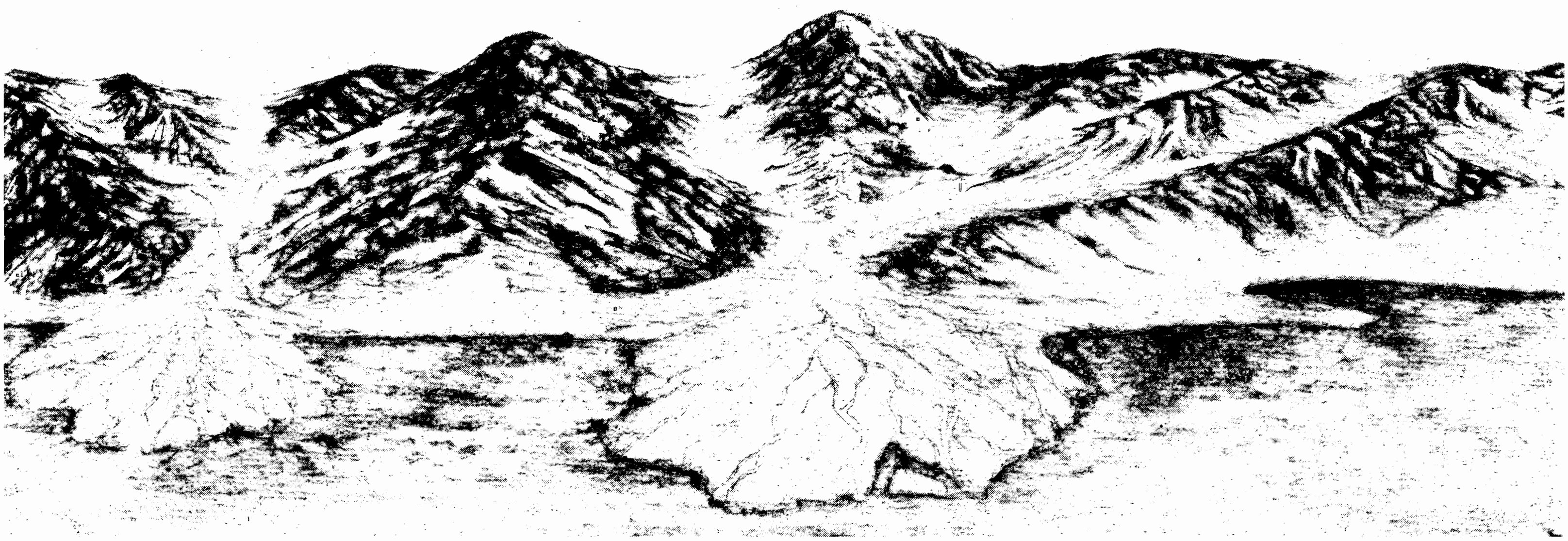
REPORT OF INVESTIGATIONS NO. 102



LOWER PERMIAN FACIES OF THE PALO DURO BASIN, TEXAS:

Depositional Systems, Shelf-Margin Evolution Paleogeography, and Petroleum Potential

C. Robertson Handford
assisted by Paul E. Fredericks

Bureau of Economic Geology
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ABSTRACT

Lower Permian (Wolfcampian) strata of the Palo Duro Basin consist of thick, terrigenous clastic and carbonate facies that were deposited in (1) fan-delta, (2) high-constructive delta, (3) carbonate shelf and shelf-margin, and (4) slope and basinal systems. Through Early Permian time, terrigenous detritus was eroded from surrounding highlands and transported by fluvial processes into the Palo Duro Basin. On the Amarillo Uplift and Bravo Dome, exposures of Precambrian basement yielded large quantities of arkosic sand and gravel (granite wash) that were deposited in progradational fan-delta systems. Concomitantly, high-constructive deltas transported subarkosic sand and mud into the southeastern Palo Duro Basin from the Wichita Uplift, or the Ouachita tectonic belt in Texas, or from both areas.

During earliest Wolfcampian time, high-constructive deltas prograded westward beyond the shelf margin into deep, open marine water. As a result, thick (200 ft) delta-front sands were deposited. By middle Wolfcampian time, the supply of terrigenous sediment was reduced and shelf margins had prograded far into the basin. Deltas were restricted to the shallow shelf behind the shelf margin where thin (50 ft) delta-front sands accumulated.

A carbonate bank and shelf-margin complex, probably composed of calcareous algae, foraminifers, and sponges, was present seaward of delta systems and faced southward into the Midland Basin. Thicknesses of stratigraphic sequences indicate that shelf-margin complexes probably stood approximately 200 to 400 ft (60 to 120 m) above the basin floor.

Basinward termination of shelf-margin strata is sharp in many places, giving rise to thick basinal and slope shales and dark-colored micritic limestones. Lenticular, basinward-thickening accumulations of shale occur along shelf margins in slope or submarine fan-head feeder channels that served as major pathways for clastic input to the deep basin. Feeder channels occur near seaward limits of delta lobes, which suggests that most deep-water sediment was derived from delta systems.

Interplay between delta-lobe advances and episodes of carbonate bank development provided a mechanism for shelf-margin progradation. As deltas prograded across shallow-shelf environments into shelf-margin terrain, carbonate productivity was reduced, and large quantities of fine-grained deltaic sediment were carried into the basin by feeder channels. As a result of increased terrigenous sedimentation, thick sediment wedges, or submarine fans, were built across the slope and the basin. Eventually, delta lobes were abandoned, clear-water conditions returned, and carbonate productivity increased. Coalescing carbonate banks accreted basinward over slope wedges and formed a new shelf margin seaward of the previous shelf margin. In contrast to highly progradational shelf margins in eastern Palo Duro Basin, western shelf margins are mainly aggradational. No major delta systems were present to furnish large quantities of sediment needed for development of thick slope wedges. Consequently, western shelf margins were not able to prograde significantly.

Repeated cycles of slope-fan sedimentation followed by carbonate shelf-margin progradation quickly filled the Palo Duro Basin. By the end of Wolfcampian time the basin was transformed from a relatively deep basin into a wide, peritidal shelf environment.

Potential hydrocarbon reservoirs occur in shelf-margin carbonates, delta-front sandstones, and fan-delta arkoses. Zones of porous (greater than 10 percent) dolomite are concentrated near shelf margins and have configurations similar to productive Lower Permian shelf-margin trends in New Mexico. Delta-front sandstones (log-computed porosity of 18 to 25 percent) are similar to producing deltaic sandstones of Morris Buie-Blaco Fields in North-Central Texas. Porous (18 percent) fan-delta sandstones along the south flank of the Amarillo Uplift may form reservoirs similar to that of the Mobeetie Field on the north side of the Amarillo Uplift in Wheeler County, Texas.

Potential hydrocarbon source beds occur in slope and basinal environments. Total organic carbon generally ranges from 1 to 2.3 percent by weight and averages 0.589 percent by weight.

INTRODUCTION

The Palo Duro Basin in the Texas Panhandle is a shallow cratonic basin bounded on all sides by prominent uplifts and stable shelf areas (fig. 1). Pennsylvanian and Permian strata constitute most of the sedimentary fill and together are approximately 10,000 ft (3,000 m) thick. Lower Permian (Wolfcampian) strata consist of carbonate and terrigenous clastic sedimentary rocks that preserve paleo-environments ranging from deep marine (~400 ft deep) to shallow shelf and delta platform. Facies prograded through time, and sediments rapidly filled the basin, thus transforming it into a wide, shallow-shelf environment.

The objectives of this report are to identify and delineate Lower Permian depositional systems and to develop a regional, process-oriented depositional model that (1) illustrates how the Palo Duro Basin was filled during Early Permian time, and (2) documents the evolution of carbonate shelf margins as well as clastic deltaic-supply systems and clastic slope-basin feeder systems. An important emphasis is on depositional controls of shelf-margin evolution.

Although the Palo Duro Basin is virtually surrounded by several giant oil and gas fields, production of hydrocarbons in the basin is generally limited to its periphery. This report presents preliminary source rock data as part of continuing studies at the Bureau of Economic Geology for purposes of assessing the petroleum potential of the Palo Duro Basin.

METHODS

More than 400 electric and sample logs were examined during the course of the study. Stratigraphic cross sections were constructed, utilizing representative suites of electric logs, and isopach maps of major lithofacies were also derived from electric logs. Stratigraphic correlations and lithologic interpretations were enhanced by integration of sample log descriptions, core lithology, and electric log patterns.

TECTONIC SETTING AND STRATIGRAPHY

The Palo Duro Basin was first recognized as a sedimentary basin as early as 1926 by Charles N. Gould of the Oklahoma Geological Survey (Nicholson, 1960). Its areal extent is approximately 19,000 mi^2 (50,000 km^2) (fig. 1). Block faulting of the Amarillo-Wichita Uplifts and the Matador Arch in Early Pennsylvanian time led to the formation of the Palo Duro Basin (Best, 1963). Totten (1956) suggested that the basin began forming in Late Mississippian time, and development continued into the Permian Period.

The Palo Duro Basin is bounded by positive Precambrian basement structures in the subsurface (fig. 1). Granitic and gabbroic rocks (1.1 billion years) of the Wichita igneous province (Flawn, 1956) constitute the Amarillo Uplift, which separates the Palo Duro Basin from the Anadarko Basin to the northeast. A narrow structural low between the Amarillo Uplift and the Bravo Dome connects the Palo Duro Basin with the Dalhart Basin to the north. The latter is flanked on the northwest by the Sierra Grande Uplift in New Mexico, and on the east by the Cimarron Arch. The Palo Duro Basin merges westward with the Tucumcari Basin in New Mexico, which is also flanked by the Sierra Grande Uplift. Block-faulted basement rocks of the Red River mobile belt (Flawn, 1956), or Matador Arch, form the southern boundary of the Palo Duro Basin and separate it from the Midland Basin. Convergence of the Amarillo-Wichita Uplifts and the Matador-Red River Arches forms the eastern boundary of the Hardeman Basin, an extension of the Palo Duro Basin.

The geographic position and structural grain of the Palo Duro Basin hold clues to the origin of the basin. Several folds mapped by Nicholson (1960) strike southeastward from the Amarillo Uplift (fig. 1). Nicholson suggested that these are secondary folds that formed in response to shear movement along the Amarillo Uplift in Early Pennsylvanian time. Wickham (1978) described similarly oriented folds in the Southern Oklahoma Aulacogen (Hoffman and others, 1974) (fig. 1), which includes the Amarillo-Wichita Uplifts and the Anadarko Basin. According to Wickham, these folds were created by major strike-slip movement during Pennsylvanian compression and deformation of the aulacogen and the Ouachita tectonic belt. South of the Palo Duro Basin, the Delaware Aulacogen (Walper, 1977) (fig. 1) was deformed at the same time. Deformation of the two aulacogens resulted in the formation of many of the structural features surrounding the Palo Duro Basin, including the Anadarko, Ardmore, Midland, and Delaware Basins, the Arbuckle and Amarillo-Wichita Uplifts, and the Central Basin Platform. Proximity of the Palo Duro

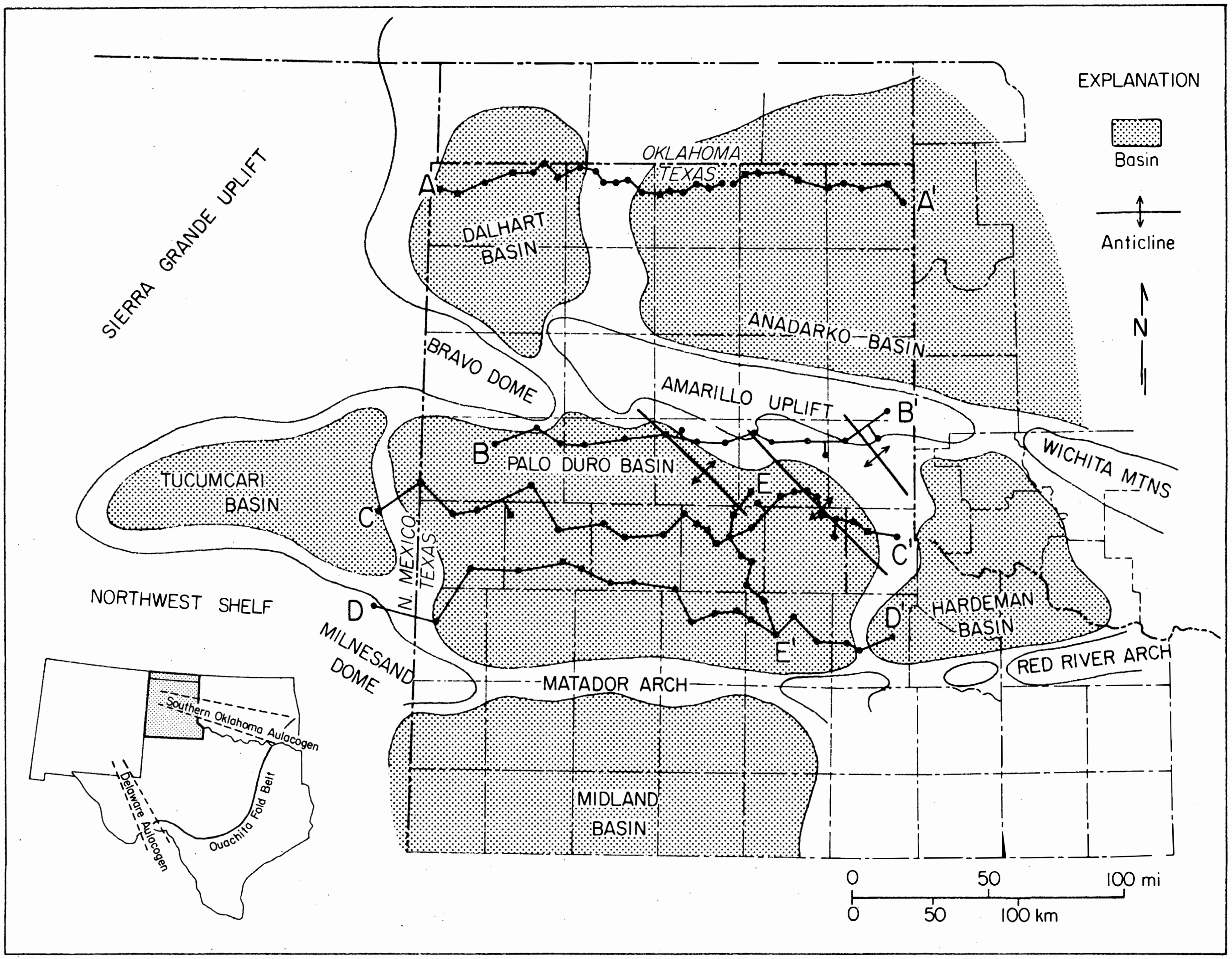


Figure 1. Index map showing major structural features of Texas Panhandle and adjacent areas, and grid of cross sections used to determine regional stratigraphic framework.

Basin to these features and their similar geologic history indicate that the Palo Duro Basin probably formed as a result of deformation of the Southern Oklahoma and Delaware Aulacogens.

The Palo Duro Basin is filled mostly with Pennsylvanian, Permian, and Triassic sedimentary rocks (fig. 2). A pre-Pennsylvanian section consists of a thin basal sandstone (Cambrian) and shallow-shelf carbonates (Ordovician and Mississippian) several hundred feet thick. Following earliest Pennsylvanian deformation in North Texas, most of these strata were removed by erosion. Pennsylvanian deposition of fan-delta sandstones and shallow marine carbonates proceeded with subsidence in the Panhandle, forming the Palo Duro Basin. Shallow marine carbonates, basinal shale, and deltaic sediments compose most Lower Permian strata (Wolfcampian), whereas thick sabkha salt, anhydrite, and red beds (Handford, 1979; Presley, 1979) make up most of the Middle and Upper Permian section. Triassic fluvial-deltaic and lacustrine facies of the Dockum Group (McGowen and others, 1977) and the Ogallala Formation constitute most of the remaining basin fill.

DEPOSITIONAL SYSTEMS

There is no formal stratigraphic division of Lower Permian rocks in the Palo Duro Basin. The sedimentary basin fill in this study is discussed in terms of informal genetic stratigraphic units or depositional systems. The concept of a depositional system as an informal stratigraphic unit was introduced by Fisher and McGowen (1967) to facilitate subdivision of basin fill into process-

System	Series	Group	General lithology and depositional setting
Quaternary			Fluvial and lacustrine clastics
Tertiary			
Cretaceous			Nearshore marine clastics
Triassic		Dockum	Fluvial-deltaic and lacustrine clastics
Permian	Ochoa		Sabkha salt, anhydrite, red beds, and peritidal dolomite
	Guadalupe	Artesia	
		Pease River	
	Leonard	Clear Fork	
		Wichita	
	Wolfcamp		Shelf margin carbonates, basin shale, and deltaic sandstones
Pennsylvanian			
Mississippian			Shelf limestone and chert
Ordovician		Ellenburger	Shelf dolomite
Cambrian			Shallow marine(?), sandstone
Precambrian			Igneous and metamorphic

Figure 2. Generalized stratigraphic column and depositional facies, Palo Duro Basin.

related sedimentary facies. A depositional system is composed of assemblages of facies that are genetically linked by inferred depositonal environments and associated processes (Brown and Fisher, 1977). Examples are meanderbelt fluvial systems, barrier bar systems, and deep-sea submarine fan systems.

The stratigraphic framework of Lower Permian facies in the Palo Duro Basin, as shown by cross sections (figs. 3, 4, 5, 6, 7, and 8), is composed of four depositional systems: (1) fan-delta system, (2) high-constructive delta system, (3) carbonate shelf and shelf-margin system, and (4) slope and basin system. Each depositional system is characterized by distinctive lithofacies assemblages, vertical sequences, spatial distribution, and electric log signature (fig. 3).

FAN-DELTA SYSTEM

During Early Permian time, Precambrian granite highlands in the Amarillo Uplift, Bravo Dome, and Sierra Grande Uplift in New Mexico shed large quantities of granitic rock fragments and arkosic sand ("granite wash") into the Palo Duro Basin. The presence of thick (greater than 500 ft), coarse-grained arkosic sandstone sequences flanking Precambrian basement highlands (fig. 5) and their lobate isolith patterns (fig. 9) suggest that deposition was in fan-delta environments (McGowen, 1970; Erxleben, 1975; Brown and Fisher, 1977).

A fan delta is an alluvial fan that has prograded into a lacustrine or marine environment from an adjacent highland (McGowen, 1970; Brown and Fisher, 1977). Fan deltas are normally associated with fault-bounded basins where short, high-gradient streams flow from a nearby source and carry large quantities of bed-load sediment. Surfaces of fan deltas are laced with braided distributary channels (McGowen, 1970; Wescott and Ethridge, 1978). A key to subsurface recognition of fan-delta deposits lies in the presence of thick, coarse-grained sandstones

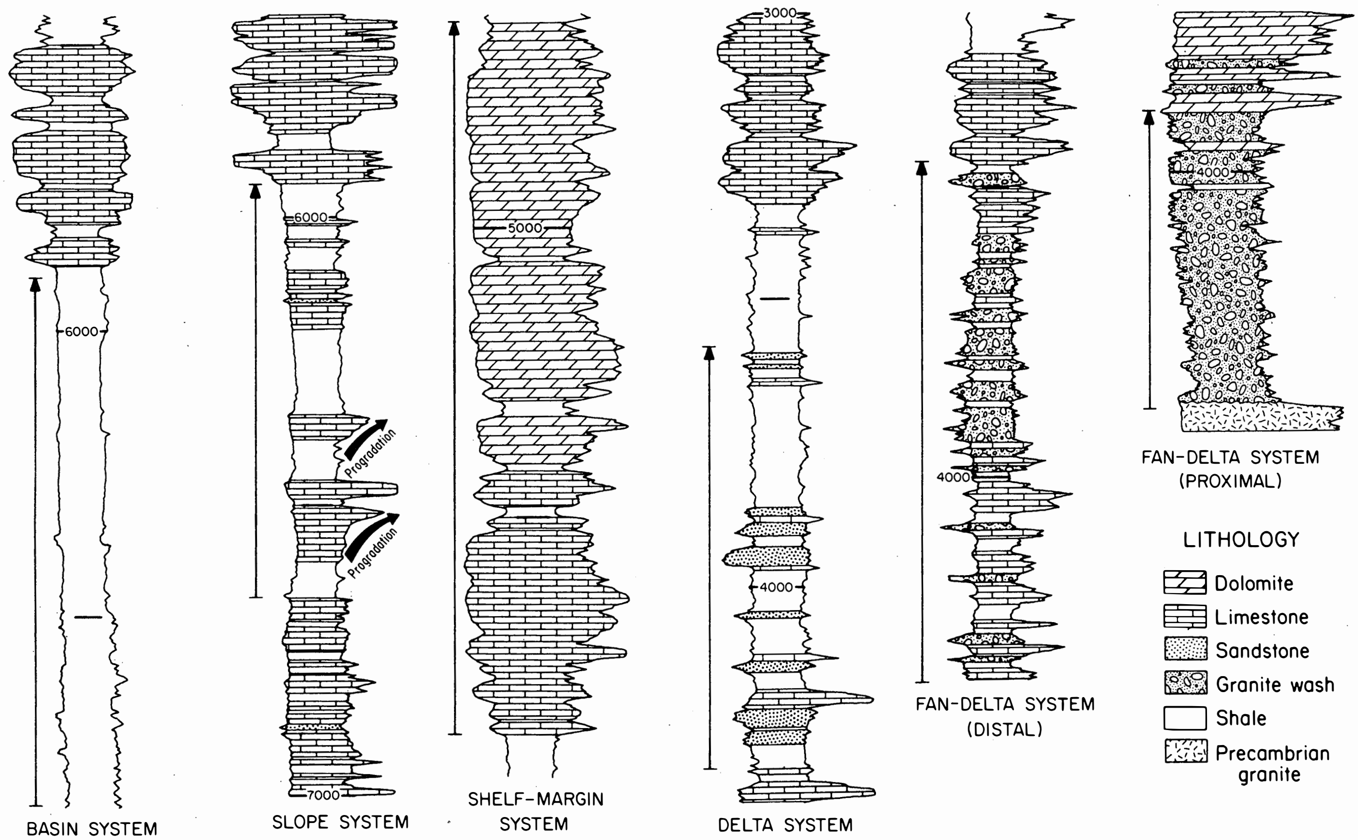


Figure 3. Typical electric log patterns of lithologic facies within sequences that characterize each system. Spontaneous potential and resistivity curves are shown. Vertical scale marked every 500 ft.

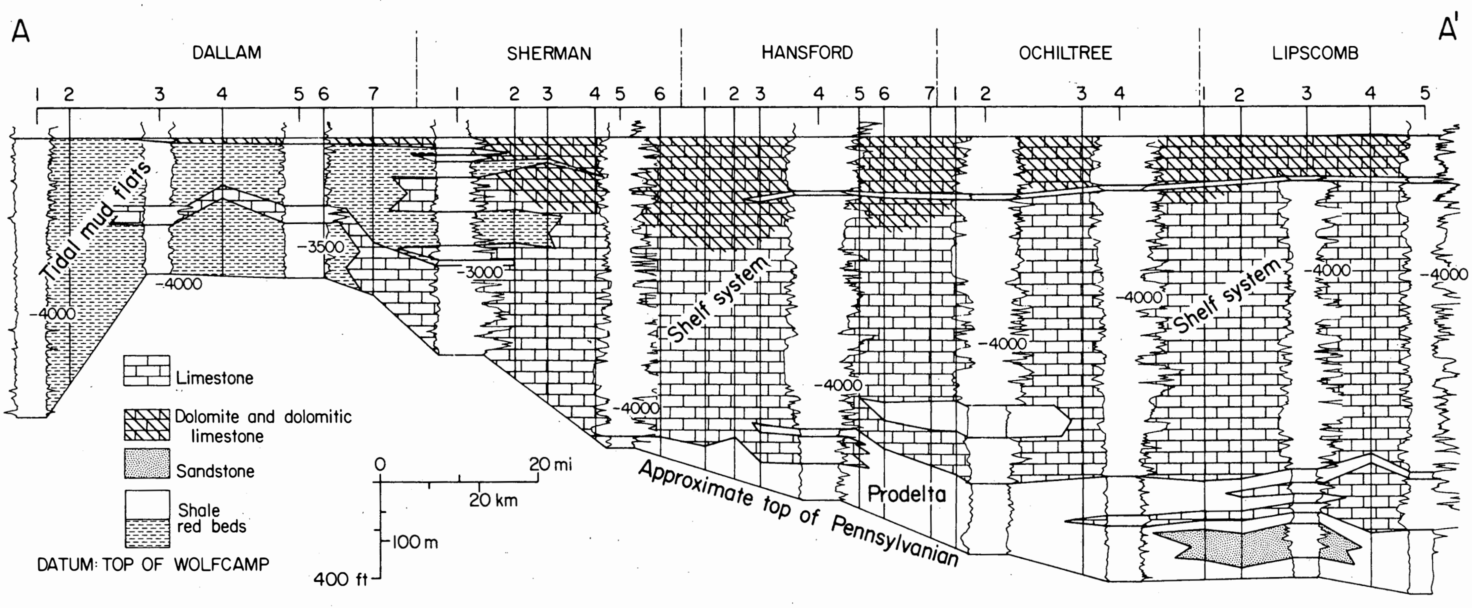


Figure 4. East-west cross section A-A', showing stratigraphic framework and depositional systems across Dalhart and Anadarko Basins. Boundary between Pennsylvanian and Permian systems in all cross sections (figs. 5, 6, 7, and 8) is approximate and based upon sample logs and regional correlations.

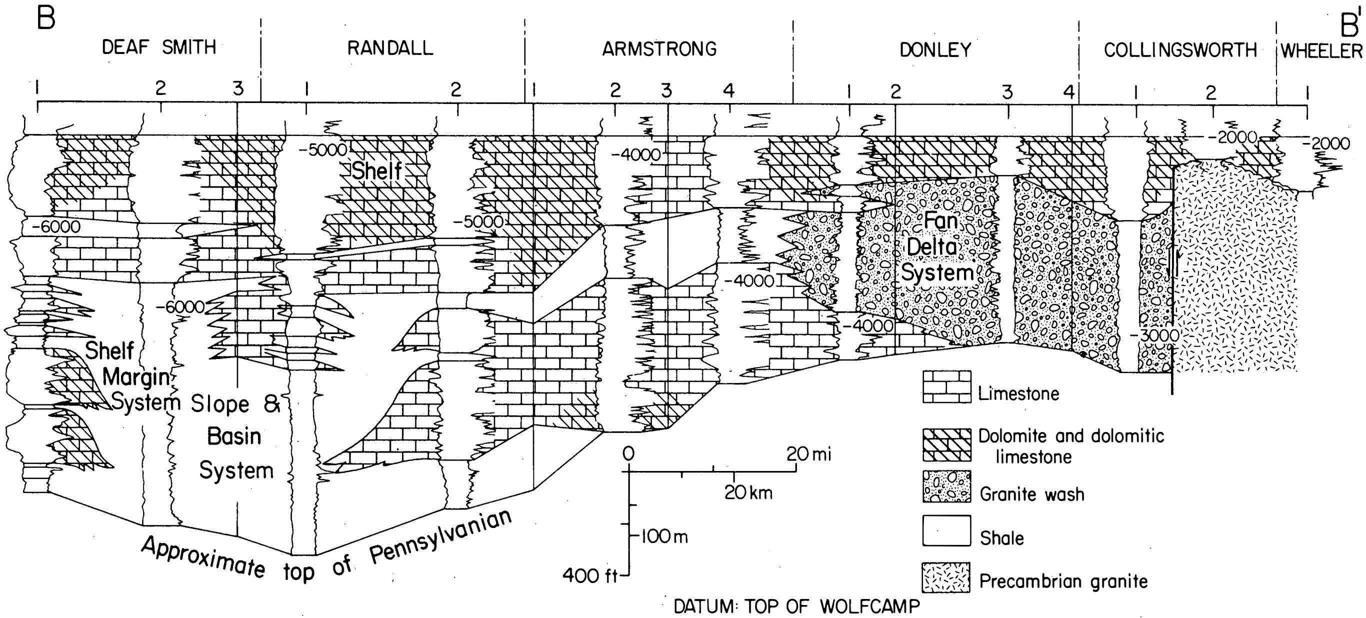


Figure 5. East-west cross section B-B′, showing stratigraphic framework and depositional systems, northern Palo Duro Basin. Normal fault in Collingsworth County inferred by abrupt thickening of strata.

adjacent to fault-bounded sources, and in the delineation of lobe-shaped isolith patterns. In Hartley County relatively dense well spacing enhanced delineation of thick, lobate, net sandstone isolith patterns (fig. 9), which probably represent general configurations of fan-delta lobes. Position and orientation of lobes indicate that in this example the sandstones were derived from the northwestern terminus of the Amarillo Uplift.

Analysis of core samples (figs. 10, 11, and 12) and variations in characteristic electric log patterns of Lower Permian fan-delta sandstones indicate relative proximity to the sediment source. Proximal fan-delta strata are characterized by thick, massive sandstone sequences that commonly overlie Precambrian basement (figs. 10a and 11a) or lie juxtaposed with basement faults (figs. 3, 5, and 7). Proximal fan-delta facies are recorded by blocky, serrated spontaneous potential patterns with sharp upper and lower boundaries (figs. 3 and 5). In distal environments, thin shale beds (less than 10 ft thick) are interbedded with sandstone and may represent distributary-channel clay plugs (Wescott and Ethridge, 1978), interfingering prodelta clay, or interdistributary bay mud.

Samples of core that are believed to represent proximal fan-delta facies indicate deposition by mass wasting and fluvial processes. Core chips from the Standard Oil Company Bivens no. 12 well of Hartley County contain a large cobble-sized fragment of gabbro within a sequence of silty mudstone, which is thus interpreted as a matrix-supported conglomerate or debris-flow deposit. As shown by Bull (1972), debris-flow deposits commonly occur in modern alluvial fan environments and are especially prevalent near fan apices (Bull, 1972; Hooke, 1967). Generation of debris-flow deposits in Lower Permian alluvial fan deltas may have been promoted by steep slopes with insufficient vegetation cover, source material that provided mud matrix, and short-lived episodes of intense rainfall (Bull, 1972).

Mid-fan braided channel-fill deposits (fig. 11b) consist of thin, multiple fining-upward sandstone units (fig. 10b) that begin with basal pebbly arkose (longitudinal bar) overlain by flat to inclined laminated, medium-grained sandstone (longitudinal bar-crest). Thin, muddy sandstone beds over tops of longitudinal bars may have accumulated at higher topographic levels during waning flood stages (Williams and Rust, 1969). In the Standard Oil Company Bivens no. 7 well, Potter County, a coarsening-upward sequence of sandy mudstone to coarse-grained, pebbly sandstone was interpreted as a minor delta-lobe deposit. Fine-grained sediment at the base of the sequence is interpreted as interdistributary bay and crevasse deposits. During flood stage, suspended sediment was washed overbank from a flooded channel and into the interdistributary bay. As flood stage rose, the levee along the margin of the channel was eventually breached by rising flood water, leading to the formation of a minor, coarsening-upward fan-delta lobe.

Core samples of distal fan-delta plain and crevasse deposits are characterized by interlaminated carbonaceous black shale and medium- to coarse-grained sandstone with plant

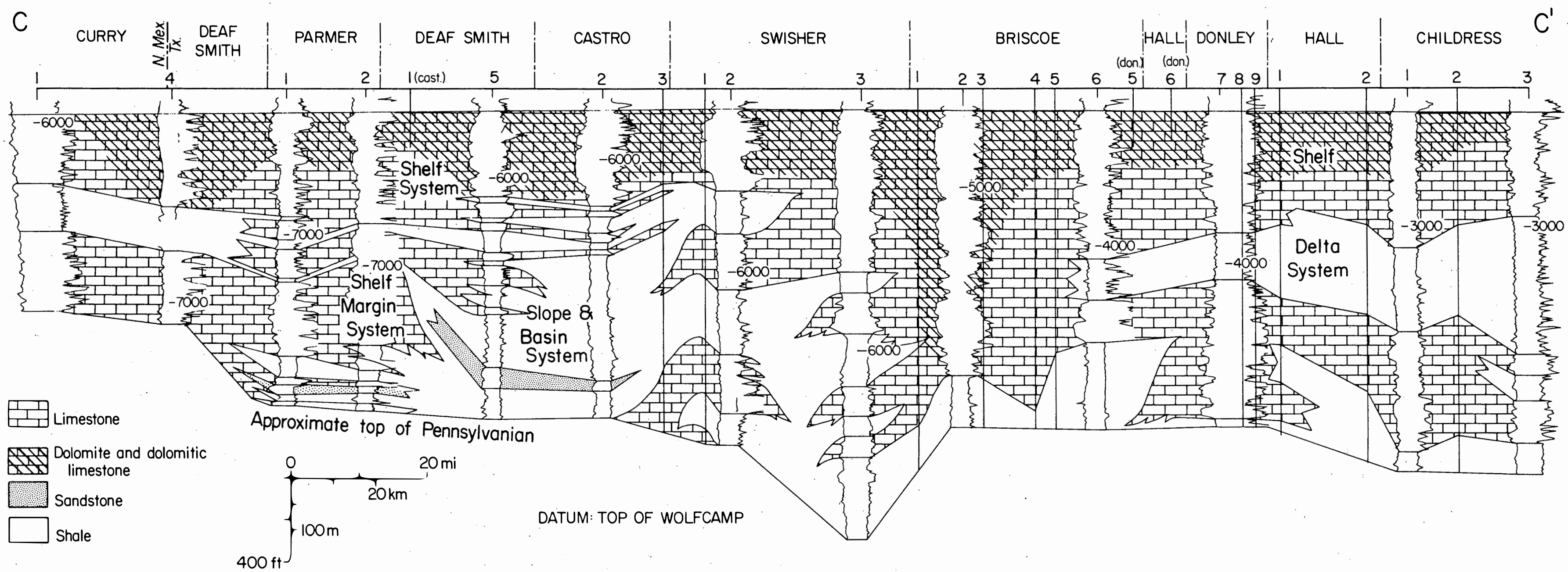


Figure 6. East-west cross section C-C′, showing stratigraphic framework and depositional systems, central Palo Duro Basin.

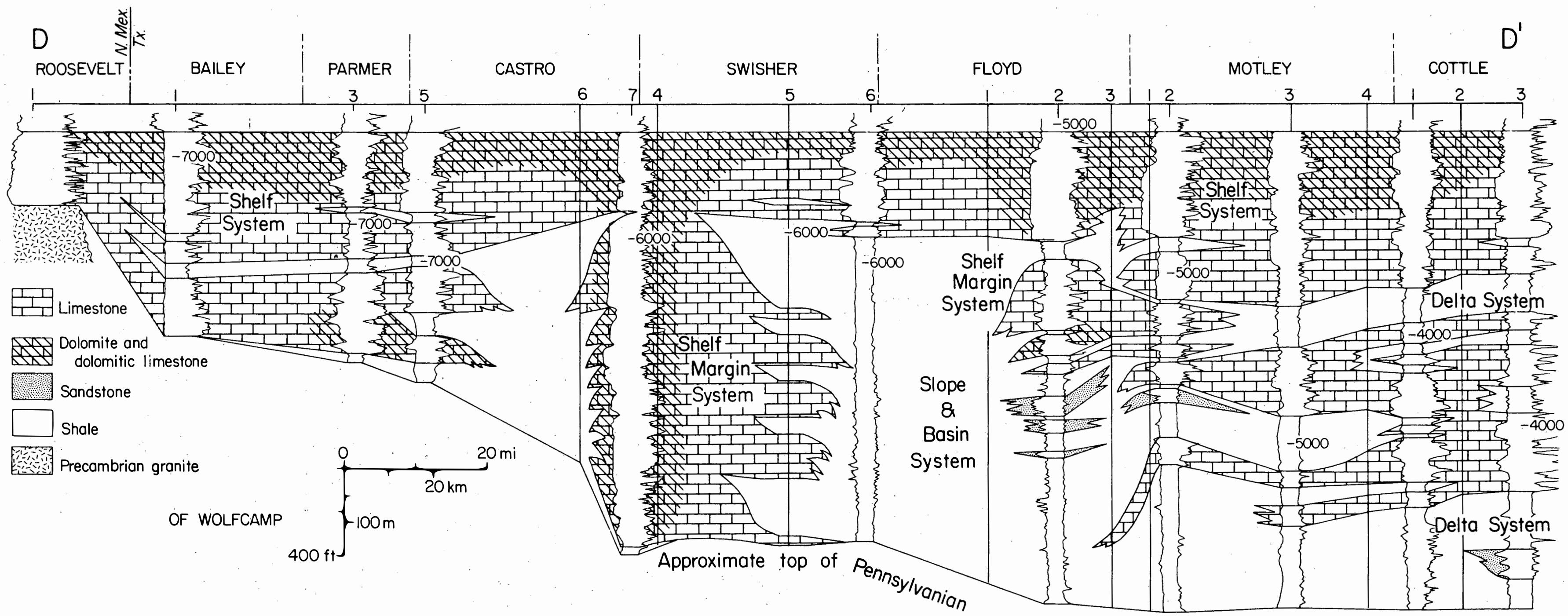


Figure 7. East-west cross section D-D′, showing stratigraphic framework and depositional systems, southern Palo Duro Basin. Stacking of shelf margins in western Palo Duro Basin and progradation of shelf margins in eastern Palo Duro Basin are evident.

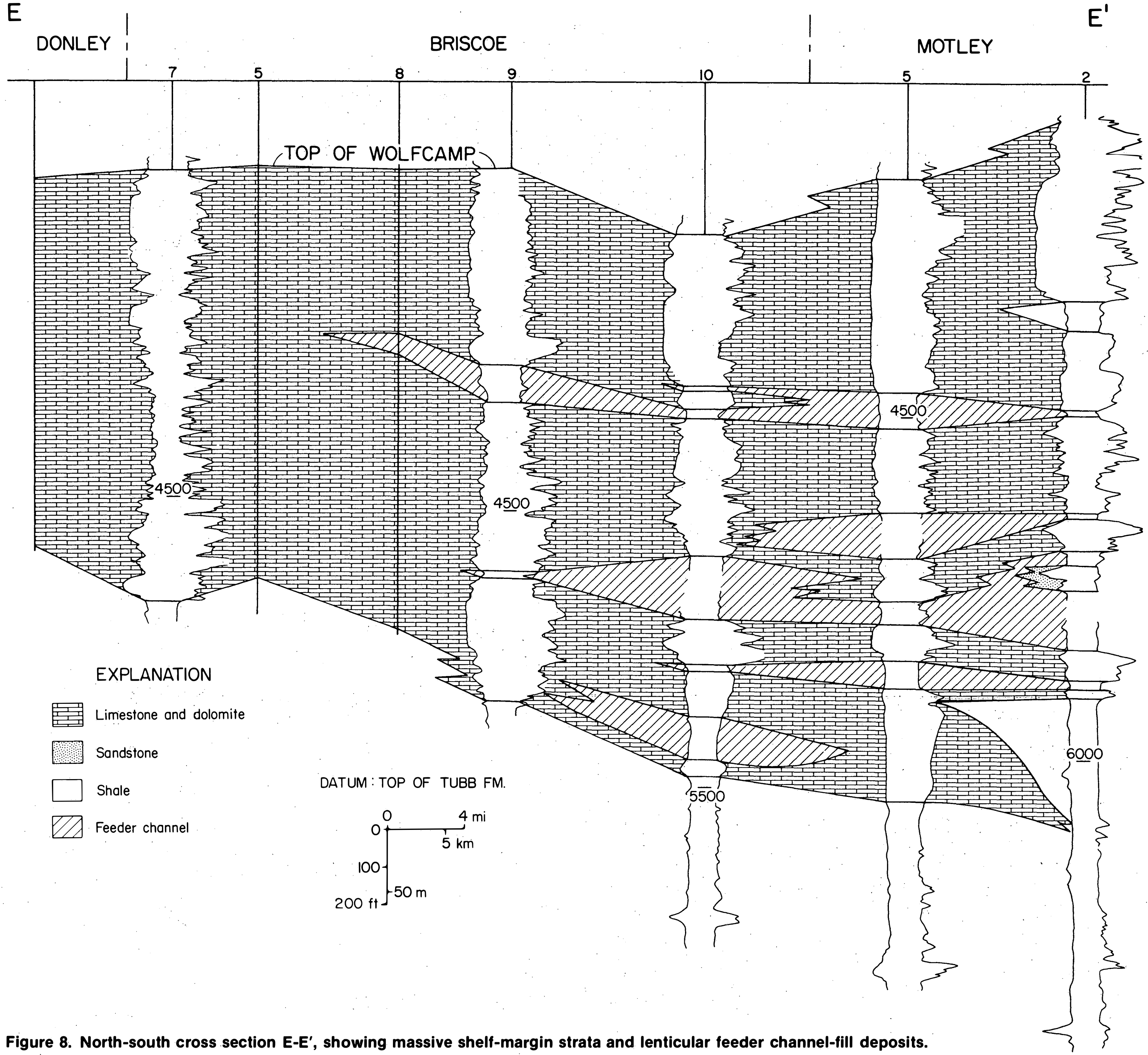


Figure 8. North-south cross section E-E', showing massive shelf-margin strata and lenticular feeder channel-fill deposits.

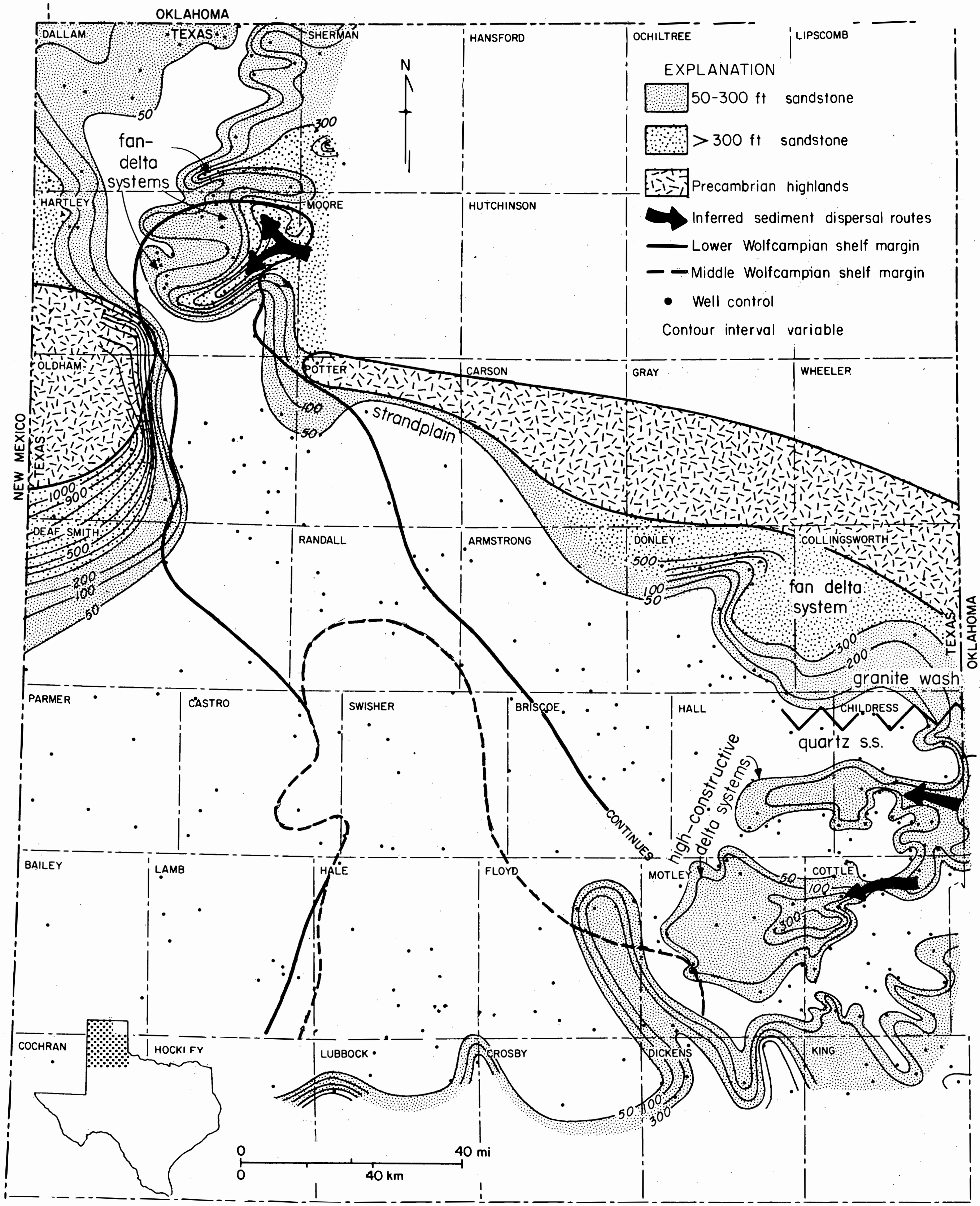
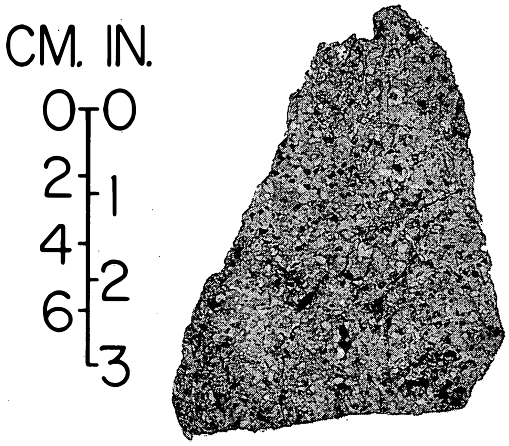
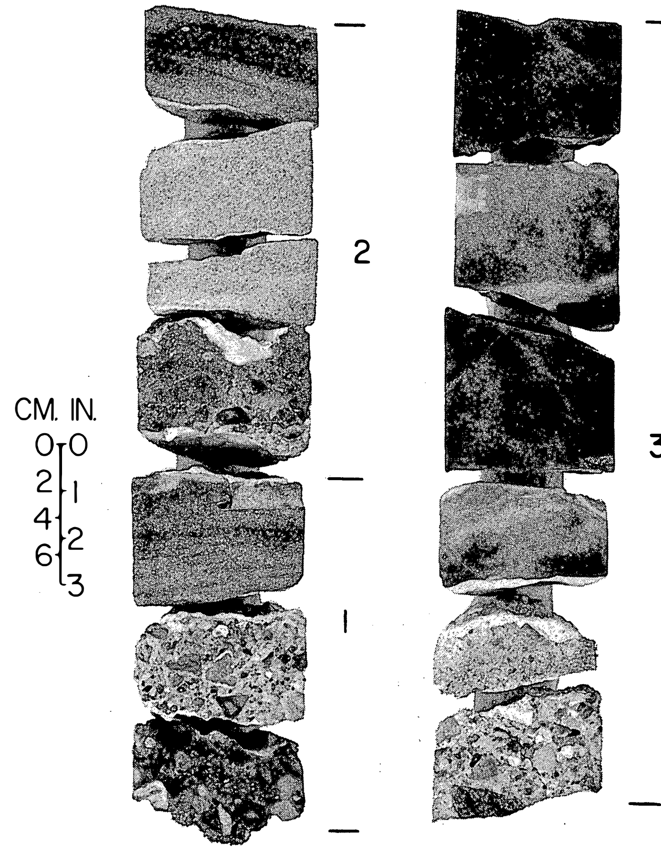


Figure 9. Sandstone isolith map of Lower Permian strata, Palo Duro Basin. Inferred sand dispersal routes highlight delta systems.



a

Figure 10. Representative cores from proximal fan-delta environments. (a) Weathered granite or grus directly overlying basement. Hartley County, Standard Bivens no. 12, 5,550 ft (1,690 m). (b) Distributary braided channel-fill sequence composed of three fining-upward sequences numbered 1, 2, and 3. Potter County, Standard Bivens no. 7, 3,606 to 3,618 ft (1,100 to 1,102 m).



b

material, burrows, load casts, and soft sediment faults (figs. 11 and 12a, b). These strata reflect pulsating or flashy deposition of sand in normally low-energy environments. Sediment was probably contributed both by channels during floods and by prodelta or shelf environments during storms or strong wind tides (McGowen, 1970).

Facies characteristics of modern fan-delta analogs indicate that Lower Permian, parallel- and cross-laminated, coarse-grained arkose with abundant crinoid debris (fig. 12c) was probably deposited in destructional bars or beaches developed along the seaward edge of fan-delta lobes. Destructional bars on the fringe of Gum Hollow fan delta, Texas Gulf Coast, form by longshore current processes or by deposition of sand from breaking waves (McGowen, 1970). The Yallahs fan delta, southeastern Jamaica, is also characterized by coarse-grained beach deposits that form by wave attack of the delta (Wescott and Ethridge, 1978).

Data collected from core samples, cross sections, and isopach maps provided raw material from which a schematic depositional model was constructed (fig. 13). This idealized model displays most environments thought to be represented in the Lower Permian fan-delta system.

HIGH-CONSTRUCTIVE DELTA SYSTEM

Prominent elongate and lobate sandstone isolith patterns, which are parallel to the paleoslope in the southeastern Palo Duro Basin, delineate a high-constructive or fluvial-dominated delta system (Fisher and others, 1969; Galloway, 1975b) that prograded westward into the basin (figs. 9 and 14). Most terrigenous sediment composing this system was probably derived from the Wichita Uplift in Oklahoma or the Ouachita tectonic belt in Texas. Superposed deltaic sandstones in the Lower Permian strata indicate that delta lobes periodically prograded over 60 mi (100 km) across the basin. Maximum cumulative thicknesses of deltaic facies range from 400 to 900 ft (120 to 275 m). Several thick deltaic sequences of early Wolfcampian age display lateral facies relationships characteristic of bar-finger deposits (Fisk, 1961; Frazier, 1967; and Galloway, 1968). Associated with log-interpreted bar-finger sandstones are frontal splay sandstones in prodelta shale, and destructional-phase or transgressive limestone (fig. 15).

These early Wolfcampian delta-front sandstones (figs. 7, 14, and 16) are up to 200 ft (60 m) thick and occur basinward of the shelf margin, suggesting that deltas prograded into the deep basin. In

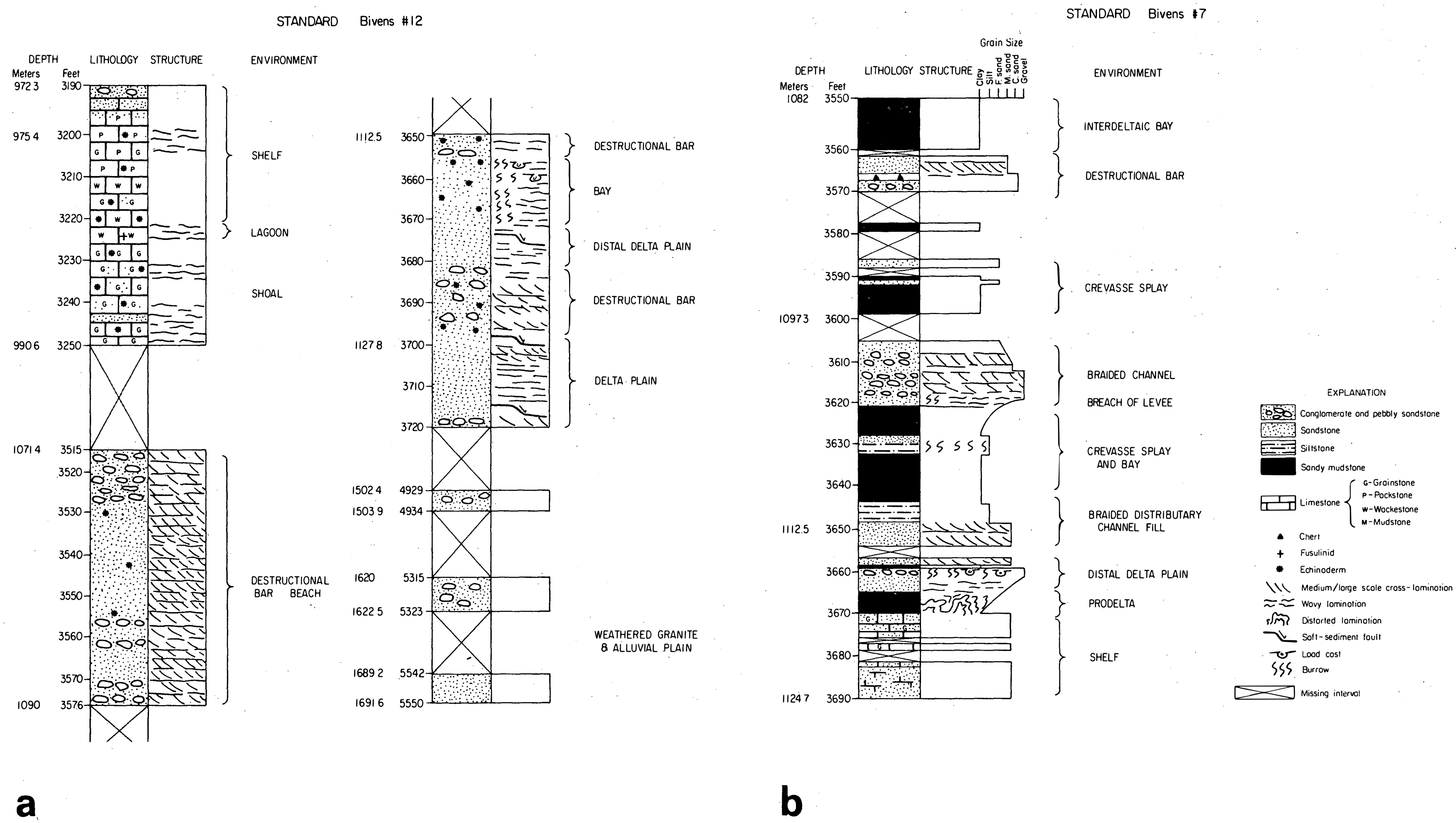
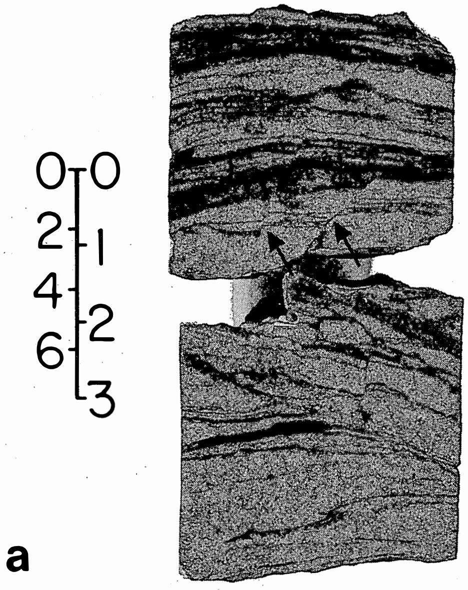
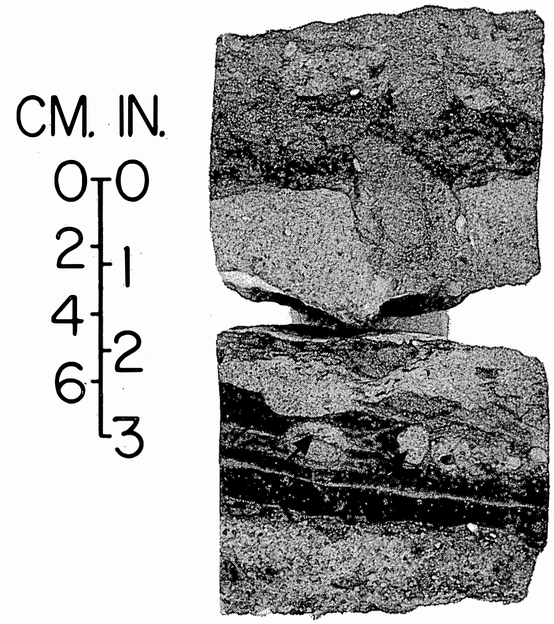


Figure 11. Lithology, sedimentary structures, and inferred depositional environments of fan-delta facies from two cores, (a) Potter County, Standard Bivens no. 7 and (b) Hartley County, Standard Bivens no. 12.





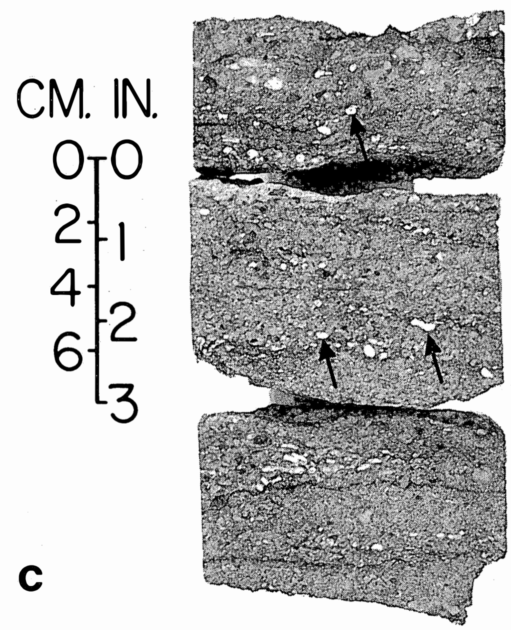


Figure 12. Representative cores from distal fan-delta plain, interdistributary bay, and destructional bar facies. Arrows point to (a) soft sediment faults, (b) load casts, and (c) worn echinoderm fragments. a and c are from Hartley County, Standard Bivens no. 12, 3,673 and 3,688 ft (1,120 and 1,124 m) respectively. b is from Potter County, Standard Bivens no. 7, 3,659 ft (1,115

comparison, deposition of thick delta-front sands (>200 ft) in the modern bird's-foot delta of the Mississippi River (Fisk, 1961) is thought to be related to active basin subsidence caused by depositional loading and progradation into water up to 300 ft (90 m) deep (Frazier, 1967).

Early Wolfcampian shelf margins prograded basinward over the older, deep-water delta facies, and terrigenous sediment input was reduced. Consequently, delta progradation was not as extensive as earlier episodes, and most delta-front sands were deposited behind the shelf margin in shallow-shelf environments, precluding the formation of thick delta-front sequences. Similarly, Galloway and Brown (1972) suggested that thin progradational facies of an Upper Pennsylvanian delta system in North-Central Texas stemmed from deposition on a stable, shallow shelf. As a present-day analog the Guadalupe Delta in Texas is characterized by deposition in a shallow, relatively quiet body of water (Donaldson and others, 1970). Its progradational facies are thin.

Deltaic sandstones are subarkosic in composition, fine to very fine grained, and contain disseminated carbonaceous material. Log computed porosities are 18 to 25 percent.

CARBONATE SHELF AND SHELF-MARGIN SYSTEM

Seaward of fan-delta and high-constructive delta systems were carbonate shelf and shelf-

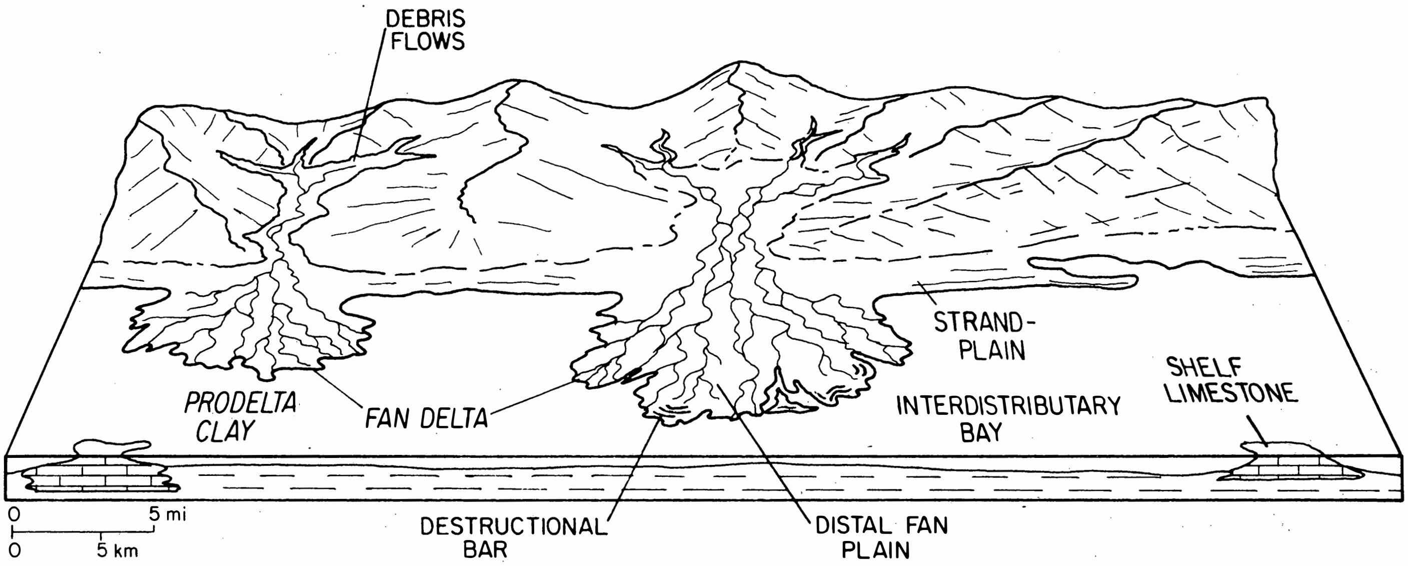


Figure 13. Schematic block diagram showing major subenvironments of a fan-delta system.

margin complexes that are preserved as 400 to 1,800 ft (120 to 550 m) of limestone and dolomite (figs. 3, 4, 5, 6, and 7). The shelf and shelf-margin system formed a relatively broad band around the Palo Duro Basin and opened southward into the Midland Basin (fig. 16). Much like other shelf-margin systems (Newell and others, 1953; Malek-Aslani, 1970; Dunham, 1969; Galloway and Brown, 1972), massive, shelf-margin carbonate strata thin abruptly and interfinger with slope and basinal facies, but toward basin margins these strata thin gradually and interfinger with shelf clastics and prodelta shale (figs. 5, 6, and 7).

Thickness and massiveness of carbonate facies are variable across shelf to shelf-margin environments. Open shelf carbonates are characterized by superposed units generally less than 100 ft (30 m) thick that are separated by thin shales. At shelf margins, carbonate strata are thicker (200 to 400 ft) and contain fewer shale beds. Stratigraphic correlations across shelf margins indicate that each massive carbonate unit probably represents an individual shelf-margin complex that stood several hundred feet above the floor of a depositional basin.

Composition of carbonate strata deposited in shelf environments reflects mixing of sediments derived from biogenic and terrigenous sources. Carbonate samples from Potter County contain variable quantities of siliciclastic and feldspathic grains. Some carbonate shelf deposits have disseminated quartz, and terrigenous-rich laminae (fig. 17a). Well-sorted, crinoidal grainstones (fig. 17b) and other grain-supported rocks with abundant bryozoans, fusulinids, pellets, and ooids are indicative of high organic productivity and high-energy conditions in shelf environments. Fusulinid lime wackestones (fig. 17c) suggest deposition in open lagoons.

Lower Permian shelf margins probably consisted of expansive shoals and carbonate banks inhabited by dense colonies of echinoderms, bryozoans, brachiopods, and fusulinids. In addition, and by analogy to other Lower Permian biohermal shelf-margin complexes in New Mexico (Malek-Aslani, 1970; Cys and Mazzullo, 1977; and Wilson, 1975), organisms such as phylloid algae, *Tubiphytes* (problematical calcareous algae), tubular foraminifera, and sponges may have been the principal components of shelf-margin banks or bioherms. These organisms were not rigid frame-builders, but encrusting and sediment-baffling forms (Wilson, 1975). Dominance of many of these organisms was probably reduced significantly when delta lobes invaded shelf-margin terrain. In these cases, organisms tolerant of suspended, fine-grained terrigenous sediment became more abundant.

Comparison to the Mahakam Delta and Shelf-Margin System

A modern analog to Lower Permian shelf-margin and high-constructive delta systems is the Mahakam Delta and adjacent marine shelf along the coast of Kalimantan (Borneo) in the Indonesian Archipelago (figs. 18 and 19). Studies by Gerard and Oesterle (1973) and Magnier and others (1975) have shown that the Mahakam Delta can be subdivided into delta plain, delta platform, delta-front, and prodelta environments. Beyond the prodelta lie carbonate shelf, shelf-edge (barrier reefs), and

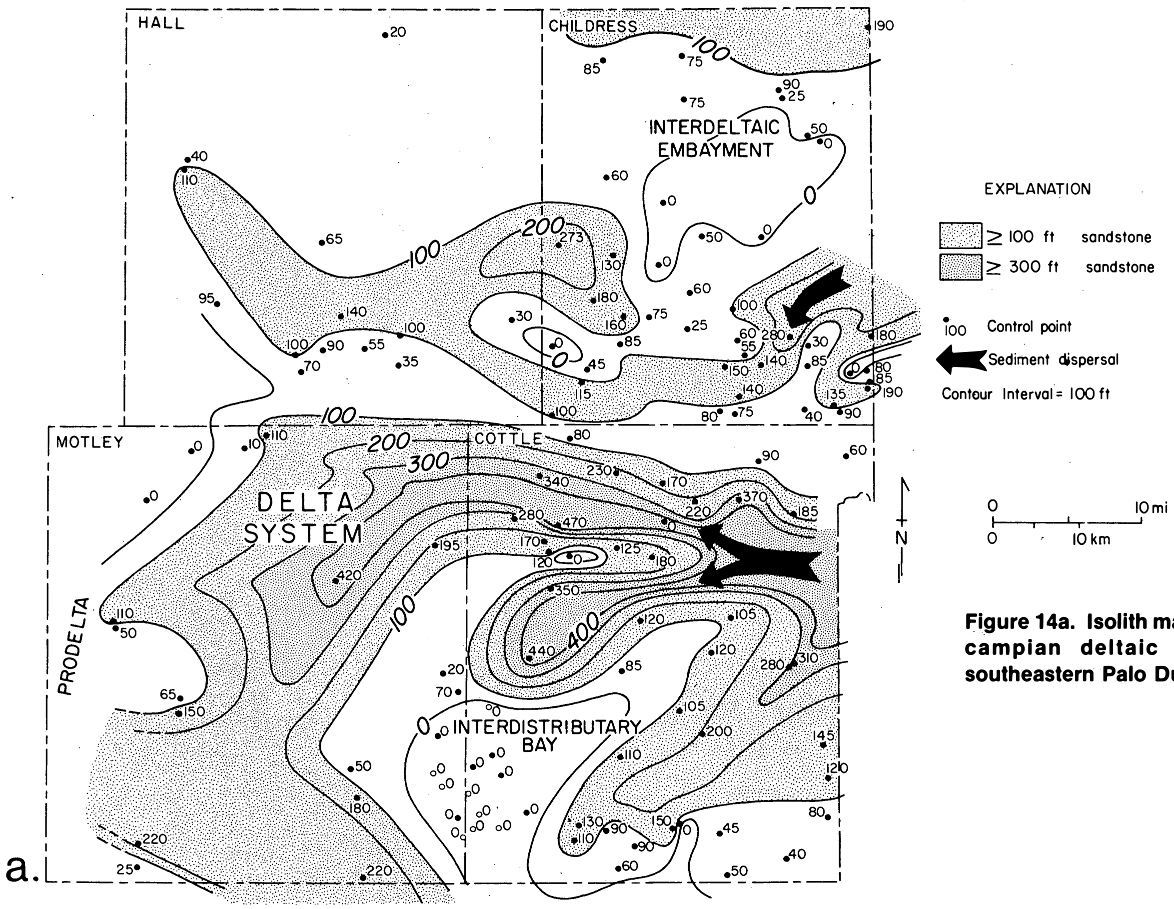


Figure 14a. Isolith maps of lower Wolfcampian deltaic sandstones in southeastern Palo Duro Basin.

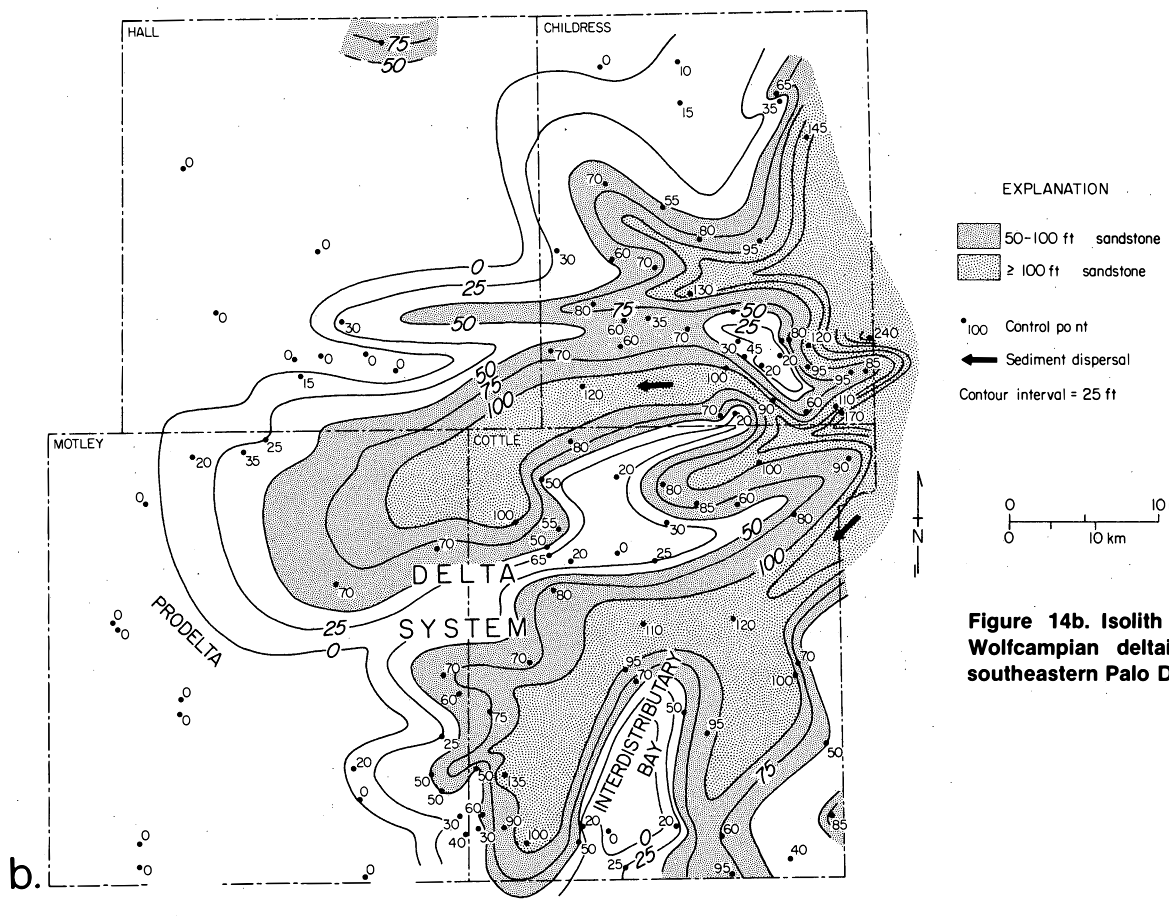


Figure 14b. Isolith maps of middle Wolfcampian deltaic sandstones in southeastern Palo Duro Basin.

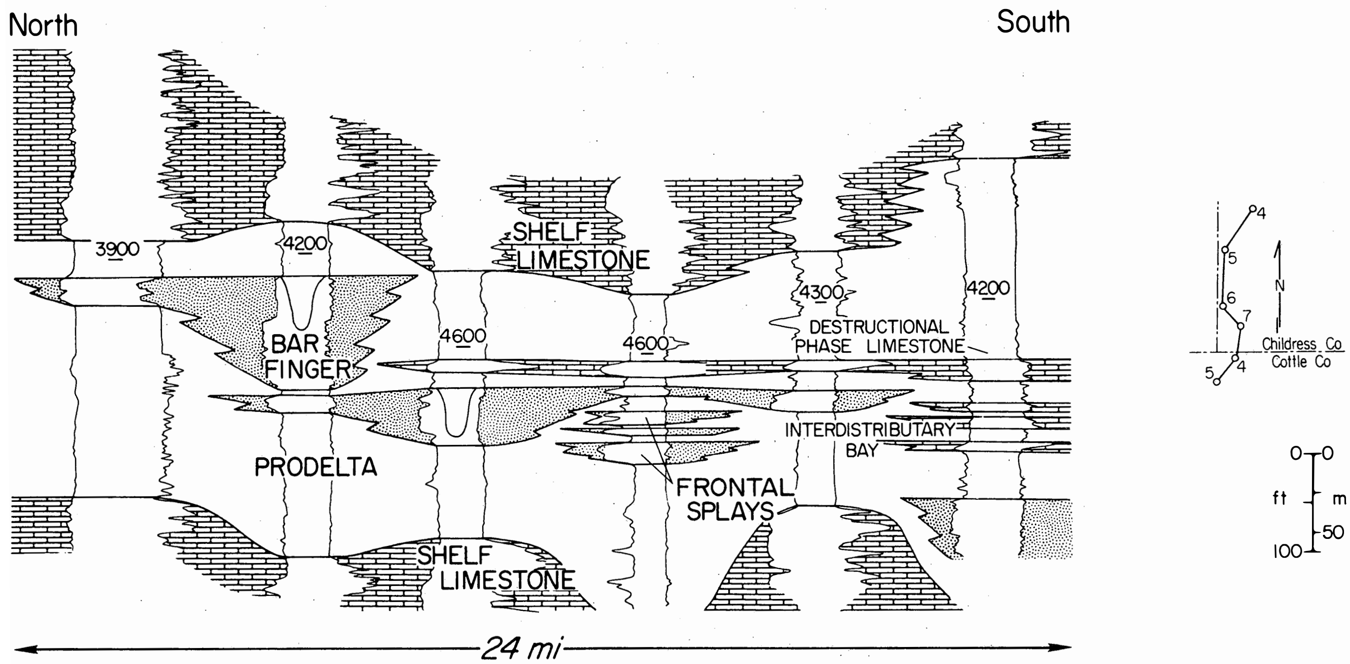


Figure 15. North-south cross section through lower Wolfcampian deltaic facies.

slope environments. The Mahakam Delta is high-constructive and lobate. Most of the river water and sediment are discharged through distributaries in the southern part of the delta. Thus, this part of the delta is dominated (though not strongly) by fluvial processes and is currently prograding. In contrast, the northern half of the Mahakam Delta is currently dominated by marine processes; tidal currents carry reworked delta-front sediment upstream through distributary channels that now function only as tidal channels.

The most striking feature of the Mahakam Delta and shelf, as modern analogs to deltaic and carbonate shelf-margin depositional systems of the Lower Permian sequence in the Palo Duro Basin, is the fact that active reefs appear only 2.5 mi (4 km) north of the prodelta slope on the inactive northern half of the delta. In contrast, the first well-developed living reefs occur 24 mi (38 km) offshore from the southern part of the delta. This modern example readily indicates that actively growing carbonate reefs can coexist with major progradational deltas, especially in association with episodes of delta lobe switching. A similar relationship is envisioned for the Lower Permian of the Palo Duro Basin; a delicate balance existed between episodes of delta lobe switching, or progradation, and carbonate bank development.

SLOPE AND BASIN SYSTEM

Toward the axis of the Palo Duro Basin, thick beds of silty, spiculitic shale and dark-colored micritic limestone and dolomite lie adjacent to massive shelf-margin carbonates. This sequence of fine-grained sedimentary rocks was deposited in slope and basinal environments.

Slope systems are lenticular in strike section, wedge-shaped in dip section, and they thicken basinward (figs. 5, 6, and 7). The updip limit of a slope succession is defined either by its termination against massive carbonate strata of the shelf margin, or by extreme thinning where it passes between two superposed shelf-margin sequences. Slope facies grade downdip into basinal shale facies.

Sediment comprising the slope sequences was probably introduced through passes between

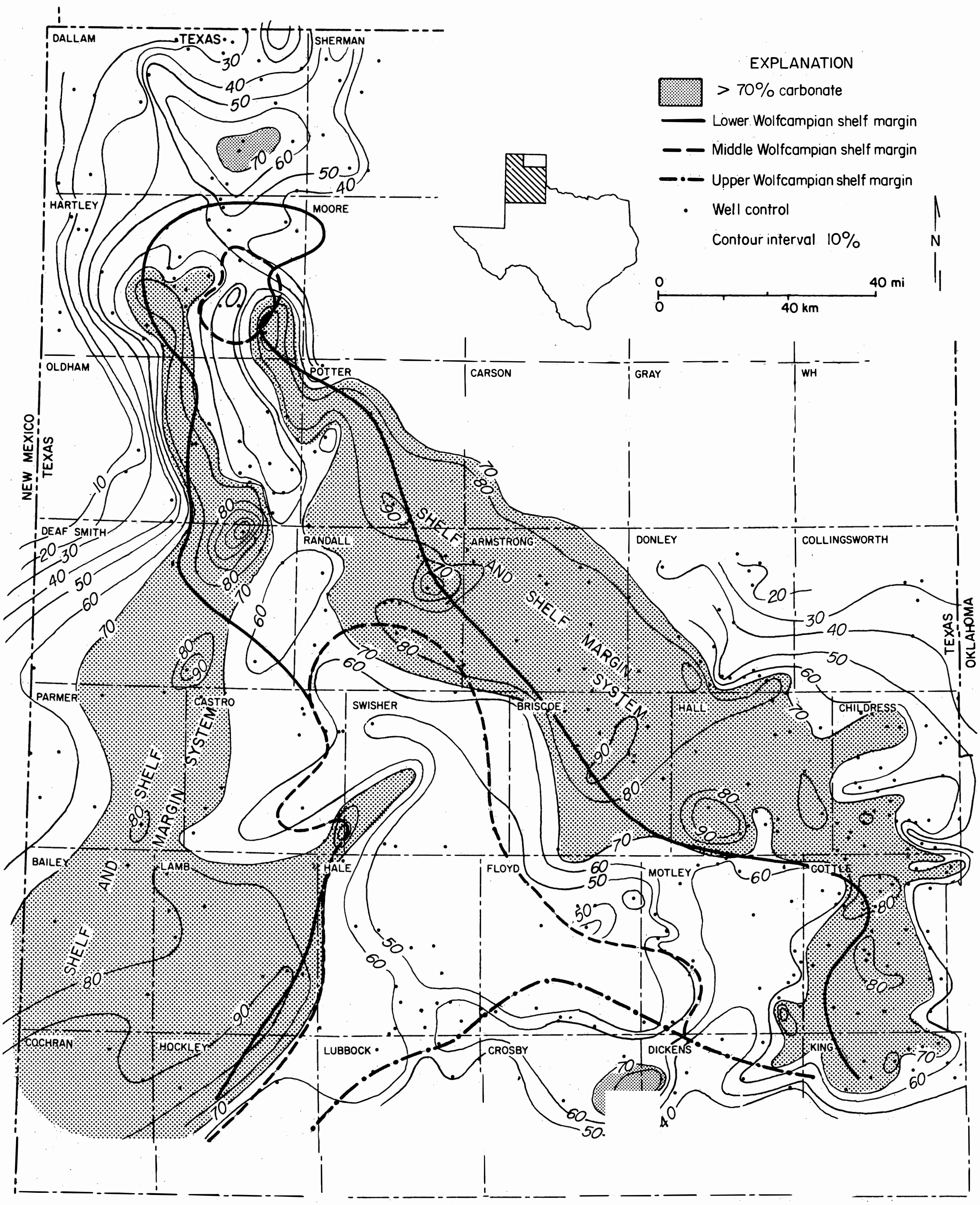


Figure 16 Percent carbonate map of Lower Permian strata in the Palo Duro Basin. Shelf-margin trends correlate with major carbonate occurrence. Lines defining lower, middle, and upper Wolfcampian shelf-margin positions illustrate shelf-margin progradation through time.

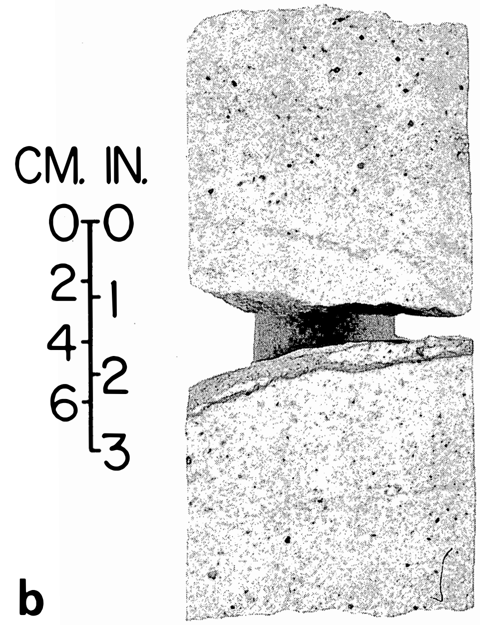
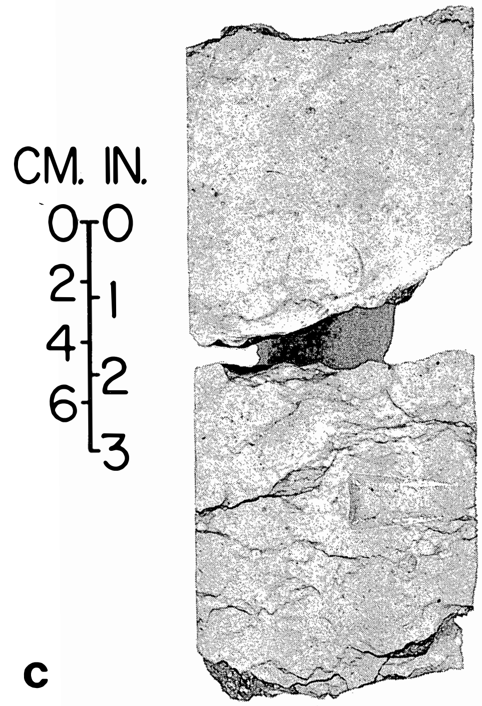


Figure 17. Representative cores from carbonate shelf environments. (a) Terrigenous-rich laminae (dark) in burrowed, skeletal grainstone. (b) Crossbedded, crinoid grainstone shoal deposit. (c) Burrowed lime wackestone from lagoonal environment. Cores from Hartley County, Standard Bivens no. 12, 3,200 to 3,250 ft (975 to 990 m).



carbonate buildups or banks along shelf margins and carried downslope in submarine fan-head feeder channels (Walker, 1978). Several offset, superposed feeder channels have been recognized in the Lower Permian section (fig. 8). Channels occur on basinward slopes of shelf margins and just beyond the progradational limits of fan-delta and high-constructive delta systems. A net shale map (fig. 20) illustrates the magnitude, geometry, and orientation of a submarine channel-fill sequence along the shelf margin. The extent to which channels could be mapped was limited downslope by disappearance of subjacent and superjacent marker beds and along strike by pinchouts of channel-fill shale. As shown in figure 20, a shale sequence was mapped from a prodelta environment across the crest of a shelf margin and downslope into a submarine fan-head feeder channel. Thickness trends indicate that the channel was filled with sediment debouched from a nearby delta on the shelf and transported westward across the shelf margin and downslope toward the basin floor.

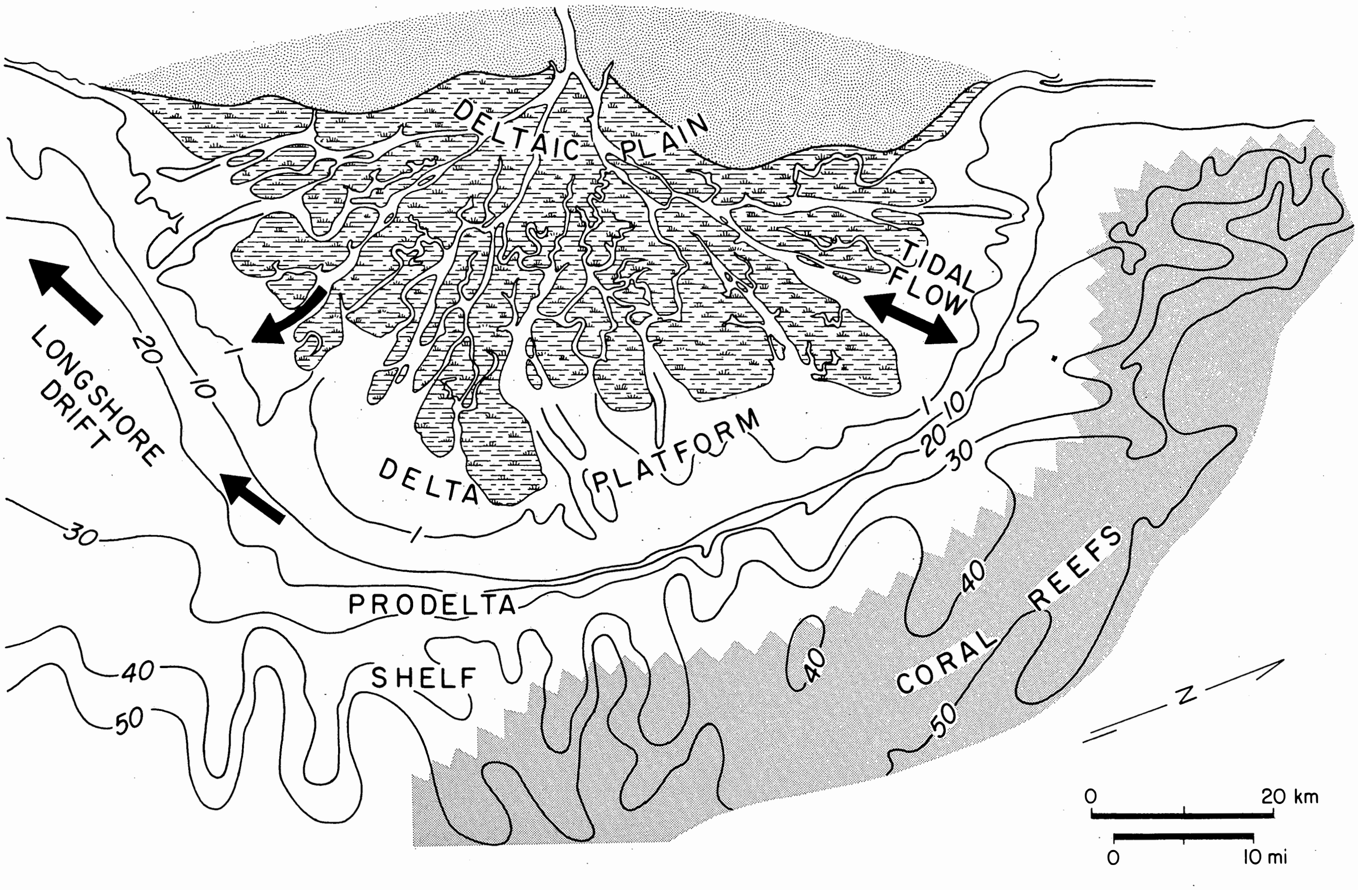


Figure 18. Modern Mahakam Delta of Kalimantan (Borneo) and bathymetry of shelf (contours in fathoms). This locality serves as a modern analog for Permian shelf and shelf-margin carbonates in close association with a high-constructive delta.

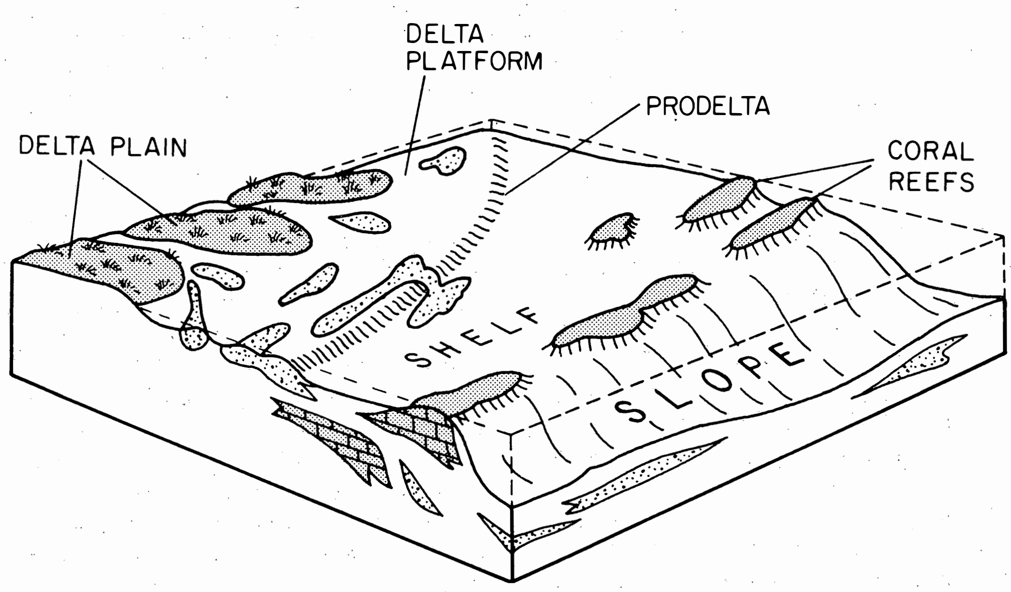
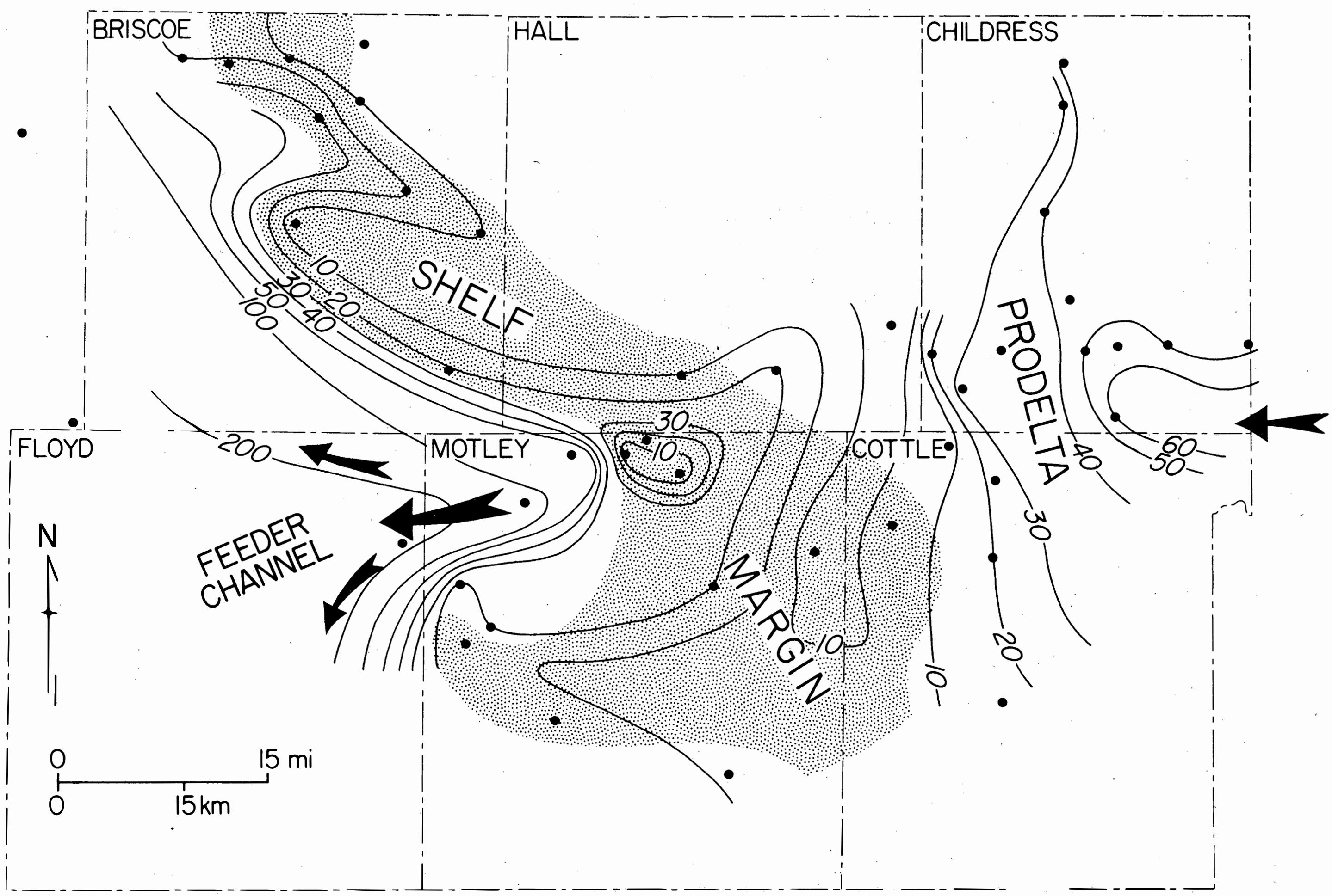


Figure 19. Block diagram of modern Mahakam Delta and shelf. Distribution of facies is analogous to Permian facies systems.



EXPLANATION

> 50 ft Carbonate

Sediment Dispersal

Well Control

Figure 20. Isopach of shale unit that was traced westward from prodelta, across shelf margin, and into slope environment. Slope or fan-head feeder channel is defined by thick net shale in northwestern Motley County. Shale thins over crest of interpreted shelf margin and thickens toward prodelta environment.

Lower Permian feeder channels are longer, wider, and shallower than other documented, ancient submarine canyons (table 1). Comparison of dimensions and characteristics of sedimentary fill of these examples indicates that Lower Permian feeder channels had low downslope gradients and gently sloping walls. These characteristics may imply minimum occurrences of highly concentrated turbidity currents.

Massive shelf-margin strata break up into thin units that are intercalated with channel-fill shale and interpreted overbank deposits along channel margins (fig. 8). This suggests that the contact is not completely erosional and that these channels may be combination erosional and aggradational types. However, precise relations are difficult to interpret owing to lack of dense well control. Active depositional valleys (as opposed to incised, erosional channels) occur in the upper parts of some modern submarine fans, and fans that are associated with deltas commonly have multiple-leveed valleys (depositional channels?) in their upper parts (Normark, 1978).

Formation of feeder channels may have been enhanced by upbuilding of shelf margins concomitant with periodic channel incision by turbidity currents (Von der Borch, 1969). Upbuilding of adjacent carbonate shelf margins and slopes relative to channel cutting may have been caused by biogenic carbonate sedimentation and possibly by syngenetic cementation. These processes would have allowed shelf margins to maintain steeper slopes and higher profiles than intervening channels. Thus channels could have easily formed as passive features between bioherms or carbonate banks.

Table 1. Characteristics of submarine canyons (modified from Walker, 1978).

Channel	Age, Location	Length mi (km)	Width mi (km)	Depth ft (m)	Fill
Meganos	Late Paleocene, Sacramento Valley	50+ (80+)	2-6 (3-10)	1970 (600)	silty shale
Yoakum	Mid-Eocene, Texas	50 (80)	10 (16)	2950 (900)	silty shale
Mississippi	Pleistocene, Louisiana	50 (80)	2 (3)	1970 (600)	clay
Hackberry	Oligocene, Louisiana	15 (24)	8.7 (14)	655+ (200+)	turbidites and shale
Rosedale	Late Miocene, Bakersfield, California	6 (10)	1.6 (2.5)	1300 (400)	turbidites and shale
Gevaram	Early Cretaceous, Israel	10+ (16+)	9 (15)	3075 (938)	silty shale
Cook	Early Permian, West-central Texas	3+ (5+)	1 (1.6)	100+ (30+)	turbidites and shale
Wolfcamp	Early Permian, Palo Duro Basin	25-30 (40-48)	8 (13)	200 (60)	shale, minor sandstone and limestone

MECHANISM OF SHELF-MARGIN DEVELOPMENT AND PROGRADATION

Construction and progradation of carbonate shelf margins during Early Permian time occurred repeatedly under a two-phase mechanism (fig. 21). During the first phase, high-constructive deltas (or fan deltas) prograded across a shelf environment and terminated near the shelf margin. Increased deposition of clastic sediment and fresh-water discharge probably led to a sharp decline of carbonate sediment production near active distributaries. Most sand-sized terrigenous sediment was deposited in delta-front environments on the shelf, but fine-grained sediment was swept seaward past the shelf margin through tidal passes between bioherms and banks. Tidal passes funneled sediment downslope into feeder channels and submarine fans. Continued deposition of clastics in slope environments formed thick progradational wedges of sediment. During the second phase, delta lobe switching or abandonment occurred, while clear-water conditions returned and carbonate productivity increased. Carbonate organisms re-established on older bioherms and constructed new bioherms on shallow platforms built by progradation of slope environments. Soon carbonate banks and bioherms coalesced and accreted basinward over the clastic foundation, thus forming a new shelf margin (fig. 21). Organisms on seaward margins of banks and bioherms probably contributed carbonate debris to slope environments. As a result, additional footing was formed for continued seaward progradation of the shelf margin. Apparently, large volumes of terrigenous sediment must be deposited beyond shelf margins in order for progradation to occur. This was recognized by Galloway (1975a), who showed that progradation of late Paleozoic carbonate complexes into the Midland Basin was dependent upon, and directly proportional to, the rates at which deltaic and slope-submarine fan platforms were constructed. Where clastics are not significant components of slope systems, carbonate shelf margins show limited progradation.

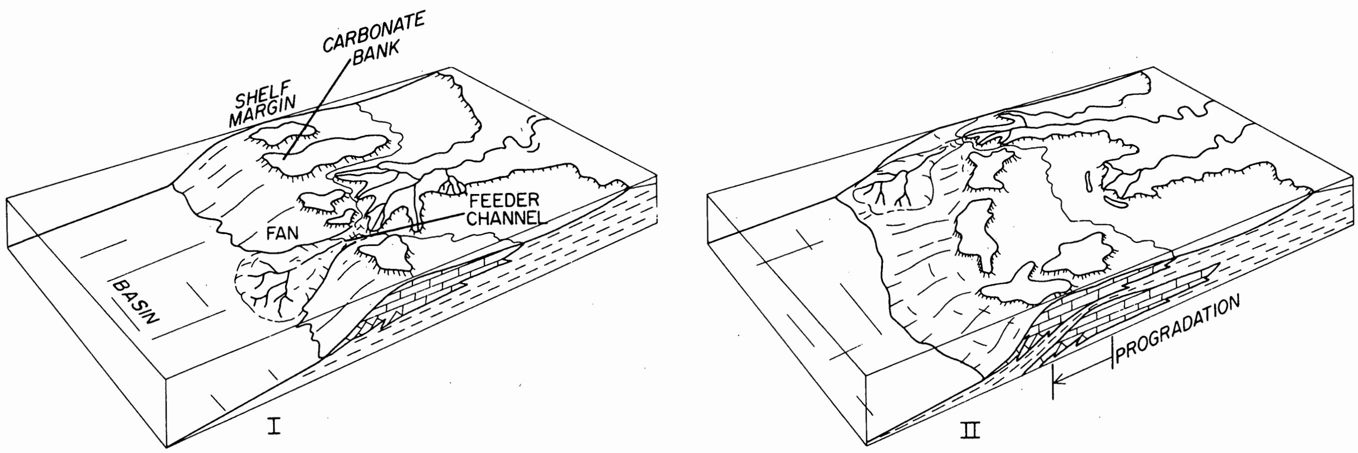


Figure 21. Two-phase model illustrating mechanisms of Lower Permian shelf-margin development assuming continuous subsidence. Phase I: Delta-lobe progradation to shelf margin accompanied by dispersal of fine-grained clastics across shelf margin via inlets between bioherms or banks and deposition of sediment in feeder channels and submarine fan. Phase II: Delta-lobe abandonment or switching and resumption of carbonate productivity over clastic slope wedge. Upbuilding and coalescence of carbonate banks result in net progradation of shelf margin over clastic foundation. Factors that may be considered in alternative models include effects of eustatic sea-level changes, tectonics, and compaction of slope wedge sediments.

PALEOGEOGRAPHY

Shelf margins on opposite sides of the Palo Duro Basin followed different progradational histories. Whereas individual, highly progradational shelf margins occur along the eastern shelf-margin trend, the western shelf margin displays limited basinward progradation (figs. 16 and 22). During early to middle Wolfcampian time, the eastern shelf margin shifted westward 10 to 30 mi (16 to 50 km) and nearly 80 mi (130 km) southward, while a portion of the western shelf margin remained stationary. Apparently, a relatively small quantity of terrigenous sediment was contributed to the basin from the west, thus the western shelf margin did not prograde great distances. However, contribution of large quantities of terrigenous sediment via high-constructive delta systems on the eastern shelf and fan-delta systems along the Amarillo Uplift promoted shelf-margin progradation.

By late Wolfcampian time, shelf margins had prograded southward into the northern Midland Basin, and the Palo Duro Basin was transformed into a wide, low-relief, peritidal-shelf environment (fig. 22). Burial of the Amarillo Uplift and other surrounding highlands cut off the immediate supply of clastics to most of the Panhandle region. In the northwestern part of the Dalhart Basin, however, shelf carbonates interfinger and pinch out laterally into red mudstones and sandstones that probably were deposited in a terrigenous mudflat system grading landward into an alluvial/eolian plain.

POTENTIAL PETROLEUM RESERVOIR FAIRWAYS

Hydrocarbon fairways may be present in at least three facies: (1) shelf-margin carbonates, (2) delta-front sandstones, and (3) fan-delta arkoses (table 2 and fig. 23). Each facies is proximal to potential source beds and consists of porous strata that are contiguous with relatively nonporous sealing beds.

SHELF-MARGIN CARBONATES

Lower Permian carbonate shelf and shelf-margin facies are commonly dolomitized. Stratigraphy of dolomite and regional discordancy of dolomite-limestone contacts across the basin indicate that Lower Permian dolomite is a diagenetic replacement mineral. It is regionally nonstratal, exhibiting cross-cutting relationships with apparent bedding and facies boundaries (figs. 4, 5, 6, and 7), and it is more porous along shelf margins. Mutual occurrences of porosity trends and dolomite along shelf margins suggest that the two have a common genesis. Mechanisms responsible for dolomitization and porosity enhancement may

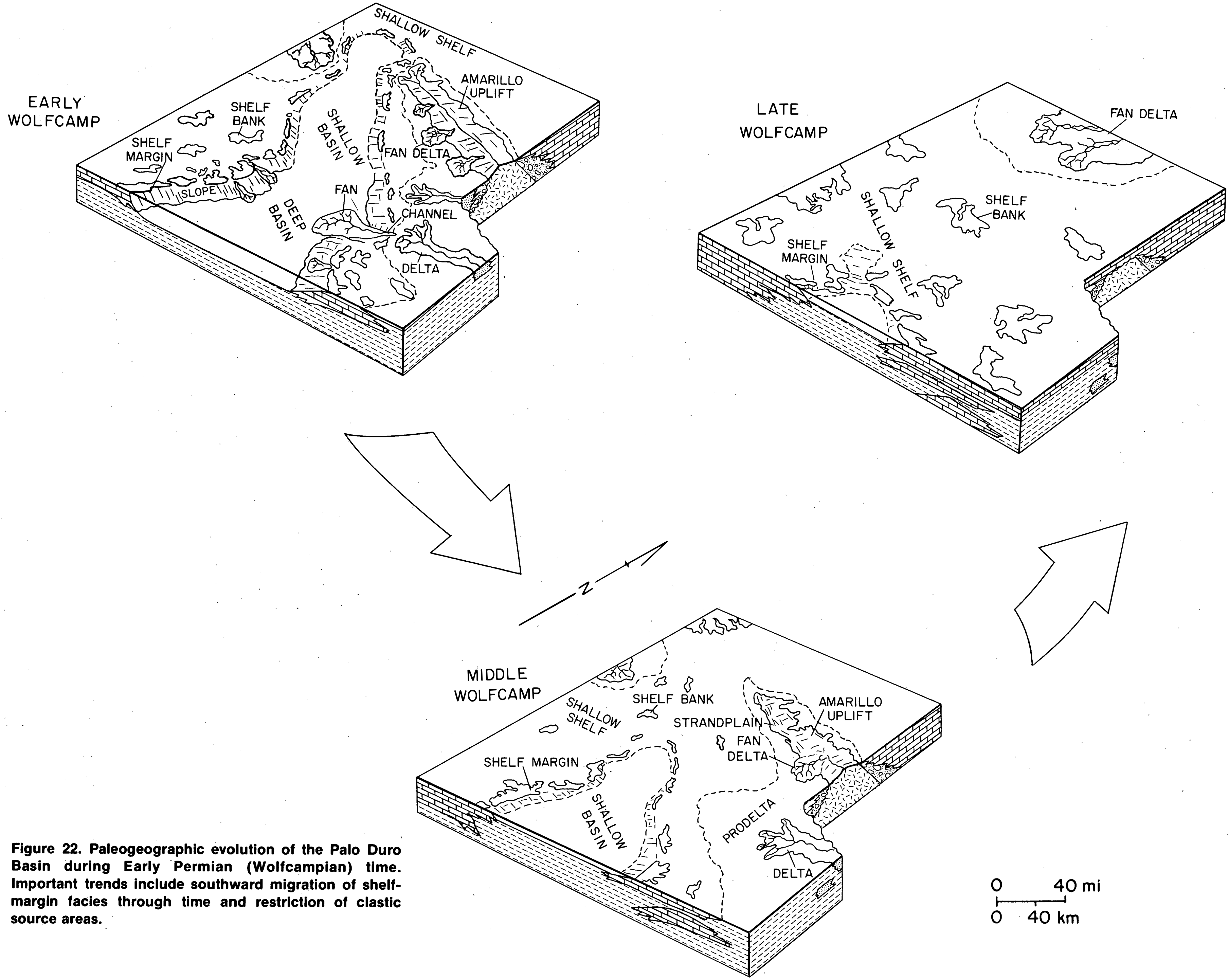


Figure 22. Paleogeographic evolution of the Palo Duro Basin during Early Permian (Wolfcampian) time. Important trends include southward migration of shelf-margin facies through time and restriction of clastic source areas.

Table 2. Potential stratigraphic hydrocarbon reservoirs in the Palo Duro Basin and producing analogs. Porosity values calculated from well logs.

Reservoir facies	Porosity	Contiguous strata	Producing analog
Shelf-margin carbonates	>10%	Shale and dolomite	Empire-Abo Field and Kemnitz Field, New Mexico
Delta-front sandstones	18 to 25%	Shale	Morris Buie-Blaco Fields, Texas
Fan-delta arkoses	18%	Shale and basement	Mobeetie Field, Texas

be fundamentally related to diagenetic processes inherent to shelf margins. Trace element and stable isotope geochemical data, in conjunction with petrographic information, are necessary, however, to evaluate properly any hypothesis. These data are currently unavailable.

According to density, sonic, and neutron logs, the porosity of Lower Permian shelf-margin dolomites is commonly greater than 10 percent. Porous zones are sealed laterally in basinward directions by contiguous slope and basinal shale, and shelfward by interfingering, nonporous shelf limestone and prodelta shale. Thin shales and anhydritic dolomite that overlie porous zones provide vertical seals. The Empire-Abo and Kemnitz Fields, New Mexico, are coeval, producing shelf-margin analogs. In each field, porous reservoir rocks are sealed laterally by nonporous shelf and basin to slope facies (Malek-Aslani, 1970; LeMay, 1972). Thin slope or basinal shales cap the Kemnitz reef cycle in a manner similar to Lower Permian shelf margins in the Palo Duro Basin. Porosity of the reservoir facies in Kemnitz Field reaches 18 percent and averages 8 percent. The producing limestone facies is characterized by primary intergranular porosity (Malek-Aslani, 1970). In contrast, the reservoir facies of the Empire-Abo Field is fractured, vuggy dolomite for which the updip seal is anhydritic dolomite and shale (LeMay, 1972).

The potential for entrapment of hydrocarbons in Lower Permian shelf-margin fairways may be enhanced by regional structure. Interplay between the depositional strike of porous shelf-margin trends and the subsurface elevation of the top of the Wolfcampian interval probably has determined reservoir and sealing bed relationships. The top of the Wolfcampian Series slopes southwestwardly and almost normal to the strike trend of the shelf margins (fig. 23). Thus potential hydrocarbon reservoirs in the western shelf margin may be sealed updip (northeast) by facies of the slope and basin system, and prodelta shale and nonporous shelf limestone are most likely to have sealed eastern shelf-margin reservoir facies.

DELTA-FRONT SANDSTONES

In southeastern Palo Duro Basin, porous delta-front sandstones are favorable, potential hydrocarbon reservoirs. As shown earlier (figs. 14 and 15), thickest sandstones occur in lower Wolfcampian rocks, and thinner deltaic facies are characteristic of middle Wolfcampian rocks. In both cases, sandstones are contiguous with fine-grained sediment that could have served as both source beds for hydrocarbons and sealing beds. Dewatering and compaction of prodelta muds may have flushed hydrocarbon-bearing fluids into adjacent porous delta-front sandstones. If structural closure within deltaic facies is present, it may have been promoted by differential compaction and thus led to creation of early hydrocarbon traps (Fisher and others, 1969).

Facies, depositional style, and tectonic settings of the Lower Permian delta system in the Palo Duro Basin and Upper Pennsylvanian (Cisco) deltaic sandstone reservoirs along the Eastern Shelf, North-Central Texas (Galloway and Brown, 1972), are similar. In both areas, delta systems dispersed sediment across shelf-margin crests and into slope environments. Furthermore, like the Eastern Shelf, the southeastern Palo Duro Basin is relatively undeformed; regional dip (elevation of top of Wolfcampian Series) is approximately 30 ft (10 m) per mi to the southwest (fig. 23).

The Morris Buie-Blaco Fields, which produce from Bluff Creek (Upper Pennsylvanian) distributary channel and channel-mouth bar sandstones in the Eastern Shelf (Galloway and Brown, 1972), are probably similar to potential hydrocarbon reservoirs in Lower Permian deltaic facies of the Palo Duro Basin.

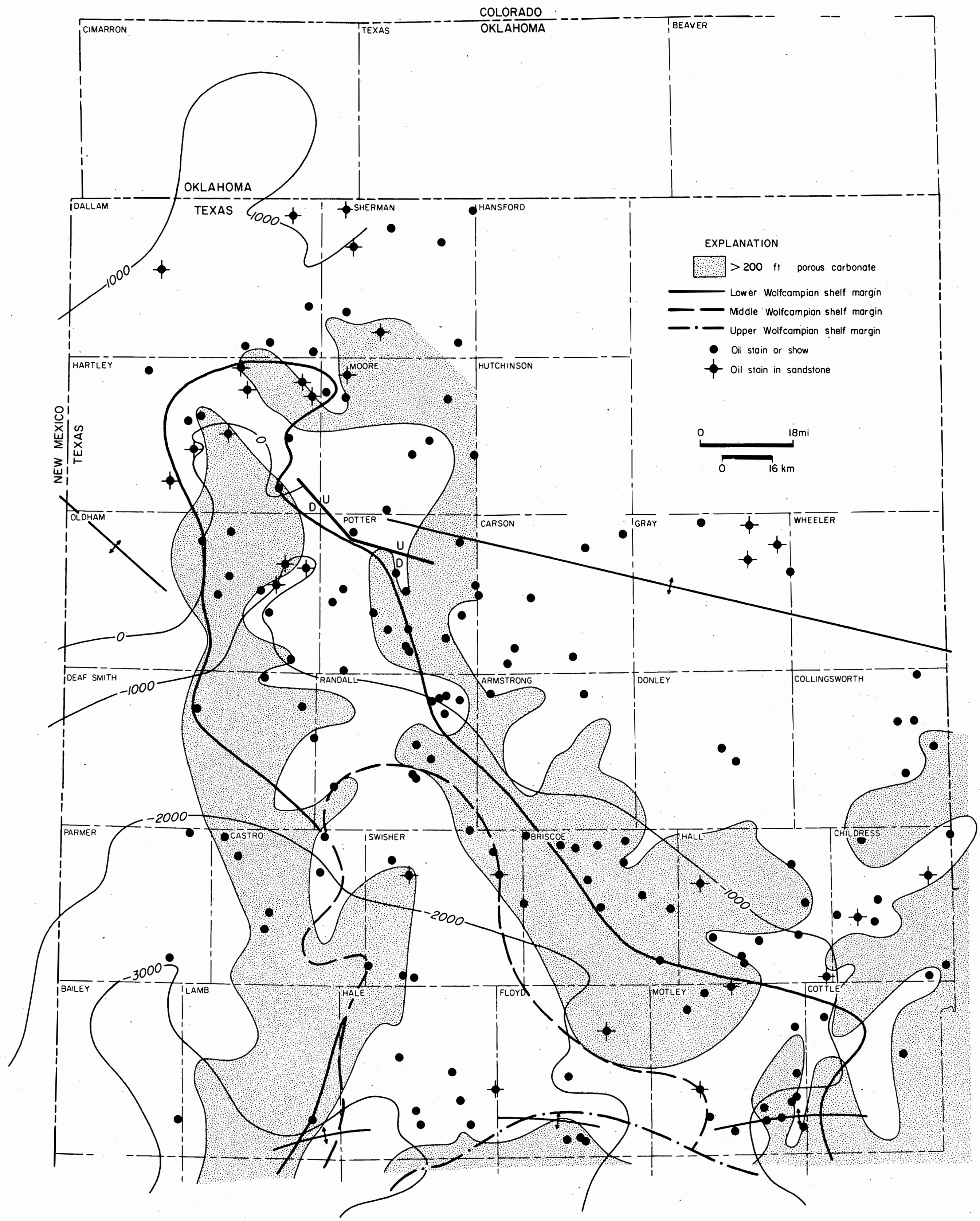


Figure 23. Distribution of oil stains and shows, as reported in sample logs, in relationship to Wolfcamp structure, porous carbonate fairways, and lithology of host rock. Hydrocarbon shows are most common in shelf carbonates and delta sandstones.

FAN-DELTA ARKOSES

Thick arkosic sandstones or granite wash, which flank the Amarillo Uplift in northern Palo Duro Basin, may contain fairways for potential oil and gas entrapment. These deposits interfinger with prodelta shale and shelf limestone; in updip directions, sandstones abut the Amarillo Uplift. In some places, sandstone is in apparent contact with uplifted fault blocks (fig. 5) along the Amarillo Uplift, and may have blocked updip hydrocarbon migration. Log-computed porosity in fan-delta sandstones averages approximately 18 percent.

In Wheeler County, Texas, which is centered within the Anadarko Basin, Pennsylvanian granite wash produces hydrocarbons in the Mobeetie Field. Producing facies include fan-delta plain, interdeltaic plain, and crevasse splay arkose (Becker, 1977). Erxleben (1975) reports that sandstones of a Pennsylvanian fan-delta system produce hydrocarbons in Wichita and Archer Counties.

SOURCE BEDS

Although Lower Permian porous reservoir facies are abundant in the Palo Duro Basin, questions concerning the presence and quality of potential petroleum source beds must be resolved before the true petroleum potential of the basin can be fully evaluated. If commercial quantities of petroleum are present in the basin, they were probably generated by thermal transformation of kerogen or organic matter during burial of source rocks. The quantity and variety of petroleum generated are related to the concentration and type of organic matter present (Dow, 1978).

Drill cuttings that are representative of all major depositional systems from various geographic localities in the Palo Duro Basin were analyzed for total organic carbon content. Ongoing studies will subsequently present kerogen and vitrinite reflectance data. Figures 24, 25, and 26 illustrate the distribution of organic carbon in samples across the basin.

Results confirm that shale and dark micrites from slope and basinal environments are the most likely potential source beds. The mean total organic carbon content is 0.589 percent by weight (57 samples). Highest values were determined from slope and basinal sediments in Hartley, Armstrong, Briscoe, Floyd, Motley, and Swisher Counties, where values generally ranged from 1 to 2.3 percent by weight organic carbon. Shelf carbonate deposits are low in organic carbon; mean content is 0.238 percent (31 samples). Anomalously high values were obtained from upper Wolfcamp carbonate in a Donley County sample, which corresponds to the same facies and stratigraphic interval ("Brown dolomite") as that which produces hydrocarbons in the nearby Panhandle Field (Totten, 1956).

Of the few samples from deltaic and fan-deltaic environments that were analyzed, all have less than 0.450 percent by weight total organic carbon. Although relatively low, this mean value is in accordance with expected lower concentrations in deltaic facies. Areas of high sedimentation rates, such as deltas, should contain sediments with relatively low organic carbon concentrations (Dow, 1978). High sedimentation rates effectively dilute the accumulation and concentration of organic matter. Currently in areas of major river runoff, terrestrial organic matter derived from higher land plants is most common (Dow, 1978). Terrestrial organic matter is generally deposited under oxidizing conditions in deltaic facies and will primarily yield gas. Thus fan-delta and delta-sandstone reservoirs might be expected to produce gas in the Palo Duro Basin.

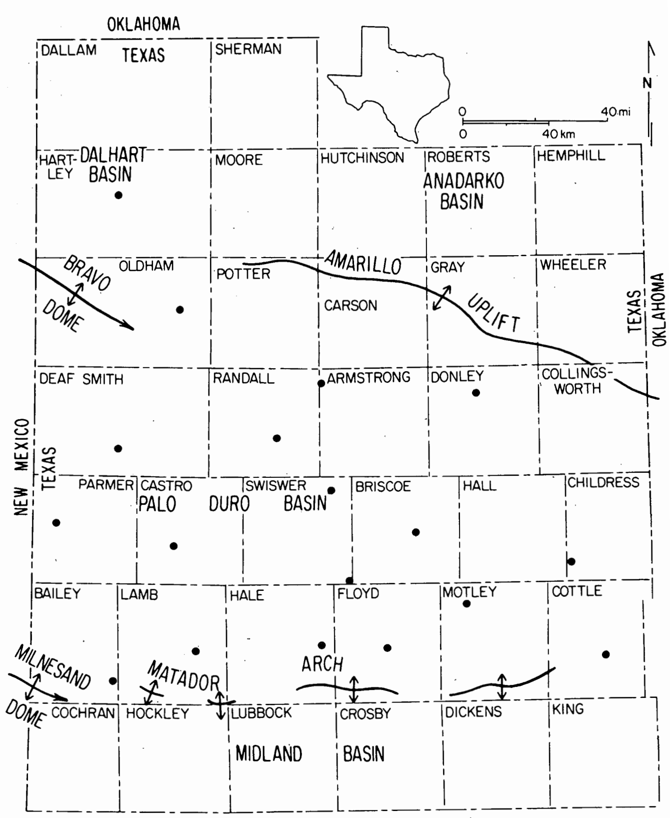


Figure 24. Index map showing locations of exploratory wells from which drill cuttings were analyzed for total organic carbon.

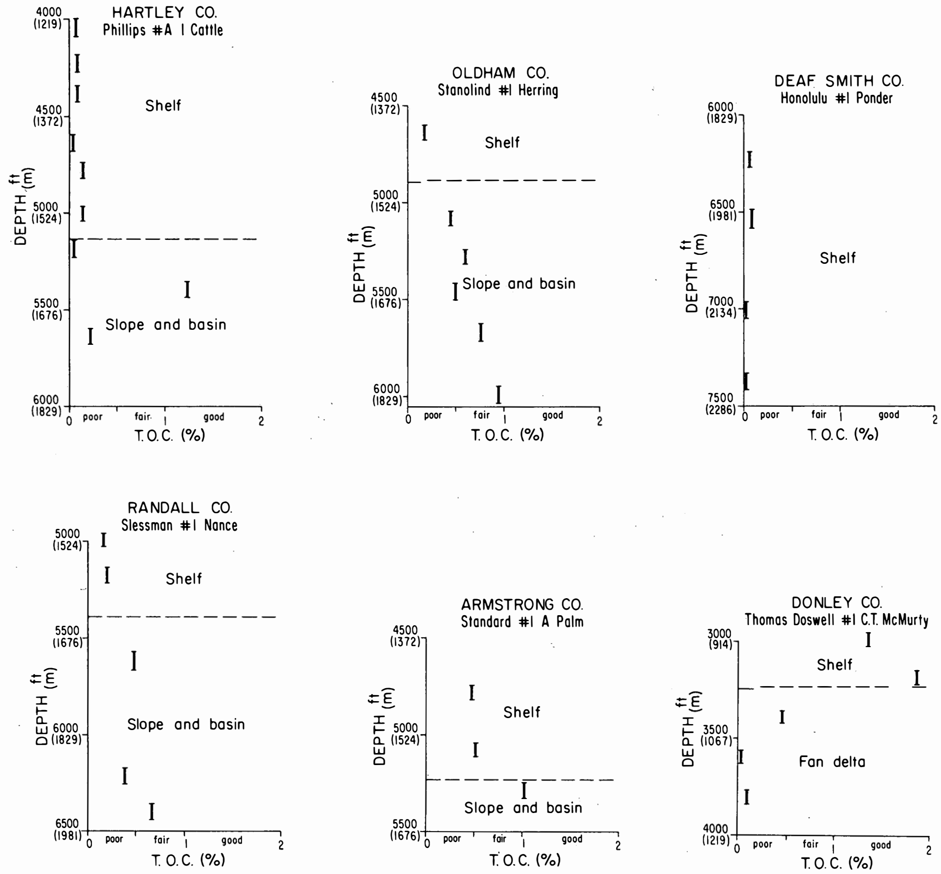


Figure 25. Total organic carbon versus depth for exploratory wells in northern Palo Duro and Dalhart Basins. Values are related to depositional systems observed in logs from each well.

Locations of exploration wells across the Palo Duro Basin are random with respect to facies patterns, suggesting that the basin has not been systematically explored. Drilling activity appears to have been dictated by structural trends; consequently, exploration techniques for facies control over hydrocarbon entrapment have been ignored. For example, shelf-margin trends have not been thoroughly explored.

Data suggest that successful exploration for stratigraphic traps in the Palo Duro Basin will require careful but imaginative approaches to stratigraphic correlation and facies mapping. To be successful, petroleum geologists must be acutely aware of the facies patterns, the depositional models, and the myriad of physical and biological processes that control facies characteristics, vertical sequences, and facies distribution.

CONCLUSIONS

(1) Four major depositional systems constitute the Lower Permian stratigraphic sequence in the Palo Duro Basin. They are (1) fan-delta system, (2) high-constructive delta system, (3) carbonate shelf and shelf-margin systems, and (4) slope and basinal systems.

(2) Fan-delta deposits are concentrated predominantly in the northern half of the basin where the Amarillo Uplift and Bravo Dome were exposed to subaerial weathering and erosion. High-constructive delta systems prograded into southeastern Palo Duro Basin from an eastern source. Clastic facies of both delta systems interfinger basinward with shelf carbonates, basinal shales, or both.

(3) Massive carbonate strata, representing shallow-shelf and shelf-margin environments, form a broad band around most of the basin, opening southward into the Midland Basin. The shelf margin stood as much as 200 to 400 ft (60 to 120 m) above the adjacent deep basin floor.

(4) Sediment derived from prograding deltas was carried through tidal passes between bioherms and banks and deposited into submarine feeder

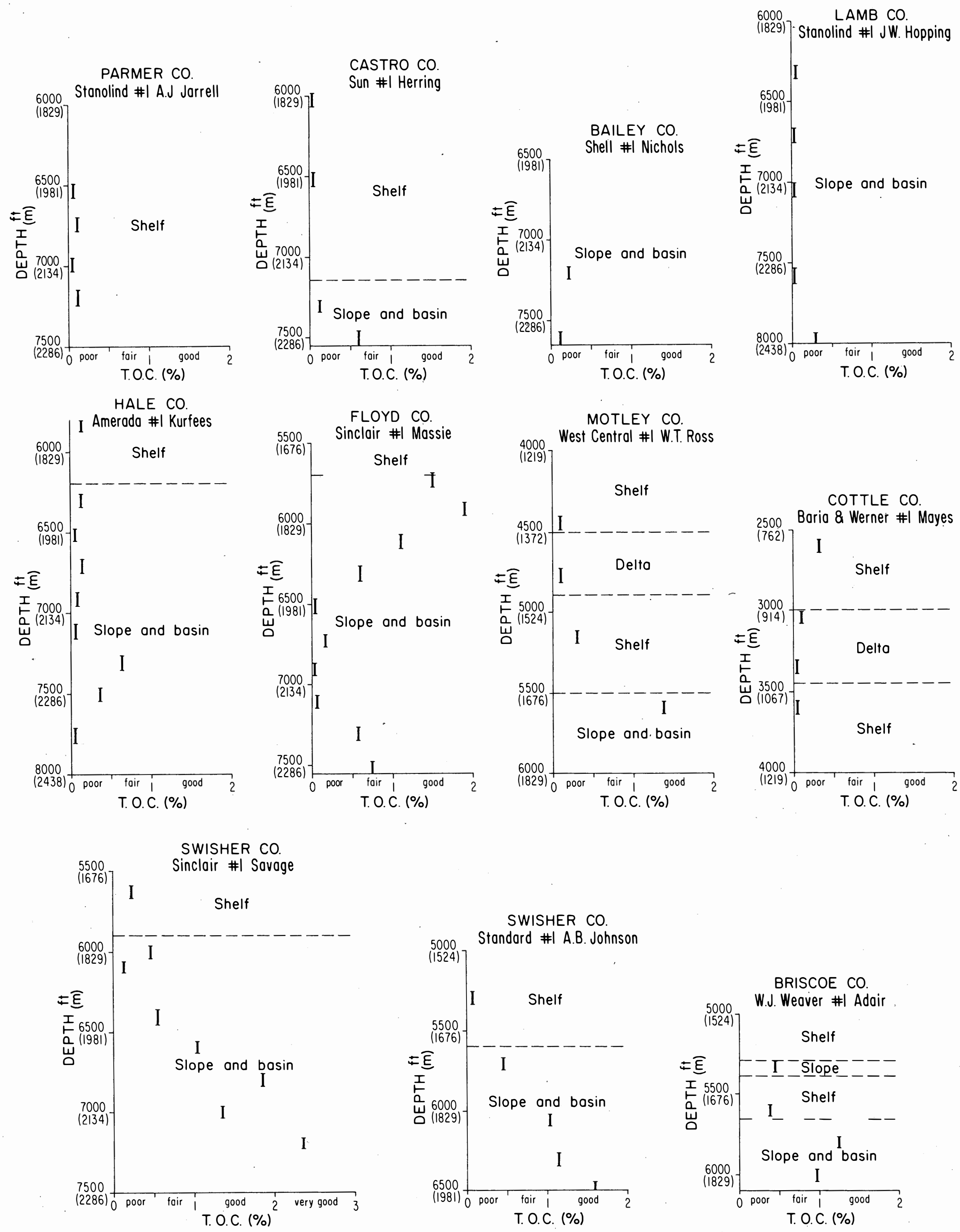


Figure 26. Total organic carbon versus depth for exploratory wells in central and southern Palo Duro Basin. Values are related to depositional systems observed in logs from each well.

channels that developed along the shelf margin and slope environments. Eventually most of this sediment was transported by feeder channels into the deeper parts of the basin. Continued sedimentation resulted in thick wedges of slope sediment, which later served as foundations for prograding shelf margins.

(5) Where clastic input was low, as in the western Palo Duro Basin, shelf margins tended to aggrade; where clastic input was high, as in the eastern Palo Duro Basin, shelf margins prograded.

(6) Porous facies of shelf-margin, high-constructive delta, and fan-delta systems are potential hydrocarbon reservoirs. Highest concentrations of organic carbon occur in slope and basinal shales and are considered the most likely potential source beds for petroleum generation.

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