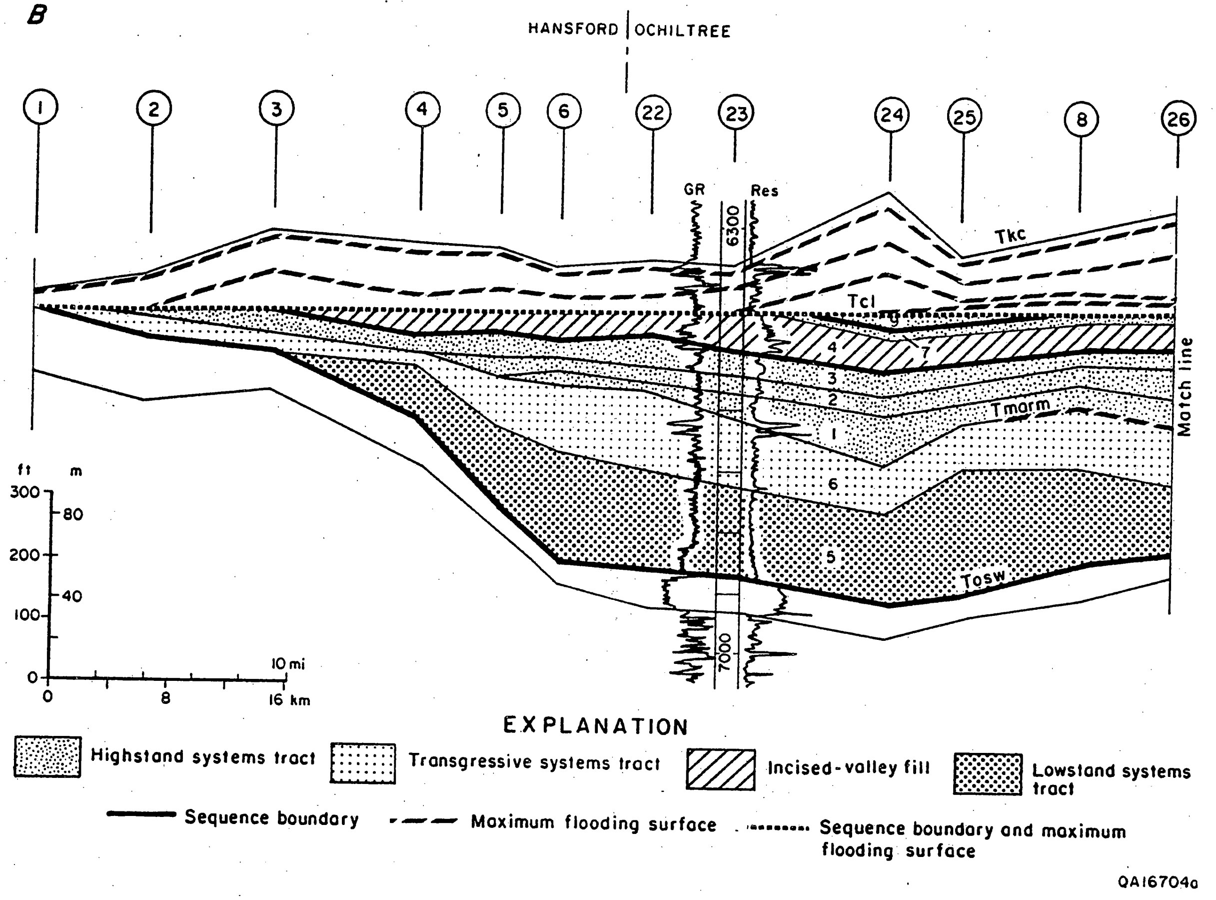
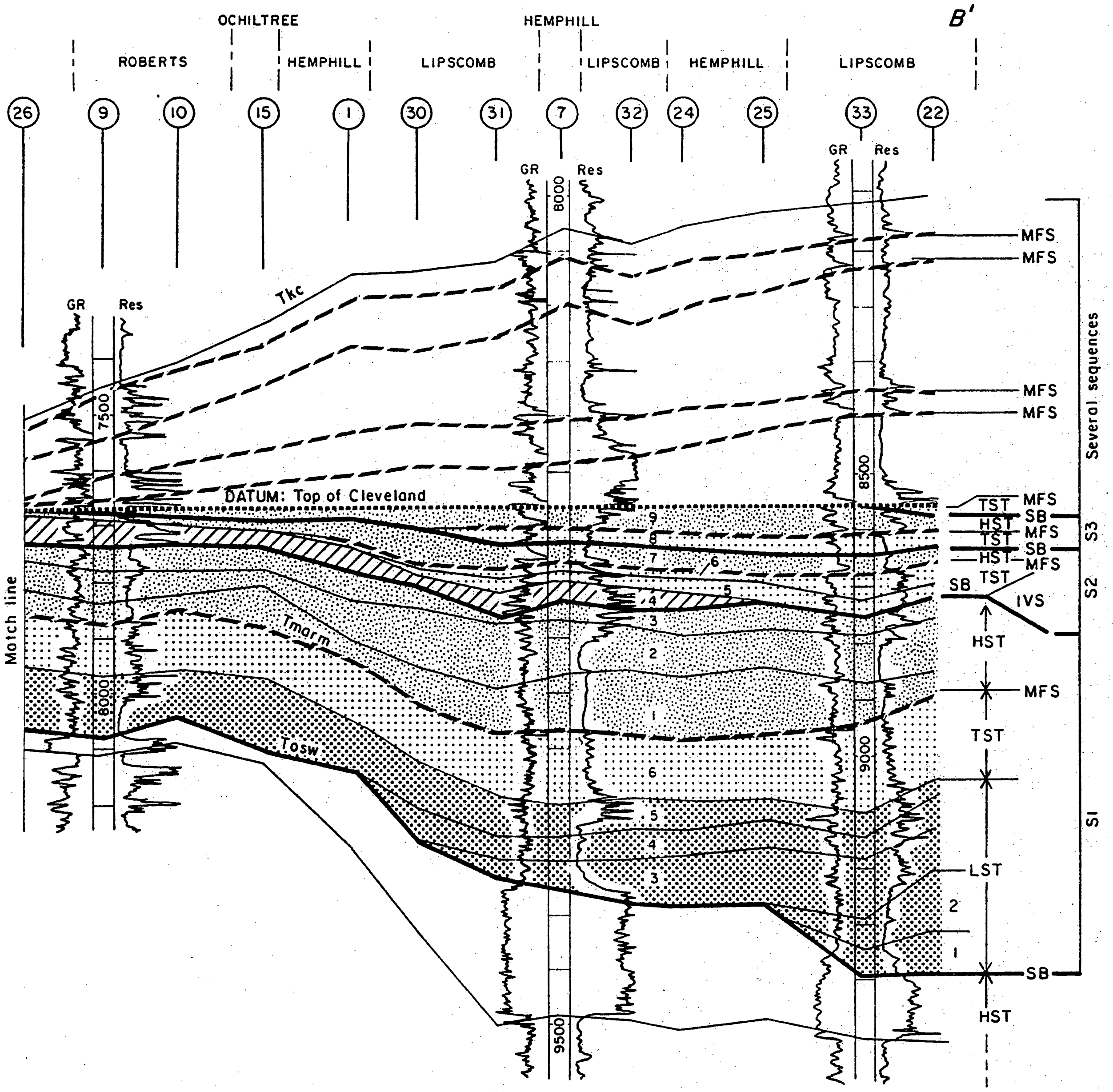


Figure 21. Regional dip-oriented cross section B–B′ of the central part of the study area. Section line crosses northwesterly trend of fault-controlled linear thick in the Cleveland Formation (fig. 5) at well 24 (Ochiltree County). Section between well 1 (Hemphill County) and eastern end of section coincides with the northern subbasin of the Cleveland Formation (fig. 14). Two interpreted Oswego shelf-platform steps (slope breaks) that affected Marmaton and Cleveland siliciclastic sedimentation occur at wells 25 and 1 (Hemphill County). Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.



QA16704b

fig. 21 (cont.)

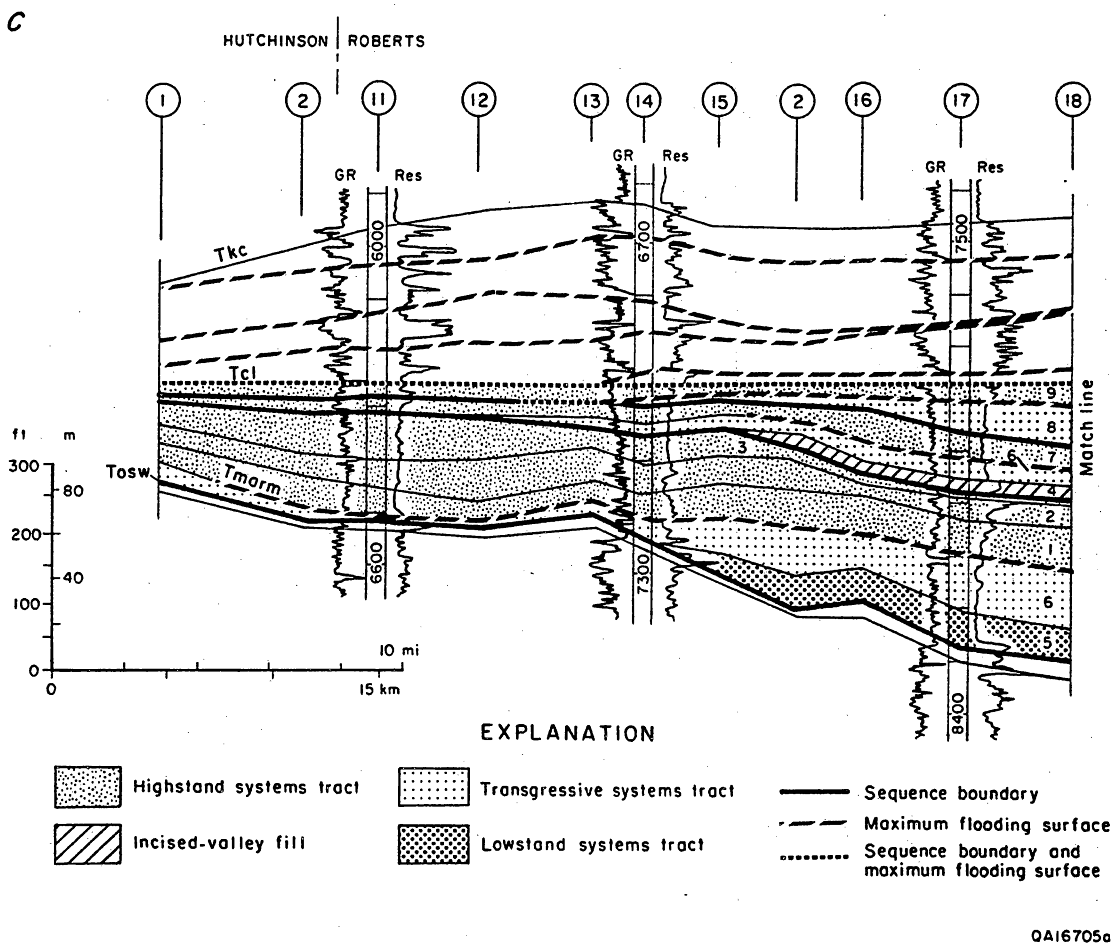


Figure 22. Regional dip-oriented cross section C–C′ of the southern part of the study area. Section line crosses northwesterly trend of fault-controlled linear thick in the Cleveland Formation (fig. 5) at well 8 (Roberts County). Section between well 18 (Roberts County) and eastern end of section coincides with the southern subbasin of the Cleveland Formation. Two interpreted Oswego shelf-platform steps (slope breaks) that affected Marmaton and Cleveland siliciclastic sedimentation occur at well 29 (Hemphill County) and well 18 (Roberts County). Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

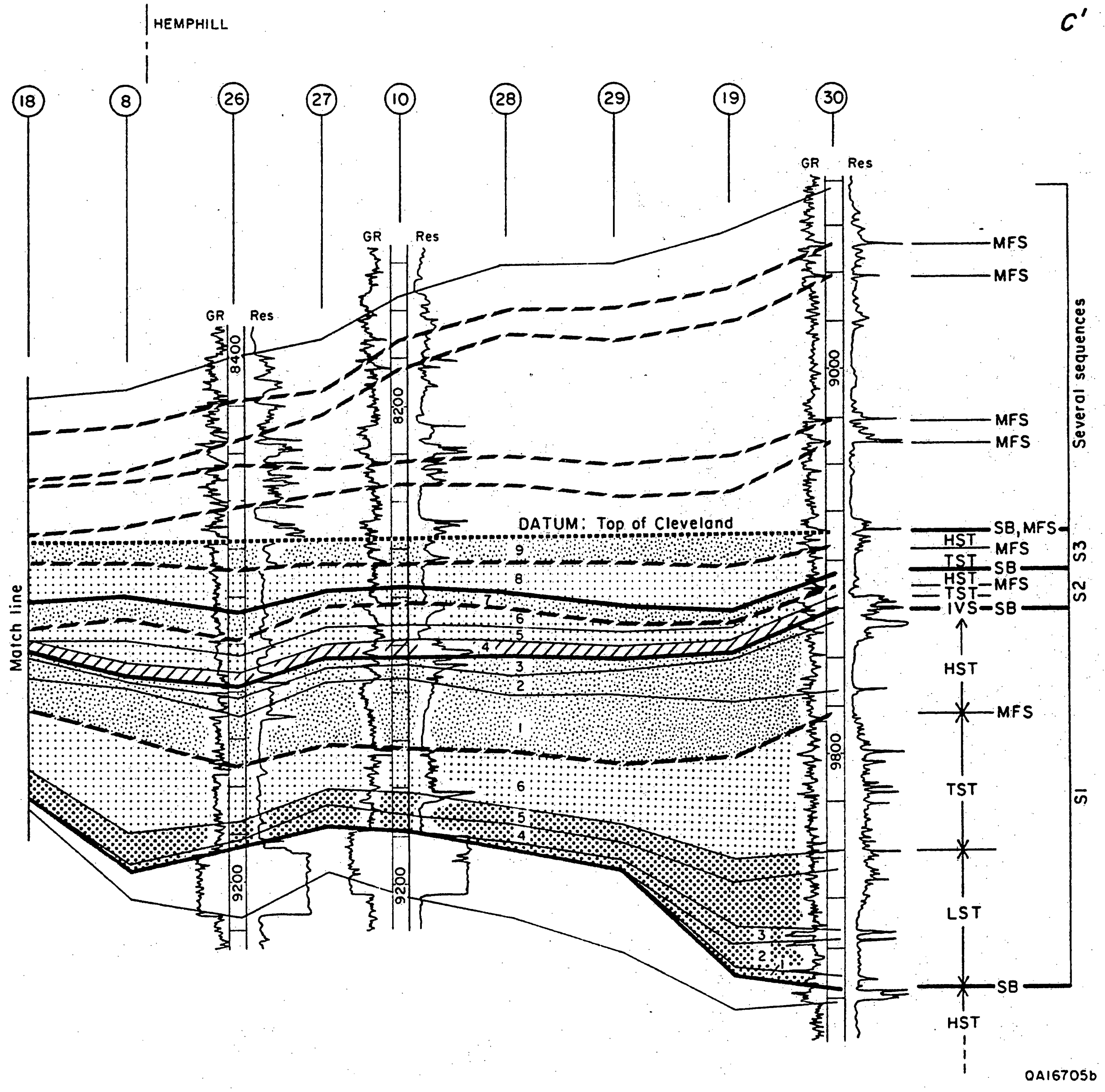

HEMPHILL
C'
18
8
26
27
10
28
29
19
30
GR
Res
8400
8200
9000
9200
9800
DATUM: Top of Cleveland
Match line
9
8
7
6
5
4
3
2
1
MFS
MFS
MFS
MFS
SB, MFS
HST
MFS
TST
SB
HST
MFS
TST
IVS
SB
HST
MFS
TST
LST
SB
HST
Several sequences
S3
S2
S1
QA16705b

fig. 22 (cont.)

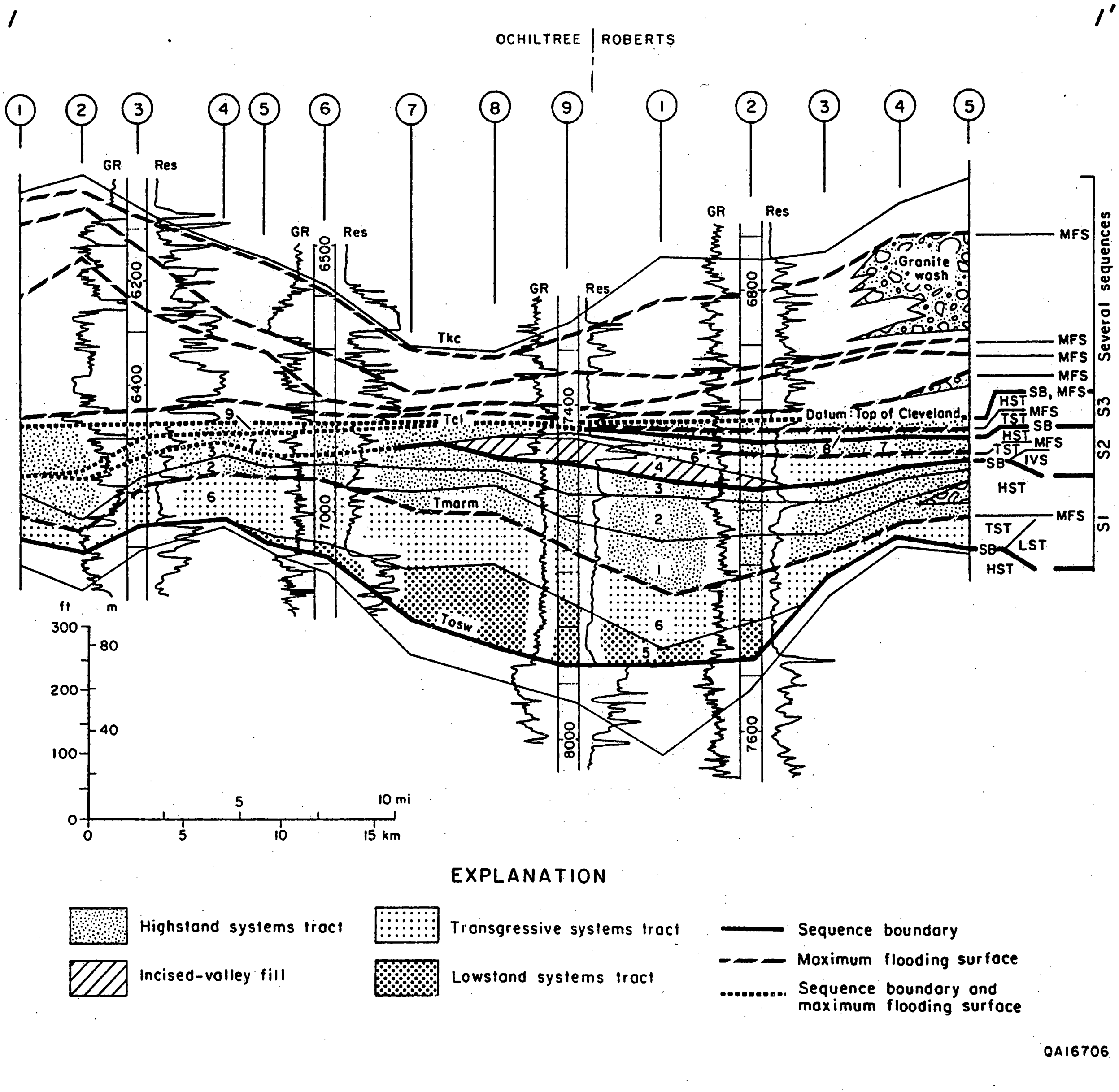


Figure 23. Regional strike-oriented cross section 1–1′. Section line crosses northwesterly trend of fault-controlled linear thick in the Cleveland Formation (fig. 5) at well 9 (Ochiltree County) and wells 1 and 2 (Roberts County). Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

Outcrop characteristics of the Oswego provide direct evidence that the top of the unit is a sequence boundary. The subsurface Oswego Limestone is equivalent to the exposed Fort Scott Limestone of Oklahoma, Kansas, and Missouri (Krumme, 1981); the upper member of the Fort Scott is the Higginsville Limestone Member (surface) or upper Oswego (subsurface) (Drexler, 1984). The top of the Oswego Limestone in the Texas Panhandle is equivalent to the top of the Higginsville Limestone Member. Knight (1985) documented the occurrence of well-developed root casts and rhizocretions at the top of the Higginsville throughout its outcrop area, indicating regional subaerial exposure of the unit and a significant drop in relative sea level after Oswego (Higginsville) shelf-carbonate deposition. In north-central Oklahoma the subsurface upper Oswego interval is immediately overlain by fluvial facies (Drexler, 1984), although no incision by fluvial channels into the Oswego is described. No evidence of channel incision of the Oswego in the study area was noted either. Observations presented in Drexler (1984) and Knight (1985) support the interpretation of a sequence boundary at the top of the Oswego.

Marmaton Group (Undivided)

Lowstand Systems Tract

The lower five siliciclastic parasequences of the Marmaton Group (undivided) form a lowstand systems tract (lowstand wedge) that prograded westward through the western part of the Anadarko Basin after a late Desmoinesian drop in relative sea level. Parasequences 1 through 5 collectively exhibit (1) an overall upward-coarsening trend and (2) an upward increase in the proportion of sandstone within each parasequence, characteristics of a progradational parasequence set (figs. 19 through 26). Although no cores of these deposits were examined, the similarity of the well log expression of these Marmaton parasequences and of their regional stacking pattern to those of the cored

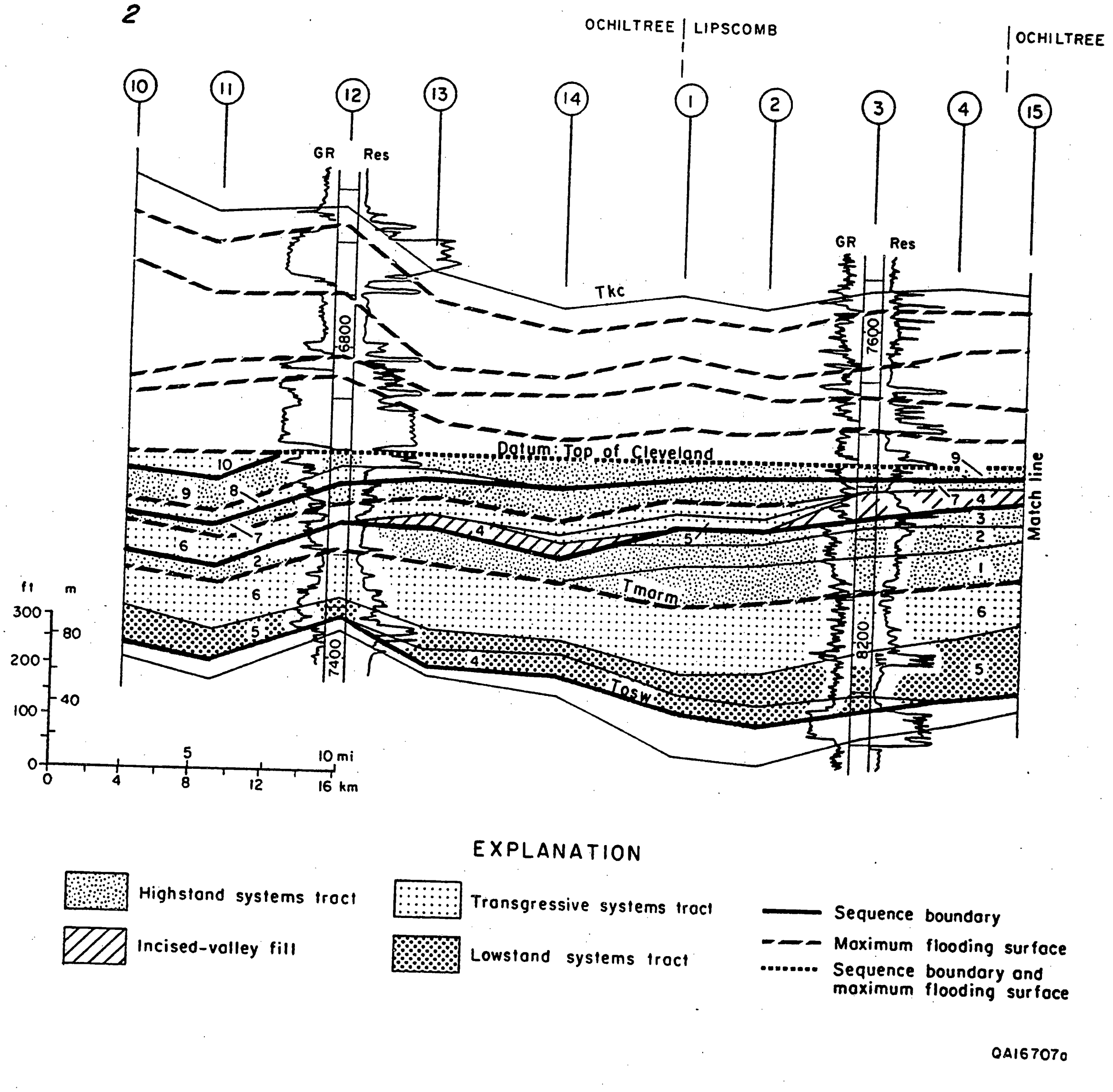


Figure 24. Regional strike-oriented cross section 2–2′. Section line crosses northwesterly trend of fault-controlled linear thick in the Cleveland Formation (fig. 5) at wells 7 and 8 (Roberts County). This area of thickened strata and also that between wells 14 (Ochiltree County) and 4 (Lipscomb County) coincide with the westernmost parts of the southern and northern subbasins, respectively, of the Cleveland (fig. 14). Note (1) lap out of Cleveland parasequences 5, 6, and 8 (transgressive systems tracts) at the northern edge of the southern subbasin, (2) lenticularity of Cleveland parasequence 10 (trangressive systems tract) in the southern subbasin, and (3) lenticularity of Marmaton parasequence 4 (part of lowstand wedge) in both subbasins. Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

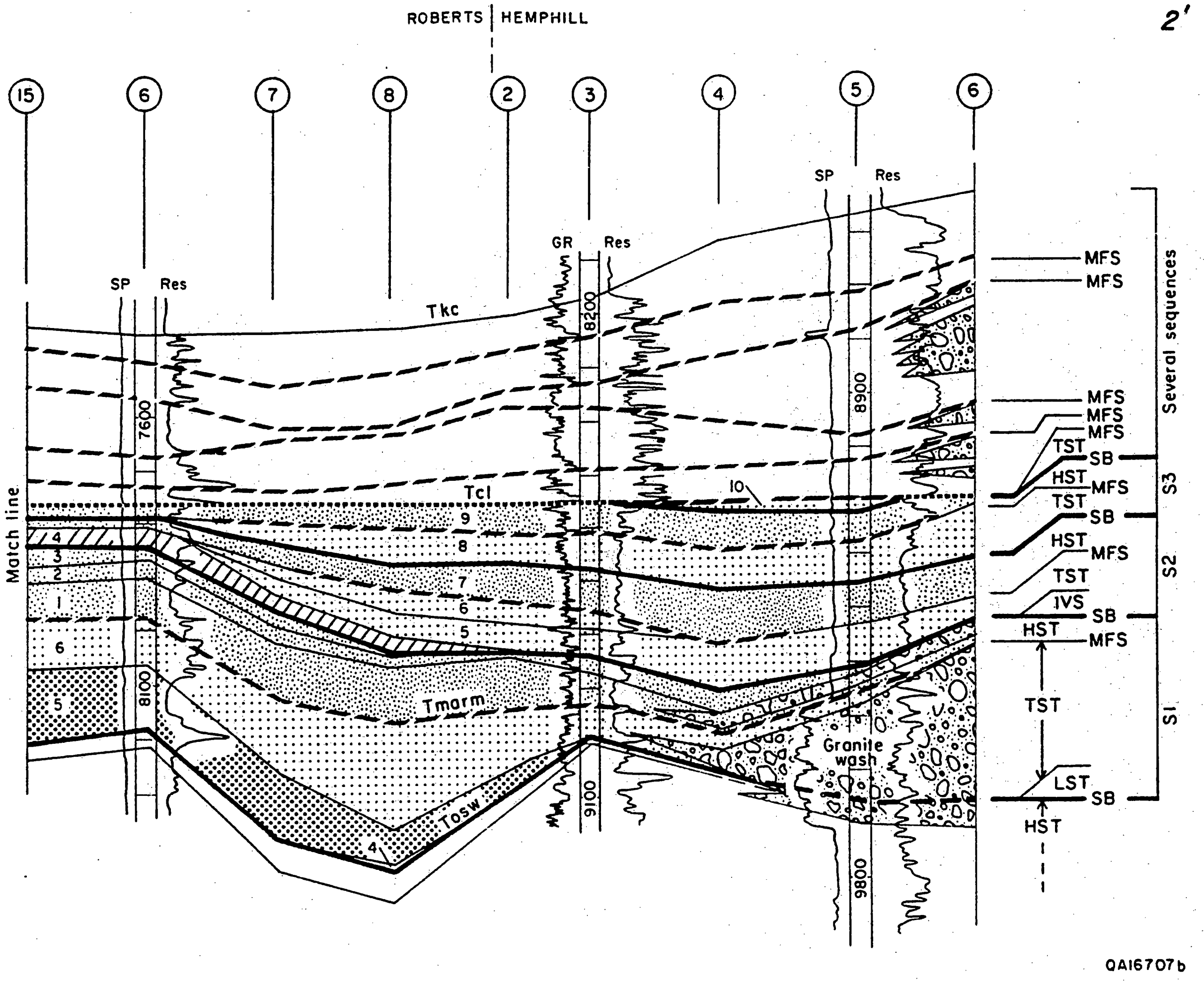

2'
ROBERTS
HEMPHILL
15
6
7
8
2
3
4
5
6
SP
Res
GR
Res
SP
Res
Tkc
Tcl
Tmarm
Tosw
Match line
7600
8100
8200
9100
8900
9800
1
2
3
4
5
6
7
8
9
10
Granite wash
MFS
MFS
MFS
MFS
MFS
TST
SB
HST
MFS
TST
SB
HST
MFS
TST
IVS
SB
HST
MFS
TST
LST
SB
HST
Several sequences
S3
S2
S1
QA16707b

fig. 24 (cont.)

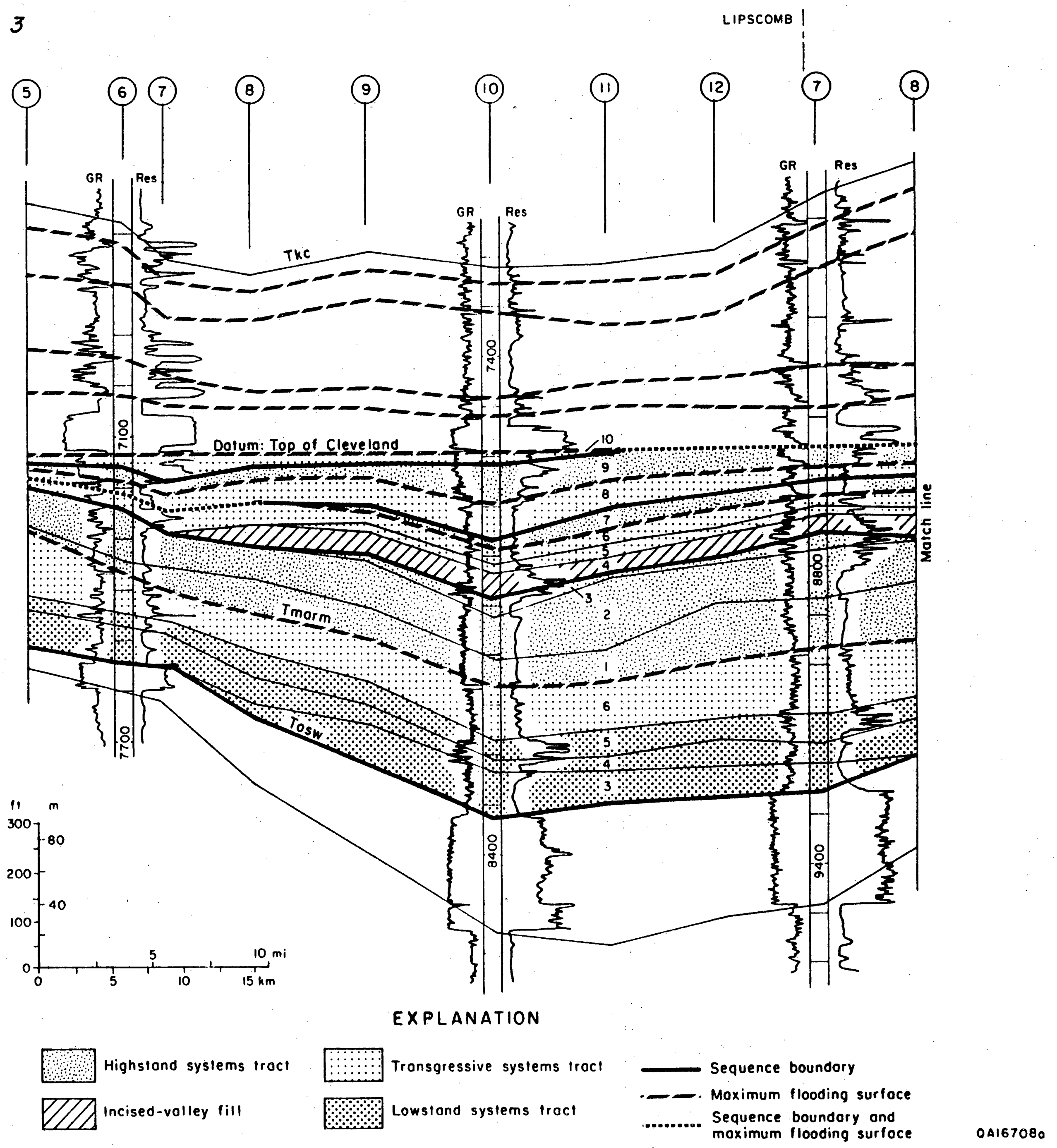
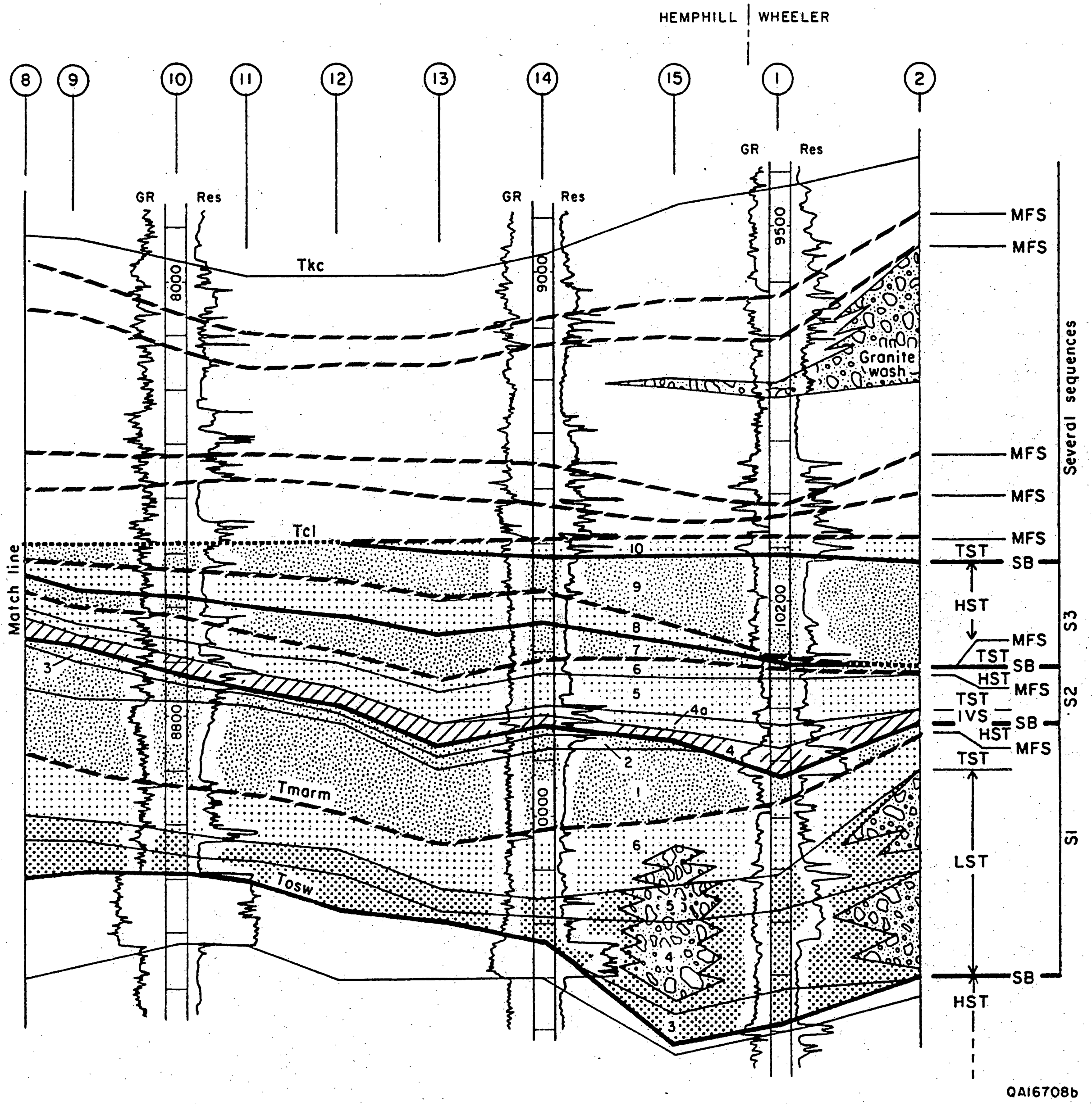


Figure 25. Regional strike-oriented cross section 3–3′. Parts of cross section between well 7 (Lipscomb County) and well 8 (Hemphill County) and between well 11 (Hemphill County) and well 2 (Wheeler County) coincide with the northern and southern subbasins, respectively, of the Cleveland Formation (fig. 14). Zone of markedly increasing dip starting at well 7 (Lipscomb County) coincides with monoclinal flexure at the northern border of the northern subbasin. Note (1) increased thickness of Oswego Limestone in the subbasins, (2) lap out of Cleveland parasequence 10 (transgressive systems tract) toward the boundary high between the northern and southern subbasins, and (3) lenticularity of Marmaton parasequence 3 in both subbasins. Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

3'


HEMPHILL
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10000
9500
10200
Tkc
Tcl
Tmarm
Tosw
Match line
Granite wash
10
9
8
7
6
5
4a
4
3
2
1
6
5
4
3
MFS
MFS
MFS
MFS
MFS
TST
SB
HST
MFS
TST
SB
HST
MFS
TST
IVS
SB
HST
MFS
TST
LST
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HST
Several sequences
S3
S2
S1
QA16708b

fig. 25 (cont.)

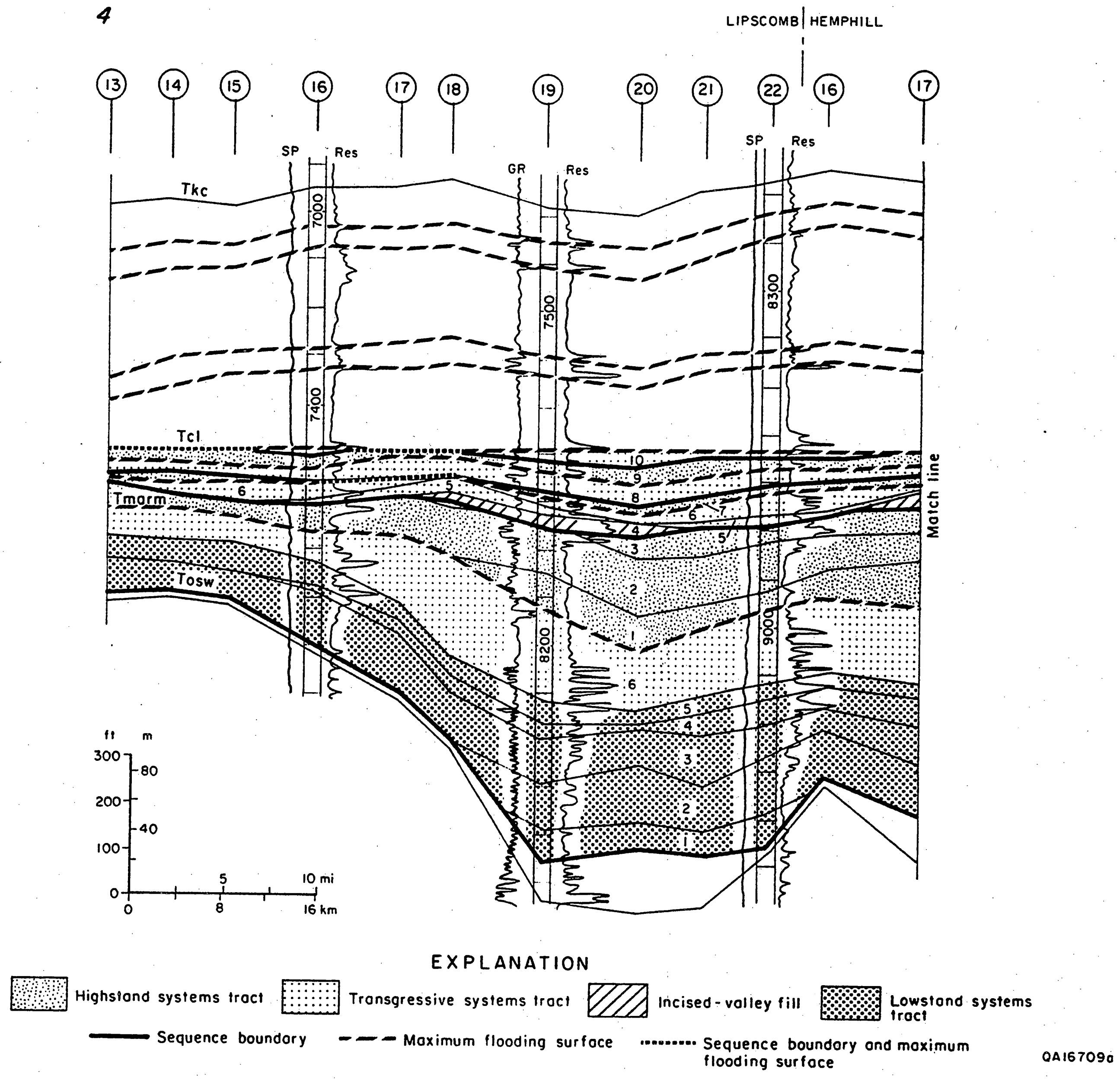
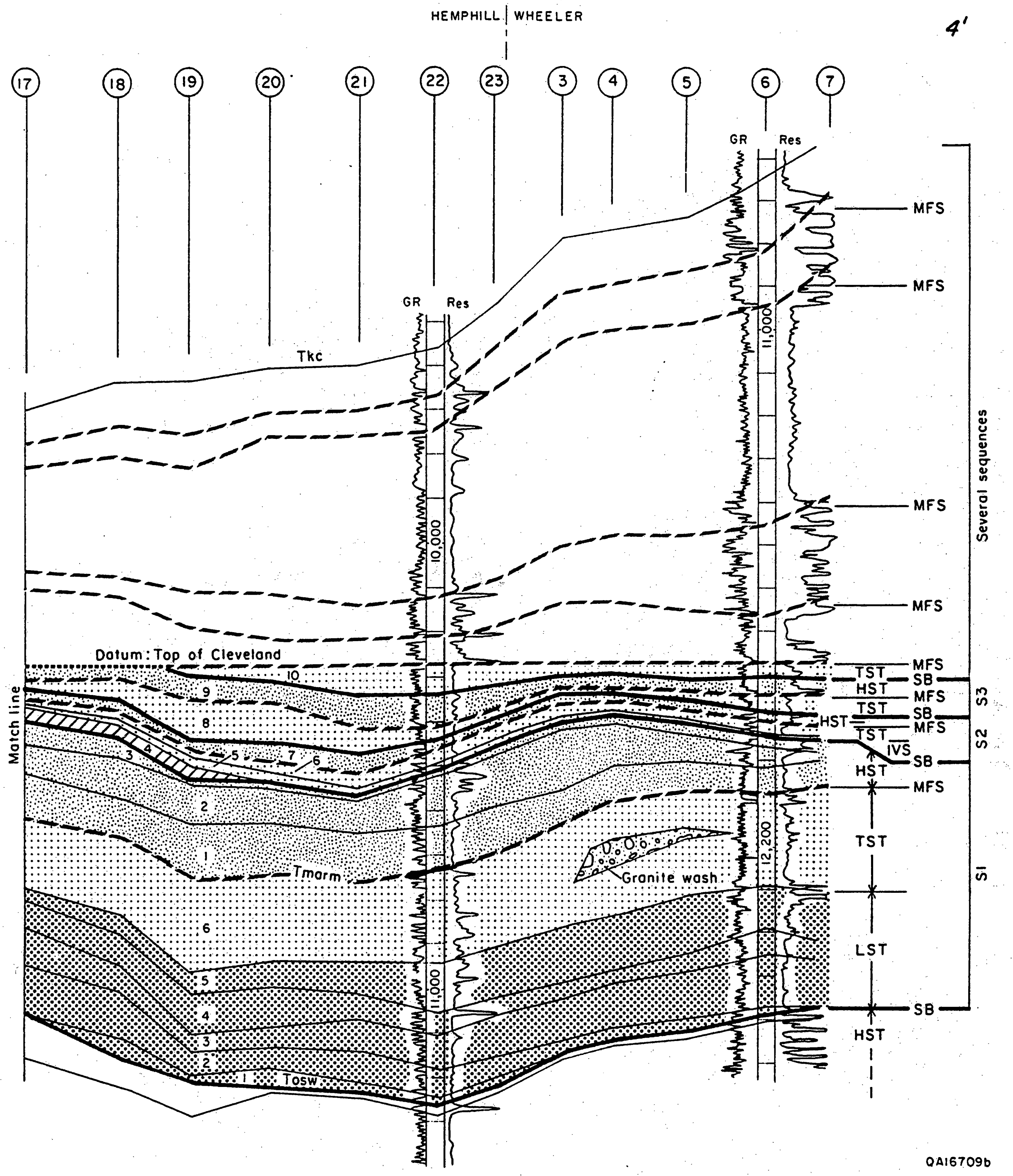


Figure 26. Regional strike-oriented cross section 4–4′. Northern and southern Cleveland subbasins occur between well 16 (Lipscomb County) and well 16 (Hemphill County), and between well 16 (Hemphill County) and well 7 (Wheeler County), respectively. Zone of markedly increasing dip starting at well 17 (Lipscomb County) coincides with monoclinal flexure at the northern border of the northern subbasin. Note (1) lap out of Cleveland parasequence 10 (transgressive systems tract) against the northern edge of the southern subbasin and lenticularity of P10 in the northern subbasin and (2) lenticularity of Marmaton parasequence 1 (lowstand wedge) in both subbasins and restriction of Marmaton parasequence 2 to the two subbasins. Tkc, Tcl, Tmarm, and Tosw identify tops of Kansas City Formation, Cleveland Formation, Marmaton Group, and Oswego Limestone, respectively; other abbreviations defined in figure 19 caption. Line of section shown in figure 2.

4'



HEMPHILL
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20
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3
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5
6
7
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Res
GR
Res
Tkc
MFS
MFS
MFS
MFS
MFS
Several sequences
10,000
11,000
11,000
12,200
Datum: Top of Cleveland
Match line
10
9
8
7
6
5
4
3
2
1
Tmarm
Granite wash
6
5
4
3
2
1
Tosw
TST
SB
HST
MFS
TST
SB
HST
TST
MFS
IVS
SB
HST
MFS
TST
LST
SB
HST
S3
S2
S1
QA16709b

fig. 26 (cont.)

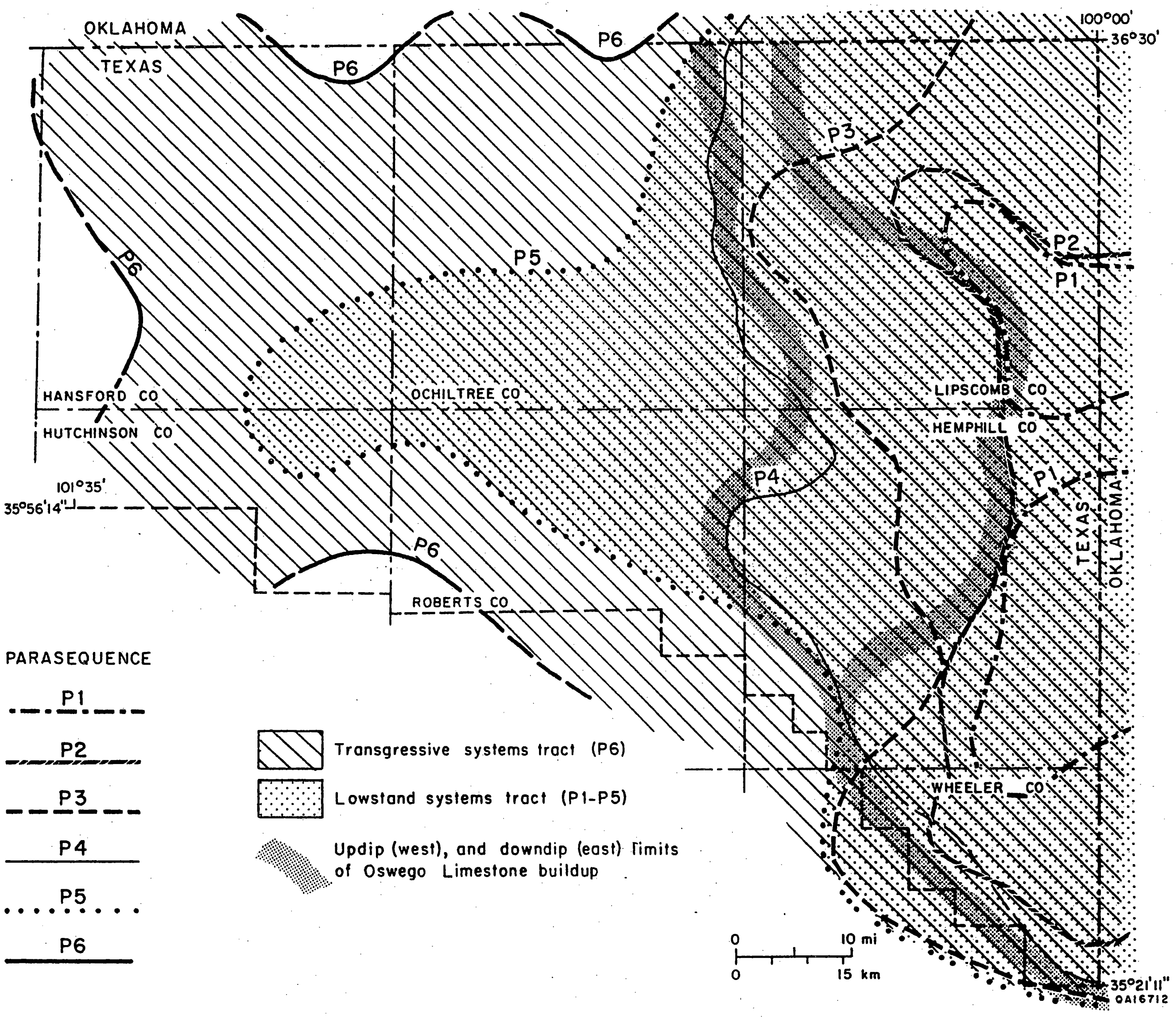

Figure 27. Areal distribution of parasequences of the Marmaton lowstand systems tract (P1–P5) and transgressive systems tract (P6).

Cleveland deltaic parasequences 2 and 3 strongly suggests that the Marmaton deposits are also deltaic, although progradational shoreface facies may compose some or all of the interval. Deltaic or shoreface sandstone at the top of Marmaton parasequence 5 forms the Hepler sandstone, a productive unit in the western Anadarko Basin.

The westerly direction of progradation (regression) of the Marmaton lowstand wedge is documented in figure 27. The western limits of progressively younger parasequences (P1 = oldest, P5 = youngest) extend progressively farther, and become progressively shalier, westward. Lowstand deltaic/shoreface cycles (parasequences) decrease in thickness westward from a maximum of 120 ft in the east to less than 40 ft in the west. It is most significant to note that Marmaton parasequences 1 and 2 terminate at the eastern limit of the immediately underlying Oswego Limestone buildup. Similarly, part of the western extent of parasequence 3 and all of parasequence 4 terminate at the western limit of the Oswego buildup (fig. 27). Moreover, cross-sectional (dip-section) views indicate that Marmaton parasequences 1 and 2 lap out against (onlap) the downdip limit of the Oswego Limestone buildup, and parasequences 3 and 4 terminate at or near the updip extent of the Oswego buildup (figs. 20 through 22). This demonstrates that the underlying Oswego shelf platform was (1) interrupted by two distinct steps, or slope breaks, that acted as depositional barriers to the westward progradation of the first four Marmaton deltaic/shoreface systems during a relative sea-level lowstand and (2) subaerially exposed updip (westward) of each slope break during deposition of the respective onlapping parasequence pairs. Because the Oswego slope breaks have generally north-south trends at high angles to the northwesterly trend of regional faults, fault control (at least by deep-seated faults) of these features is unlikely. The parasequence pairs thicken abruptly downdip of the Oswego shelf breaks, marking areas of greater differential subsidence (figs. 20 through 22). Strike cross-sectional view of the lowstand parasequences reveals that the structural high separating the two Cleveland subbasins (fig. 14) was also a depositional barrier during Marmaton (parasequences 1, 3, and 4) time (figs. 24 through 26). Marmaton parasequence 5, the uppermost parasequence of the lowstand wedge, overlaps all these paleophysiographic barriers and extends westward to the Cimmaron Arch and the western terminus of the linear, fault-controlled thick (fig. 5) that influenced both Marmaton and Cleveland sedimentation.

Transgressive Systems Tract

Parasequence 6 of the Marmaton Group (undivided) composes a transgressive systems tract that records deposition during the rise of relative sea level after Marmaton lowstand deposition. Parasequence 6 is composed of several (three to six) very thin, upward-coarsening depositional cycles (parasequences) and thus actually forms a parasequence set (fig. 19). Regional correlation of these individual parasequences was found to be impractical due to their limited thicknesses (as little as 10 ft) and thus, inconsistent regional well-log expression. This interval occurs throughout the study area and exhibits (1) an overall upward-fining trend and (2) an upward decrease in the proportion of sandstone within each parasequence, characteristics of a retrogradational parasequence set (figs. 20 through 26). The contact between the Marmaton lowstand and transgressive systems tracts (transgressive surface) is generally marked by an abrupt increase in shale above the contact. The Marmaton transgressive systems tract is represented only in the basal 24 ft of the Maxus Glasgow No. 2 core (7,310.5 to 7,287.0 ft, fig. 6). These deposits compose the distalmost parts of at least two deltaic parasequences: (1) 7,310.5 to 7,303.5 ft and (2) 7,303.5 to 7,287.0 ft. Interval 1 contains lower distal delta-front facies similar to that shown in figure 15a; this is only the upper part of a thin, upward-coarsening deltaic cycle. Interval 2 consists of prodelta facies grading upward to distal shelf deposits. Intervals 1 and 2 form the upper part of an overall upward-deepening succession of inferred deltaic cycles (parasequence 6) that culminates in a marine-condensed section, which records pelagic or hemipelagic sedimentation during maximum regional transgression of the shoreline (see "Condensed Section").

Condensed Section

A marine-condensed section occurs at the top of Marmaton parasequence 6 (fig. 19) but actually composes part of both this upper Marmaton transgressive systems tract and the lower Cleveland highstand systems tract. However, this interval is described separately in this section because of its importance as (1) a readily recognizable lithostratigraphic marker that represents nearly uniform regional depositional conditions and (2) a precise chronostratigraphic tie between basin and shelf sections (Loutit and others, 1988). This deposit's lithological and mineralogical characteristics, areal distribution, organic content, and well-log expression are discussed in "Base of Cleveland." The paleontology of the Marmaton condensed section is described in "Paleontology and Age of Cleveland Formation," and aspects of the deposit's environment of deposition and paleoecology are discussed in "Distal Shelf Facies." However, in summary, the upper Marmaton condensed section is a thin (<10 to 28 ft), organic-rich, fossiliferous, black clay shale that is continuous throughout most of the study area (extending from basin to shelf areas) and is expressed on well logs as a high-gamma-ray marker bed at the top of the Marmaton Group (figs. 4, 6, and 19 through 26). The features of this interval and those detailed elsewhere in this report are characteristics of other marine-condensed sections (for example, Baum and Vail, 1988; Leckie and others, 1990). Deposited in an anaerobic to dysaerobic distal shelf environment, the interval represents the culmination of relative sea-level rise (maximum flooding conditions) during the latest stage of the Marmaton transgressive episode and the earliest period of Cleveland highstand deposition.

In the sequence stratigraphic model a condensed section is a thin marine unit extending from basin to shelf that was deposited in areas of sediment starvation during maximum shoreline transgression (Loutit and others, 1988). It consists of pelagic or hemipelagic sediments that accumulated under very low sedimentation rates and that contain evidence of apparent sedimentation hiatuses. The high-gamma-ray black clay shale at the top of the Marmaton Group, which was cored in the Maxus Glasgow No. 2 well between about 7,290 and 7,282.5 ft (fig. 6), displays evidence of depositional condensation: (1) significantly higher concentration of organic material relative to Marmaton and Cleveland deltaic shales, (2) marked abundance (concentration) of fossils relative to the mostly barren, higher energy deltaic silty shales (table 6) that were deposited under high sedimentation rates, (3) uniform very fine texture (clay-sized particles predominate) and fine lamination, both indicative of sedimentation from suspension, and (4) presence of a hardground in the carbonate grainstone that caps the condensed section.

The zone of maximum sediment starvation (maximum flooding surface) of the condensed section in the Maxus Glasgow No. 2 core is inferred to be close to or at 7,287.0 ft, near the middle of the black clay shale interval, where (1) organic (TOC) concentration is highest, (2) the fauna is highly restricted to only abundant conodonts (table 6), and (3) the occurrence of calcium phosphate nodules is restricted. From this zone upward to the top of the condensed section (top of grainstone bed at 7,282.5 ft), a well-developed oxygen gradient is recorded by the fossil assemblages (table 6). The upward change in assemblages within the upper half of the condensed section from a restricted conodont community to a well-developed, diverse *Trepospira*-Ammonoid Community (grainstone bed; table 5), which indicates nearly aerobic bottom-water conditions (Boardman and others, 1984), suggests an upward-shallowing trend. However, it is inferred that the condensed section above the maximum flooding surface (7,287 ft) records the earliest period of deposition by the lower Cleveland highstand systems tract.

Therefore, the maximum flooding surface is also the downlap surface. Relative sea level is still rising at this time, but the rate of relative sea-level rise is decreasing with the onset of highstand deposition, as is predicted by the sequence stratigraphic model. This, in combination with progressive eastward progradation of updip highstand deltas toward the Glasgow well site, would allow (1) minor transport of progressively shallower water fauna and (2) influx of increasingly more oxygenated water, thereby progressively (upwardly) increasing the in situ faunal diversity at the well site. Overall faunal abundance during this period would be maintained by the low sedimentation rate at the depositional site recorded at the Glasgow well. With the eventual progradation of distal deltaic facies (Cleveland parasequence 1) above the top of the grainstone bed and the attendant high sedimentation rate, most biological production ceased, as is recorded by the largely barren strata above the condensed section (table 6).

The thin carbonate grainstone bed at the top of the condensed section in the Maxus Glasgow No. 2 core (figs. 6 and 18) is interpreted to represent a current-reworked concentrate of fossils derived from mostly in situ faunas, from minor current transport of more shoreward faunas, from minor erosion of underlying fossiliferous shale, and from minor pelagic carbonate fallout. The bed records (1) a period of deposition when the rate of biological production under well-oxygenated bottom-water conditions greatly outpaced the existing low rate of sediment influx and (2) the zenith of the progressive upward increase in faunal diversity observed in the condensed section above the inferred maximum flooding surface at 7,287 ft. The presence of only abrasion-resistant robust conodont forms in the grainstone bed (D. R. Boardman II, personal communication, 1991) and the bed's sedimentary texture indicate that relatively gentle water currents, probably mostly geostrophic, acted as a sorting mechanism. Division of the grainstone bed by the hardground (fig. 18) records a period of decreased current activity and depleted oxygenation of the bottom waters. The grainstone bed is probably not a storm deposit because of (1) its uniqueness in the section (storm lags reflect episodic depositional processes and should therefore occur repeatedly in the section) and (2) the presence of mostly in situ faunas in the grainstone bed, indicating little long-distance transport of more shoreward faunas.

Banerjee and Kidwell (1991) related similar, areally extensive, thin fossil beds in organic-rich, black, marine shales (condensed sections) of the Lower Cretaceous Mannville Group of Alberta, Canada, to the sequence stratigraphy of the interval. They found that isolated, thin shell beds systematically occur at the top of upward-deepening intervals composed of black shales (deepest water facies in the middle of sequences) and represent sediment-starved hiatal concentrations that accumulated under aerobic conditions (their "mid-sequence shell beds"). The grainstone bed from the Glasgow core shares many of these characteristics, but the areal extent of the bed is uncertain. However, description of a thin limestone bed near the base of the Cleveland Formation in sporadic sample logs mostly from the northern part of the study area suggests that this fossil bed may have considerable areal extent.

Skiatook Group

Cleveland Formation

Highstand Systems Tract

The first three Cleveland parasequences overlying the marine-condensed section compose a progradational parasequence set (fig. 19) that accumulated during a relative sea-level highstand. The greater areal extent of these lower Cleveland parasequences (fig. 28), compared with the extent of the upper Marmaton lowstand deposits, indicates that relative sea level was higher during early Cleveland time. Near overlap of the areal limits of the highstand parasequences (fig. 28) suggests that relative sea level during

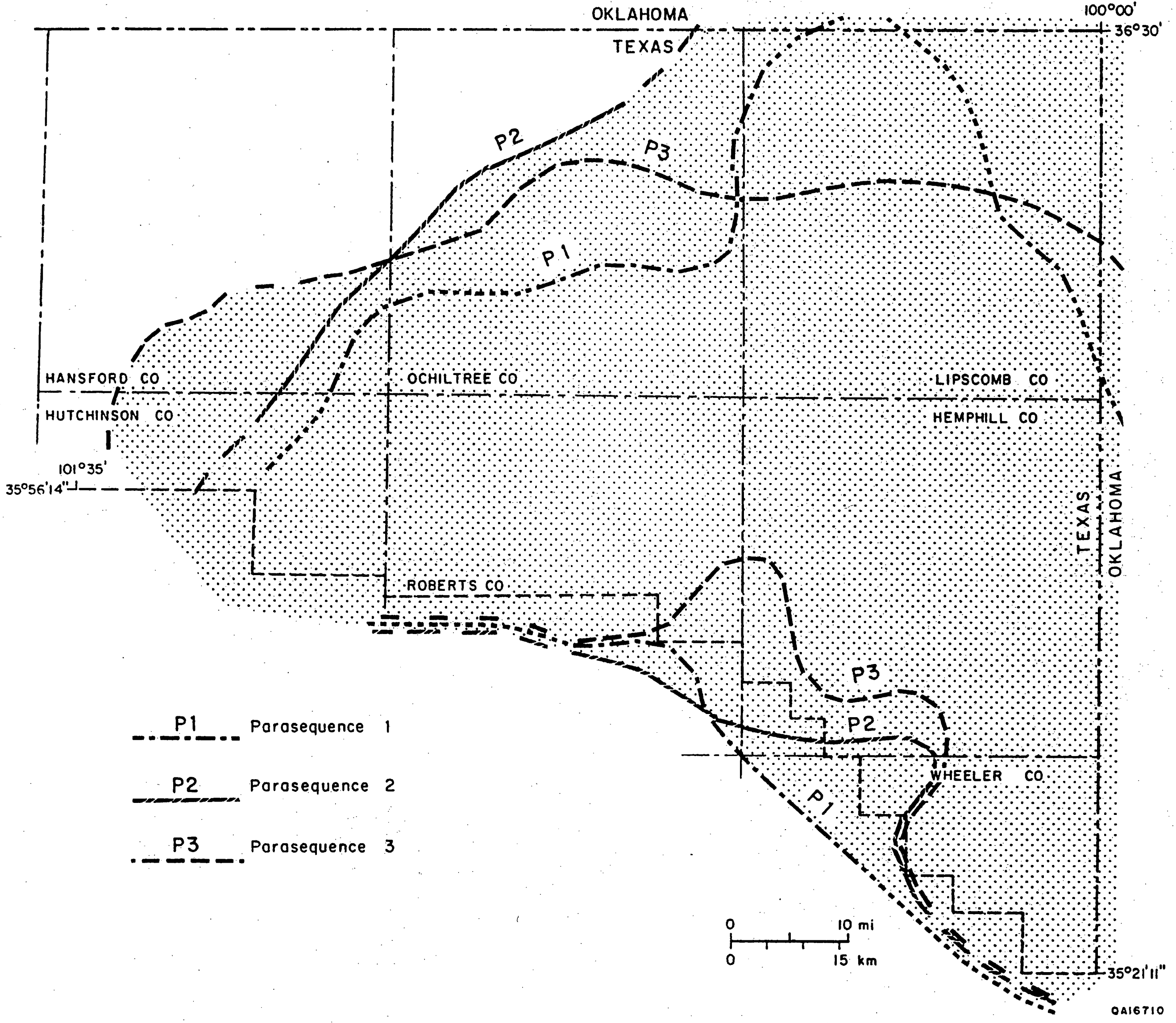

Figure 28. Areal distribution of parasequences of the Cleveland highstand systems tract (P1–P3).

early Cleveland time was also experiencing only minor fluctuation (near-stillstand conditions).

The upper two parasequences (P2 and P3) were cored in the Maxus Glasgow No. 2 and Maxus Shrader No. 3 wells (figs. 6 and 7); all three upward-coarsening cycles of the lower Cleveland highstand systems tract are inferred to have been deposited by prograding deltas (see "Deltaic Facies"). Thickness of individual deltaic cycles range from about 30 to 160 ft, generally thinnest in the central part of the study area and thickest in the eastern and southeastern parts. Coastal plain facies are inferred to predominate in the western part of the highstand systems tract; parasequences 1 through 3 are characterized by upward-fining, probably fluvial channel-fill siliciclastic deposits in southwestern and south-central Ochiltree County, western Roberts County, southeastern Hansford County, and northeastern Hutchinson County. Generally east-west-trending linear sandstone belts shown in figures 10 and 11 in this region represent the coastal plain fluvial systems of this highstand episode and of the subsequent Cleveland lowstand period (see "Incised-Valley System"). The eastward limit of progradation of delta-front facies in the highstand systems tract occurs in the central to eastern parts of Lipscomb and Hemphill Counties (see "Proximal Delta Front"), although more distal deltaic facies extended into west-central Oklahoma and the Oklahoma Panhandle (fig. 28). The western, central, and minor eastern net-sandstone trends (fig. 10) are localized thicks of stacked proximal delta-front sandstones from all three highstand parasequences.

Cleveland highstand deposition was affected by significant differential subsidence along preexisting structural and paleophysiographic features. The near alignment of (1) the western net-sandstone trend with the updip edge of the western Oswego shelf-platform slope break and (2) the central and eastern sandstone trends with the updip part of the eastern Oswego slope break suggests that the differential subsidence in this part of the study area that affected Oswego and Marmaton deposition continued into

Cleveland time, and that the updip parts of the two slope breaks mark positions of Cleveland delta (shoreline) stabilization (compare fig. 10 with fig. 27). The easternmost of the two Oswego shelf-platform slope breaks (fig. 27) is inferred to mark the approximate position of the Cleveland depositional shelf edge. The Cleveland depositional shelf, at least during early to middle Cleveland time, was an irregular, two-tiered surface (tiers approximately coincide with the two underlying Oswego shelf-platform slope breaks) that encompassed most of the Cleveland physiographic basin in the study area (see "Physiographic Shelf Platform and Basin"). The highstand parasequences either thin toward or pinch out against the monoclinal flexure that defines the northern boundary of the half-graben-like Cleveland structure (figs. 25 and 26). The parasequences thicken across the northwest-oriented, linear, fault-controlled trough (figs. 21 through 24), indicating differential syndepositional subsidence in the trough. Apparent thinning of parasequences 2 and 3 in parts of the trough (figs. 23 and 24) is actually erosional truncation by the overlying incised-valley system.

Incised-Valley System

Cleveland parasequence 4, interpreted to be a fluvial incised-valley fill (fig. 19), differs from other parasequences described in this study by being consistently upward-fining, indicating aggradational depositional processes, and by having a regionally erosional contact with the underlying deposits. Sedimentary characteristics of the fluvial channel-fill facies from core description (Maxus Tubb "D" No. 3) include sandstone that fines upward in both grain size and in scale of sedimentary structures, coaly organic debris throughout, a rooted zone capped by a coal bed at the top of the sandy part of the channel fill, and a sideritic, nodular shale at the top of the entire channel fill (fig. 8). The channel fill incises deltaic parasequences 2 and 3 of the Cleveland highstand systems tract in the central and eastern parts of the study area where the valley fill is thickest (figs. 20 through 26) and probably also cuts into coastal plain facies of Cleveland parasequence 3 in the western part of the study area (figs. 21 through 23). Most of the sandstone composing the east-west-trending linear belts in the west (figs. 10 and 11) is the incised-valley system (fig. 21).

Cleveland fluvial deposition probably was initiated during late highstand time, but river downcutting occurred during early lowstand time when base level dropped after a rapid fall in relative sea level (Posamentier, 1988). Initially, fluvial deposits were fed directly to lowstand-shoreline and submarine-fan systems and did not accumulate in the incised valleys. The Cleveland valley fill did not aggrade until relative sea level stabilized and started to rise during early transgression. Deposition of estuarine facies may have predominated in drowned, downdip parts of the incised valley.

The incised-valley system is distributed throughout most of the study area (fig. 29) and extends eastward beyond the lower Cleveland shelf edge (= eastern Oswego shelf-platform slope break) in eastern Lipscomb and Hemphill Counties, thus forming a type 1 sequence boundary (unconformity) that extends across the Cleveland depositional shelf and into the basin. Lowstand basinal facies, which are predicted by the sequence stratigraphic model to have been deposited contemporaneously with fluvial downcutting and sediment bypass in updip coastal plain areas, do not exist within the study area but should be found farther east (basinward) in western Oklahoma. Kumar and Slatt (1984) described Cleveland submarine-fan facies composing two superimposed, lobate deposits located basinward of the underlying Oswego shelf edge in Blaine, Custer, and Caddo Counties of west-central Oklahoma (about 75 mi east of the eastern border of the study area). These deposits may be part of the basin-floor fan or lowstand-wedge complex deposited during the Cleveland lowstand, although northern and eastern sources were inferred by the authors.

The sequence boundary exists not only at the base of the valley-fill facies as an unconformity but also occurs as a relatively conformable exposure surface outside the

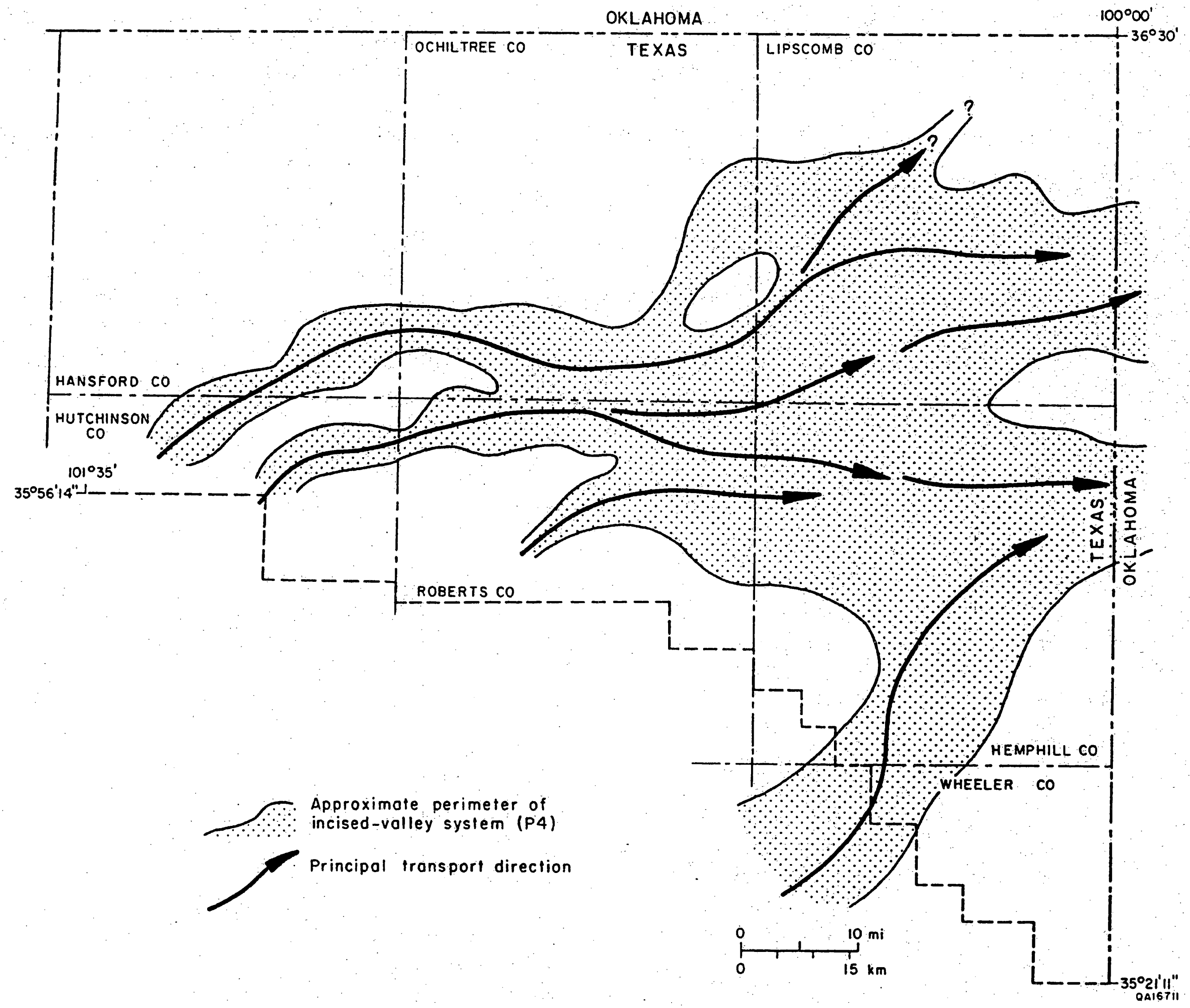

Figure 29. Areal configuration of the Cleveland fluvial system (parasequence 4) occupying the incised valley formed during middle to late Cleveland time. Fluvial transport routes represent areas of thickest incised-valley fill.

incised valley at the top of Cleveland highstand parasequence 3 and locally above parasequence 2 (figs. 20 through 26). In the Maxus Shrader No. 3 core (fig. 7), the upper part of Cleveland parasequence 3 (6,996.5 to 6,995.0 ft) contains a grayish-red, bioturbated (possibly rooted) zone in otherwise light-gray proximal delta-front sandstone. The reddish coloration, the only example in all three cores, and possibly root casts, may have been imparted by subaerial exposure of the sediment during valley incision. However, the equivalent interval (7,194 ft) in the Maxus Glasgow No. 2 core (fig. 6) shows no such evidence of exposure. Ravinement of the exposure surface (transgressive surface) during subsequent transgression may account for the apparently local preservation of incipient soil characteristics.

The lasting effects of syndepositional differential subsidence in the eastern half of the study area had less apparent influence on deposition of the incised-valley system than on that of older systems tracts, suggesting waning structural activity and a decrease in the rate of addition of accommodation, which would be expected during lowstand conditions. However, the northwest-trending, fault-controlled trough (figs. 5 and 14) was the preferred path of fluvial flow in the western part of the study area (fig. 23). The western edge of the Cleveland physiographic basin, which coincides with the underlying western Oswego shelf break, also marks the western limit of valley incision in the northwestern part of the incised-valley system (fig. 20). Moreover, the absence of valley-fill facies along the Lipscomb/Hemphill county line at the eastern border of the study area (fig. 29) indicates the presence of a contemporaneous topographic high that was probably controlled by the east-west-trending anticlinal structure separating the two Cleveland subbasins (fig. 14). An area of underlying thick Cleveland sand composing proximal delta-front facies of the highstand systems tract probably produced the relatively resistant topographic high that locally prevented valley incision in eastern Ochiltree and western Lipscomb Counties (compare fig. 10 with fig. 29).

Transgressive Systems Tract

Cleveland parasequences 5 and 6 form a retrogradational parasequence set deposited during a relative rise in sea level. These two parasequences compose the transgressive systems tract in most of the study area (figs. 19 through 26); a third upward-coarsening interval (parasequence 4a) of the systems tract was correlated locally below parasequence 5 in southern Hemphill and northwestern Wheeler Counties (fig. 25).

The lower part of parasequence 5 was cored in the Maxus Tubb "D" No. 3 well (8,056 to 8,042 ft; fig. 8); both parasequences 5 and 6 are probably represented in the Maxus Glasgow No. 2 well (7,194 to 7,171 ft; fig. 6) but are not clearly distinguishable because the well is located where both lapout at their updip limit (compare fig. 2 with figs. 20 [Ochiltree well 21] and 30). These cored intervals share many of the sedimentary and lithologic characteristics of the cored Cleveland highstand deltaic deposits, although parasequences of the transgressive systems tract are much thinner (10 to 40 ft) than those of the highstand deltaic deposits (30 to 160 ft). Parasequence 5 contains an upward-coarsening interval of laminated grayish-black prodelta shale overlain by lenticular laminated and burrowed distal delta-front facies (fig. 8); the well-developed sandstone capping the parasequence (see well log, fig. 8) is the proximal delta-front deposit. Both parasequences 5 and 6 are more intensively burrowed than the highstand deltaic deposits, recording the lower sedimentation rates of the transgressive deltaic deposits. A thin (<5 ft), high-gamma-ray black shale, interpreted to be a marine-condensed section and depicted as a maximum flooding surface in the regional cross sections (figs. 20 through 26), overlies parasequence 6 in much of the study area.

Parasequences 5 and 6 exhibit coastal onlap (figs. 21, 22, and 30), clear evidence of a rise in relative sea level during deposition of the units. Initial progradational deposition (parasequence 4a) was locally restricted to within the northeast-trending

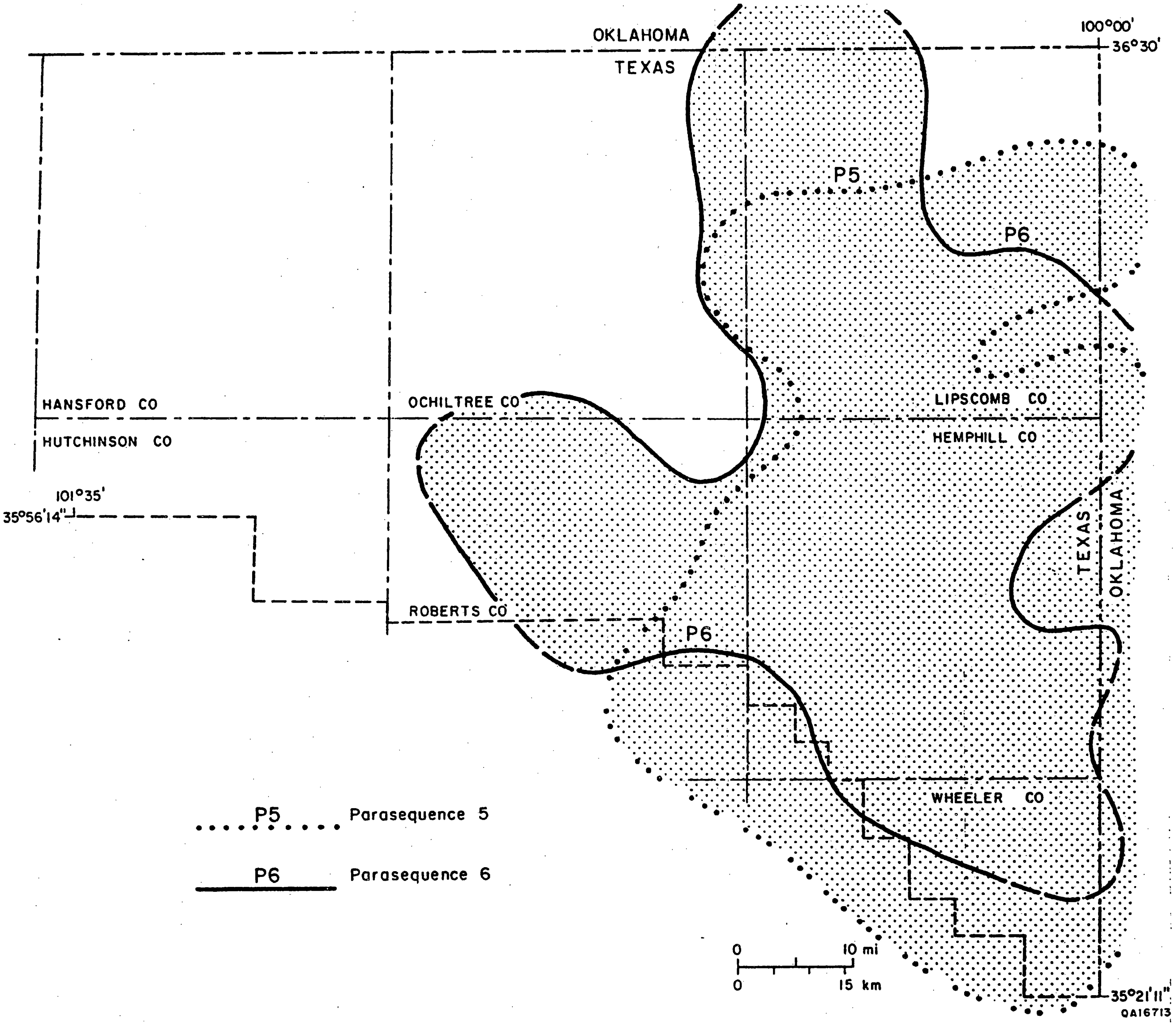

Figure 30. Areal distribution of parasequences of the Cleveland transgressive systems tract (P5 and P6).

tributary of the incised valley in southern Hemphill and northwestern Wheeler Counties (fig. 29). This area coincides with (1) the region of thickest Cleveland (fig. 5), which is within the fault-controlled trough (fig. 14), and (2) the location of the thickest valley-fill succession (fig. 25), indicating in part that this area was the most rapidly subsiding part of the study area during relative sea-level rise in middle to late Cleveland time. Therefore, this localized basinward area probably was the first to flood during initial transgression. Parasequence 5 subsequently prograded from a paleoshoreline (= lap-out position) that closely corresponded to the western perimeter of the Cleveland physiographic basin (figs. 20 through 22 and 24 through 26), but it was not deposited over the northward-shifted eastern paleohigh (near the Lipscomb/Hemphill county line) that was also present during valley-fill deposition (compare fig. 29 with fig. 30). In turn, the parasequence 6 shoreline transgressed farther inland to form an embayment extending northwestward along the fault-controlled trough (figs. 23 and 30) and northward into the Oklahoma Panhandle (figs. 20, 24 through 26, and 30). Incursion into the Oklahoma Panhandle may have been controlled by residual subsidence along the inferred northwest-trending monoclinal flexure marking the northern boundary of the Cleveland physiographic basin (fig. 15). Initial sediment accumulation during transgression, which includes some of the aggradation of the fluvial valley fill (see "Incised-Valley System"), was restricted mostly to the incised valley. Later transgressive deposition favored areas of most pronounced syndepositional subsidence (fault trough, Cleveland physiographic basin).

Systems Tracts of Upper Cleveland Formation

Parasequences 7 through 10 of the upper Cleveland were correlated throughout the study area, and their lithologies could be determined from lithologic sample logs and well-log analysis (figs. 19 through 26). However, no other geologic data were gathered for these units primarily because they do not contain potential siliciclastic reservoir rocks. The upper Cleveland divisions are largely rich in shale and carbonates, and each probably consists of several thin (<10 ft) parasequences and are thus actually parasequence sets. Two subregionally distributed, thin, high-gamma-ray, black shale intervals (depicted as maximum flooding surfaces in figs. 20 through 26) are interpreted to be marine-condensed sections and provide excellent correlation markers in the upper Cleveland. They cap upward-fining intervals of transgressive systems tracts (parasequences 6 and 8). Upward-coarsening cycles (progradational parasequence sets) are interpreted to be highstand systems tracts. Inferred sequence boundaries (top of parasequences 7 and 9) were identified by the stacking pattern of the systems tracts (fig. 19); no evidence of valley incision at the sequence boundaries was observed in the study area.

Evidence of depositional control on upper Cleveland systems tracts by differential subsidence appears mainly in the regional geometry of the two transgressive systems tracts (parasequences 8 and 10). The landward limit of parasequence 8 is close to the western edge of the Cleveland physiographic basin (figs. 20 and 21). In its updip area, parasequence 8 is restricted mainly to the southern Cleveland subbasin (figs. 23 and 24); however, the unit extends, but thins, across the structural high separating the two subbasins (figs. 25 and 26). The transgressive systems tract of parasequence 10 has shifted eastward (basinward) relative to that of parasequence 8, but its distribution is also controlled by the geometry of the Cleveland subbasins (figs. 24 through 26).

Kansas City Formation

The Kansas City interval contains five regionally correlative beds of radioactive black shale that represent marine-condensed sections, each of which contains a maximum flooding surface (figs. 4 and 20 through 26). Therefore, the Kansas City consists of several sequences. The black shale beds extend beyond the study area, probably as far shelfward as northern Kansas and southern Nebraska where Watney (1980) correlated several thin (2 to 20 ft), green to black, high-gamma-ray shale beds at the bases of cyclic, upward-shoaling successions within the Lansing–Kansas City Groups. No Kansas City systems tracts were differentiated in this Cleveland study, but distinct, correlative upward-coarsening and -fining carbonate and shale intervals record regional upward-shoaling and -deepening depositional events that are progradational and retrogradational systems tracts, respectively. In the study area, there is no evidence of river incision at potential sequence boundaries within the interval.

Differential subsidence within the Cleveland subbasins had largely ended by the time of Kansas City deposition. Kansas City strata thicken subregionally into the Cleveland fault-controlled trough; the northwestern end of the trough shows marked thickening of the unit (figs. 21 and 23), but thickened Kansas City is not evident elsewhere (figs. 22 and 24).

Source Areas of Systems Tracts

The lower and middle Cleveland Formation (highstand systems tract, incised-valley system, and part of transgressive systems tract: Cleveland parasequences 1 to 6), the relatively sandstone-rich part of the formation, compose a wedge of westerly derived siliciclastics that lie between sediments from much more distant northeastern to southeastern sources. The reason for a shift in source area to the west near the start of Cleveland deposition is unclear. However, the ubiquitous metamorphic and nongranitic plutonic rock fragments and plagioclase framework grains in highstand and incised-valley sandstones suggest local rejuvenation of mainly nongranitic terranes near the western end of the Anadarko Basin.

Marmaton Group (Undivided)

The source area for the Marmaton lowstand siliciclastics (parasequences 1 to 5), from the perspective of the areal distribution of component parasequences in the study area, is due east (fig. 27). This finding is supported by regional studies that document primary late Desmoinesian (upper Marmaton) to early Missourian sediment sources in the Ouachita foldbelt at the southeastern end of the Anadarko Basin (Visher and others, 1971; Moore, 1979; Rascoe and Adler, 1983). Local sources in the Amarillo Uplift also existed. During the late Desmoinesian at least five major deltaic/shoreface systems (Marmaton parasequences 1 through 5) in the eastern Anadarko Basin prograded westward, perhaps almost entirely across the Anadarko Basin, to the western part of the basin during a relative sea-level lowstand.

Deposits of the upper Marmaton transgressive systems tract (parasequence 6) record a gradational shift in sediment source area from the east (Marmaton lowstand deposits) to the west and southwest (overlying Cleveland highstand, incised-valley fill, and transgressive deposits). The Ouachita foldbelt to the southeast, possible source terranes to the northeast, and point sources in the northwest and southwest (fig. 27), contributed detritus to the Marmaton transgressive deposits. Difficulty in regional correlation of individual deltaic cycles within Marmaton parasequence 6 may be due to the shingling of depositional cycles that prograded from at least three different directions in the study area. The northwestern source area was probably the Sierra Grande–Apishapa Uplift in eastern Colorado (Hills, 1963); southwestern sources were the Sierra Grande Uplift of northeastern New Mexico and, more locally, the Amarillo Uplift.

According to the sequence stratigraphic model, which assumes a uniform source area for all systems tracts, the first progradational cycle during rising relative sea level after lowstand deposition should not extend as far basinward as the lowstand wedge.

Subsequent parasequences in the transgressive systems tract should backstep landward relative to the first progradational pulse. However, in the Cleveland study area the near-radial distribution of multiple source areas funneling sediment into the western end of the Anadarko Basin during a rapid rise in relative sea level (rapid addition of accommodation, whether by eustatic or eustatic/subsidence factors) in upper Marmaton time probably accounts for (1) the complete overlap, and extension beyond the western limit of progradation, of the Marmaton lowstand wedge (parasequence 1 through parasequence 5) by the transgressive systems tract (parasequence 6) (fig. 27) and (2) the unusually great relative thickness of the entire Marmaton transgressive interval.

Cleveland Formation

The lower Cleveland highstand systems tract (parasequences 1 through 3) was fed by sediments originating west to southwest of the Anadarko Basin, representing completion of the gradational shift of primary sediment transport direction from the northeast to southeast (Marmaton lowstand deposits) and multiple directions (Marmaton trangressive deposits) to the west. Designation of a western source for the lower Cleveland highstand deposits is based primarily on the westward position of inferred coastal plain deposits relative to the deltaic and marine depositional environments. Potential source areas are the Sierra Grande–Apishapa Uplift of northeastern New Mexico and southeastern Colorado, the Cimarron Arch, and the western part of the Amarillo Uplift. Extensive highstand Cleveland deltaic units in eastern Oklahoma that are probably equivalent to but areally segregated from the Texas Cleveland deltas had source areas to the south and east of the Anadarko Basin (Visher and others, 1971; Krumme, 1981).

Sediment sources for the Cleveland incised-valley system (parasequence 4) were also mostly in the west to west-southwest, with subsidiary, local point sources in the south (figs. 10, 11, and 29). West to southwest sources were probably the same as those for the Cleveland highstand systems tract and included the Sierra Grande–Apishapa Uplift of northeastern New Mexico and southeastern Colorado, the Bravo Dome of the western Texas Panhandle and northeastern New Mexico, the northwestward extension of the Panhandle volcanic terrane in the northwestern part of the Texas Panhandle (Flawn, 1956), the Cimarron Arch, and the western part of the Amarillo Uplift. The northern flank of the Amarillo Uplift immediately south of the study area provided proximal point sources of sediment to the incised-valley system. Except for the Panhandle volcanic terrane and the Cimarron Arch, these highlands were dominantly granitic, although other igneous and metamorphic lithologies were exposed in these areas during the Middle to Late Pennsylvanian (Flawn, 1956; Hills, 1963).

The petrology of Cleveland sandstones indicates that principal source terranes for the incised-valley fill (table 4) and the underlying highstand systems tract (tables 2 and 3) were at least in part metamorphic (muscovite-rich phyllite and schist) and plutonic (quartz diorite). Surprisingly, potassium feldspar grains, indicators of a granitic source, are absent or few in the core samples, although plagioclase content in sandstones is moderately high (average of 12.8 percent). However, petrographic evidence suggests that some potassium feldspar was dissolved/replaced in the diagenetic environment: (1) some calcite-replaced framework grains contain remnant laths of orthoclase, (2) presence of kaolinite-replaced grains, (3) existence of secondary pores from which the grain has been totally dissolved, and (4) presence of ankerite and calcite totally replacing grains. Item (1) indicates orthoclase had been replaced, whereas item (2) indicates that a feldspar had been replaced. Items (3) and (4) only establish that some kind of grain had been replaced, but the grains were probably feldspars. Depth of burial of the Cleveland sandstone samples (7,000 to 8,100 ft) may have induced dissolution of potassium feldspar grains (Land and others, 1987) that were originally more abundant at the time of deposition. Moreover, most arkosic detritus was probably restricted to the southern part of the study area (table 1), where short northward transport distances from the granitic Amarillo Uplift and synorogenic sediment trapping along the more rapidly subsiding edge of the Amarillo fault block would allow preservation of this nonresistant mineral. The core samples are from the northern part of the study area, and sediment transport routes were primarily east-west. The relative abundance of plagioclase grains attests to the existence of a significant nongranitic plutonic source terrane.

Sediment that fed the thin deltaic intervals of the Cleveland transgressive systems tract (parasequences 5 and 6) was derived from multiple sources: (1) the Amarillo Uplift to the south, (2) western to southwestern sources drained by poorly defined fluvial systems that flowed seaward along the fault-controlled trough, and (3) probable sources to the north and northeast. Evidence for northern and northeastern sources is equivocal, but they are suggested by the areal configuration of the systems tract in those areas (fig. 30). The upward thinning of systems tracts and the trend of upward decreasing numbers of discernible parasequences per systems tract in the upper Cleveland (fig. 19) offer stronger evidence that a transitional shift in source area, probably back to the distant, generally eastern, source of early Marmaton time, occurred during deposition of this trangressive systems tract.

The source areas of the upper Cleveland siliciclastics (parasequences 7 to 10) were much more distant than those of the lower and middle Cleveland. Evidence includes the marked thinning of systems tracts and component parasequences, dominance of shale, and upward-increasing carbonate content within the entire section. Decrease in relief of more local source terranes is not an entirely viable explanation for these stratal characteristics; Missourian fan-delta deposition off the Amarillo Uplift (Dutton, 1982) indicates continued synorogenic sedimentation at least in the southern part of the region. The highstand and transgressive systems tracts are composed of the distal toes of progradational cycles that were probably fed by siliciclastic sediment sources in the Ouachita foldbelt and Arbuckle Mountains, the dominant regional sources for the Anadarko Basin during the Missourian (Moore, 1979; Rascoe and Adler, 1983).

Kansas City Formation

Kansas City shale and minor siltstone and sandstone were also probably derived from distant, generally eastern sources, although direct evidence is not available. However, each of the component sequences of the Kansas City are much thinner than the sequence composing the Marmaton and lower to middle Cleveland siliciclastics (sequence 1 of figs. 20 through 26), which were in part derived from proximal sources to the west. The trend of increasing distance from source area and possible decreasing relief of some proximal source terranes that started in upper Cleveland time continues through the Kansas City interval.

CLEVELAND FORMATION AND LATE PENNSYLVANIAN EUSTASY

The assemblage of conodonts, particularly several terminal species of *Neognathodus* (table 5), from the uppermost Marmaton Group marine-condensed section indicates that this stratum is latest Desmoinesian in age. From the conodonts and the distinctive associated fauna within the condensed section, the interval can be precisely correlated with the exposed Nuyaka Creek Black Shale Bed of the upper Holdenville Formation of Oklahoma and of the Lost Branch Formation of Kansas; additionally, the condensed section is equivalent to the unnamed black shale bed of the East Mountain Shale exposed in North-Central Texas (D. R. Boardman II, personal communication, 1991). On the basis of this correlation with the well-studied Upper Pennsylvanian Midcontinent cyclothemic successions, deposition of the uppermost Marmaton Group condensed section during a relative sea-level highstand can be determined as being coeval with a major maximum transgressive phase ("Lost Branch major cycle") that occurred throughout the North American Midcontinent (Heckel, 1986; Boardman and Heckel, 1989). The continental-scale extent of eustatic rise was thus probably a major control on relative sea level during latest Marmaton and Cleveland time, although as described above, subregional tectonic effects also markedly influenced relative sea-level change in the western Anadarko Basin during the Late Pennsylvanian.

REGIONAL HYDROCARBON DISTRIBUTION

Major Cleveland oil and gas fields occur primarily in Ochiltree and Lipscomb Counties (fig. 31, tables 7 and 8). In this two-county area, subsea depth to the top of the Cleveland Formation is about 3,600 ft (west) to 5,400 ft (east); depth of the top of the Cleveland below land surface is about 6,600 ft (west) to 8,000 ft (east). The hydrocarbon trap styles of most of the fields are either combination types (stratigraphic and structural) or stratigraphic (both lithofacies and porosity/permeability pinch-outs) (table 9). Purely structural traps are associated with fault displacement and fault-related folds along the two major fault zones in southwestern Ochiltree (Lips fault) and northern Hutchinson Counties (fig. 31). Combination traps typically involve pinch out of reservoir facies within generally southeast-plunging anticlines (structural noses) in central Ochiltree and Lipscomb Counties. Cleveland net-sandstone trends are largely parallel to the anticlines (compare fig. 10 with fig. 31). An areal coincidence of sandstone trends and folds may in fact compose many of the reservoirs. Most of these folds are local structures that are no more than several miles long (National Petroleum Bibliography, 1965). The Camrick–Perryton Arch of Ochiltree County (fig. 13) is the largest of these structures.

Table 7. Producing Cleveland gas fields of the Texas Panhandle.[1]

Field	Number of wells[2]	Cumulative production (Mcf)[3]	Discovery year
Hansford Co.			
Horizon* (M)	14	16,153,378 (N)	1957
Morse	1	822,163	1973
Morse, N	3	2,708,153	1978
Spearman Park	1	3,078,419 (N)	1959
Twin	1	131,891 (N)	1958
Hemphill Co.			
Allison Parks	0	17,131	1984
Humphreys	1	190,152	1980
Mathers	2	449,193	1978
Hutchinson Co.			
Hutchinson, N (M)	4	3,829,319 (N)	1956
Shirley	8	2,910,539 (N)	1969
Lipscomb Co.			
Boker	0	99,940	1977
Bradford	125	88,083,149 (N)	1959
Bradford, N	0	226,048 (N)	1964
Bradford, SE	1	237,640	1977
Follett, W	1	176,611	1976
Higgins, W	1	105,896	1975
Horse Creek, NW	11	4,756,449	1973
Kiowa Creek	3	2,888,069	1979
Lipscomb	22	10,526,138 (N)	1959
Lipscomb, S	0	0 (N)	1961
Lipscomb, SW	56	28,903,453	1975
Mammoth Creek, N (M)	82	51,787,606 (N)	1961
Mammoth Creek, NW	1	366,089	1988
Mammoth Creek, S	0	0 (N)	1968
Patti Cake	0	1,033,789 (N)	1958
Peery* (M)	6	1,454,367 (N)	1962
Peery, N	1	706,520 (N)	1964
Peery, SE	3	449,660	1980
Skunk Creek*	0	32,468	1984
Trenfield	11	2,870,401	1983
Wolfcreek	0	0 (L)	1979
Ochiltree Co.			
Dude Wilson	4	2,087,763 (N)	1900
Dutcher*	3	970,959 (N)	1959
Ellis Ranch	142	123,269,991 (N)	1958
Farnsworth	4	1,939,563 (N)	1961
Farnsworth, SE	12	7,035,814 (N)	1963
Lips (M)	3	2,398,693 (N)	1960
Northrup (M)	40	17,365,000 (N)	1959
Perryton, W*	0	0 (L)	1986
R.H.F.	2	1,051,457 (N)	1958

Table 7 (cont.)

Field	Number of wells[2]	Cumulative production (Mcf)[3]	Discovery year
Ochiltree Co.			
Stekoll*	0	0 (N)	1960
Turner	0	2,846	1981
Waka, W	4	2,788,768	1980
Wamble	0	9,036 (N)	1960
Roberts Co.			
Lips, W (M)	32	28,120,678 (N)	1959
Sherman Co.			
Coldwater Ranch	1	228,113	1987

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[1] Data source: Railroad Commission of Texas (1989)
[2] Total number of producing wells in 1989 in entire field (all counties)
[3] Production to 1/1/90
* = Associated field
(L) = Designated field but has not produced as of 1/1/90
(M) = Multiple counties
(N) = Gas production data prior to 1970 not included in total

Table 8. Producing Cleveland oil fields of the Texas Panhandle.[1]

Field	Number of wells[2]	Cumulative production (bbl)[3]	Discovery year
Hansford Co.			
Hansford, N	3	207,303	1959
Horizon (M)	161	9,142,181	1957
Horizon, NW	1	105,326	1962
Morse	0	2,452	1973
Hemphill Co.			
Allison Parks	0	647	1985
Glazier	0	658	1984
Horse Creek, SE	1	8,954	1975
Parsell	0	1,817	1980
Riley	1	91,558	1967
Urschel	0	1,270	1983
Lipscomb Co.			
Bradford	10	124,807	1959
Bradford, SE	0	3,311	1961
Carroll	0	14,183	1981
CNB	0	7,961	1980
Follett, NW	0	2,913	1963
Frass	1	37,375	1960
Glazier, NW (M)	2	15,812	1978
GEX	0	15,429	1957
Higgins, W	2	91,327	1966
Horse Creek, NE	0	2,136	1983
Kiowa Creek (M)	0	22,238	1960
Lipscomb	35	682,319	1958
Lipscomb, SE	2	34,881	1983
Lipscomb, SW (M)	3	50,190	1975
Mammoth Creek, N	10	164,749	1963
Mammoth Creek, S	0	887	1968
Patti Cake	0	2,033	1958
Peery (M)	25	916,522	1962
Rader	0	5,285	1975
Skunk Creek	5	86,277	1982
Trenfield	3	10,741	1986
Turner (M)	5	38,407	1982
Warren	1	4,877	1983
Wassel	1	14,354	1981
Ochiltree Co.			
Booker, SW	1	16,586	1988
Buler, N	21	500,734	1973
Dude Wilson	0	12,347	1982
Dutcher	57	2,444,053	1959
Ellis Ranch	4	22,379	1976
Ellis Ranch, NE (M)	0	49,818	1961
Farnsworth, SE	1	60,069	1978
Lone Butte (M)	30	1,281,367	1979

Table 8 (cont.)

Field	Number of wells[2]	Cumulative production (bbl)[3]	Discovery year
Ochiltree Co. (cont.)			
Northrup	1	756	1986
Pan Petro	4	109,557	1974
Paul Harbaugh (M)	3	268,751	1957
Perryton	0	323,243	1959
Perryton, W	13	427,375	1958
Schroeder	0	2,469	1978
Share, SE	1	9,124	1976
Stekoll	0	52,310	1960
Wagner	0	1,167	1984
Waka, W	2	15,240	1960
Roberts Co.			
Hodges	1	13,864	1978
Lips (M)	2	67,425	1958
Lips, W	1	36,037	1958
Morrison Ranch	0	18,597	1976

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[1] Data source: Railroad Commission of Texas (1989)
[2] Total number of producing wells in 1989 in entire field (all counties)
[3] Production to 1/1/90
(M) = Multiple counties

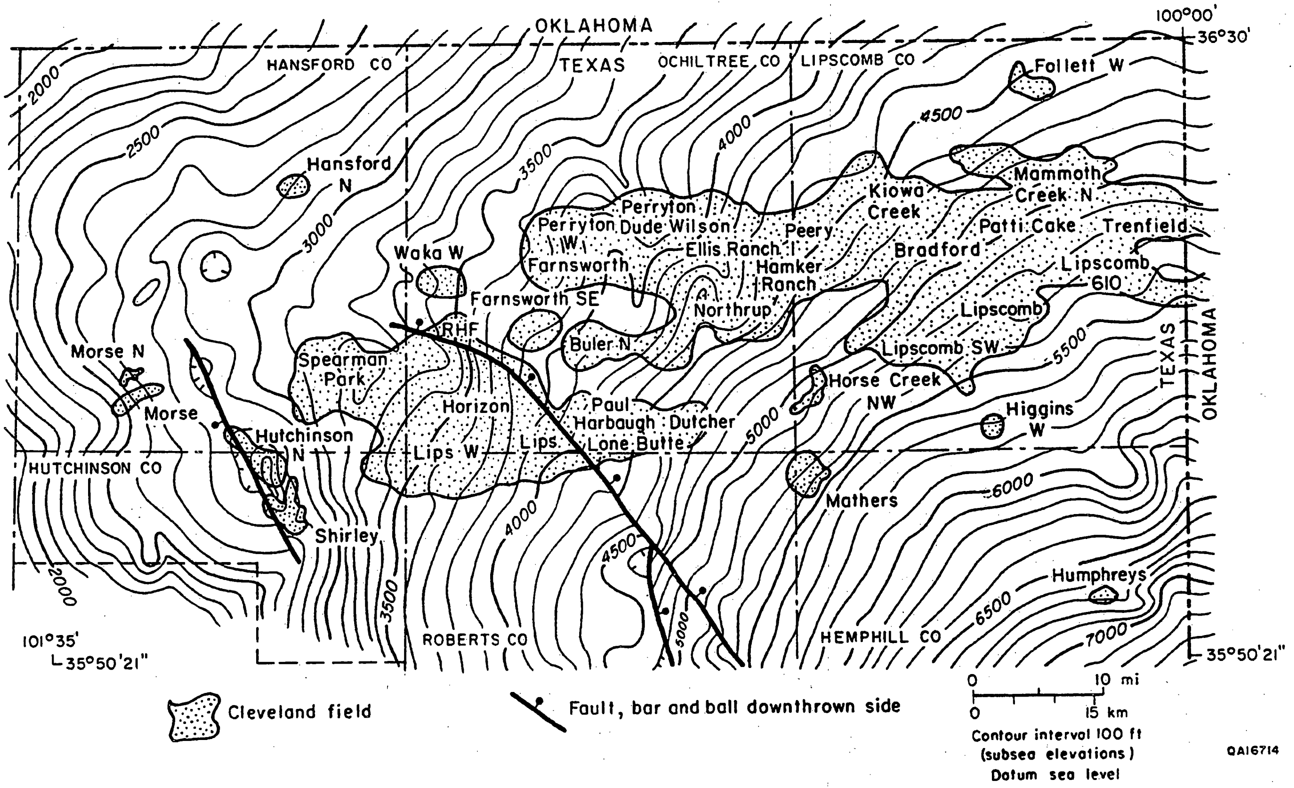

Figure 31. Map of major Cleveland hydrocarbon fields superimposed on structure-contour map of top of Cleveland. Although the Cleveland is absent in parts of Hansford and Hutchinson Counties (fig. 5), the top-of-Cleveland correlation marker extends into these areas. Precise boundaries of individual Cleveland fields are not depicted because boundaries overlap or adjoin in most areas. Field locations were determined from unpublished Texas Railroad Commission data. All fields except Morse, Mathers, Higgins West, Humphreys, and Follett West had produced at least 1 Bcf and/or 1 Bcf-equivalent (oil) as of January 1, 1990 (tables 7 and 8). Hamker Ranch (Cleveland) field is not listed in the Railroad Commission of Texas (1989) data but is included on the map because it is a field name used by Maxus Exploration Company, a major Cleveland gas producer in the Texas Panhandle. Production totals for Lipscomb and Lipscomb 610 fields were combined and listed as Lipscomb field in tables 7 and 8. See table 9 for description of trap types for many of these fields.

Table 9. Trap types of selected Cleveland oil and gas fields.

Field	Trap type	Net pay (ft)	Sources
Bradford	Combination—stratigraphic associated with structural nose	20	Best (1961), RRC files[2], Stevens and Stevens (1960)
Dude Wilson	Combination—stratigraphic associated with structural nose (Upper Morrow)[1]	16	RRC files[2], Stevens and Stevens (1960)
Dutcher	Data unavailable	14	Stevens and Stevens (1960)
Ellis Ranch	Combination—stratigraphic associated with structural nose	45	Britt (1961), RRC files[2]
Farnsworth	Stratigraphic (Oswego)[1]	14	Stevens and Stevens (1960)
Hansford N	Stratigraphic (Cherokee)[1]	6	Stevens and Stevens (1960)
Horizon	Combination—stratigraphic associated with structural nose	?	RRC files[2], Stevens and Stevens (1960)
Hutchinson N	Structural—series of closures aligned along NW-trending anticline	12	Ridgell (1961), Stevens and Stevens (1960)
Kiowa Creek	Combination—stratigraphic associated with structural nose (Upper Morrow)[1]	?	RRC files[2]
Lips	Combination—stratigraphic associated with NW-trending anticline on SW side of fault separating field from Paul Harbaugh field	30	Brashear (1961), Stevens and Stevens (1960)
Lips W	Stratigraphic	16	Stevens and Stevens (1960), RRC files[2]
Lipscomb	Stratigraphic—updip porosity and permeability pinch-out	10	Eckstrom (1961), RRC files[2], Stevens and Stevens (1960)
Mammoth Creek N	Combination—stratigraphic associated with structural nose	12	RRC files[2]
Northrup	Data unavilable	24	Stevens and Stevens (1960)
Patti Cake	Data unavilable	29	Stevens and Stevens (1960)
Paul Harbaugh	Combination—stratigraphic associated with faulted anticline (Morrow)[1]	14	Stevens and Stevens (1960)
Perryton W	Stratigraphic (Des Moines and Marmaton)[1]	19	Stevens and Stevens (1960)
Twin	Stratigraphic (Des Moines)[1]	10	Stevens and Stevens (1960)

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[1] Trap type of nearest stratigraphic unit (in parentheses) underlying the Cleveland for which data are available

[2] RRC files = unpublished hydrocarbon-production records of the Texas Railroad Commission

Hydrocarbons are trapped primarily in upstructure stratigraphic or porosity/permeability terminations of fluvial sandstone of the Cleveland incised-valley fill and of proximal delta-front sandstones at the tops of Cleveland highstand parasequences 2 and 3. Sandstones of parasequences 2 and 4 are the primary reservoir rocks in the Cleveland fields of easternmost Ochiltree County and all of Lipscomb County (fig. 24, fields between Ochiltree well 13 and Lipscomb well 1; fig. 25, fields between Lipscomb wells 8 and 12; and fig. 26, fields between Lipscomb wells 16 and 19), whereas pinch-outs of deltaic facies of parasequences 2 and 3 compose traps in central Ochiltree County (fig. 23, fields between Ochiltree wells 4 and 6). Fields in the southwestern part of the producing area (Dutcher, Paul Harbaugh, Lone Butte, Lips, Lips West, Horizon, Spearman Park, Hutchinson North, Shirley, Morse, and Morse North) produce from the thick sandstone of the incised-valley system (parasequence 4) (fig. 21, fields between Hansford well 4 and Roberts well 9, and fig. 23, fields between Ochiltree well 8 and Roberts well 1). Interestingly, the Cleveland Formation of these southwestern fields produces mainly oil on the eastern side of the Lips fault and mainly gas on the western, upthrown side (tables 7 and 8). The anomalous Hansford North field in northeastern Hansford County (fig. 31) exists in an area of no net Cleveland sandstone (fig. 10); "Cleveland" sandstone in this field is actually probably part of the upper Marmaton transgressive systems tract (parasequence 6) that extends into this area (fig. 27).

SUMMARY AND CONCLUSIONS

Low-permeability (generally <0.10 md) sandstones of the Upper Pennsylvanian (lower Missourian) Cleveland Formation compose major gas-producing reservoirs in the western Anadarko Basin of the northeastern Texas Panhandle. Existing fields of the Cleveland gas play are restricted to folded and minor faulted zones that have deformed the northern occurrences of Cleveland sandstones in Ochiltree and Lipscomb Counties. Regional characterization of the lithostratigraphy, structure, depositional systems, and sequence stratigraphy of the Cleveland Formation provides a basis for more accurate subregional and reservoir-scale geologic study. The ability to predict and explore for other possible Cleveland pay zones outside this region has been hampered by the very limited published information regarding the regional and subregional lithostratigraphic, structural, and depositional architecture of the formation. The areal coincidence of abundant sandstone, vertically proximal potential source rock underlying the Cleveland reservoir facies (black shale marker bed at the top of the Marmaton Group and distal delta shales of the Marmaton and lower Cleveland), and potential trap-producing structures and facies pinch-outs throughout much of the western Anadarko Basin indicate the possibility for new field discoveries outside the known producing region.

The Cleveland Formation is a well-constrained lithostratigraphic division, being bounded by regionally continuous high-gamma-ray black shale marker beds that extend beyond the study area to the north and at least as far east as west-central Oklahoma and probably well beyond in the Anadarko Basin. The Cleveland section contains mostly siliciclastics between the Amarillo Uplift and the northern part of the study area, where the sandstones thin markedly and grade into thin shale intervals between much thicker, massive limestone facies of the Kansas Shelf. To the south, Cleveland strata interfinger with wedges of granite wash along the northern flank of the Amarillo Uplift. Eastward toward the deep Anadarko Basin, the thickening formation becomes shalier.

Reservoir sandstones originated in proximal delta-front and fluvial depositional environments. The lower to middle Cleveland comprises stacked, upward-coarsening deltaic intervals that prograded eastward and were fed by fluvial systems that had sediment sources west of the Anadarko Basin. These successions in cores can be divided into prodelta, distal delta-front, and proximal delta-front facies. A regional fluvial channel fill incises the uppermost deltaic cycles in most of the study area; incision is inferred to have occurred during a sudden drop in regional base level.

Distinctive trends of Cleveland thickness variation record penecontemporaneous structural elements that greatly affected sediment dispersal and accumulation patterns. Areas of thickest Cleveland (as much as 590 ft) mark a paleophysiographic basin in most of Lipscomb and Hemphill Counties that was formed by syndepositional faulting and localized downwarping along a monoclinal flexure at its southern and northern borders, respectively. The basin was the site of primary sand accumulation during Cleveland time. A generally east-west-trending paleohigh within a broad physiographic shelf platform updip to the west separates Cleveland siliciclastic deposits (in the south) from coeval carbonate facies (in the north). The Cleveland depositional shelf edge overlies a pronounced slope break in the Oswego shelf platform and marks the basinward limit of Cleveland delta progradation. Both the Oswego and Cleveland slope breaks were formed, and their geomorphic expression sustained, by differential subsidence. Structural activity during Cleveland time is in part an expression of the Pennsylvanian orogenic episode that affected most of the Anadarko Basin and surrounding highlands.

The siliciclastic interval between the Oswego Limestone and the Kansas City Formation can be divided into well-defined parasequences/parasequence sets (P) and systems tracts composing three sequences (S1 through S3). Sequence 1 (S1) includes the Marmaton Group (undivided) and the lower half to two-thirds of the Cleveland in most of the western Anadarko Basin. Marmaton P1 through P6 overlie a type 1 sequence boundary that coincides with the top of the Oswego Limestone. P1 through P5 represent a series of westward-prograding, delta and/or shoreface systems deposited during a relative sea-level lowstand. Subsequent retrogradation of deltaic/shoreface systems during rising relative sea level is recorded in Marmaton P6. A regional, fossiliferous condensed section (base-of-Cleveland marker bed) occurs at the top of this transgressive systems tract or straddles the boundary (maximum flooding surface) between the Marmaton transgressive systems tract and the overlying lower Cleveland highstand systems tract. Cleveland P1 through P3 form generally sandstone-bearing deltaic cycles that prograded eastward during a relative sea level maximum. The top of P3 and locally of P2 is a regional erosional surface (type 1 sequence boundary) created by incision of a westerly sourced fluvial system (P4, incised-valley system) during a rapid fall in relative sea level. Sandstones of Cleveland P2 through P4 compose the Cleveland reservior facies in the northern part of the study area. A relative sea-level rise followed, allowing aggradation of the valley fill and formation of the overlying retrogradational parasequence set that includes P5 and P6. Component systems tracts of the upper Cleveland (P7 through P10) and Kansas City Formations are thin and were dominated by carbonate and shale deposition, probably at the distal margins of progradational cycles sourced far to the east or southeast.

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APPENDIX: Wells used in cross sections in this report. (See fig. 2 for index of cross-section locations.)

Hansford County

Well no.	Company	Lease
1	Drilling & Exploration Co., Inc.	#1 Cator
2	Western States Producing Co.	#1 Rafferty
3	Texaco	#1 V.P. Quible Gas Unit
4	Roy Furr	#1 George M. Whitson
5	Southern California Petroleum Co.	#1 Yanda
6	Phillips Petroleum Co.	#2 Meek "A"

Hutchinson County

Well no.	Company	Lease
1	Claro, Inc.	#2 M.A.T. Petroleum "A"
2	Page Petroleum, Inc.	#1 Brainard

Ochiltree County

Well no.	Company	Lease
1	Shell Oil Co.	#1 S.R. George
2	Gulf Oil Corp.	#3 C.E. Haar
3	Alpar Resources, Inc.	#1-24 Carnes
4	May Petroleum, Inc.	#1 Spicer
5	Horizon Oil & Gas of Texas	#2-17 Bruhlman
6	Sinclair Oil & Gas Co.	#1 J.W. Jines
7	Maxus Exploration Co.	#3 W. Paul Shrader
8	Shamrock Oil & Gas Corp.	#1 C.P. Dickinson "A"
9	Maxus Exploration Co.	#2 Clem G. Flowers
10	H & L Operating Co.	#1 Sell
11	Samedan Oil Corp.	#1 Fagg
12	C & K Petroleum	#1 Altmiller
13	Cleary Funds, Inc.	#1-913 Schoenhals
14	Paul Haywood	#1 Kay Nell Hamker Trust
15	Pan American Petroleum Corp.	#1 Parsell Unit "B"
16	Amarillo Oil Co.	#1 Cole
17	Falcon Petroleum Co.	#1 O.C. Rogers
18	Horizon Oil & Gas Co.	#3-20 Sellers
19	H & L Operating Co.	#1 Pshigoda
20	Diamond Shamrock Corp.	#3 Carl Ellis "D"
21	Diamond Shamrock Corp.	#2-759 ODC "A"
22	Roy Furr et al.	#1 Dodson
23	TXO Production Corp.	#1 Daniel "E"
24	Stekoll Panhandle Ltd. Partnership	#1-123 Albert McGarraugh
25	Shamrock Oil & Gas Corp.	#1 Dale McLain
26	Hamilton Brothers Ltd.	#1-128 J.E. Brownlee

Roberts County

Well no.	Company	Lease
1	Atlantic Richfield Co.	#3 Killebrew
2	Hawkins Oil & Gas	#1-1 Tolbert

Roberts County (cont.)

Well no.	Company	Lease
3	Glenn McCarthy, Inc.	#1 J.D. Lard
4	MacDonald Exploration, Inc.	#1 Rasor
5	Gulf Oil Corp.	#1 Ida Clark et al. "A"
6	Pan American Petroleum Corp.	#1 Ben A. Hill
7	Sun Oil Co.	#1 Marjorie Campbell
8	Pan American Petroleum Corp.	#1 J.B. Waterfield "D"
9	Brooks Hall	#1 Conrad
10	Diamond Shamrock Corp.	#1-168 Warren B. Parsell "I"
11	MacDonald Exporation, Inc.	#1-30 Morrison "A"
12	E.B. Clark Drilling Co.	#1 Morrison
13	E.B. Clark Drilling Co.	#1 Inez Carter
14	Statex Petroleum Corp.	#1-1 T. Boone Pickens
15	Honolulu Oil Corp.	#1 Osborne Ranch
16	C.E. Lee, Inc.	#1 D.D. Payne
17	Amax Petroleum Corp.	#2-8 Payne
18	Pan American Petroleum Corp.	#1 Chambers

Lipscomb County

Well no.	Company	Lease
1	Diamond Shamrock Corp.	#1-558 W.C. Merydith "D"
2	Diamond Shamrock Corp.	#1 Gaston "D"
3	Donald C. Slawson	#1-294 Good
4	Yucca Petroleum Co.	#1-147 Parker Estate
5	Mewbourne Oil Co.	#1 Weber
6	Cotton Petroleum Corp.	#1 Latham
7	Shamrock Oil & Gas Corp.	#1 Hazel Weinett
8	ARCO Oil & Gas Co.	#2 Loesch Unit
9	Sun Oil Co.	#1 Schultz
10	TXO Production Corp.	#1 Webb "D"
11	K & H Operating Co.	#1 C.C. Freeman
12	Hoover & Bracken, Inc.	#1 Popham
13	H & L Operating Co.	#1 Sperry
14	Petroleum, Inc.	#1 Mason
15	Cominco American	#5 Stuart Ranch
16	Search Drilling Co.	#1-967 Ballentine
17	Slagter Production Co.	#1 Trenfield
18	Humble Oil & Refining Co.	#C-1 W.D. Price
19	Woods Petroleum Corp.	#522-A Landers "E"
21	Amarillo Oil Co.	#1 Fritzlen Unit
22	Mobil Oil Corp.	#6 Olive T. Jones
23	Mewbourne Oil Co.	#4 Peery
24	Hall-Jones Oil Corp.	#1-A H.L. King
25	Cotton Petroleum Corp.	#1 Bradford "B"
26	Scarth Oil & Gas Co.	#1-689 Piper
27	Humble Oil & Refining Co.	#B-2 Schultz
28	Diamond Shamrock Exploration Co.	#2-609 Augusta Walton
29	Humble Oil & Refining Co.	#1 J.B. Doyle
30	El Paso Natural Gas Co.	#1 Kelln
31	Union Oil Company of California	#1-109 Babitzke

Lipscomb County (cont.)

Well no.	Company	Lease
32	Bracken Energy	#1-73 Imboden
33	Cambridge & Nail	#1 Barton

Hemphill County

Well no.	Company	Lease
1	Monsanto Co.	#1 Brainard
2	Humble Oil & Refining Co.	#1 R.A. Flowers
3	Dyco Petroleum Corp.	#2-36 J.W. Campbell
4	Kerr-McGee Corp.	#60-1 Locke
5	Humble Oil & Refining Co.	#1 Cecil Gill
6	Sun Oil Co.	#1 O.V. Bailey
7	Phillips Petroleum Co.	#4 Kelley-B
8	Diamond Shamrock Corp.	#1-70 Lester B. Urschel
9	Mobil Oil Corp.	#20 L.B. Urschel
10	TXO Production Corp.	#A-1 Newton
11	Diamond Shamrock Corp.	#7 Billy Jarvis & Sons
12	HNG Oil Co.	#3 Hoover
13	Getty Oil Co.	#1 Yarnold
14	Woods Petroleum Corp.	#26-1 Waterfield
15	Clarcan Petroleum Corp.	#1 Fillingim
16	Humble Oil & Refining Co.	#1 C.G. Newcomer
17	Phillips Petroleum Co.	#2 Jones "N"
18	Phillips Petroleum Co.	#1 McQuiddy "A"
19	Amarex, Inc.	#1-130 Kritser
20	Mesa Petroleum Co.	#1-64 Henderson
21	Earl T. Smith & Associates, Inc.	#12 Bowers
22	Earl T. Smith & Associates, Inc.	#6-7 Bowers
23	Kerr-McGee Corp.	#1-6 Kiker
24	Malouf Abraham	#2 Hext
25	Internorth, Inc.	#10-1 Lockhart
26	Gulf Oil Exploration & Production Co.	#3-198 Isaacs
27	Diamond Shamrock Corp.	#1 David Quentin Isaacs, Sr.
28	Sun Oil Co.	#1 Studer
29	Philcon Development Corp.	#2 Humphreys
30	Cotton Petroleum Corp.	#2 Marsh

Wheeler County

Well no.	Company	Lease
1	Tom F. Marsh	#1-36 Hefley
2	Ferguson Oil & Gas	#1 Quail Creek Ranch
3	Arkla Exploration Co.	#1-29 Boydston
4	Arkla Exploration Co.	#1-1 Kiker
5	Pioneer Production Corp.	#1-39 Johnnie Reed
6	HNG Oil Co.	#1-69 Atherton
7	Hunt Energy	#1-57 Bryant