BUREAU OF ECONOMIC GEOLOGY

Geological Circular 69-4

GEOMETRY AND DISTRIBUTION OF FLUVIAL AND DELTAIC SANDSTONES (PENNSYLVANIAN AND PERMIAN), NORTH-CENTRAL TEXAS[1]

By

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REPRINTED FROM TRANSACTIONS OF THE
GULF COAST ASSOCIATION OF GEOLOGICAL SOCIETIES
VOL. XIX, 1969

The University of Texas at Austin
October 1969

GEOMETRY AND DISTRIBUTION OF FLUVIAL AND DELTAIC SANDSTONES (PENNSYLVANIAN AND PERMIAN), NORTH-CENTRAL TEXAS[1]

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ABSTRACT

Upper Pensylvanian and lower Permian rocks of the Eastern Shelf in North-central Texas are composed of 10 to 15 repetitive sequences including open shelf, deltaic, fluvial, and interdeltaic depositional systems. Sediments derived from the Ouachita Mountains and associated piedmont were transported westward across a narrow coastal plain. Fluvial and deltaic sandstone facies define a southwest paleoslope of about 5 feet per mile. Sandstone facies are delta front sheets, distributary mouth bars, distributary and fluvial channels, and destructional bars.

Sandstones displaying distributary patterns represent distal deposition in the upslope area. Belt sandstones, typified by uncommonly thick fluvial channel deposits, prograded far downslope. Composite patterns include distributary and belt sandstones representing complex progradational history. Rocks display one-half degree northwest regional dip; negative structure residuals outline a broad area within which 70 percent of the deltaic facies were deposited.

Elongate sandstones are generally arranged parallel to paleoslope in vertically offset patterns controlled by differential compaction of fluvial and deltaic sands and interdistributary muds. Multistory sandstone bodies were deposited along narrow, structurally unstable belts which were periodically overloaded and later reoccupied by prograding deltas. Initial Cisco deltas followed a paleosurface grain controlled by underlying bank limestones; this orientation was maintained during deposition of 1,200 feet of Cisco strata. Each fluvial-deltaic system inherited its geometry from previous systems and, in turn, provided control for the next deltaic episode. Stratigraphic and structural mapping utilizing mud decompaction techniques confirms the roles played by compaction and structure in controlling the geometry of sandstone bodies.

INTRODUCTION

Upper Pennsylvanian and lower Permian rocks of the Virgil and Wolfcamp Series on the Eastern Shelf in North-central Texas are composed of fluvial, deltaic, interdeltaic, and open shelf facies (Fig. 1). Ten to fifteen repetitive sequences contain limestones, coals, clays, shales, sheet and elongate sandstones (Fig. 2). Elongate sandstone bodies occur at more than 30 stratigraphic levels within the 1,200-foot section of predominantly nearshore facies. Sandstone bodies provide information concerning depositional environments, paleoslope, and the role played by compaction and tectonics in controlling fluvial and deltaic deposition.

A depositional model for these rocks in North-central Texas has been proposed (L. F. Brown, 1969). The goal of this investigation is understanding the respective roles played by compaction and tectonics in controlling fluvial and deltaic depositional sites. The spatial distribution of elongate sandstones and the structural framework of the region provided principal data for interpretation.

In addition to standard stratigraphic and structural methods, decompaction of mudstones provided a tool to estimate differential compaction and differential shelf subsidence. Conclusions based on decompaction are necessarily speculative because of the status of research on compaction and the nature of assumptions which must be made.

Significance of Elongate Sandstones

Elongate sandstones have been important exploration targets for decades, and they will increase in importance as the location of subtle stratigraphic traps becomes more critical. Pennsylvanian and Permian sandstones are attractive shallow targets for independent operators in North and West-central Texas and in other Midcontinent areas. Continuing interest in Wilcox and Frio sandstones of the Gulf Coast Basin, as well as the currently intense interest in the Muddy Sandstone of the Rocky Mountains and Cretaceous facies of the Alaskan north slope, points to the importance of understanding fluvial and deltaic facies relationships and processes. Similar facies remain to be found in these and other basins. Factors which controlled the distribution of these facies are of considerable economic importance.

The Eastern Shelf of the West Texas Basin provides an unusual opportunity to investigate elongate sandstones

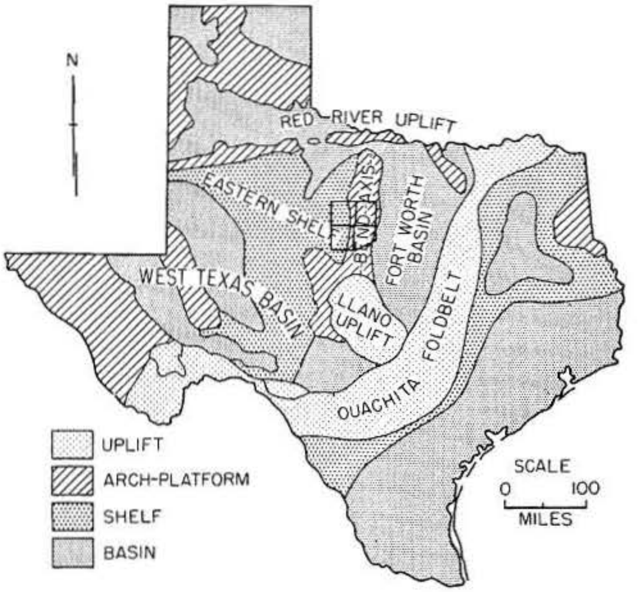

Figure 1. Index map and major structural features of Texas. After Dallas Geological Society, Texas Highway Map.

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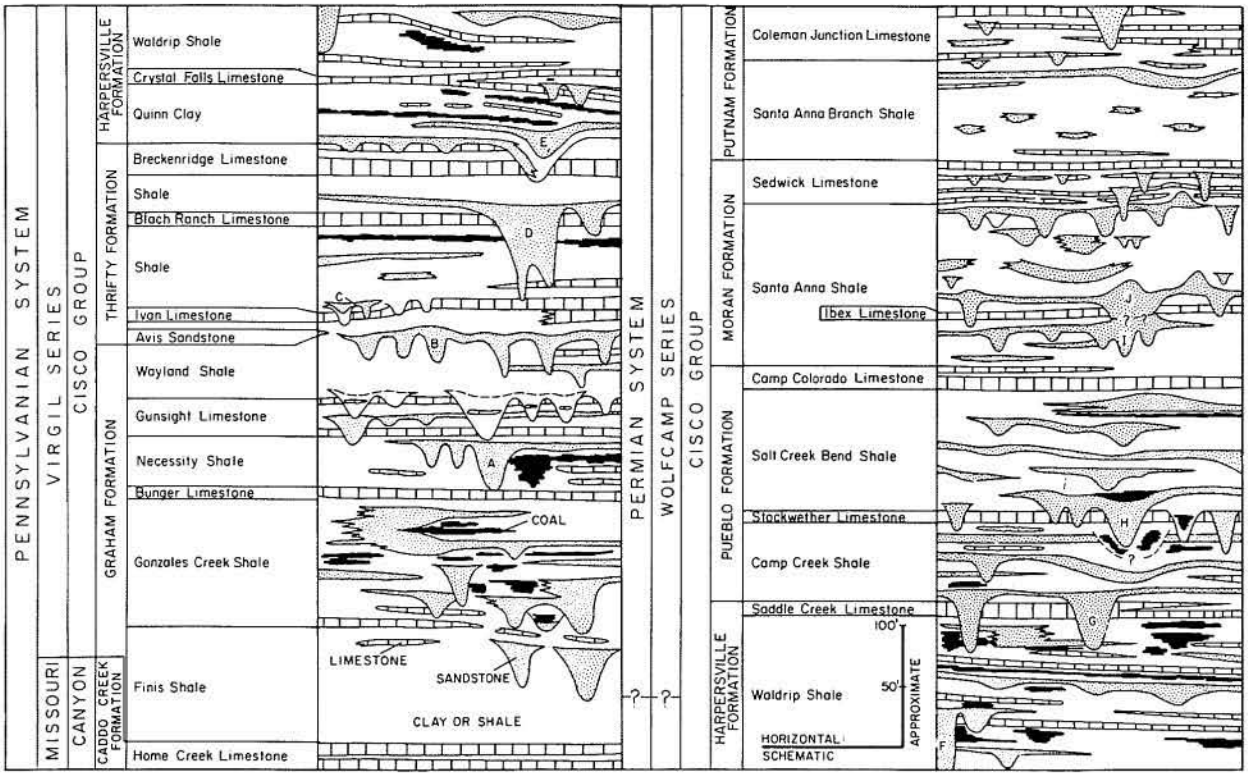


Figure 2. Schematic outcrop section, Cisco Group, Stephens and Shackelford counties, Texas. Sandstones A-J are principal sandstone systems. After McGowen (1964), Waller (1966, and Ray (1968).

where excellent surface and subsurface data are available. Deltaic and fluvial facies are interstratified with thin, areally extensive limestones, providing exceptional control for detailed stratigraphic and structural studies.

The erratic and meandering distribution of fluvial and deltaic sandstones makes these facies among the most difficult stratigraphic traps to locate. Although distribution of many sandstone systems has been delineated using standard subsurface methods, continuing effort should be applied toward developing additional stratigraphic and structural tools.

Elongate sandstones are potential ground-water reservoirs in many areas, but at best they rarely provide more than a local water supply. Perhaps more important is the potential of these sandstone systems as conduits and reservoirs which can be used for storage of desalinated water or water imported by canal or pipeline. These sandstones also provide a means of disposing of waste fluids, but they are also capable of piping contaminants and must be plugged or dammed before safe disposal is possible.

A problem in North-central Texas and most older oil field areas is contamination of surface water supplies by saline water from poorly plugged or leaking oil wells and from surface disposal pits. The labyrinth of sandstone bodies within fluvial and deltaic facies serves to pipe contaminants into alluvium or directly into streams. This problem will become increasingly critical during the next several decades when casing and plugs disintegrate in some of the thousands of abandoned oil wells in older oil areas. A thorough knowledge of these shallow sandstones will be necessary if economical and practical programs are to be devised for isolating and restricting migration of brines into potable water supplies.

Elongate sandstones are important in unraveling the depositional history of many nearshore facies. Dip-fed sandstones are important skeletal elements which distinguish fluvial and deltaic systems from other depositional systems, as well as outline the geometry of the facies complex. Within dominantly mudstone facies, sandstone distribution is a useful guide to paleoslope direction and general paleogeography. Economic deposits such as coal and kaolinite are closely related to the distribution of deltaic and fluvial facies.

Prograding delta systems are sensitive to slight variations in topography. The three-dimensional distribution of superposed deltaic sandstone bodies provides a key to processes affecting the depositional surface–tectonic subsidence or subsidence due to mud compaction.

Scope of the Investigation

Developing knowledge of the external geometry of elongate sandstones and the factors which controlled their distribution in upslope areas on the Eastern Shelf was the primary goal. More specifically, the investigation involved (1) construction of a stratigraphic framework which included the spatial distribution of major sandstone systems; (2) interpretation of dominant source direction, paleoslope, and depositional model from stratigraphic and sedimentary information; (3) development of a structural framework using both conventional and residual mapping techniques; (4) comparison of stratigraphic and structural data in order to evaluate possible structural control of elongate sandstone patterns; and (5) approximation of paleosurface and subsidence trends using decompaction techniques.

The area investigated comprises approximately 2,000 square miles in Stephens, Shackelford, Callahan, and Eastland counties, Texas. It is sufficiently large to contain significant parts of elongate sandstone systems, but the size minimizes regional facies and tectonic variations.

Earlier workers who contributed to the knowledge of the geology of North-central Texas were Cummins (1891), Drake (1893), and Plummer and Moore (1922). Lee (1938) first clearly reported the complexity of the stratigraphy and contributed significant ideas on environmental conditions. Cheney (1929) and Cheney and Goss (1952) examined regional structural history. Shankle (1960), Eargle (1960), Stafford (1960a, b), Terriere (1960), Rothrock (1961a, b), L. F. Brown (1960, 1962), and Myers (1965) recently described Pennsylvanian and Permian elongate sandstones in the region. Adams *et al.* (1951, 1960), Rall and Rall (1958), Van Siclen (1958), and Jackson (1964) considered deposition on the Eastern Shelf. L. F. Brown (1959) proposed a general depositional model for Virgil and Wolfcamp rocks in the central part of the Eastern Shelf. Regional Pennsylvanian facies on the Eastern Shelf were discussed by Wermund and Jenkins (1968).

Elongate sandstones occur in rocks of many ages and areas. Investigations involving Paleozoic sandstones similar to Virgil and Wolfcamp facies on the Eastern Shelf were tabulated by Friedman (1960), Pettijohn (1962), and Potter (1963, 1967). Studies have been concentrated in the Appalachian Basin, Eastern Interior Basin, and Mid-continent region; there is very little published information on Paleozoic sandstones in Texas.

A number of depositional models have been proposed for rocks similar to those in North-central Texas: for example, Pepper *et al.* (1954), D. Moore (1959), P. Allen (1959), Feofilova (1959), Pryor (1961), Wanless *et al.* (1963), Beerbower (1964), Swann (1964), Williams *et al.* (1964), Duff (1967), Wright (1967), and others. Several studies of Recent sediments, which bear on the depositional interpretation of these upper Paleozoic rocks, include Kruit (1955), Treadwell (1955), Fisk *et al.* (1954), Welder (1959), Coleman and Gagliano (1964), J. R. L. Allen (1965), Kolb and van Lopik (1966), Bernard and LeBlanc (1965), and Frazier (1967).

Stratigraphic and structural control was based on surface and subsurface data. Thin, relatively persistent limestone beds were key stratigraphic units. Elongate sandstones outline the skeletal framework of delta lobes and fluvial channels. Surface control was based on 800 described localities, 300 measured sections, limestone facies maps, and reconstructed elongate sandstone patterns tied by maps of all members and key beds at 1:20,000 scale. Subsurface control included 250 wells correlated with 12 dip and strike sections tied to the outcrop section.

J. H. McGowen, T. H. Waller, M. J. Seals, and J. R. Ray contributed much basic data. Bureau of Economic Geology staff members W. L. Fisher, P. U. Rodda, and P. T. Flawn read the manuscript and contributed ideas and criticism. J. L. Goodson computed much of the decompaction data and provided critical evaluation of the results. Miss Josephine Casey and Mrs. Elizabeth T. Moore processed the manuscript; drafting was under the supervision of J. W. Macon. The West Texas Geological Society kindly permitted the use of several illustrations from "Cyclic Sedimentation in the Permian Basin" (L. F. Brown, 1969).

VERTICAL SEQUENCES: STRATIGRAPHIC UNITS

Repetitive Sequences

Virgil and Wolfcamp rocks in upslope areas of the Eastern Shelf are composed of thin, persistent limestones which are interstratified with thicker mudstone or shale units containing sheet sandstones, elongate sandstones, and less common coal or bituminous shales (Fig. 2). Ten to fifteen mudstone and sandstone sequences (or "cycles") are separated by regionally persistent limestone beds within the 1,200-foot section.

Sequences normally display an orderly vertical arrangement of facies (Fig. 2). A generalized sequence of facies (upward) includes: (1) thin, persistent limestone beds; (2) extensive clay-shale facies containing marine fossils near the base becoming unfossiliferous and silty near the top; (3) local elongate sandstone bodies commonly oriented east-west and laterally equivalent to clay-shale facies, which in places contain limestone lenses, coals, bituminous shales, and lenticular sandstones; (4) clay-shale facies overlying elongate sandstones, containing some coal and bituminous shale, sheet and bar sandstones; and again (1) thin, persistent limestone beds. Although ten to fifteen such repetitive sequences occur, many local variations exist in the vertical succession of facies. Aside from minor variations, the most significant regional variation is the presence or absence of dip-fed elongate sandstone facies.

Formal stratigraphic classification developed by early workers was unsatisfactory (Plummer and Moore, 1922). Formation names rarely coincide with stratigraphic units significant in combined surface and subsurface analysis. Names applied to individual limestone and sandstone beds were utilized where applicable. Most major sandstone systems are unnamed; they are denoted by letters **A-H** (Fig. 2).

Formats

Superposed sequences of limestone-bounded, dominantly terrigenous clastic rocks are extensively distributed throughout approximately 25 counties on the Eastern Shelf (Fig. 3). Bounding limestone units are not necessarily time-stratigraphic but represent the best time-markers in the section (L. F. Brown, 1969). Limestone-bounded stratigraphic units or sequences are persistent, mappable rock units at the outcrop and in the subsurface and have genetic significance important in understanding the origin of the repetitive shelf facies (Figs. 2, 3). In this report, these subdivisions are called *formats* (Forgotson, 1957). The marker-defined operational units are informal stratigraphic subdivisions designated by the names of bounding limestones *e.g.,* Home Creek–Bunger format). Virgil and Wolfcamp formats are commonly 100 feet

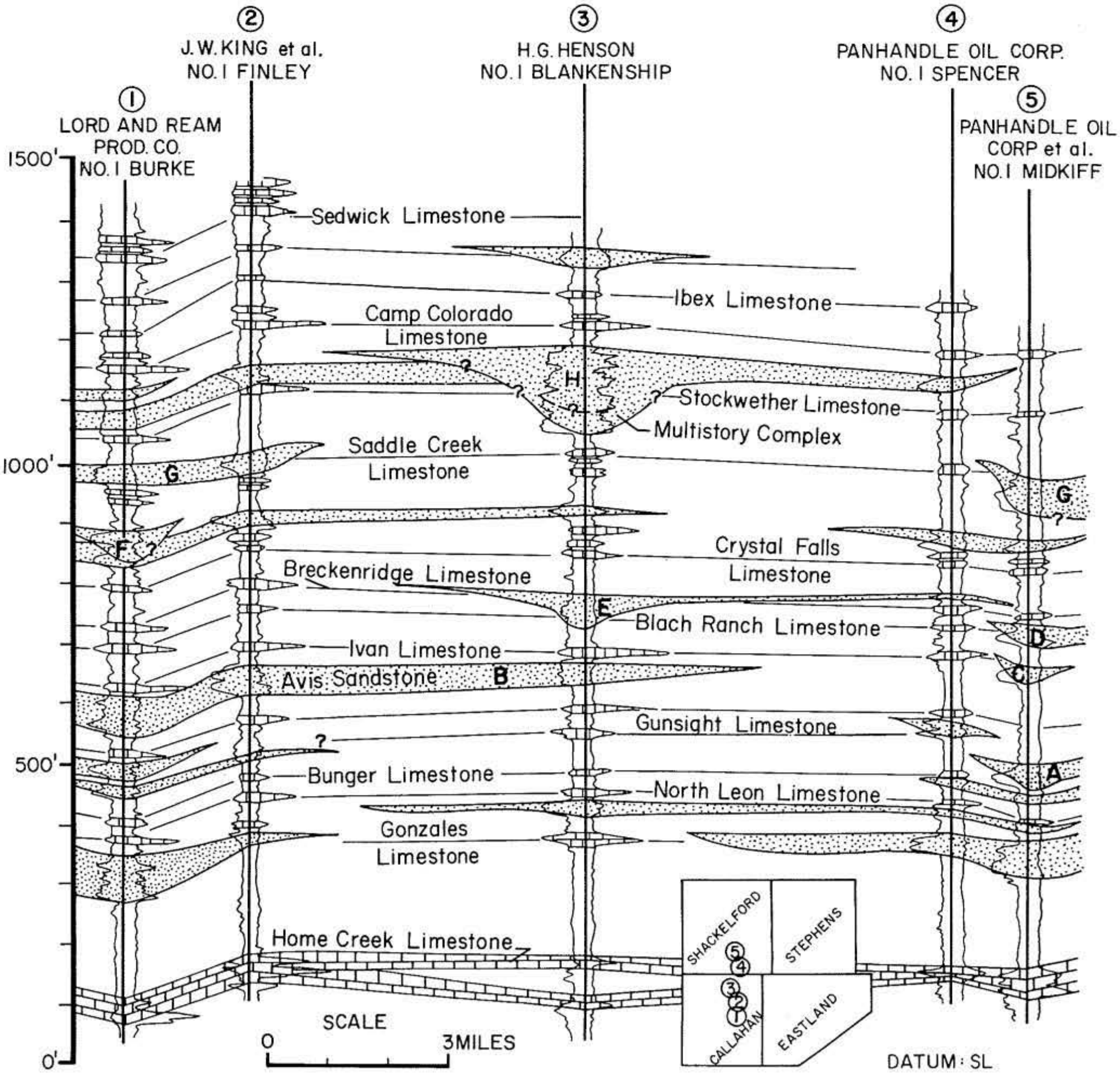


Figure 3. Subsurface reference section, Cisco Group, Callahan and Shackelford counties, Texas. After Seals (1965). Formats are arbitrarily defined units bounded by limestones.

thick in upslope areas, but several superposed sequences may be combined into thicker formats useful in specific problems of stratigraphic analysis. Format boundaries used herein are regionally persistent limestones–Home Creek, Bunger, Gunsight, Blach Ranch, Breckenridge, Crystal Falls, Saddle Creek, Stockwether, and Camp Colorado (Fig. 3).

The term Cisco has been modified many times (Cheney, 1940). This report follows the original definition (Plummer and Moore, 1922) which refers to nearshore, primarily terrigenous rocks between the underlying open marine Canyon facies and Wichita-Albany facies (Fig. 2). Cisco rocks crop out in the Brazos and Colorado Valleys. Cisco Group is, therefore, not necessarily synonymous with Cisco Series (L. F. Brown, 1959). Dominantly non-marine rocks, which are approximate upslope equivalents of the Cisco Group, crop out in the Trinity Valley. These fluvial and associated facies are informally designated "Bowie rocks."

SANDSTONE SYSTEMS: GEOMETRY AND ORIGIN

Two general classes of sandstones occur within Virgil and Wolfcamp rocks in North-central Texas–elongate and sheet sandstones. More common elongate sandstones can be mapped from outcrop westward into the subsurface of the Eastern Shelf; sheet sandstone facies are thin and difficult to map. Interpretations of origin of sandstone bodies are based on sedimentary structures, internal geometry and stratigraphic relationships, and more importantly on external geometry, sand-body distribution, and facies relationships.

Elongate Sandstones

Most elongate sandstones within the area are oriented northeast-southwest (Fig. 4A). Some sandstones are of channel origin, displaying prominent erosional contacts with subjacent rocks. Other sandstones display gradational contacts; locally they contain small channel bodies or extensive channels are superimposed on the non-channel facies. Sedimentary and stratigraphic evidence indicates that most elongate sandstones are segments of dip-fed fluvial and/or deltaic facies deposited on a surface sloping southwestward at less than 5 feet per mile. Few significant strike-fed, elongate bar sandstones have been observed.

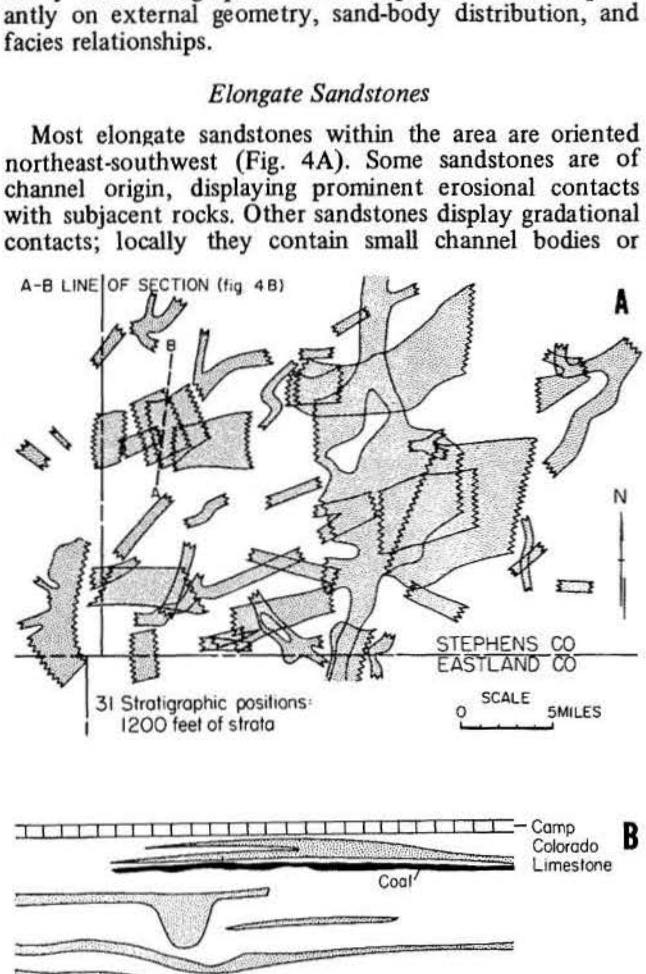


Figure 4. Geometry of outcropping sandstones, Stephens County, Texas. A, Restored areal distribution of elongate sandstones. B, Cross section of elongate sandstones. After McGowen (1964), Waller (1966), and Ray (1968).

Elongate sandstones at the outcrop are parts of major fluvial and delta complexes which normally extend tens of miles down paleoslope. Individual sandstone bodies commonly include more than one facies. For example, a sandstone may be composed of superposed delta front, channel-mouth bars, distributary channels, as well as superimposed fluvial sandstones and destructional sheet and bar sandstone bodies deposited along the periphery of the deltas, all of which might be mapped in outcrop or subsurface as a single sand unit. Progradation of fluvial and delta facies resulted in sandstone geometry ranging from relatively simple distributary bodies to complex belt sandstones. Although many sandstones have erosional bases, they are not significantly discordant with other strata.

Fluvial Sandstone Facies

Channel deposits are sandstones and conglomerates, rarely mudstones. Sandstone channels range from bodies deposited contemporaneously with associated rocks to those which cut tens of feet into subjacent strata (Fig. 4B). Few levee and overbank deposits have been recognized, although these facies may be common in predominantly fluvial Bowie rocks upslope in Jack and Montague counties. Channel sandstones and conglomerates at the outcrop contain sedimentary structures which confirm westward to southwestward paleoslope.

Abrupt contacts of channel deposits with regionally persistent limestone marker beds clearly outline channel boundaries. In the subsurface the local replacement of a limestone bed with a sandstone along a linear belt indicates channel erosion.

Fluvial sandstones are medium to fine grained. Lenses of chert conglomerate are common, especially near the base of channels. Locally derived limestone conglomerates occur near the base and along the flanks of some channel bodies. Simple fluvial channels display asymmetric cross sections with maximum erosion near one bank of the channel. Most fluvial sandstones are composed of numerous superimposed channels resulting in complex internal structure.

Plant fragments and clay clasts are common constituents. Marine fossils occur in the upper part of some channel sequences. Upward fining of sediment characterizes most fluvial channel units. Festoon cross-bedding is more common near the base of channels, and ripple cross stratification typifies uppermost sandstones. Some channels, especially those containing extensive chert gravel, show horizontal and foreset bedding typical of braided stream deposits. Few point-bar sequences have been recognized, possibly because of insufficient data on internal composition of channels.

Fluvial sandstones grade upward into mudstones, marine sandstones, and marine limestones (Fig. 5). Bituminous shales or impure coal beds occur within some

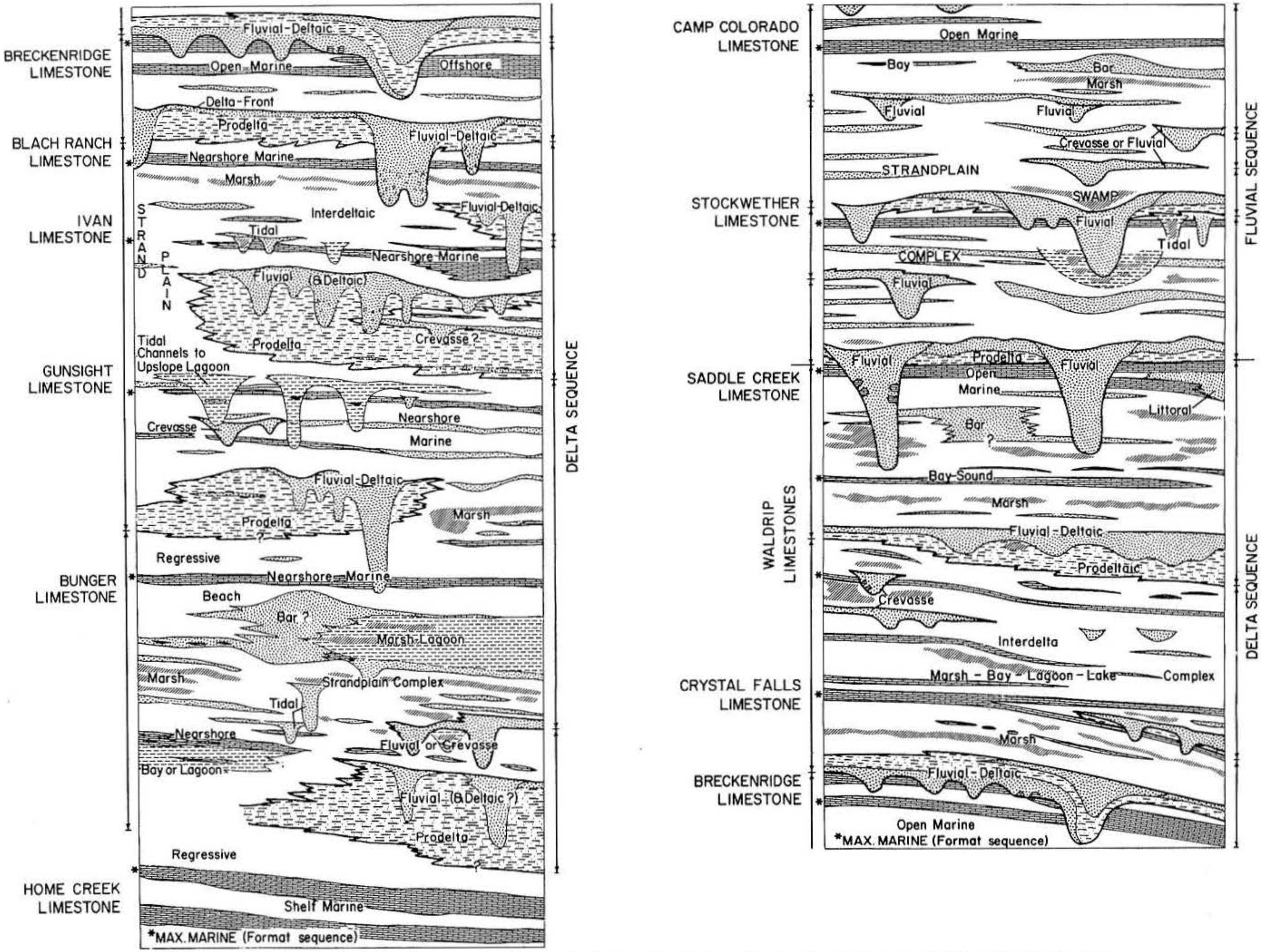


Figure 5. Facies relationships of outcropping Cisco and Bowie rocks, Stephens County, Texas. Compare sequences between bases of fluvial or deltaic facies and sequences bounded by transgressive limestones (format sequences).

channels, indicating cut-off and filling with suspended sediment (Fig. 4B). Fluvial channels commonly cut into or through underlying deltaic facies; larger channels commonly cut deeply into marine facies of the previous repetitive sequence. At the outcrop lower Cisco fluvial channels are normally incised into thick subjacent delta facies. Upper Cisco channels cut into thin deltaic facies or rest directly on marine facies, suggesting erosion of deltaic facies in upslope areas or, more probably, rapid progradation across nearshore marine facies.

The lack of extensive subaerial erosion indicates that most fluvial sandstones were deposited on a low-lying plain near regional base level, probably the upper part of a delta plain. Fluvial channels in the area do not fit a piedmont or upper coastal plain fluvial model, although such models explain Bowie fluvial rocks exposed upslope in the Trinity Valley.

Deltaic Sandstones

Sandstones of deltaic origin exhibit vertical sequences composed of constructional delta front sheet sands and distributary mouth bars, and distributary channel facies (Fig. 5). In addition, some local sandstone bars of destructional origin occur along the fringes of the delta. Fluvial channel deposits, which prograde over the upper delta plain and occupy many previous distributary channels, are difficult to differentiate from distributary channel deposits, especially in the subsurface.

Delta front facies are normally well-bedded and well-sorted sandstones which contain parallel laminae, some ripple cross laminae, and symmetrical ripple bedforms on upper surfaces. The base of delta front sandstones commonly exhibits highly contorted bedding. Delta front sandstones are gradational below with laminated, plant-rich prodelta clays and siltstones. Distributary mouth bars are composed of well-sorted, highly contorted sand. Relict parallel laminae and some trough cross-bedding are normally preserved. Injection of sand from below, along with rolled and squeezed structures, indicates progradation over water-saturated prodelta muds. Near the top of the bars are shallow, symmetrical distributary channels. These channels may be cut into the underlying bar, or they may occur within overlying delta plain mudstones. Erosion within the delta sequence is restricted to the base of channels. Distributary channels are rarely more than 30 or 40 yards wide. Some smaller channels display crevasse splay characteristics, including climbing ripples and subaqueous levees. Later fluvial channels may cut into or through the delta facies, leaving a strong imprint of fluvial character on the sandstone facies complex.

Sheet Sandstones

Sheet sandstones compose a small part of the total volume of sandstone within the Cisco Group. Sheet and thin bar sandstones primarily occur fringing deltaic facies and in interdeltaic areas.

Delta front sands were reworked and redistributed along strike during deltaic deposition, and this redistribution of sand continued during destruction of various lobes. At the outcrop these extensive, thin (2 to 8 feet thick), well-bedded sandstones normally occur within interdeltaic areas at the approximate stratigraphic position of fluvial and deltaic sandstones (Fig. 5). Sheet sandstones contain burrowing pelecypods and wave ripples on upper surfaces. At some localities, distributary channels cut the sandstones, indicating delta front origin. It is probable, however, that sheet sandstones flanking elongate deltaic sandstones represent both delta front deposition and marine destructional facies.

Along the flank of deltas, thin bar sandstones and sandy limestones (1 to 4 feet thick) were deposited during marine reworking of deltaic sands. These bars are very local, rippled, commonly repetitive and highly burrowed. Bars may grade upward into clastic limestones.

Within interdeltaic areas, sheet and bar sandstones (1 to 20 feet thick), interbedded with relatively unfossiliferous mudstones, are strike-fed strandplain or chenier facies (Fig. 5). These sandstones, which commonly show beach characteristics, were derived from abandoned deltas during marine destruction. They were transported along strike into delta flank basins and other embayed interdeltaic areas. Sheet sandstones are genetically important facies within the Cisco, but in the subsurface these units are normally too thin to map.

Sandstone Distribution

Depositional Patterns

In plan view, dip-fed sandstones display three general patterns–distributary, belt, and composite. These patterns are similar to Eastern Interior Pennsylvanian sandstones (Friedman, 1960, and Potter, 1963).

Distributary sandstone patterns bifurcate down paleoslope from single trunk streams (Fig. 6A). Similar patterns in Illinois (Swann, 1964), in Oklahoma (Busch, 1953, 1959), and in Kansas (S. L. Brown, 1967) were interpreted to be of deltaic origin. (These bifurcating sandstone bodies are composed of barfinger sandstones (Fisk, 1961).) Distributary sandstones commonly terminate downslope within about 20 miles of the principal trunk stream. They represent relatively small deltas restricted to upslope areas. Since they failed to prograde far downslope, deeply eroding fluvial channels did not significantly modify the deltaic facies.

Belt sandstone patterns characterize more extensive elongate sandstone systems which extend far down paleoslope (Fig. 6B). At the outcrop these sandstones show deltaic sequences, but prominent fluvial channels commonly cut the deltaic sandstones, modifying and eroding these upslope deltaic facies as the delta-fluvial complex prograded. Deposition was maintained by relatively steady sediment supply. Individual sandstones within a belt complex are not necessarily contemporaneous.

Within belt sandstones are many small coalescing lobes composed of delta front sheet sands and distributary mouth bars, distributary channels, and destructional bars and sheet sands. Superimposed fluvial channels at the outcrop are commonly conglomeratic and deeply erosional.

Composite sandstone patterns are intermediate between distributary and belt geometry (Fig. 6C, D). Within some formats, relict distributary sandstones in upslope areas occur with belt sandstones which extend farther down

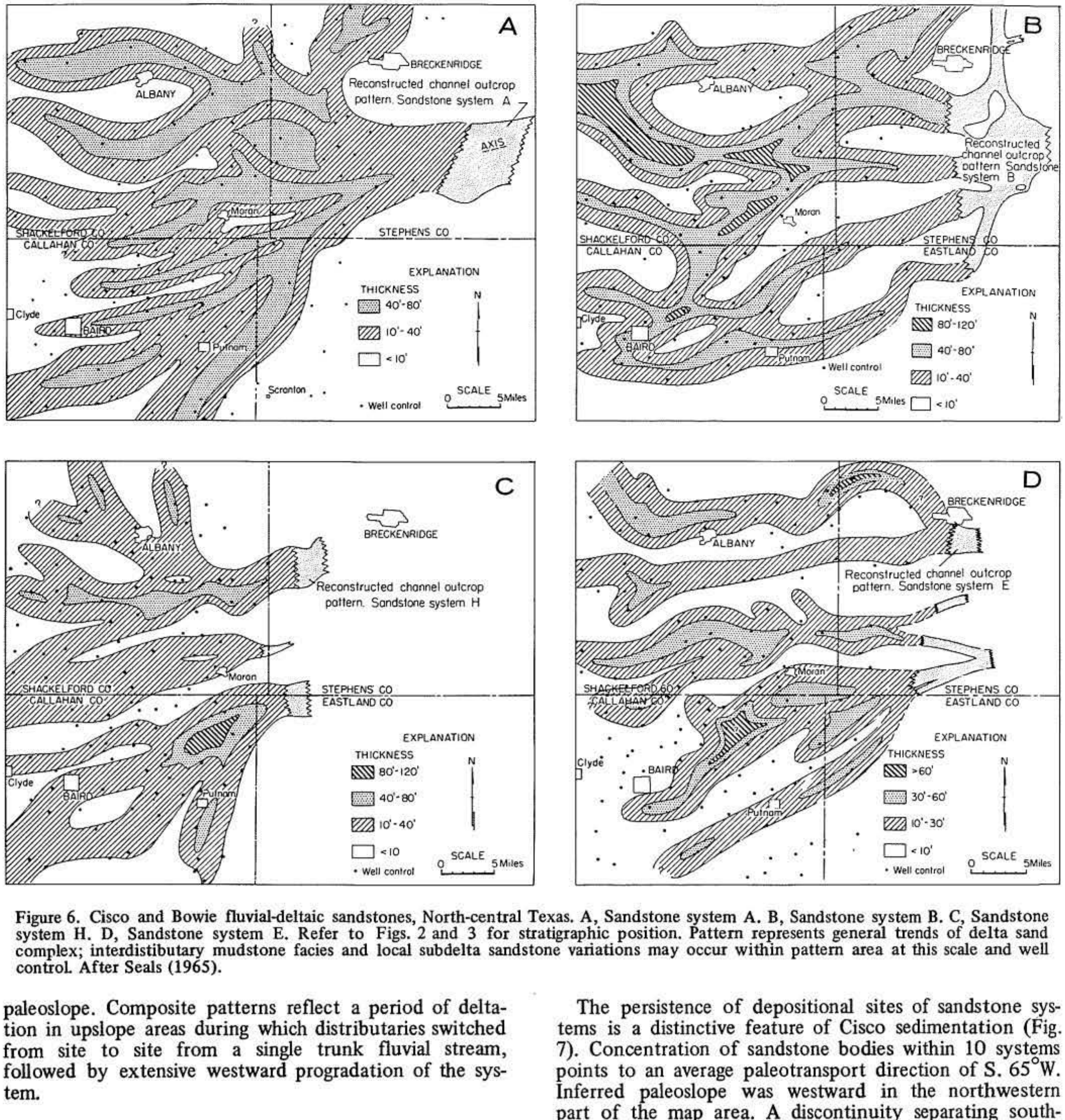


Figure 6. Cisco and Bowie fluvial-deltaic sandstones, North-central Texas. A, Sandstone system A. B, Sandstone system B. C, Sandstone system H. D, Sandstone system E. Refer to Figs. 2 and 3 for stratigraphic position. Pattern represents general trends of delta sand complex; interdistibutary mudstone facies and local subdelta sandstone variations may occur within pattern area at this scale and well control. After Seals (1965).

paleoslope. Composite patterns reflect a period of deltation in upslope areas during which distributaries switched from site to site from a single trunk fluvial stream, followed by extensive westward progradation of the system.

Paleoslope

Most Cisco sandstone systems display dominant northeast-southwest orientation. Detailed mapping and reconstruction of sandstone geometry at 31 stratigraphic positions illustrate west to southwest paleotransport routes (Fig. 4A). Sedimentary structures within these linear sandstone facies confirm this transport direction. Principal sediment source was to the northeast, probably in the Ouachita Mountains and associated piedmont.

The persistence of depositional sites of sandstone systems is a distinctive feature of Cisco sedimentation (Fig. 7). Concentration of sandstone bodies within 10 systems points to an average paleotransport direction of S. 65°W. Inferred paleoslope was westward in the northwestern part of the map area. A discontinuity separating southwestward trends from westward trends coincides with structural axes discussed below.

Gradients during deposition of dip-fed sandstones were less than 5 feet per mile. Regionally parallel sandstones, limestones, and coal beds indicate little difference in gradient during deltaic progradation and limestone deposition. Prodelta mud slopes probably increased the gradient at which distributary mouth bars and channels were deposited.

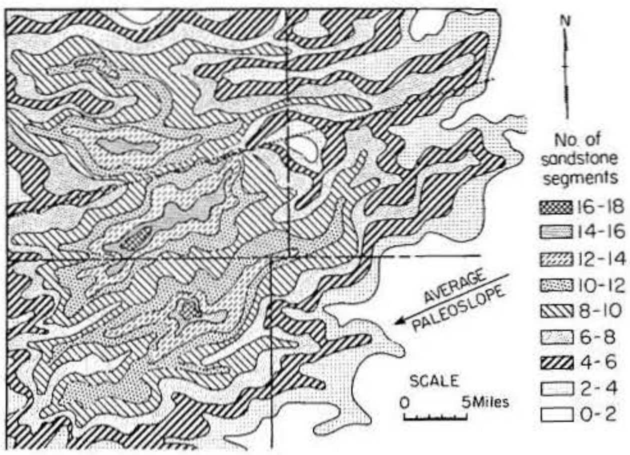


Figure 7. Concentration of Cisco and Bowie elongate sandstones, North-central Texas. Based on number of sandstone segments per 4 square miles within ten major sandstone systems (A-J, Fig. 2). Dotted line along discontinuity in sandstone concentration.

Present structural configuration at the base of elongate sandstones is evidence of erosional and/or compactional nature of basal channel surfaces (Fig. 8). Structural contours at the base of sandstones define V-patterns with axes plunging westward to southwestward at about 50 feet per mile. Asymmetry of structural contours at the base of sandstones, especially those with northeast-southwest orientation, confirm post-depositional tilting to the northwest during the Permian (Fig. 8B). When regional structure (50 feet per mile northwest) is subtracted from structure at the base of a sandstone system, resulting structural residual values outline the sandstone trend and indicate that regional gradients were consistently less than 5 feet per mile. Sandstone deposition was, therefore, upon surfaces with very low gradients. Variations probably reflect local scouring or subsidence of sandstones into water-saturated prodelta muds.

Isopach maps were prepared of intervals between the base of sandstones and overlying or underlying stratigraphic datum surfaces in order to estimate the configuration of basal sandstone surfaces at or soon after deposition (Siever, 1951; Andresen, 1961, 1962). These methods, commonly referred to as "paleotopographic mapping," eliminate some distortion resulting from post-depositional mud compaction. Maps of distributary sandstone patterns display closed contour patterns in distributary branches (Fig. 8B). Because unusually deep channel erosion in distributary lobes is unlikely, closed patterns apparently reflect (1) distal barfinger sandstones which are laterally gradational with prodelta mudstones; and (2) differential compaction of barfinger sands and interdistributary muds resulting in closed thick areas. Decompaction of mudstones within the isopach interval (*see* discussion of decompaction) did not significantly change isopach patterns, confirming that distributary patterns most likely represent barfinger sandstones rather than deep-cutting, valley-fill sandstones.

Belt sandstones display fluvial patterns on similarly constructed isopach maps. Closed thick areas occur where the sandstone is thickest, suggesting some compactional distortion, but when the mudstones within the interval are decompacted, the isopach patterns open down paleoslope (Fig. 8A). Such patterns are typical of uppermost Cisco sandstones which occur within deeper erosional channels at the outcrop. Far downslope these sandstones exhibit less basal channel erosion where they grade into dominantly deltaic facies.

The nature of sandstone facies along dispersal routes within a single sandstone system varies markedly from upslope deltaic areas to distal depositional sites. In upslope areas, fluvial channels commonly cut subjacent shelf limestones (Fig. 9, section M-N). Downslope in the same sandstone system barlike sandstones rarely cut subjacent limestone beds and are generally gradational with adjacent strata (Fig. 9, section A-B). Greater compactional distor-

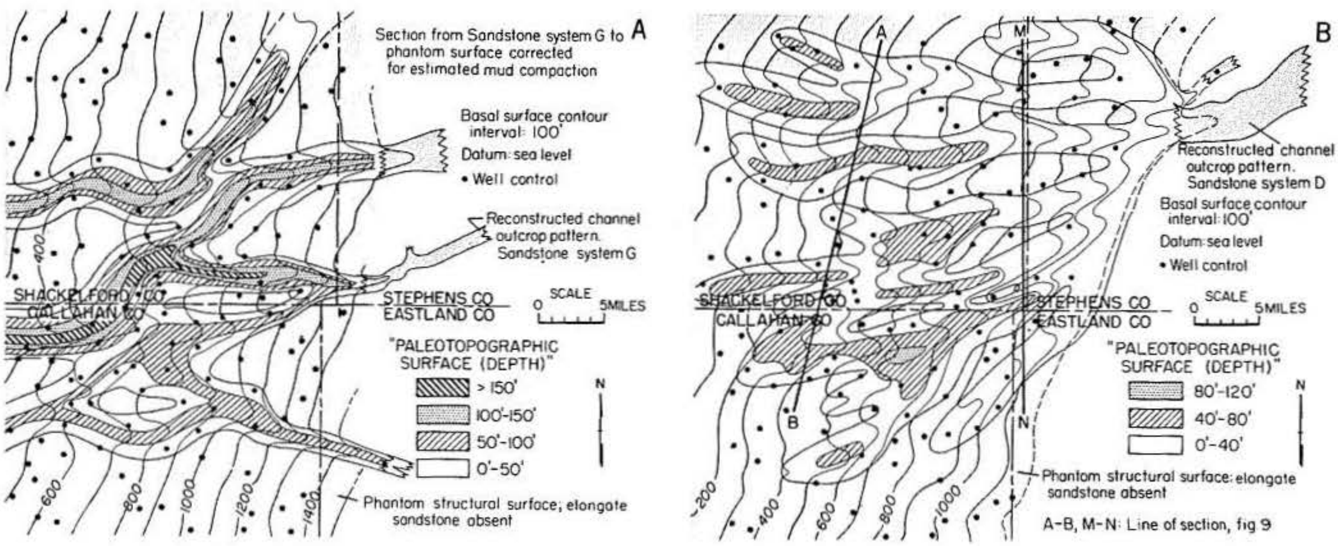


Figure 8. Structure and inferred paleotopography at base of elongate sandstones. A, Sandstone system G. B, Sandstone system D. Paleosurface configuration is isopach map from base of sandstone to overlying phantom structural surface near top of sandstone system. After Seals (1965).

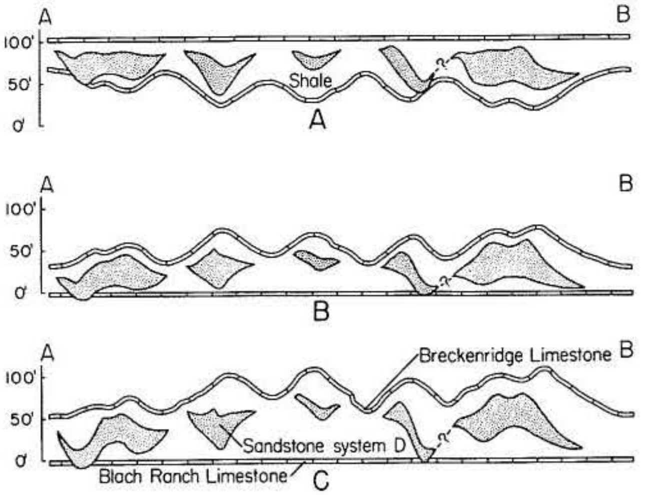


Figure 9. Cross sections, Blach Ranch-Breckenridge format. A, Breckenridge Limestone datum (downdip). B, Blach Ranch Limestone datum (downdip). C, Decompacted downdip section. D, Blach Ranch Limestone datum (updip). E, Decompacted updip section.

tion also occurs in downslope barfinger bodies where thicker, water-saturated prodelta muds surrounded deltaic sands.

Use of structural and stratigraphic methods to estimate paleogradients in distal parts of distributary sandstone systems is impractical because of the gradational nature of the basal contact and the effects of differential compaction of barfinger sands and prodelta muds (Fig. 8B). Paleogradients of upslope fluvial channels, however, can be approximated using structural residual or paleotopography (isopach) mapping techniques. Gradients at the base of Cisco fluvial sandstones were less than 5 feet per mile, which is within the proper order of magnitude to support other evidence of delta plain fluvial origin rather than piedmont or upper coastal plain fluvial deposition (Fig. 8A).

Spatial Distribution: Vertical Patterns

Spatial distribution of principal sandstone bodies is a key to factors controlling depositional sites. It was noted above that Cisco sandstones were deposited within distributary, belt, and composite systems (Fig. 6). The vertical relationship between these superposed sandstone systems provides evidence of the respective roles played by compaction and structure in determining the distribution of sand depositional sites within each repetitive sequence.

Most Cisco sandstones display vertically offsetting relationships with overlying and underlying sandstone systems (Fig. 10A). Along several narrow east-west belts, however, superposed sandstones are commonly stacked in vertical multistory arrangement (Fig. 10B). Offset and multistory vertical patterns persist throughout 1,200 feet of fluvial and deltaic facies.

Coastal plain fluvial systems, which occurred updip from the present outcrop, must have maintained relatively permanent routes. The distribution of ten Cisco sandstone systems indicates that most deltaic systems originated at common point sources, suggesting little shifting of river channels upslope from their junction with widely shifting delta distributaries.

Offsetting sandstones.—The common occurrence of vertically offset sandstones is compatible with deposition on

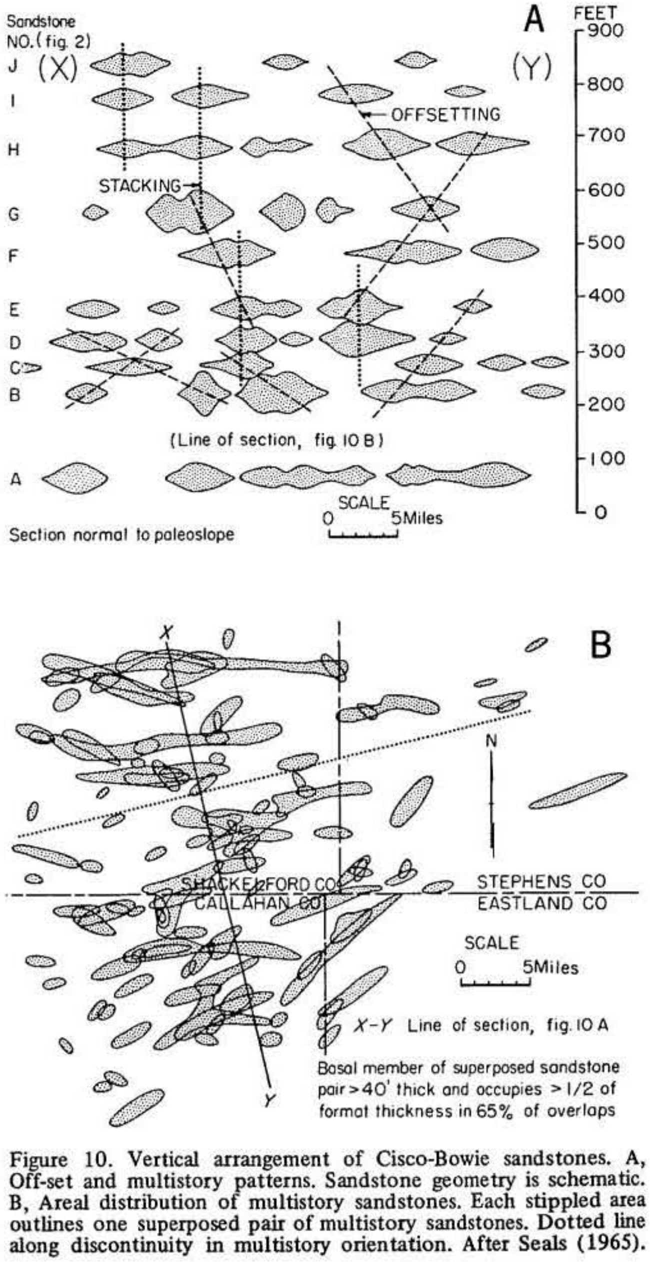


Figure 10. Vertical arrangement of Cisco-Bowie sandstones. A, Off-set and multistory patterns. Sandstone geometry is schematic. B, Areal distribution of multistory sandstones. Each stippled area outlines one superposed pair of multistory sandstones. Dotted line along discontinuity in multistory orientation. After Seals (1965).

a slowly subsiding, slightly tilting shelf where dip-fed deltaic sands were deposited on water-saturated muds. Slight topographic depressions or troughs, which developed above highly compacted interdistributary and interdeltaic muds, provided an efficient site or tract for subsequent delta progradation. Differential compaction of relatively non-compactible deltaic sands and highly compactible muds should, therefore, result in vertically offset deltaic depositional sites.

Following delta deposition in the area, delta destructional and marine transgressive facies were deposited over the abandoned delta platform. The effect of differential compaction of delta facies was transmitted to these subsequent facies, for delta sands of the next overlying sequence commonly offset underlying sandstones. Offset sandstone deposition is further discussed under "Sandstones and paleosurface trends." Throughout most of the area, superposed Cisco sandstones are arranged in offset patterns (Fig. 10A). This spatial distribution is compatible with deltaic deposition of sand and water-saturated muds on a slowly subsiding shelf. Not all sandstones in the section, however, display offset patterns, e.g., multistory patterns.

Multistory sandstones.—Stacked or multistory sandstones occur in narrow belts oriented along paleoslope. These belts, illustrated by charting areas where maximum thickness axes of superposed sandstones overlap (fig. 10B), correspond closely with belts of maximum sandstone concentration (Fig. 7).

In 65 to 70 percent of multistory sandstone occurrences, the underlying sandstone displays greater than average thickness. Subsidence of thick barfinger sands into subjacent muds provided subtle overlying paleotopographic depressions which guided progradation of superposed delta systems. Persistence of multistory belts throughout 1,200 feet of Cisco section is difficult to explain, however, by only differential compaction. Subsidence of unusually thick linear sand bodies into underlying muds might locally have produced overlying paleotopographic depressions responsible for diverting a subsequent delta system. Compactional subsidence sufficient to stack multiple superposed sandstones does not appear likely within thin shelf sequences. Slight structural weakness or instability, coupled with loading of these less stable belts, is more likely a dual mechanism for multistory deposition in North-central Texas. The relationship of unstable structural belts and multistory sand deposition is discussed under "Sandstones and subsidence trends."

Spatial distribution of Cisco fluvial and deltaic systems points to interplay between differential compaction of deltaic sand and mud facies, and slight contemporaneous subsidence related to structurally unstable belts. Differential compaction exerted greater control, except in local belts where overriding tectonics produced multistory relationships.

DEPOSITIONAL MODEL

The Eastern Shelf is a relatively stable tectonic area developed on the early Pennsylvanian Concho Platform (Cheney and Goss, 1952), which was obscured by late Pennsylvanian and early Permian westward tilting. The north-south axis of westward tilting, which approximately coincides with the western flank of the Fort Worth Basin, has been designated the Bend Axis (*idem*). Cisco strata display little evidence of the axis, but slight structural adjustment along the feature may have been responsible for localized structural activity on the shelf. East of the shelf lay the Ouachita Mountains and exposed Fort Worth Basin rocks termed piedmont; north of the shelf was the Wichita structural system in southern Oklahoma; and southward the shelf apparently deflected around the Llano structural complex (Fig. 11).

Southeastward post-Triassic tilting was related to development of the Gulf of Mexico. Lower Cretaceous strata dip southeastward at about 30 feet per mile over a dissected sub-Cretaceous surface cut into Permian and Pennsylvanian rocks.

Virgil and Wolfcamp rocks dip northwest at approximately 50 feet per mile. Strike migrates from N. 25° E. at the base of the Virgil Series to N. 10° E. at the base of Wolfcamp rocks. Wermund and Jenkins (1964) reported counter-clockwise shift in strike from N. 45° E. in Desmoines rocks to north-south strike in lower Wolfcamp rocks, indicating accelerated development of the West Texas Basin and gradual decline of Fort Worth Basin subsidence.

Depositional Systems

Virgil and Wolfcamp facies compose fluvial, deltaic, interdeltaic, and shelf depositional systems (Fig. 12). Depositional systems are stratigraphic packages of genetically related facies comparable to modern facies complexes readily apparent from physiographic characteristics, such as bar, delta, and fluvial systems (Fisher and McGowen, 1967, p. 106).

Fluvial systems contain channel and overbank facies primarily upslope and northeast of the area in Jack and Montague counties. Coastal plain and piedmont fluvial facies upslope within Bowie rocks (Fig. 13) have rarely been recognized within the Brazos or Colorado River valley outcrop belt where fluvial channels were deposited on lower coastal plains and delta plains.

Prograding Cisco *delta systems* contain prodelta mudstones and siltstones, delta front sheet sandstones and distributary mouth bars, and delta plain facies (distributary channel sandstones, interdistributary coals, mudstones, and crevasse splays) deposited during delta construction (Fig. 12). Many bar and sheet sandstones, mudstones, coals, and impure limestones were deposited during destruction of the delta. Barfinger sandstones are composed of various sand facies deposited during delta construction. These facies, along with superimposed fluvial sandstones, constitute the elongate sandstone facies of this report.

Most mudstone facies interstratified downslope with shelf limestones are probably of prodeltaic origin. Delta progradation is the only significant mechanism capable of transporting mud across the broad, shallow-water Cisco shelf. Prodelta mud and silt transported to the shelf edge by deltas constitute the major volume of slope sediment responsible for prograding the shelf.

Cisco *interdeltaic systems* are principally upslope mudstone facies deposited within embayments flanking delta systems (Fig. 12). Deltaic sediments redistributed by marine currents were deposited as sheet and bar sands and

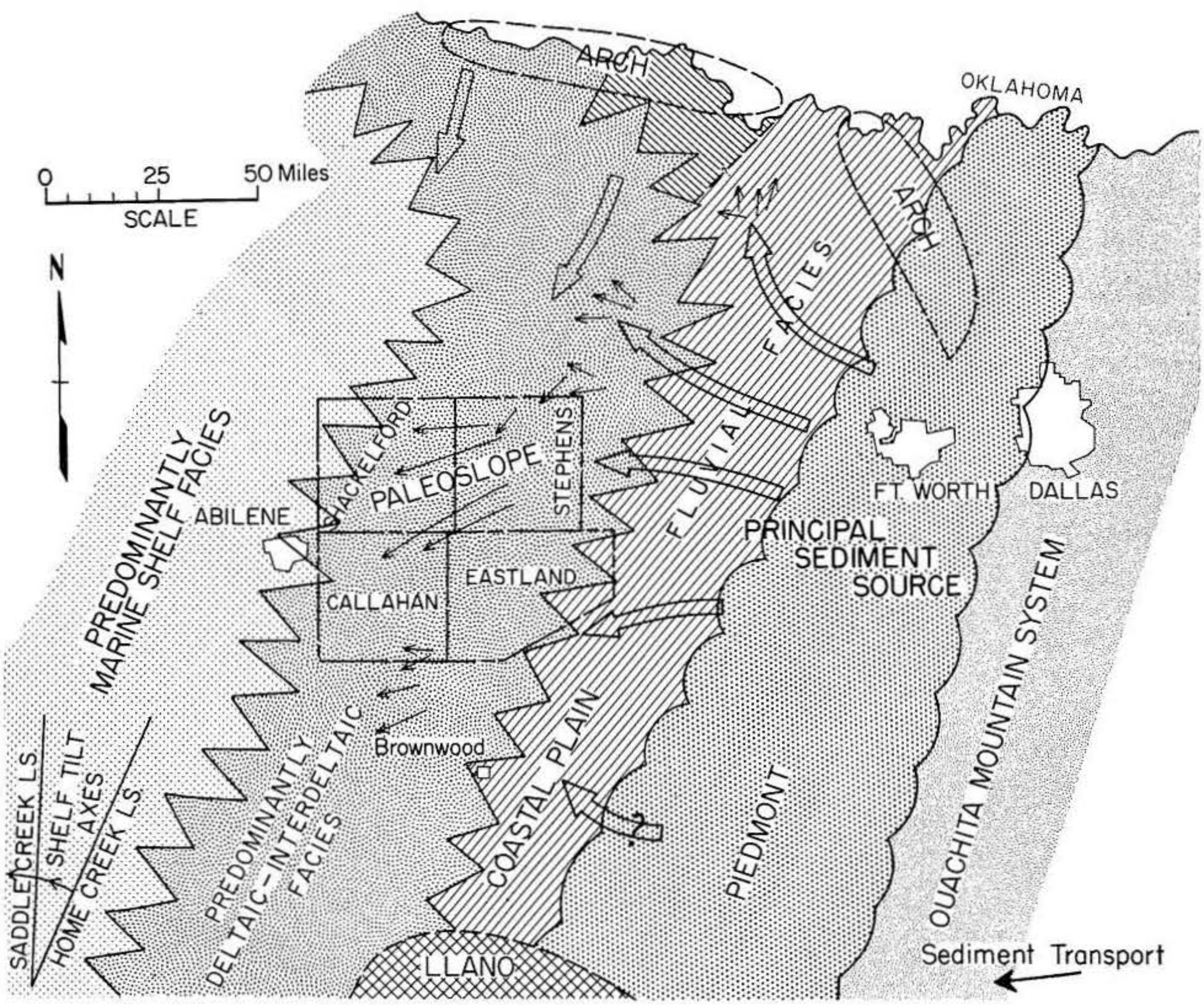


Figure 11. Paleogeographic map, Cisco and Bowie rocks, North-central Texas. Sediment transport directions after Lee (1938); Terriere (1960); Stafford (1960); Rothrock (1961); and Brown (1960, 1969).

nearshore muds. Specific facies recognized within interdeltaic systems include lagoon, bay-sound, marsh, and strandplain and mudflat deposits. Interdeltaic sandstones are primarily thin, strike-fed facies.

Cisco *shelf systems* are composed principally of various limestone facies (Fig. 12). Possibly some thin shelf mudstones occur in downslope areas, but most muds interstratified with shelf limestones are of prodeltaic origin. It is possible that with more data, it can be demonstrated that some downslope muds were derived by longshore drift from major deltas in North Texas and southern Oklahoma. Shelf limestones in the lower Cisco are commonly thin, but some upper Cisco shelf-edge limestones are very thick and may occupy an entire format. Shelf limestones were deposited in shallow water in the absence of local terrigenous clastic supply. Limestones on the shelf edge thin upslope into transgressive tongues which separate delta sequences. Downslope, shelf limestones thin into basinal facies.

Depositional Summary

Delta systems prograded rapidly across the slowly subsiding Eastern Shelf (Fig. 13). Sediments from the east supplied crevassing delta lobes until avulsion of overextended systems occurred. Delta construction, accompanied by deposition of complementary facies within nearby interdelta areas, restricted open shelf limestone facies to downslope areas beyond the effects of local deltaic deposition. Upper delta plain facies were cut by fluvial channels. Shelf edges migrated basinward primarily in response to offlapping mudstone deposits supplied by delta systems.

Marine processes slowly modified abandoned, compacting, and subsiding deltas. Winnowed sediments were swept onto interdeltaic mudflats and strandplains; complex mudstone facies occupied coastlines and foundering delta plains. Widespread open shelf limestone environments, in the absence of local delta deposition, trans-

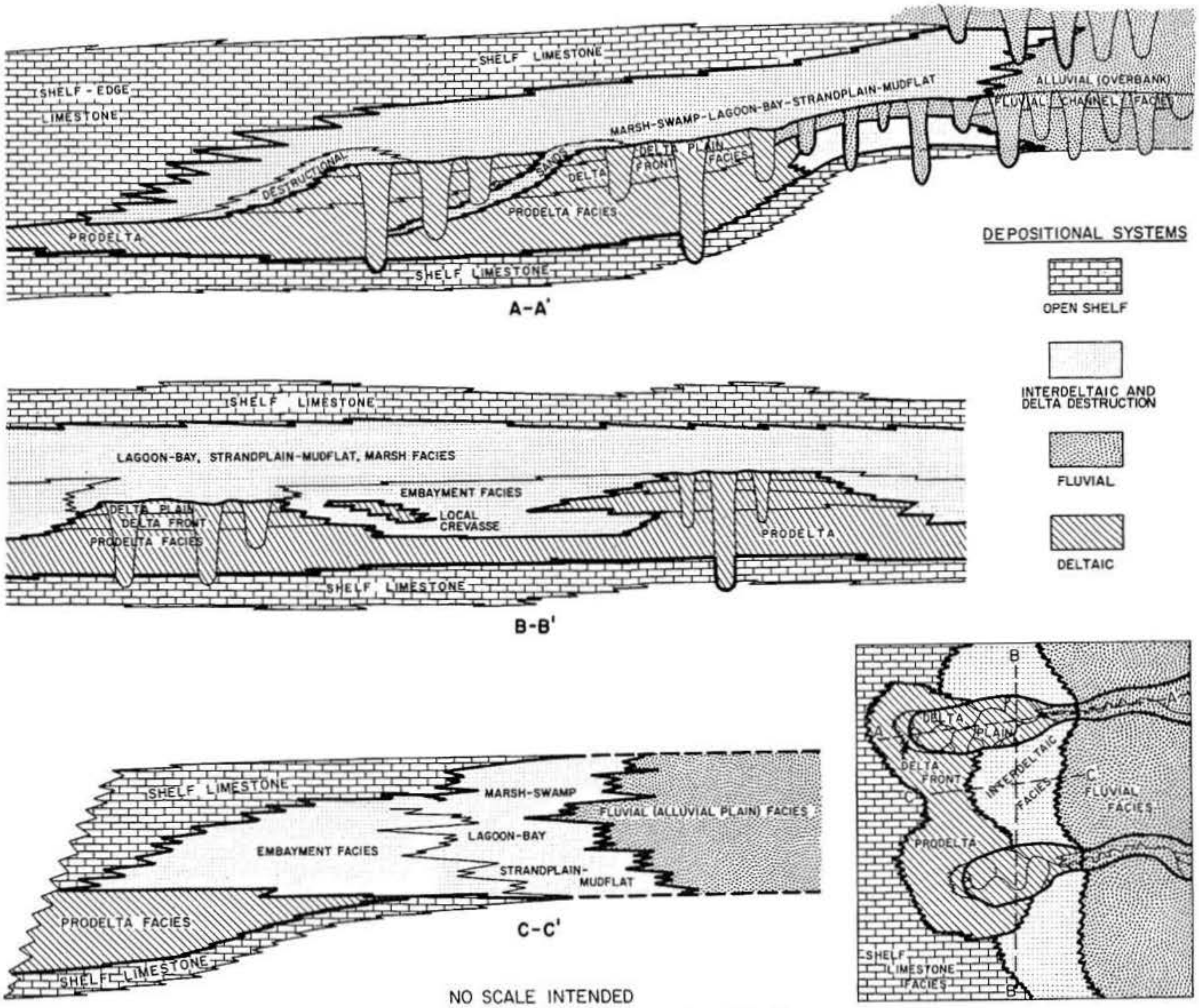


Figure 12. Distribution of component facies, Cisco and Bowie depositional systems, North-central Texas.

gressed upslope and along the coast to coalesce over marsh-stabilized, subsiding deltas and interdelta areas.

Within the proposed shelf model, all environments occur simultaneously, shifting with distribution of delta sites to produce repetitive sequences composed of thin, superposed depositional systems, each displaying a more or less homotaxial sequence of component facies (Fig. 13). At any point on the shelf, each limestone bounded sequence or format contains some variation of the following vertical arrangement of facies: (1) open shelf limestone system; (2) delta system (prodelta, delta front and distributary mouth bar, distributary channel, mudstone and coal, sheet and bar sandstone); (3) fluvial system (channel facies); and/or (4) interdelta system (marsh, lagoon-bay-sound, strandplain and mudflat); and again (1) open shelf limestone system. These format sequences are diachronous and aperiodic, but they represent the most synchronous stratigraphic package on the shelf. Constructional fluvial and delta facies occupy small discrete time intervals within the format, while deposition of destructional and transgressive facies occupies most of the time consumed by deposition. Cisco and Bowie depositional systems (and component facies) shifted southwestward through time as the eastern flank of the West Texas Basin was filled by the westward prograding shelf.

FACTORS CONTROLLING SANDSTONE DISTRIBUTION

The geometry and spatial distribution of Cisco sandstones indicate that the configuration of surfaces over which deltas prograded was controlled principally by differential sand-mud compaction of subjacent deltaic facies. Multistory sandstones point to subtle, local control of delta sites by differential rates of structural subsidence. Within such a model, each deltaic episode should inherit a paleosurface resulting from compactional and minor structural effects during deposition of the subjacent delta sequence. The relationship of each of these factors—tectonics, compaction, and inherited paleotopography—is considered independently.

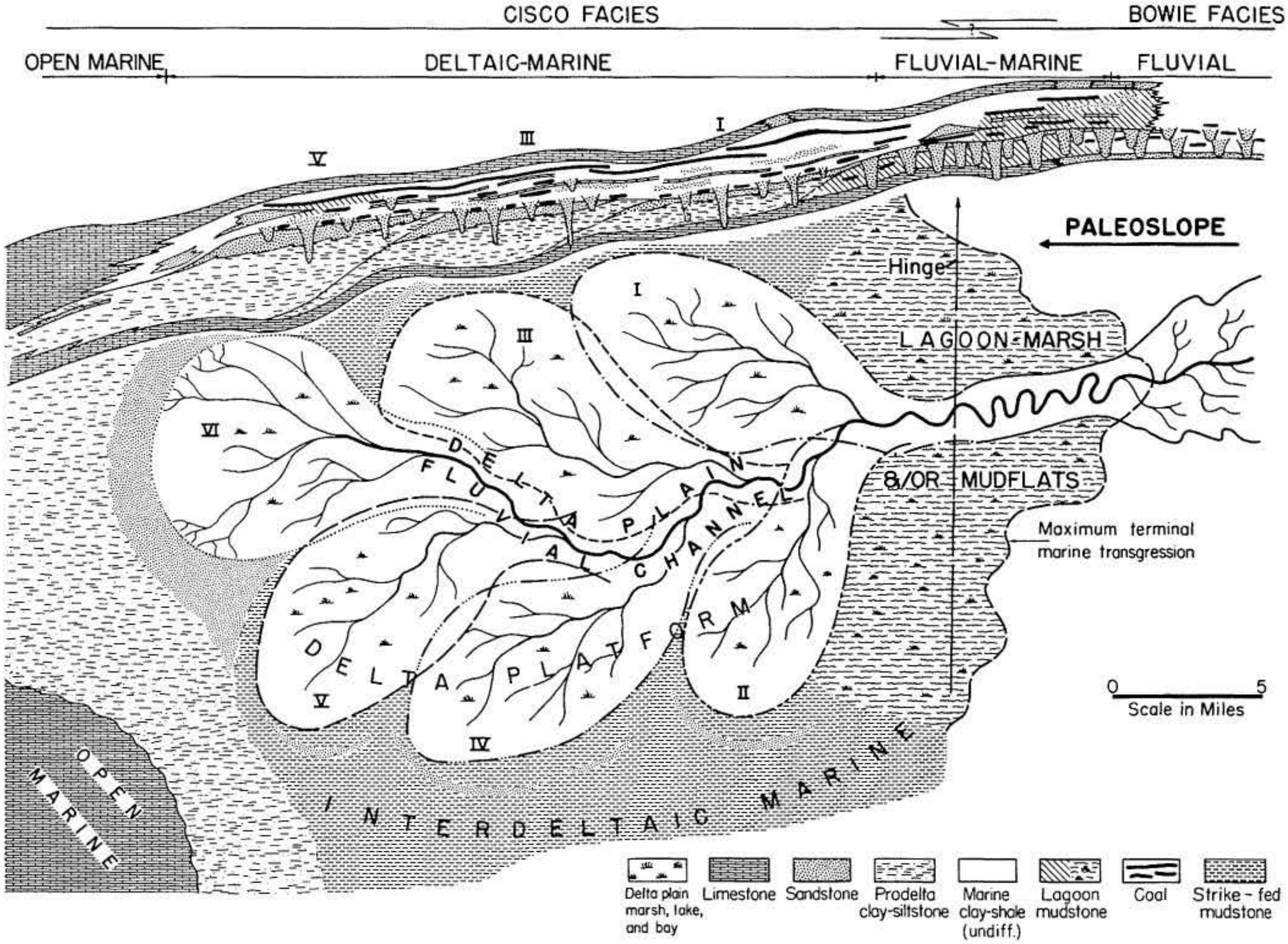


Figure 13. Depositional model, Cisco and Bowie rocks, North-central Texas. Many fluvial systems display braided stream geometry and sedimentary structures.

Structure and Sandstone Trends

Cisco rocks on the Eastern Shelf dip northwest at about 50 feet per mile (Fig. 14A). Northwest-trending minor structural axes commonly have local closure of less than 50 feet (Abilene Geological Society, 1949, 1950, 1952). Multistory sandstone belts and axes of maximum density of sandstone bodies locally coincide with regional synclinal trends (Figs. 10B, 7). Elongate sandstone trends and inferred paleoslope deviate about 30° to 35° from present structural axes.

A meaningful display of structural data is obtained by mapping structural residual values. When regional structure is subtracted from structure at the base of key limestone beds, resulting positive and negative residual values define strong northeast-southwest trends. Approximately 70 percent of all Cisco elongate sandstone in the area, including multistory belts, occurs within a broad negative residual belt trending northeast-southwest (Fig. 14B). Elongate sandstones within positive residual areas normally coincide with minimum positive values. Cisco sandstones are commonly absent in areas of maximum positive residual values. Coincidence of sandstone multistory trends and maximum sandstone density belts with negative structural residual trends suggests persistent but subtle structural control of some deltaic sandstones.

Residual structural patterns clearly delineate broad belts where shelf subsidence was considerably more or less than average for the region. These structural trends apparently affected the general location of Cisco delta deposition and, therefore, other facies related to delta deposition. Boundaries separating major positive and negative residual belts probably represent subtle flexures contemporaneous with deposition. A prominent flexure (zero residual contour) trends northeast-southwest across the northwestern part of the area (Fig. 14B). This structural discontinuity coincides with discontinuities in multistory and sandstone density trends (Figs. 10B, 7). The flexure probably exerted some persistent control of delta distribution in this part of North-central Texas.

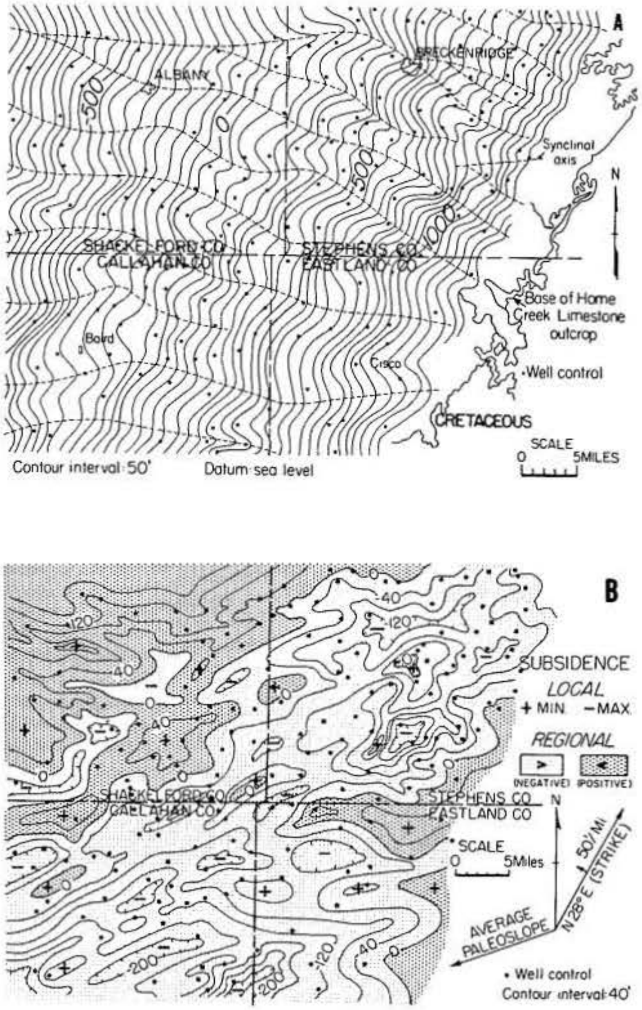


Figure 14. Structure of Home Creek Limestone, North-central Texas. A, Structure at base of limestone (after Seals, 1965). B, Residual structure at base of limestone. Structural residuals derived by subtracting regional structure from Fig. 14A. Note discontinuity of residual values along zero contour in northwest quadrant.

Importance of Compaction

Because Cisco rocks in North-central Texas are primarily clays and shales, the effects of mud compaction must be considered when analyzing the configuration of erosional or depositional surfaces. The original geometry of fluvial and deltaic depositional units is distorted by differential compaction of sandstone facies and water-saturated mudstone facies. Insufficient data limit the use of decompaction techniques to restore original geometry. The potential of decompaction in combined stratigraphic-structural problems, however, should encourage its cautious application.

Evidence of Compaction

Isopach patterns of Cisco formats reflect differential sand-mud compaction. Thick isopach trends consistently coincide with the distribution of elongate fluvial and deltaic sandstone bodies within the format (Figs. 9, 15A).

Regionally, Cisco shelf formats are tabular to slightly wedge-shaped stratigraphic units which display local thickness variations. Significant regional erosional unconformities have not been recognized. Local channels within fluvial and delta systems, which removed minor volumes of sediment, were immediately filled with sand or mud. Reefs or limestone bank deposits are absent in upslope Cisco areas where thin limestones and sheet sandstones, along with elongate fluvial-deltaic sandstones, compose the relatively non-compactible part of the section. Thickness variations within upslope areas resulted principally from differential compaction of fluvial and deltaic sediments.

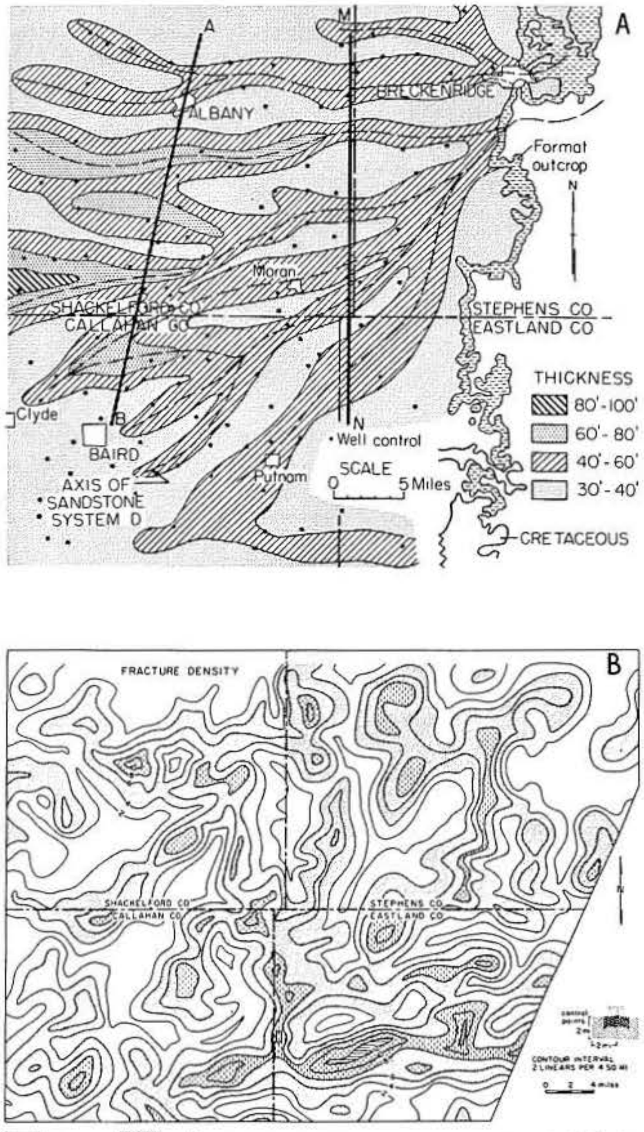


Figure 15. Evidence of differential sand-mud compaction, Cisco rocks, North-central Texas. A, Isopach map, highly compacted Blach Ranch-Breckenridge format (after Seals, 1965). Sections A-B, M-N on Fig. 9. B, Inferred compactional fracture density patterns. Based on aerial photographic linears within 4 square miles, centered on square-mile grid. Compare with trends on Figs. 7, 10B, 14B, 17, 19.

Thickness of an interdistributary mudstone section is commonly as little as 50 percent of adjacent barfinger sandstones (Fig. 15A). Similar compaction estimates were obtained by Mueller and Wanless (1957) for Pennsylvanian rocks in Illinois. Compactional distortion is extremely significant in producing local structural anomalies.

Fracture patterns based on air photograph lineations commonly coincide with fluvial and deltaic sandstone bodies. Fracture density patterns (Fig. 15B) suggest intense differential compaction along multistory belts and maximum sandstone concentration belts (Figs. 10B, 7). At the outcrop many local structural anomalies result from drape of strata over relatively noncompactible sandstones.

Cisco rocks have been significantly distorted by differential sand-mud compaction, as well as moderate contemporaneous subsidence. Eliminations of compactional distortion should ideally provide avenues for restoring original geometry and for estimating differential structural subsidence.

Problems of Decompaction

Early work by Athy (1930) and Hedberg (1936), among others, provided empirical data related to decreasing shale porosity with depth of burial. Weller (1959) summarized much of the Athy and Hedberg data and graphically illustrated the potential of decompaction in stratigraphic analysis.

Within the past fifteen years, a growing number of workers have been investigating fundamental aspects of fluids, pressures, and mineralogical changes with increasing depth (Dickinson, 1953; Powers, 1967; Rochon, 1967; Jones, 1968; Burst, 1969; and others). These studies have been primarily concentrated in Gulf Coast Tertiary rocks where porosity and depth data are available from thousands of logs and cores. Martin (1966) and Conybeare (1967) recently showed the importance of decompaction in stratigraphic restoration studies in Canada.

There is general agreement among workers (Burst, 1969, p. 90) that dehydration and compaction of clays occur as a three-stage process. To depths of about 3,000 feet, pore water and excess water layers (more than two) are expelled; the second to last water monolayer is in part thermally removed from about 3,000 to 15,000 feet; and a final stage below 15,000 feet results in expulsion of the last water layer. Most recent workers (Weller, 1959, Fig. 1; Dickinson, 1953, Fig. 15; Conybeare, 1967, Fig. 1) present porosity-compaction-depth curves generally similar to those presented by Athy (1930) and Hedberg (1936). These graphs are relatively consistent, at least within a general order of magnitude. Application of these curves (or derived curves) to Cisco data results in a reasonably close spread of compaction percentages (Fig. 16).

Cisco rocks probably were never buried below 3,000 or 4,000 feet. Fluvial and deltaic sandstones were conduits by which fluids were expelled during compaction. It is assumed that upslope deltaic Cisco rocks have reached compaction equilibrium. It is speculation whether or not the time factor has resulted in significant volume reduction in these Paleozoic rocks beyond that of burial pressure and temperature. Possible volume increase by rebound during regional uplift and erosion is probably insignificant, but this phenomenon has not been investigated.

In addition to basic problems of mud compaction, Cisco strata present unique stratigraphic problems: (1) effect of thin, tabular limestone and sandstone beds on fluid migration during compaction; (2) variable clay mineral facies (*e.g.*, prodelta, delta plain, interdeltaic) possessing different compaction properties; (3) limitation of estimating composition and thickness by electric logs; (4) and the arbitrary decision to ignore sandstone compaction. Obviously decompaction procedures at present must be strictly qualitative. Qualitative estimates of mud compaction, however, require the use of numbers just like paleoecological or paleoenvironmental reconstruction. Decompaction is a second order interpretation or approximation, and maps resulting from decompaction procedures should not be interpreted quantitatively. Numbers simply illustrate relative, approximate values, and if related to a datum, the datum is also arbitrary and interpretative. Compaction data presented by Athy (1930), Hedberg (1936), Dickinson (1953), Weller (1959), and Conybeare (1967) provided the basis for theoretical decompaction of Cisco rocks (Fig. 16).

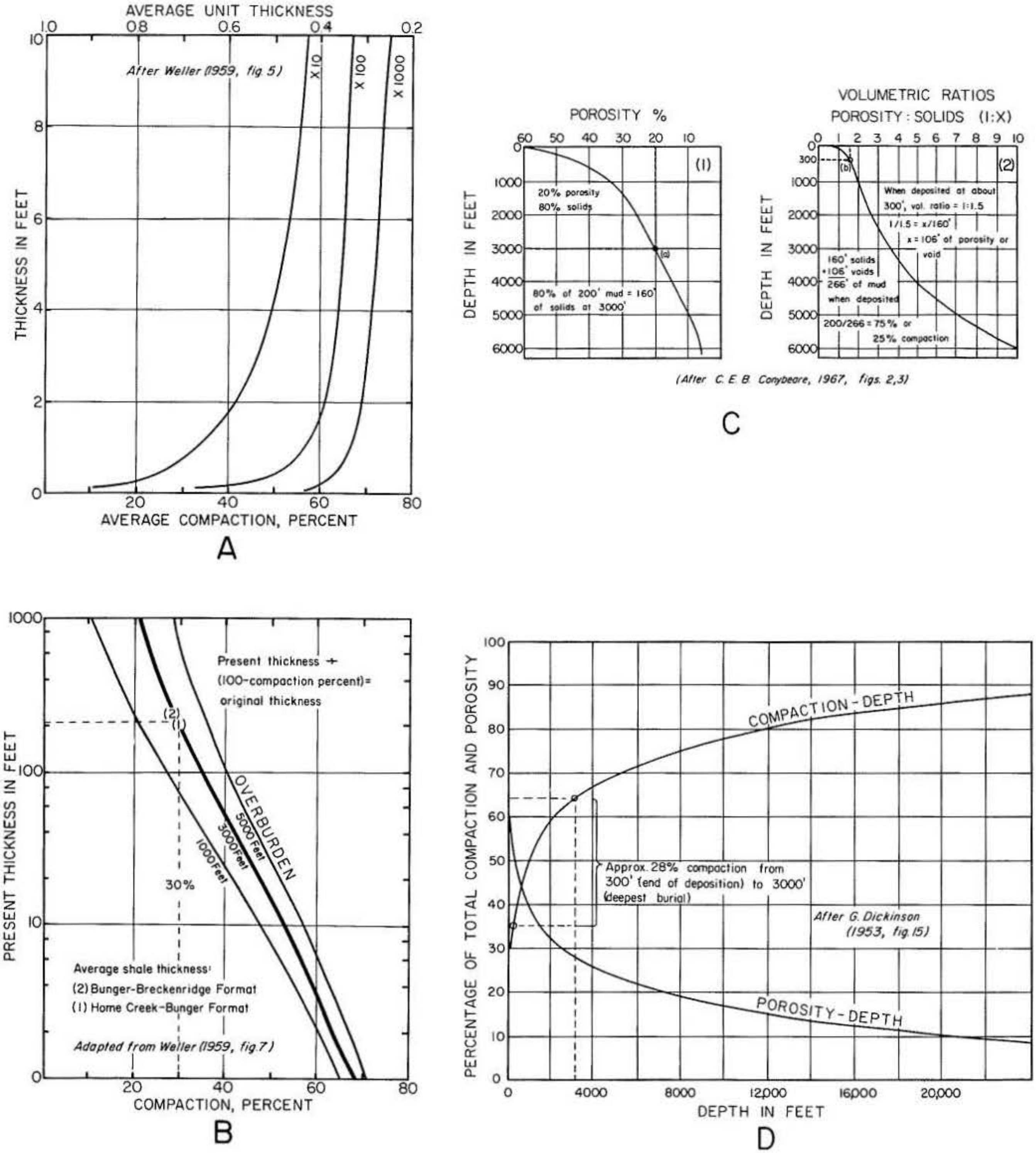
Control of Depositional Surfaces

Inherited Paleotopography

The orientation of Cisco fluvial and delta facies was apparently influenced by paleotopography inherited from subjacent limestone bank deposits of the Canyon Group. Initial Cisco deltas prograded over the Home Creek Limestone, uppermost shelf limestone of the Canyon Group (Fig. 2). An isopach map of the Home Creek in the area exhibits indistinct northeast-southwest thick and thin trends reflecting irregular rates of deposition (Fig. 17A).

Regional structure was subtracted from the structural configuration at the top of the Home Creek Limestone. The residual surface was reoriented along paleoslope (based on sandstone orientation) with 5 feet per mile southwest dip and recontoured using an arbitrary datum. Strong northeast-southwest grain appeared which may reflect paleotopography which controlled initial Cisco progradation routes (Fig. 17B). The first fluvial and deltaic sequence deposited during Cisco regression (Home Creek to Bunger format) displays maximum sandstone percentage axes which coincide with inferred paleotopographic depressions or troughs on top of the underlying Home Creek Limestone. Prograding deltas apparently followed subtle interbank low areas on the upper Home Creek surface where thicker sections of prodelta muds compacted to provide more efficient progradational routes.

West to southwest paleosurface grain persisted throughout Cisco deposition in this area. Deltaic deposition within each successive sequence followed the most favorable paleosurface routes inherited from the succeeding sequence. The configuration of paleosurfaces at the end of each Cisco sequence (format) apparently resulted from two principal factors—rates of shelf subsidence and differential sand-mud compaction.


After Weller (1959, fig 5)

Adapted from Weller (1959, fig.7)

(After C. E. B. Conybeare, 1967, figs. 2,3)

After G. Dickinson (1953, fig.15)

Figure 16. Mud compaction data. A, Average compaction of mud columns. B, Mud compaction from overburden. C, Compaction of mud with depth of burial. D, Relation of porosity and compaction of shales with depth of burial. After Dickinson (1953), Weller (1959), and Conybeare (1967).

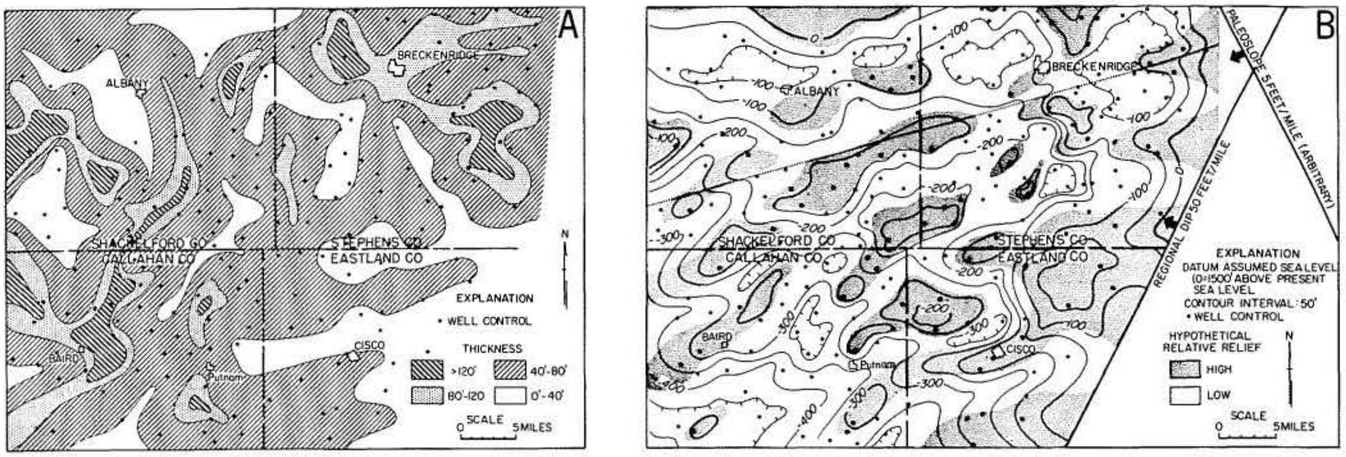


Figure 17. Geometry of Home Creek Limestone. A, Isopach map of Home Creek Limestone (after Seals, 1965). B, Inferred paleotopography, upper surface of Home Creek Limestone. Inferred paleosurface is structure map following arithmetic tilting to paleoslope. Dotted line along discontinuity in contour pattern.

Differential Subsidence

Isopach maps of conformity-bounded units are commonly used for estimating contemporaneous structural activity when there are no significant depositional breaks in the section. Compactional distortion of Cisco deposits precludes direct use of isopach maps for approximating relative rates of subsidence during deposition. A hypothetical non-compaction model of formats, which theoretically reflects format geometry as if no compaction occurred during deposition and burial, provides a method for estimating relative rates of shelf subsidence.

Estimation of subsidence.—Non-compaction models were constructed by decompacting all mudstones within each format to hypothetical pre-compaction (or initial depositional) thickness (Fig. 18B). Limestones and sandstones were arbitrarily assumed to be non-compactible. For example, 235 feet of mudstones within a format, which has theoretically undergone 30 percent mud compaction during burial, was 335 feet thick at the end of format deposition (Fig. 16B). Hypothetically, this 335 feet of mudstone represents about 930 feet of 80 percent porosity mud which underwent compaction during and immediately after deposition (Fig. 16A). Empirically, a column of mud 150 feet thick will undergo about 60 percent average compaction while 700 feet of mud will theoretically display but 65 percent average compaction (Fig. 16A). Formats containing more than 150 feet of mudstone were selected to minimize the percentage error.

If the geometry of shelf sand and mud formats resulted primarily from differential rates of structural subsidence and from differential sand-mud compaction, removal of compactional distortion should produce geometry reflecting structural effects. Residual thickness (isopach) values of non-compaction models (based on mean thickness), which have theoretically had the effects of compaction removed, should approximate relative (positive and negative) shelf subsidence rates (Fig. 18). For convenience later in applying residuals to paleosurface (isopach) restoration, the values were arithmetically returned to hypothetical thickness at end of format deposition.

Residual map patterns of various formats based on this technique define northeast to southwest-trending belts of negative and positive values (Fig. 19). If such residual patterns reflect relative rates of structural subsidence, a relationship should exist between sandstone distribution and subsidence patterns.

Sandstones and subsidence trends.—Areas containing high concentrations of elongate sandstones and multistory belts commonly coincide with northeast to southwest-trending negative isopach residual belts (Fig. 20). Non-compaction isopach residuals are interpreted to reflect relative rates of shelf subsidence. Residual patterns of successive formats display progressive changes reflecting slight structural evolution, but the fundamental orientation of negative and positive belts persists throughout deposition of the Cisco sequence (Figs. 19, 20).

A northeast-trending discontinuity displayed by isopach residual patterns in the northwest quadrant of the area (Fig. 19) coincides with similar features on stratigraphic maps and residual structural maps (Figs. 7, 10B, 14B). This similarity strengthens arguments for some local structural control of fluvial and deltaic depositional sites. The area northwest of the discontinuity near Albany, for example, was predominantly negative during deposition of the Home Creek-Bunger format (Fig. 19), but during deposition of the Bunger-Breckenridge format an east-west positive belt divided the earlier negative area (Fig. 20). Each sandstone system deposited within the latter format reflects the local positive belt by splitting around the more structurally stable area (Figs. 6A, B; 8B).

Areas where sandstones are absent commonly coincide with unusually positive isopach residual areas, and channel sandstone concentration and multistory belts generally coincide with extremely negative residual areas. Persistent non-depositional belts, such as one trending northeast-southwest through the extreme southeastern corner of Shackelford County (Fig. 7), coincide with strong positive residual trends (Fig. 19) and areas of maximum paleosurface relief inferred from restored isopach maps (Fig. 21).

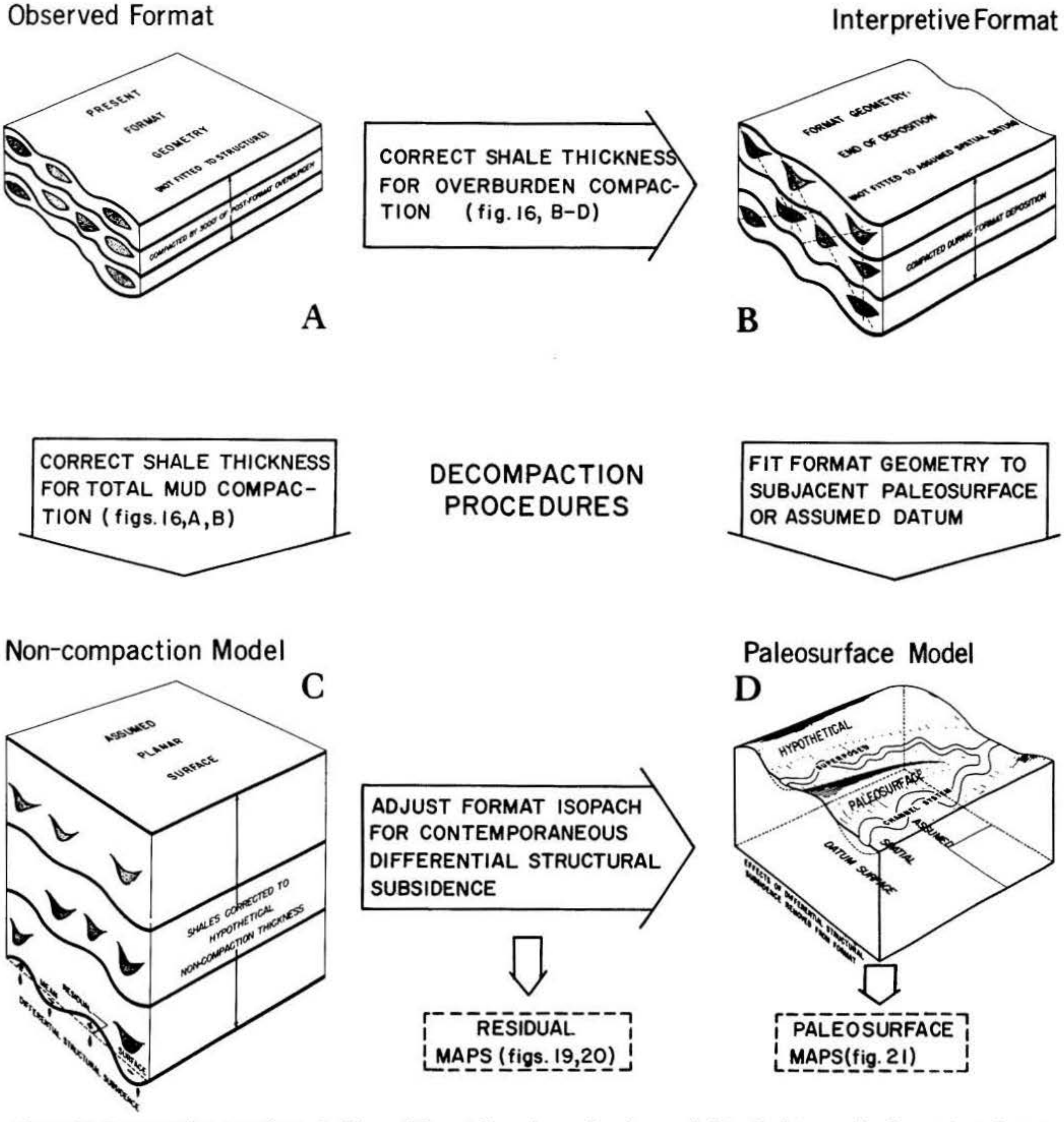


Figure 18. Decompaction procedures. A, Observed format. Isopach map based on well data. B, Interpretative format. Isopach map decompacted to pre-overburden thickness. C, Non-compaction model. Isopach map decompacted to hypothetical thickness assuming no compaction. D, Paleosurface model. Isopach map decompacted, corrected for structural subsidence, and fitted to arbitrary subjacent surface; thickness reflects relative paleotopographic relief.

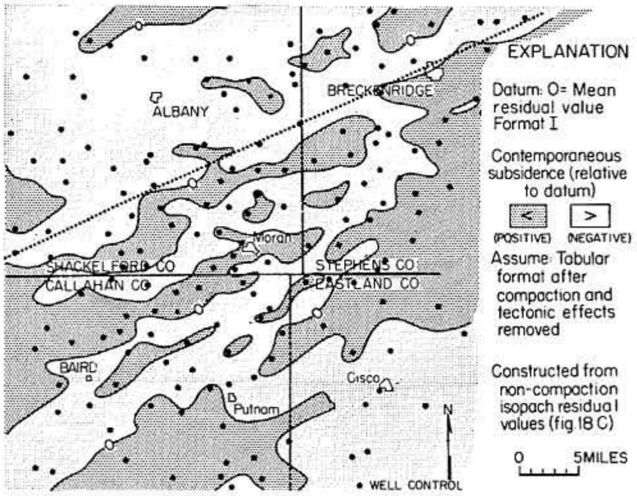


Figure 19. Inferred structural subsidence, Home Creek-Bunger format. Isopach residual map using positive or negative values based on mean thickness of non-compaction isopach map (fig. 18C). Contours omitted. Dotted line along discontinuity in residual patterns.

In summary, fluvial and deltaic sandstone geometry and inferred unstable structural trends indicate that (1) unusually high or low rates of structural subsidence along narrow west to southwest-trending belts controlled location of highly concentrated and multistory sandstone belts (negative) or persistently non-sandstone belts (positive), respectively; and (2) dominant differential sand-mud compaction in larger areas with intermediate subsidence rates apparently resulted in common offsetting vertical patterns.

Differential Compaction

Offset vertical relationships exhibited by sandstone facies point to control by differential sand-mud compaction. Although multistory sandstone belts coincide with inferred trends of maximum shelf subsidence, most delta deposition occurred within areas underlain by interdistributary and interdeltaic mud facies of the previous sequence.

Decompaction procedures.–If mudstones within a format containing fluvial and deltaic facies can be decompacted to approximate thickness at the end of deposition (before burial by overburden), geometry or thickness variations displayed by the format could logically be a guide to paleosurface configuration on top of the format. For example, if thin areas or trends coincide with interdistributary facies within the format, and if thick trends coincide with fluvial and deltaic sandstone facies, it is likely that these thickness trends were reflected by subtle differences in relative paleotopographic relief. This assumption is further confirmed when an overlying sandstone system coincides with thin areas or inferred paleosurface lows on the underlying format.

Compaction of mud begins with deposition, but the degree of compaction following deposition is critical when attempting to restore geometry. It is assumed that Cisco rocks were buried by at least 3,000 feet of strata, although precise thickness of overburden makes little difference in average percent compaction (Fig. 16B, C, D). Graphs (*idem*) illustrating percentage of mud compaction with increasing depth show that under approximately 3,000 feet of overburden, 250-foot mud columns have been compacted by approximately 25 to 30 percent. Cisco mudstones at 200 well locations were decompacted using a 30 percent compaction estimate.

Differential rates of shelf subsidence, especially within a terrigenous clastic province, would result in local thickness variations which would not necessarily affect the paleosurface. For this reason, isopach residual values were algebraically added to format thickness values for each control point (Fig. 18D). Resulting format thickness trends theoretically represent only the effects of differential sand-mud compaction during deposition of the format.

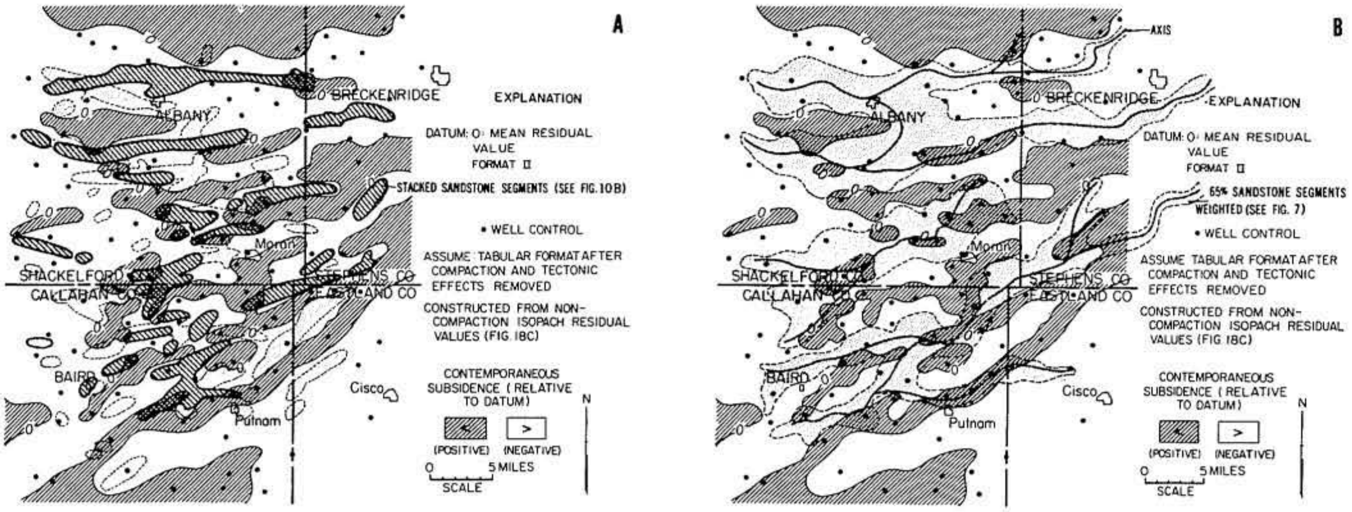


Figure 20. Relationship between inferred structural subsidence and distribution of elongate sandstones, Bunger-Breckenridge format. A, Structural subsidence and multistory sandstones. Heavy lines outline multistory sandstones within this format. B, Structural subsidence and concentration of elongate sandstones. Structural subsidence map is non-compaction isopach residual map (Fig. 18C). Contours omitted.

When the decompacted isopach map is fitted to a horizontal, tilted or assumed subformat surface, the isopach values reflect areas of relative paleotopographic relief at the end of deposition (Fig. 21). Each format inherits some paleosurface relief from subjacent formats, so that a decompacted isopach map is not quantitative but supplies additional confirmation that interdistributary or interdeltaic mudstone areas were prime depositional sites for superjacent deltas. The best and final test of the validity of such inferred paleosurface (isopach) maps is comparison with the superjacent sandstone systems.

Sandstones and paleosurface trends.—Fluvial and deltaic sandstones, which prograded over each Cisco format, generally followed paleotopographic depressions or troughs inferred from decompacted isopach maps. For example, axes of maximum thickness for sandstone A generally coincide with interdistributary depressions displayed on the subjacent Home Creek-Bunger format (Fig. 21A). Distributary sandstone bodies clearly deflect around areas of greater than average thickness or inferred paleosurface relief. Compaction of the underlying format provided sufficient relative relief to control depositional sites of prograding distributaries which deposited deltaic sandstone system A. Similarly, the distribution of sandstone system E, which is composed dominantly of fluvial channel deposits, closely follows a series of closed depressions on the decompacted isopach map of the underlying format (Fig. 21B).

The close fit between fluvial and deltaic sandstones and thin trends (or inferred paleosurface lows) displayed by subjacent, decompacted formats is confirmation of the role played by sand-mud compaction in controlling progradational routes. Greater paleosurface relief over relatively non-compactible deltaic sandstones may have provided higher energy sites during subsequent transgressions (Waller, 1969).

Use of decompaction techniques for restoring cross sections to approximate geometry at the end of deposition provides another tool for studying sandstone geometry. Proper datum surfaces for restoring as much original sandstone geometry as possible have been explored by various workers (Andresen, 1962; Potter, 1963). Application of decompaction methods to mudstones within a section containing elongate sandstones restores the sandstones to more probable cross sectional shape, especially when the section is fitted to a subjacent limestone datum (Fig. 9C, E). Such restorations assume that most distortion resulted from compactional drape over relatively non-compactible sands, but obviously some subsidence of sand bodies into underlying muds also occurred. Sections restored in this manner (*idem*) display channel shape in upslope areas and barfinger geometry in downslope areas.

The study of terrigenous clastic deposition, which is closely related to depositional surface configuration, should benefit from conservative use of various decompaction procedures. With caution and continued research, decompaction may eventually provide a relatively reliable technique for investigating paleosurfaces and differential subsidence.

Evolution of Paleosurfaces: Summary

Cisco deltaic deposition developed initially over limestone bank deposits of the underlying Canyon Group, probably in response to an increasing sediment supply related to Ouachita uplift. Deltaic and associated facies built westward rapidly over subtle paleotopographic relief on the subjacent limestones. Compaction of prodelta muds over bank and interbank limestones provided west to southwest paleosurface depressions along which delta lobes crevassed. Following a decrease in sediment supply, increase in subsidence or possible eustatic rise in sea level, a long period of deltaic destruction and marine transgression ended the local repetitive sequence.

Differential delta sand and interdistributary mud compaction of the first Cisco deltaic sequence resulted in compactional depressions overlying former mud facies, while sites of earlier fluvial and deltaic sand deposition

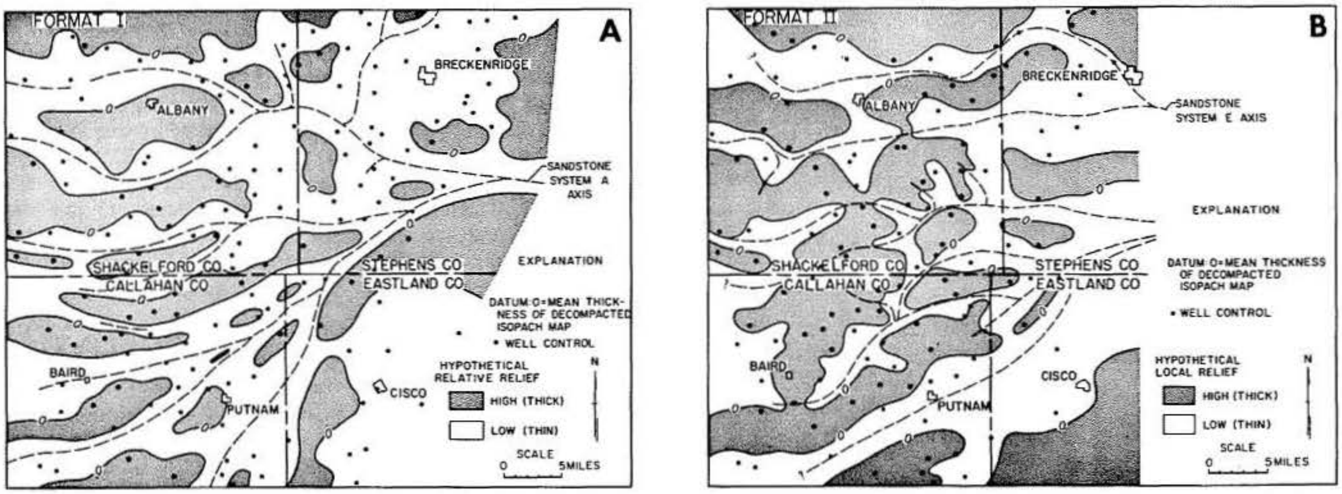


Figure 21. Inferred paleosurface map. A, Decompacted isopach map, Home Creek-Bunger format (pre-sandstone system A surface). B, Decompacted isopach map, Bunger-Breckenridge format (pre-sandstone system E surface). Superjacent fluvial and deltaic sandstone trends indicated by dashed line. Refer to Fig. 18D. Contours omitted.

stood slightly higher (Fig. 22). The heavy load of terrigenous clastic sediments apparently overloaded narrow, structurally weak belts, resulting in local but relatively persistent subsidence.

When the second period of delta deposition occurred in the area, caused by upstream avulsion, increased sediment supply, or filling of earlier drowned channels, deltas prograded principally across compactional depressions. Compactional control was responsible for offset vertical sandstone patterns. Greater than average structural subsidence along local belts countered the effect of compaction, resulting in some multistory sand deposition. During each subsequent Cisco fluvial and deltaic episode, the distribution of sand depositional sites was similarly controlled.

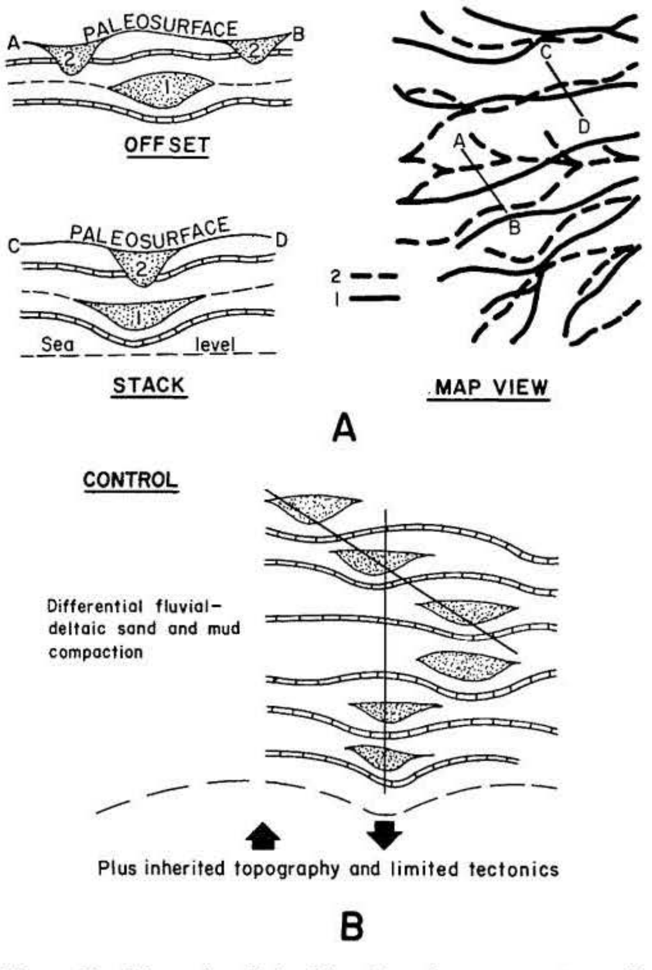


Figure 22. Schematic relationship of sandstone geometry and inferred controlling factors.

Paleosurface grain was maintained throughout the Cisco but successive pre-delta surfaces displayed progressive changes in configuration which shifted delta sites. The configuration of surfaces over which successive delta systems prograded evolved through the interplay of compaction and structural instability. The distribution of each sandstone system inherited its pattern from the previous system and, in turn, controlled the paleosurface on which the next deltaic sandstones were deposited.

CONCLUSIONS

1. Virgil and Wolfcamp rocks in upslope areas of the Eastern Shelf of North-central Texas are composed of 10 to 15 repetitive sequences including (upward) superposed (1) open shelf, (2) deltaic, and (3) fluvial, and/or (4) interdeltaic, and (1) open shelf facies. Elongate dip-fed sandstones are composed of delta front sheet sandstones and distributary mouth bars, distributary channels, and superimposed fluvial channel facies which occur in three general areal patterns: distributary, belt, and composite. Sheet sandstones are extensively reworked, strike-fed delta front sands and thin sheet and bar sands of delta destructional origin.

2. The common orientation of sandstones points to a southwestward paleoslope which persisted throughout deposition of the Cisco Group. Structure and special (decompacted) isopach maps of sandstone systems indicate that paleoslope was less than 5 feet per mile. Bases of elongate sandstones parallel regional limestones and coals, indicating an absence in this area of progressive regional truncation of underlying strata. Significant erosion is restricted to distributary and delta plain fluvial channels. Fluvial deposition in the area does not fit a piedmont or upper coastal plain model but occurred primarily on upper delta plains. Sandstone bodies in upslope areas commonly display channel-shaped cross section; in downslope areas, sandstone cross sections are normally bar shaped.

3. Superposed sandstone systems are offset vertically except along relatively narrow multistory belts. Greater compaction of interdistributary and interdeltaic mud facies, relative to elongate fluvial and deltaic sands, provided sites for subsequent delta deposition. Sites of multistory sandstone deposition were controlled by narrow belts of structural instability.

4. Distribution and composition of Cisco facies in upslope areas indicate that sandstones were deposited within a deltaic system supplied with sediment from an eastern Ouachita Mountain source. Facies fit into four depositional systems—fluvial, deltaic, interdeltaic, and open shelf. Deltaic sequences were aperiodic and diachronous. Average shoreline moved westward through time as deltas supplied the clastics which prograded the shelf into the West Texas Basin.

5. Paleoslope trends based on the orientation of elongate sandstone do not coincide with modern structural grain. Residual structural maps of Cisco limestones exhibit southwest-trending positive and negative residual belts. Seventy percent of the Cisco sandstones occur within negative residual belts; other sandstones coincide with minimum positive residual trends. Multistory sandstones coincide with extremely negative belts; extremely positive

residual belts contain few sandstones. A broad but very subtle structural depression apparently concentrated deltaic and fluvial deposition in the area. Within the area, however, only local belts of unusual structural instability affected specific depositional sites.

6. Differential compaction of deltaic sand and mud facies produced local compactional structural anomalies, as well as distorted the original geometry of sand-mud depositional units. Thick trends displayed by conformity-bounded isopach maps closely coincide with maximum thickness axes of contained fluvial and deltaic sandstones. Fracture density patterns outline compactional structures coincident with multistory sandstone belts.

7. Efforts to interpret contemporaneous subsidence using isopach maps and attempts to reconstruct pre-delta surfaces necessitate decompaction of mudstones. Although data on sediment compaction preclude precise decompaction of mudstones, qualitative or relative values are possible. Consistency of compaction data provided by various workers indicates that decompaction estimates are in the proper order of magnitude.

8. Fluvial and deltaic depositional sites are controlled by three principal factors—inherited paleotopography, belts of structural instability, and differential compaction. Initial Cisco delta systems prograded over Canyon Group limestone bank deposits, apparently following subtle paleosurface depressions oriented northeast-southwest. This inherited paleosurface grain was passed on to subsequent deltaic sequences.

9. Isopach residual maps of formats containing fluvial and deltaic facies, which were totally decompacted, display strong northeast-southwest negative and positive residual trends similar to structural residual trends. Negative isopach residual trends coincide with multistory sandstone belts. Extremely positive residual trends contain few Cisco sandstones. Thickness variations displayed by a depositional unit after all mud compaction has been removed is interpreted to reflect relative differences in rates of subsidence during deposition of these clastic facies.

10. Common offset vertical patterns displayed by fluvial and deltaic sandstones can be explained by differential sand-mud compaction. Deltas prograded across subjacent mudstone facies where maximum compaction produced paleotopographic depressions. Thin trends on decompacted isopach maps are consistently areas of interdistributary and interdeltaic mudstone facies, and thick trends coincide with barfinger sandstones. Superjacent fluvial-delta systems followed thin format isopach trends which reflect subtle paleotopographic troughs or depressions. Southwest paleoslope inherited from Canyon bank limestones was maintained throughout the Cisco, but pre-delta surfaces evolved as successive sandstone patterns changed.

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