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Virgil and Lower Wolfcamp Repetitive Environments and the Depositional Model, North-Central Texas

By

L. F. Brown, Jr.

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ERRATA

Page 115, paragraph 2: Following line 10, insert: "concentrated upslope, open shelf variants dominate extensive areas"
and
on line 11, change "downslopes" to "downslope"

Page 122, figure 6 (*D*): Replace caption with "*Saddle Creek Limestone (outcrop)*."

Page 124, paragraph 2: Begin paragraph with side heading: "*Delta depositional systems*.--"

Page 134, line 14: Delete ________ and insert: "Wanless, H. R.,"

Virgil and Lower Wolfcamp Repetitive Environments and The Depositional Model North-Central Texas[1]

L.F. Brown, Jr.[2]

ABSTRACT

Virgil and lower Wolfcamp rocks on the Eastern Shelf in North-central Texas are composed of several intergradational depositional systems comprising 1,200 to 1,500 feet of off-lapping, predominantly terrigenous sediments.

At least a dozen major and numerous minor repetitive sequences consist of superposed deposittional systems, composed of more or less homotaxial component facies. Rapidly shifting fluvial-delta sites and associated interdeltaic and open shelf environments on the slowly subsiding shelf were subjected to marine destruction, mud compaction-subsidence, and marine transgression. Variations of the basic sequence in time and space resulted from shifting depositional systems. Fluvial variants are downslopes, and deltaic and interdeltaic variants are concentrated in intermediate areas. These facies tracts shifted irregularly southwestward during Virgil and Wolfcamp deposition as the average strandline migrated with westward shelf progradation. Westward pointing deltas locally extended subaerial environments far downslope.

Delta sequences between bases of successive delta systems are diachronous and aperiodic as deltation irregularly reoccupied former delta sites. Sequences between bases of successive transgressive limestone facies are also interpreted to be aperiodic and diachronous, but bounding limestones display regional continuity. Delta and fluvial constructional facies represent relatively brief, discrete time intervals, while destructional, interdeltaic, and transgressive facies involved greater time resulting in complex chronology within sequences.

The fluvial-deltaic model for Virgil and Lower Wolfcamp rocks make it unnecessary to invoke external cyclic control to explain these North-central Texas deposits. The self-regulating model can operate under continuous sediment supply and continuous but slow shelf subsidence. The model is based on facies relationships and processes rather than absolute scale and geometrical comparison with Recent models. The diachronous nature of facies required by the model and supported by stratigraphic evidence indicates that repetitive deposition was primarily governed by sedimentary processes active within the local basin.

INTRODUCTION

Strata of Virgil and lower Wolfcamp age (Cisco-Bowie rocks) on the Eastern Shelf in North-central Texas were deposited in at least four kinds of systems - - fluvial, deltaic, interdeltaic, and open shelf. These shallow water, predominantly terrigenous clastic depositional systems off-lap westward into the West Texas basin and are part of a thick Permo-Pennsylvanian sedimentary wedge which filled the Fort Worth Basin and constructed the Eastern Shelf.

Within the Cisco-Bowie complex at least a dozen major and numerous minor repetitive depositional sequences are recognized. Each fully developed depositional system is composed of predictable homotaxial sequences of component facies. Repetitive sequences are either delta or fluvial sequences representing strata between the bases of successive delta or fluvial systems or format sequences which include rocks between successive open shelf transgressive limestones. Delta sequences are areally restricted; format sequences are regionally extensive stratigraphic units which lose identify as bounding limestones pinch out upslope.

Several terms are either not in general use or have been modified specifically for this discussion. Depositional system is a three-dimensional unit composed of distinctive facies related by depositional processes, and defined by the interrelationship and distribution of these component facies. These stratigraphic packages of genetically related

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Former Baylor University graduate students J. H. McGowen, T. H. Waller, M. J. Seals, and J. R. Ray provided much basic data. Bureau of Economic Geology staff W. L. Fisher, J. H. McGowen, P. U. Rodda, and P. T. Flawn, Director, and A. J. Scott, Department of Geology, The University of Texas at Austin, read the manuscript and contributed significant ideas and criticism. Miss Josephine Casey and Mrs. Elizabeth Moore processed the manuscript; drafting was under the supervision of J. W. Macon.

[2] Bureau of Economic Geology, The University of Texas at Austin.

facies are comparable to modern depositional systems or complexes such as barrier bar system, delta system, fluvial system, or lagoon-bay system.

Formal stratigraphic terminology in the outcrop area of North-central Texas is inadequate and an informal terminology has been adopted. Cisco rocks dominated by deltaic, interdeltaic and open shelf depositional systems crop out principally in the Brazos and Colorado valleys and extend westward into the subsurface. Bowie rocks are primarily fluvial facies which crop out in the Trinity valley and occur in the subsurface in southern Oklahoma and extreme northern Texas. Cisco of this report is not synonymous with Cisco Series (Brown, 1959, p. 2866 - 2871) but approximates the original Cisco Group of Plummer and Moore (1922, p. 121-124). Cisco-Bowie rocks contrast with subjacent, dominantly open shelf Canyon rocks.

Formats (Forgotson, 1957) in this report refer to informal arbitrarily defined rock units bounded by persistent limestone marker beds. Formats are used in surface and subsurface analyses where formal stratigraphic terminology is inadequate.

Cycles, cyclothems, or other classic cyclic terms have been avoided. This does not necessarily preclude a genetic relationship between Cisco-Bowie repetitive sequences and cyclothems of other regions.

This report attempts to explain the origin of complex, repetitive sequences within the Virgil and lower Wolfcamp rocks of North-central Texas. Only by examining Cisco-Bowie rocks using a depositional model concept can one hope to understand factors controlling repetitive sedimentation here.

There has been no adequate explanation of the spatial distribution of upper Pennsylvanian and lower Permian facies in North-central Texas. Establishing depositional models which simplify and explain complex facies relationships is the ultimate research goal in North-central Texas.

REGIONAL SETTING

Rocks of Virgil and lower Wolfcamp age (Fig. 1) in North-central Texas were deposited on the Eastern Shelf of the West Texas basin. Northward the shelf grades into terrigenous clastics derived from the Wichita structural system in southern Oklahoma. Southward the shelf apparently deflected around the Llano positive element. To the east lay the Ouachita Mountains and Fort Worth Basin rocks which formed the piedmont (Fig. 2).

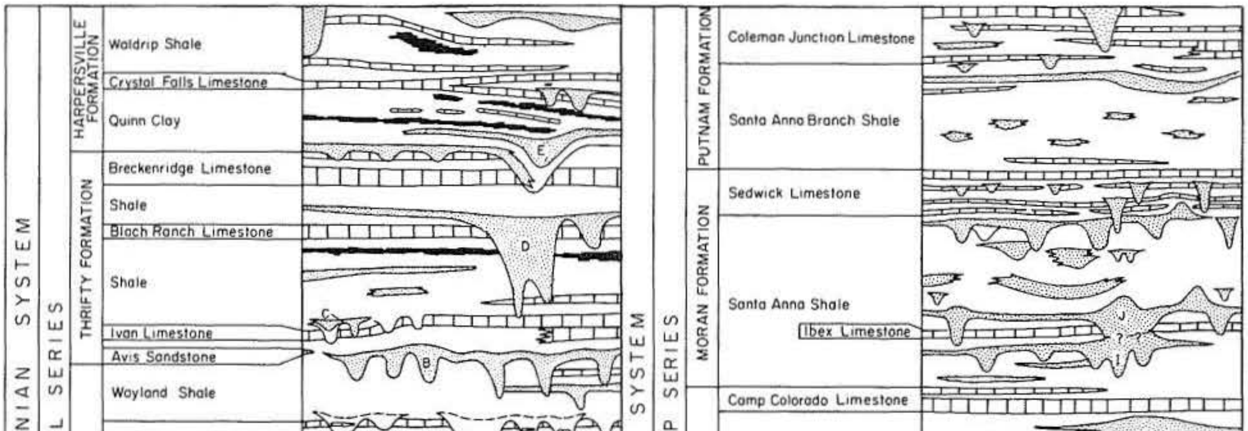

Fig. 1 - Virgil and lower Wolfcamp outcrop section, North-central Texas. Section illustrates 20 to 30 miles of outcrop in Stephens, Eastland, Shackelford, and Callahan counties. Refer to Fig. 3 for subsurface correlatives of sandstones A-J.

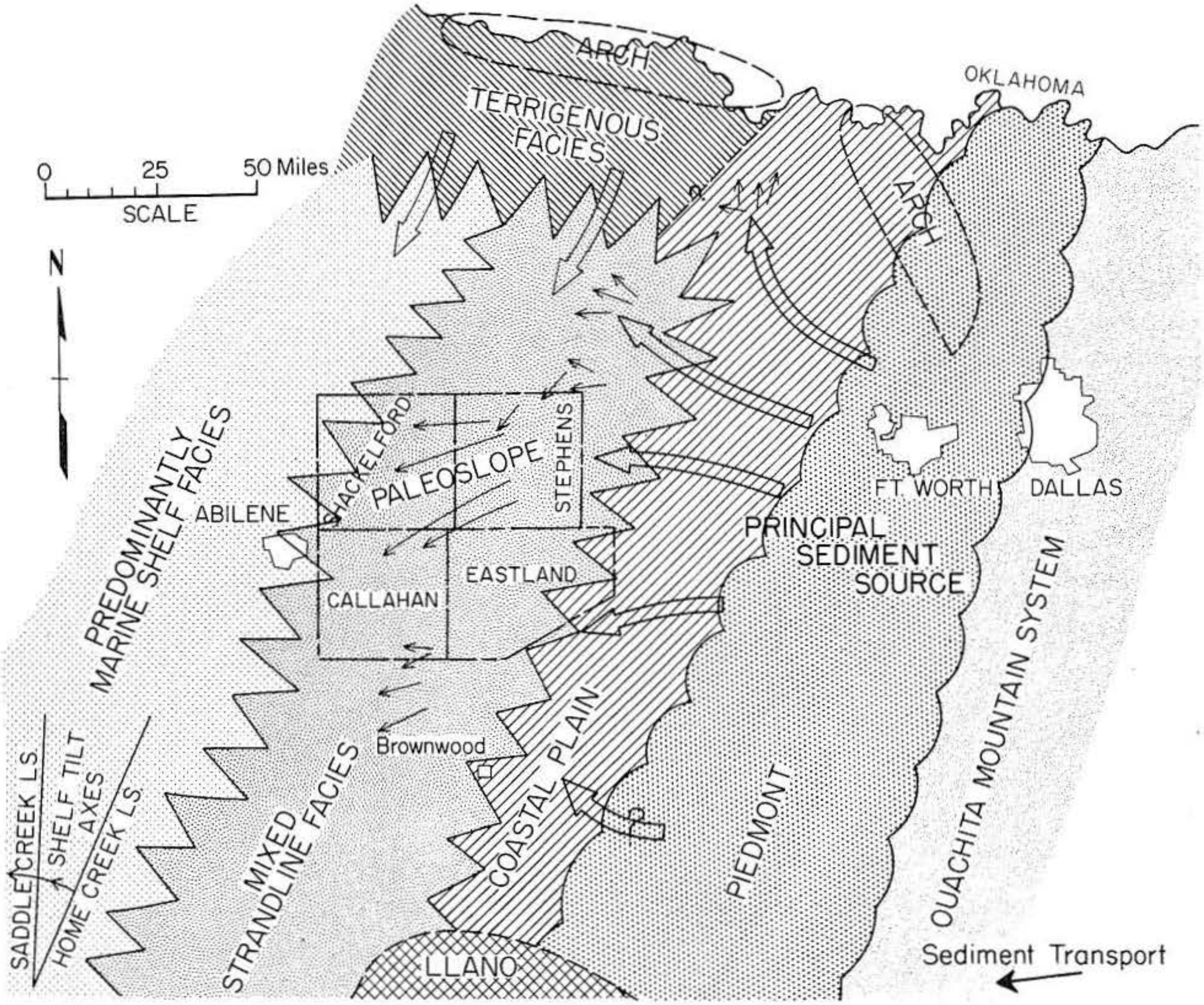

Fig. 2 - Inferred paleogeography during Virgil and Wolfcamp deposition, North-central Texas. Data in part after Lee (1938), Rothrock (1961a, b), and Terriere (1960).

The Eastern Shelf developed on the early Pennsylvanian Concho Platform which was obscured by late Pennsylvanian and early Permian westward tilting (Cheney, 1929; Cheney and Goss, 1952). The north-south axis of westward tilting, which approximately coincided with the western flank of the Fort Worth Basin, has been designated the Bend Arch (idem); Virgil and Wolfcamp strata display little, if any, evidence of the axis. The overlying Lower Cretaceous strata dip southeastward about about 30 feet per mile.

Average northwest dip of Virgil and Wolfcamp strata in the area is 50 feet per mile. The strike migrates from about N. 25 degrees E. at the base of the Virgil Series to N. 10 degrees E. at the base of Wolfcamp rocks. Wermund and Jenkins (1964) reported a counter-clockwise shift in strike from N. 45 degrees E. in Strawn strata to north-south strike in lower Wolfcamp rocks. This 45 degree shift, coincides with westward tilting that defined the Bend Axis.

Virgil and lower Wolfcamp strata of the Eastern Shelf are predominantly fluvial-deltaic, shelf and strandline facies (Figs. 4, 5). They are primarily conformable and significant erosion occurred only at the base of channels on alluvial and delta plains (Figs. 1, 3).

The paleoslope direction varied from northwest to southwest as indicated by orientation of elongate fluvial-deltaic sandstones. Terrigenous clastic sediments at the outcrop and in the shallow subsurface were derived predominantly from the Ouachita Structural Belt and uplifted Fort Worth Basin deposits via streams traversing a relatively narrow coastal plain. Longshore current distributed these sediments along the shelf. An apparent

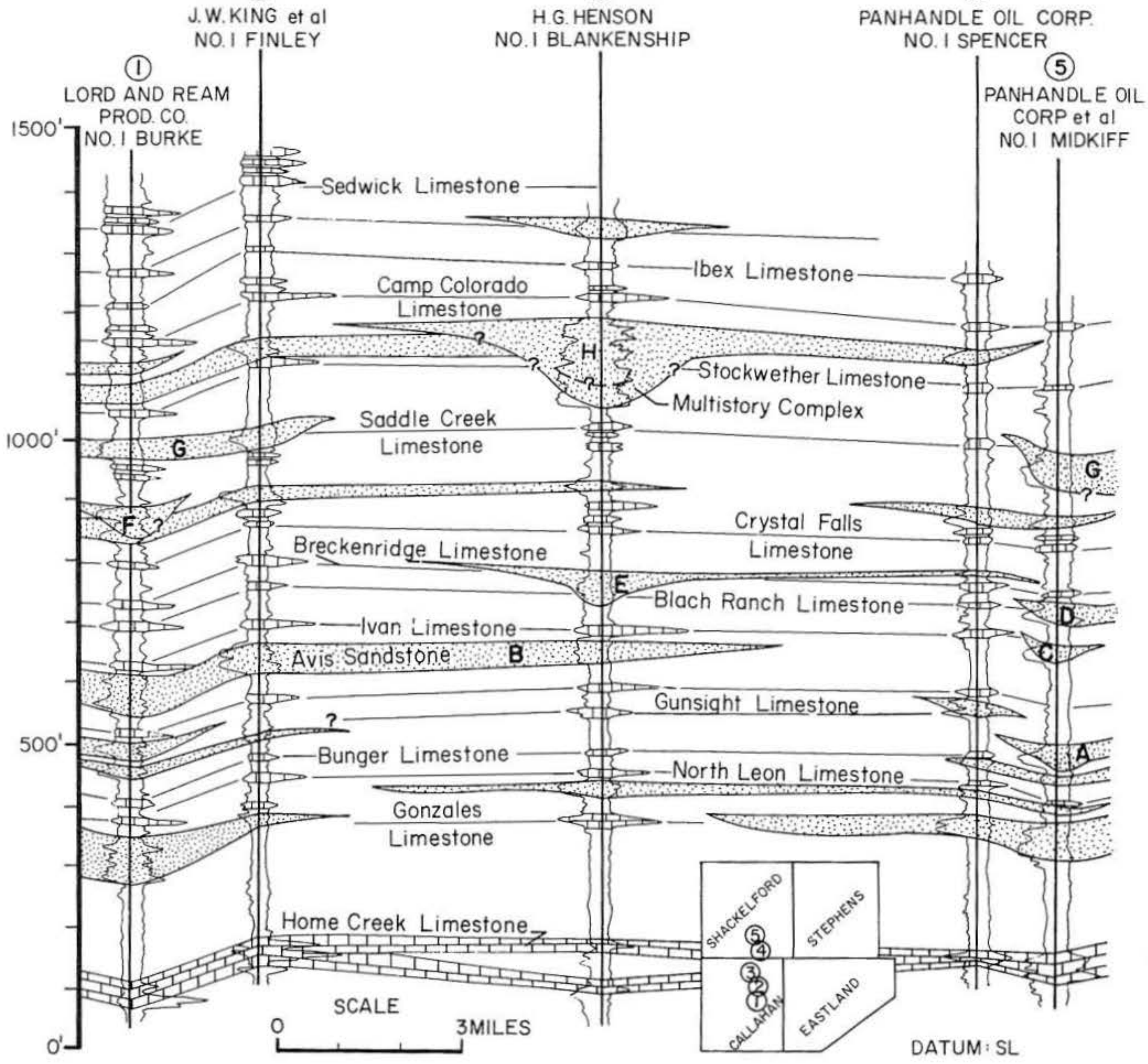

Fig. 3 - Subsurface reference section, Callahan and Shackelford counties, North-central Texas. No interwell interpolation of sandstone facies attempted. Surface correlatives of sandstones noted on Fig. 1.

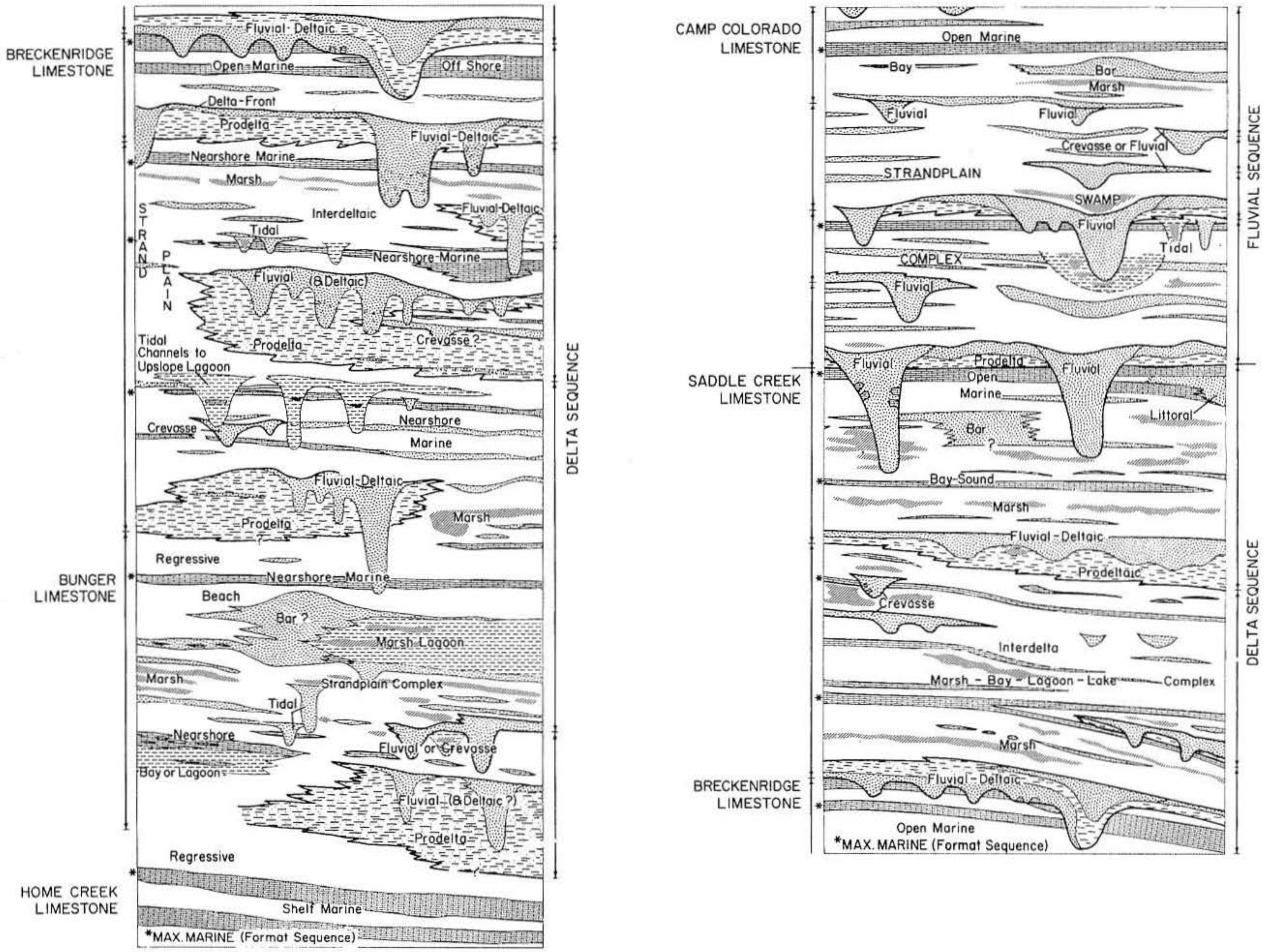

Fig. 4 - Facies relationships, outcrop section, Virgil and lower Wolfcamp rocks, Stephens County, Texas. Note relationship between fluvial-delta sequences and format sequences.

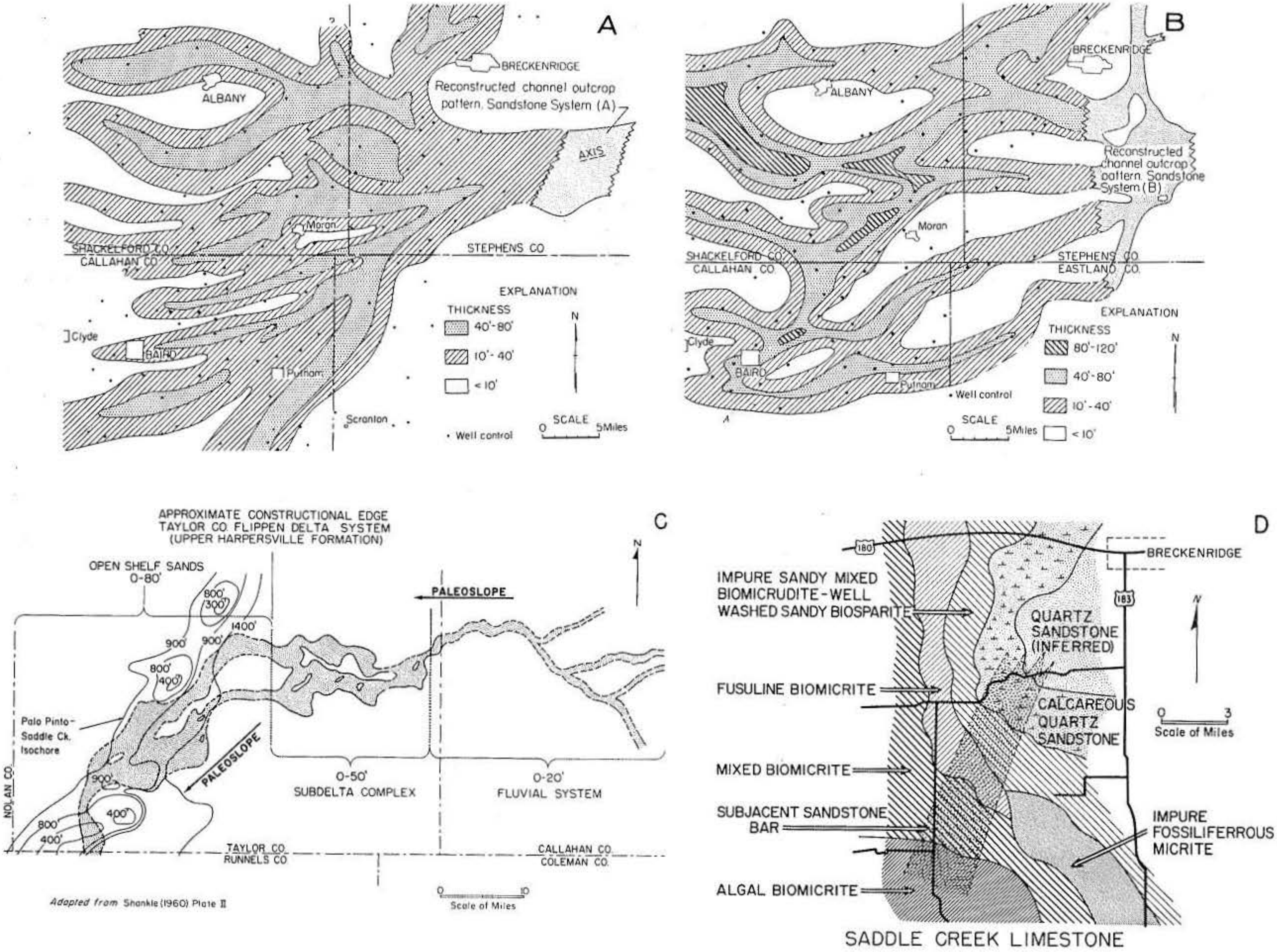

Fig. 5 - Examples of facies patterns, Virgil and lower Wolfcamp rocks, North-central Texas. (A) Post-Bunger – pre-Gunsight sandstone system; (B) Avis Sandstone system; (C) Flippen Sandstone of Taylor and Callahan counties; and (D) Postulated diachronous, aperiodic Cisco repetitive sequences.

decrease in delta-fluvial facies southward across the region, with corresponding increase in strandplain and mudflat facies, indicate dominate southward current drift.

DEPOSITIONAL FACIES MODEL

Stratigraphic Control

A stratigraphic framework in the Cisco-Bowie outcrop belt in North-central began with work by Cummins (1891) and Drake (1893), and was consolidated by Plummer and Moore (1922). Lee (1938) provided farsighted environmental interpretations; Eargle (1960), Stafford (1960a, b), Terriere (1960), and Myers (1965) recently completed areal studies in the region. Rothrock (1961a, b) pointed to the need for surface-subsurface research on sandstone bodies. Cheney (1929) and Cheney and Goss (1952) discussed the structure in the region. Abilene Geological Society publications (1948-1960) provide a source of data; Shankle (1960) investigated one elongate sandstone system.

Studies of extensive marine destructional-transgressive facies within Cisco-Bowie rocks by Brown (1960; 1962) were followed by studies in a 2000-square mile test area of outcrop (McGowen, 1964; Waller, 1966; Ray, 1968) and adjacent subsurface (Seals, 1965). Structural and stratigraphic framework for the detailed area was based on 600 described localities, 300 measured sections, preliminary facies maps of 15 limestone units, outcrop channel trends at 30 stratigraphic levels, and clay-shale facies data, tied by maps of all members and key beds at 1:20,000 scale. Subsurface studies provided isopach maps, sandstone percentage maps, structural maps, residual structural maps. multistory and areal density sandstone maps. and isolith maps of ten major sandstone systems.

Concept of Models

Delineation of three-dimensional facies relationships within a major rock unit such as the Cisco-Bowie complex is hopefully an objective procedure based on adequate stratigraphic control. Interpretation of ancient depositional environments (Figs. 6, 7, 8) represented by these facies, however, is principally subjective using available lithologic, sedimentary, and paleontologic features to relate ancient facies to modern environmental analogs. Key studies of modern depositional environments have recently provided models of several significant depositional systems. A delta-fluvial model (the chief interest in coal-bearing cyclic deposits), for example, is emerging from studies by Kruit (1955), Treadwell (1955), Fisk et al. (1954), Welder (1959), Coleman and Gagliano (1964), Allen (1965), Kolb and van Lopid (1966), Bernard and LeBlanc (1965), Frazier (1967), and several others. Similarly, a number of studies of other associated depositional systems are becoming available; for example, Gould and McFarland (1959), on chenier plains, Curray and Moore (1964) on strandplains, and Hayes and Scott (1964) on barrier bar and lagoon systems. Of primary importance is the fact that several of these studies are fundamentally Recent stratigraphic studies in which cores are used to relate depositional environments and processes to three-dimensional facies models.

A few workers are constructing Paleozoic facies models in rocks similar to Cisco-Bowie facies of north-central Texas: for example, Pepper et al. (1954), 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.

The model concept is applied to Cisco-Bowie rocks by (1) interpreting the depositional significance of component facies; (2) grouping the component facies into related genetic packages or systems; and (3) recognizing the dynamic processes (e.g., delta construction, marine destruction, mud compaction, avulsion) which explain the geometry, facies distribution, dominance of facies, or other attributes of the model.

Cisco-Bowie Model

Cisco-Bowie rocks are currently divided into fluvial, deltaic, open shelf, and interdeltaic depositional systems (Fig. 7). Certain elements of interdeltaic systems may, after additional study, be designated individual systems, such as strandplain-mudflat system or lagoon-bay system.

Cisco-Bowie depositional systems contrast with many areally restricted, relatively thick modern deltaic and related systems. Sites of certain Recent and Tertiary deltaic and related depositional systems were commonly persistent and demonstrate similar paleogeographic distribtion for long periods. Cisco-Bowie systems on the stable shelf, however, shifted through time and space, resulting

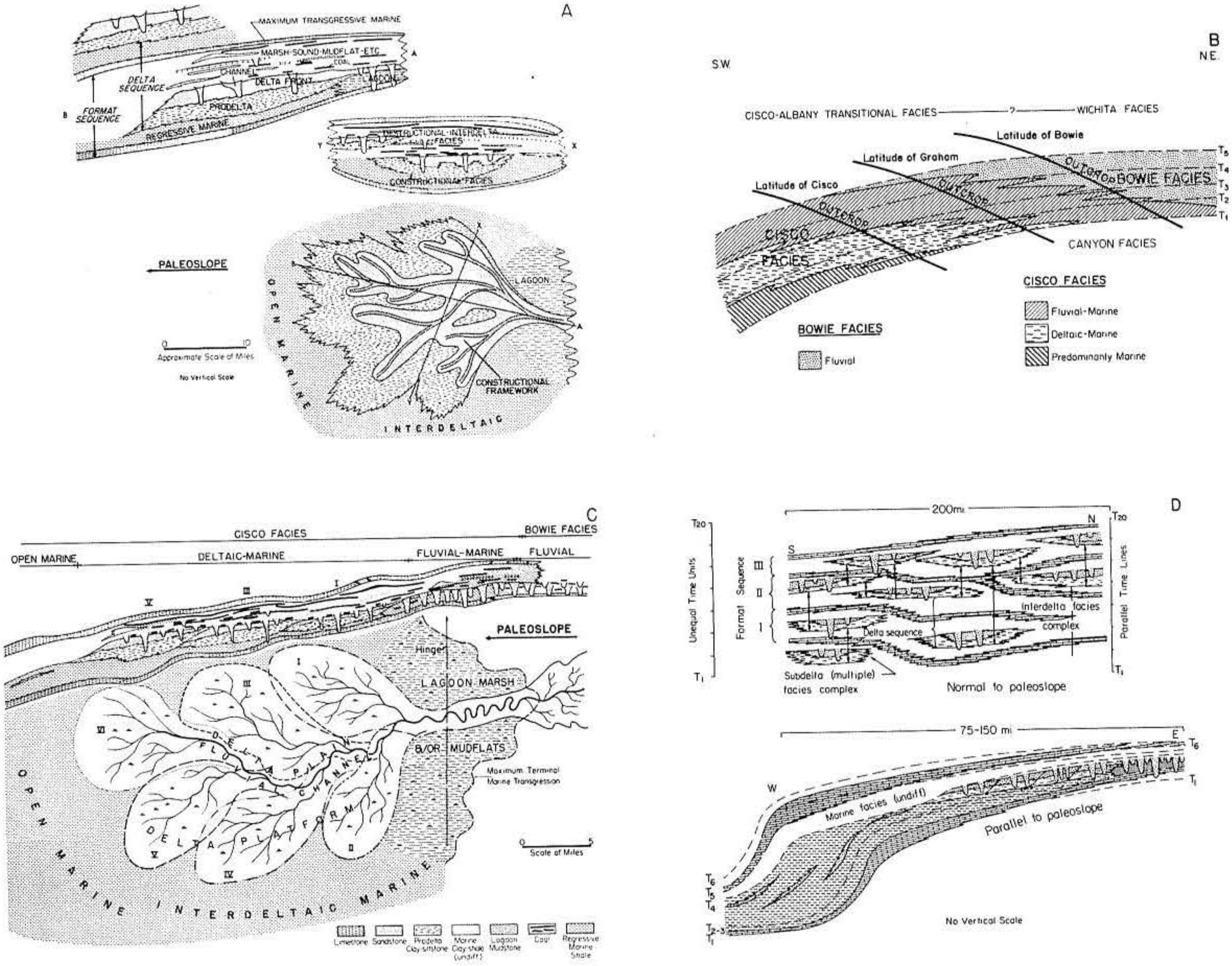

Fig. 6 - Depositional models of Virgil and lower Wolfcamp rocks, North-central Texas. (A) Nature or repetitive units, Cisco rocks; (B) Off-lapping Cisco-Bowie rocks, (C) Subdelta cratonic shelf model, Cisco rocks; and (D) postulated diachronous, aperiodic Cisco repetitive sequence.

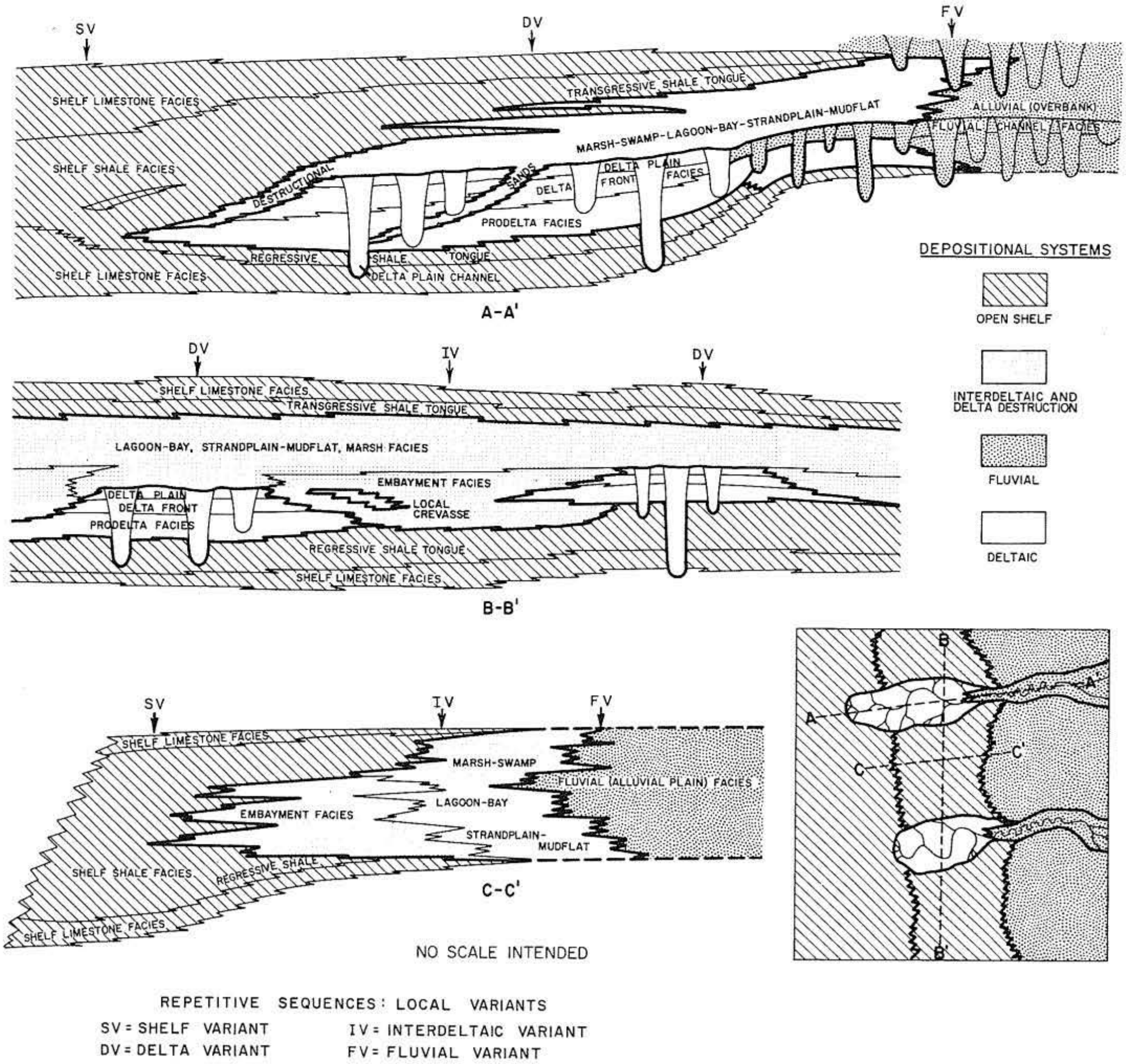

Fig. 7 - Distribution of component facies, Cisco-Bowie depositional systems, North-central Texas. Inferred model is strictly schematic. Much of the strike-fed shale facies may actually prove to be dip-fed prodelta clay facies.

in sequences composed of thin, superposed, depositional systems. (Fig. 6C).

Fluvial depositional systems.—Fluvial depositional systems are composed primarily of alternating channel sandstone and overbank mudstone facies (Fig. 7).

Fluvial systems (Bowie complex) are best exposed in the Trinity River Basin in northeastern Jack, southeastern Clay, and southwestern Montague counties. These fluvial systems intertongue with interdeltaic facies and locally grade downslope into delta systems. Post-Paleozoic erosion has removed the Bowie fluvial complex throughout most of the present Brazos and Colorado valleys.

Fluvial systems of the Bowie complex slowly shifted westward and southwestward through time from Montague County (Graham Formation) to Coleman County (Putnam Formation) as environments of the Eastern Shelf were displaced toward the axis of the West Texas basin. (Fig. 6B).

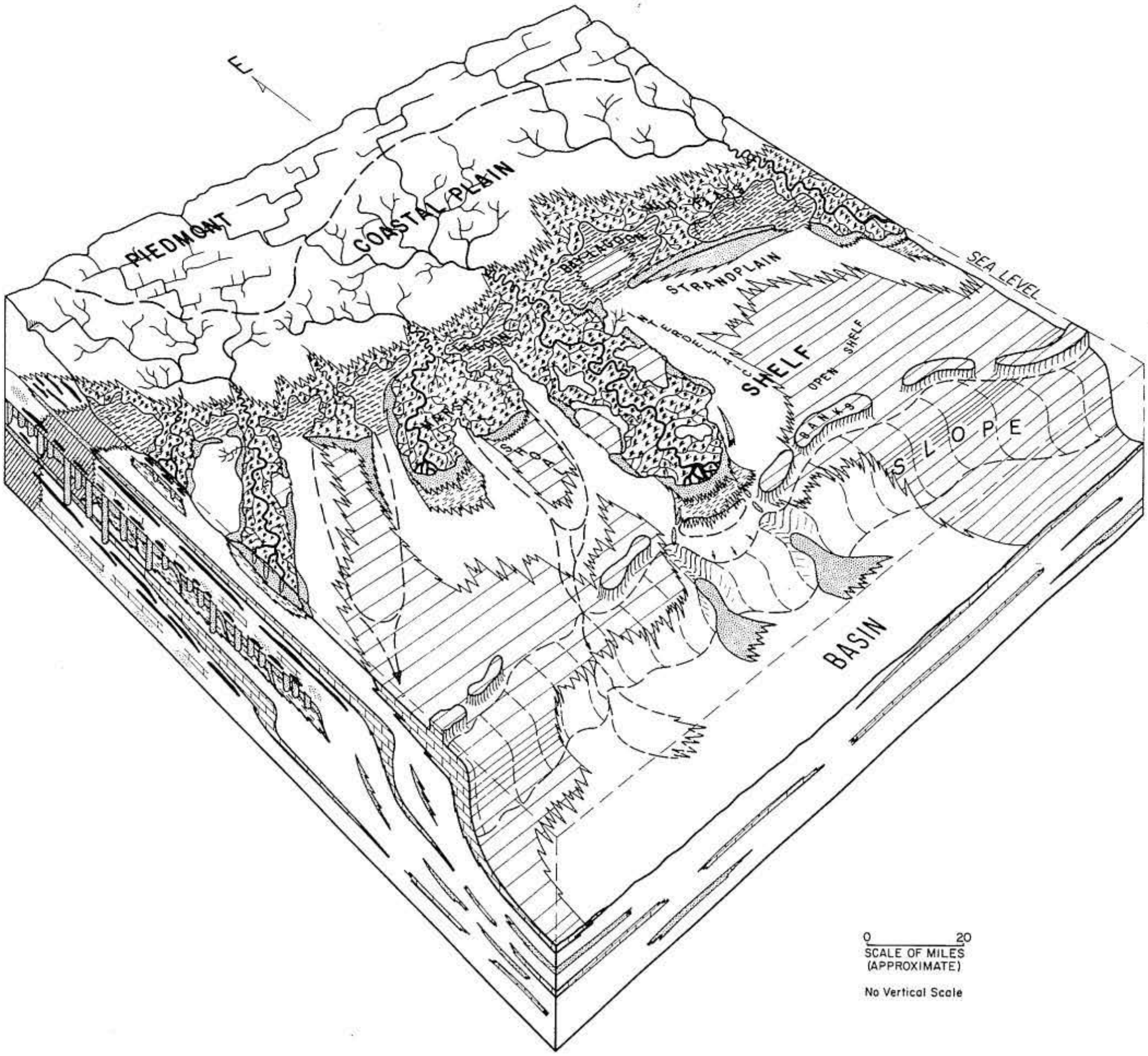

Fig. 8 - Block diagram of Eastern Shelf during Virgil and lower Wolfcamp deposition, North-central Texas. Diagram is hypothetical and illustrates interrelationship of processes and environments. Refer to Fig. 6 for legend.

Other fluvial systems occur in the subsurface at the northern terminus of the Eastern Shelf where southern Oklahoma source areas provided sediment for southward prograding fluvial-deltaic systems.

Component facies recognized in Cisco delta depositional systems include prodelta, delta front, distributary mouth bars, crevasse, and delta plain (Fig. 7). Prodelta facies are relatively unfossiliferous, laminated, thin clays and siltstones. They grade vertically and/or laterally into regressive marine shales (shelf system), delta front sandstones, and various interdeltaic facies (Fig. 6A). Delta front facies are sandstones composed of reworked distributary mouth bars and other shallow water sands winnowed by contemporaneous marine processes at the distal portion of prograding deltas. These sandstones are thin sheet to lenselike bodies cut by superjacent distributaries and perhaps by fluvial channels. Differentiation of thin delta front sandstones and extensive interdeltaic sheet sandstones of possible delta destructional origin is yet unsolved but should yield to detailed study (Hopkins, 1958, p. 38-43). Distributary mouth bars are elongate sandstone bodies displaying highly distorted internal geometry resulting from differential mud-sand compaction. These bodies deposited at the mouths of prograding distributaries, along with underlying delta front sands and overlying distributary channels, comprise elongate sandstone masses analogous to bar-finger deposits (Fig. 5A) described from modern and ancient delta systems (Fisk, 1961; Brown, S.L., 1967).

Crevasse facies and small subdelta lobes occur within subembayment facies (interdeltaic system) or interdistributary facies, apparently emanating from trunk streams on adjacent delta plains (Fig. 4). Channels within these facies are normally sand filled; finer grained crevasse sediment grades into subembayment and interdistributary mud facies. Local marsh facies may develop over subdeltas. Delta plain facies include remnant distributary channel sandstones, interdistributary muds and marsh coals. Progradational, meandering upper delta plain fluvial trunk streams (fluvial system) altered much of the upper delta plain geometry (Fig. 5C). Interdistributary muds and coals grade laterally into subembayment muds of the interdeltaic depositional system.

Elongate sandstone isopach patterns recognized in Cisco rocks display belt, distributary (Figs. 5A, B) or composite areal geometry although subsurface studies in progress may modify this classification (Potter, 1963, p. 15-19). Distributary lobes and many belt patterns are normally composed of a bar-finger complex composed of distributary-mouth bars, delta front sandstones, and superimposed distributary channel sandstones deposited within numerous subdeltas (Fig. 6C) which were modified by later delta plain fluvial systems. Widespread delta front sheet sandstones occupy areas between thicker belts and lobs. Belt patterns resulted from extensive delta-fluvial progradation down the stable shelf. Downslope belt patterns may terminate with distal distributary patterns and belt patterns grade upslope (if preserved) into tributary patterns (Fig. 5C).

Cisco fluvial and deltaic deposition is interpreted to have been principally located within broad, subsiding structural depressions presently defined by negative anomalies on residual structure and decompacted isopach maps. Within these broad areas, differential mud-sand compaction commonly controlled local sites of elongate sandstone deposition, as evidenced by off-setting vertical stratigraphic relationships displayed by superposed sandstone systems. Several narrow multistory sandstone belts within the broad structural depressions, however, were apparently localized by relatively high rates of structural subsidence. Multistory sandstone patterns of probable structural control are more common in fluvial systems, while off-setting vertical relationships resulting from differential mud-sand compaction dominate downslope delta systems where a large volume of compactable prodelta mud was deposited.

Delta destructional facies overlying foundering deltas are recognizable but difficult to separate from similar nearshore facies along interdelta areas. These marsh muds and coals, thin lenticular sandstones, bay-sound limestones, lagoon, and mudflat deposits have not been investigated sufficiently to warrant subdivision. Perhaps stable, cratonic shelf deposition typical of many upper Paleozoic coal-bearing sequences is responsible for absence of extensive destructional facies as well as for difficulty of differentiating interdelta and delta destructional facies (Duff et al., 1967, p. 243). For convenience, delta destructional facies are currently combined with interdelta facies (Fig. 7).

Open shelf depositional systems.–Relatively uniform open shelf systems extend over vast areas of the Eastern Shelf, and are presently subdivided into two general component facies – shelf shale and shelf limestone (Fig. 7). Limestone bank facies along the shelf edge, as well as slope and adjacent basin facies, are not specifically considered in this discussion.

Shelf shale facies as defined in this report compose the greatest volume of open shelf rocks except near shelf edges where limestone may locally dominate the section. For convenience, local, thin, interbedded limestone beds and localized marine standstones (submarine channel-fill?) are included within the facies. This facies intergrades with interdeltaic and deltaic facies and is conformable with overlying and underlying shelf limestones. Shelf shale facies thicken downslope into a thick shale wedge which was primarily responsible for westward construction of the shelf (Fig. 6D).

Differentiation of dip-fed prodelta mudstone and strike-fed open shelf shale facies is highly subjective, but continued studies may prove that most of the open shelf shale wedge is actually composed of dip-fed prodelta mudstone (Figs. 6,7). In either case, the Cisco-Bowie model, which has been developed and documented in nearshore facies, can be extended logically into shelf-edge and slope areas. Prodeltaic muds, for example, which by-passed upslope environments, were debouched onto downslope shelf areas (Fig. 8). Marine currents (and perhaps submarine turbidity flow) undoubtedly transported large volumes of this mud to slope areas where the muds constituted the principal sediment supply responsible for prograding the shelf. Lesser amounts of sand transported locally to the shelf edge were available for downslope transport into the basin (Jackson, 1964, p. 323 Swann, 1964, p. 653; Walker, 1966). Meandering and bifurcating undaform or shelf edges (Jackson, 1964; Van Siclen, 1958) can be interpreted to reflect irregular westward growth of the shelf edge by laterally shifting major delta systems. Deposition of irregularly supplied downslope clastic sediment alternated with limestone deposition on the prograding shelf.

Shelf limestone facies were deposited in the absence of local terrigenous clastic sediment supply. These limestones represent very shallow water environments as indicated by outcrop facies studies (Fig. 5D). Shelf limestone environments probably transgressed or occupied areas upslope or along sedimentary strike as terrigenous clastic sediment from earlier deltas was stabilized by dense marsh vegetation, and gradually subsided beneath wave base. Shelf limestones were deposited over extensive marsh environments which occupied sites over numerous abandoned delta platforms and upslope interdelta coastlines (Figs. 6C, 8).

Stratigraphic evidence points to slow limestone deposition relative to fluvial-delta facies. Transgressive Cisco limestones grade upslope into littoral sandstones and lagoonal muds of the interdeltaic system (Fig. 6D).

Interdeltaic depositional systems. – These are principally mudstone systems (Fig. 7) deposited upslope between delta systems (subembayment mud facies) or in nearshore enviornments (lagoon-bay facies, strandplain-mudflat facies, and marsh-swamp facies). These mudstone or lenticular sandstone facies can be identified locally in outcrop, but their thin, intergradational and commonly erratic nature make precise mapping difficult. Boundaries between such facies will at best be approximate, except where extensive core data are available.

Delta destruction begins as soon as avulsion or crevassing eliminates the sediment supply to a delta system. (Scruton, 1960, p. 98-100). Margins of delta platforms are eroded by marine waves and currents, and the sediment is redistributed as bars, sheet sandstones, mudflats and open shelf mud facies. Subsidence of the compacting delta mass provides sites for extensive marshes, as well as lakes, bays, and lagoons on or adjacent to the foundering delta platform. Although delta destructional facies are recognized at the outcrop, it is presently more convenient to group these predominantly mudstone facies with interdeltaic facies.

Subembayment mud facies commonly resemble and intergrade with prodelta facies and subsequent delta destructional facies. Subembayment muds grade downslope into shelf shales and upslope and along sedimentary strike into various nearshore sediments associated with interdelta coastlines and moribund delta platforms. A gross distinguishing characteristic of subembayment rocks is the common occurrence of crevasse or subdelta facies and probably tidal channels originating along the margins of adjacent delta plains. Local, impure, micritic limestones and thin, sheet sandstones have been recognized within the facies.

Lagoon-bay facies are recognized, but the physiographic model for these more restricted Cisco marine facies is still very speculative. Effective barriers in the Cisco, for example, could have been but a few feet thick, making detection of barriers most difficult. Very few Cisco barrier bar facies have been recognized to date within the study area. Mudstones containing faunas of probable embayed origin are gradational laterally with mud-coal facies of marsh origin. Local, impure limestone lentils and small mud-filled channels of possible tidal creek origin have been recognized. Faunas, sedimentary structures, and possible physiographic setting must be investigated before definition of these complex mudstone facies will be possible. Some facies represent restriction in delta flank embayments, which were not necessarily physically barred from open marine currents on the very broad, shallow shelf. Fluvial systems commonly cut interdeltaic facies, suggesting rapid, crevasse development of new delta sites.

Strandplain-mudflat facies consist of mudstones and interbedded, thin, sheetlike sandstones which are intergradational with other interdeltaic facies. Two such sequences occur south of contemporaneous fluvial-delta systems, pointing to southward drift of sand and mud from destructional deltas (Fig. 4). Based upon regional reconnaissance, more extensive strandplain-mudflat facies appear to occur southward in the Colorado River valley.

Marsh-swamp facies are typically organic-rich mudstones with interbedded coals and carbonaceous shales; plant debris may vary from well preserved fern and reedlike material to macerated fragments, but large tree trunks and other evidence of dominant swamp facies are sparse. Kaolinite-rich clays are normally concentrated in this facies, which represent the nearest analog to Midcontinent underclays. Mud and coal-filled channels are associated with marsh beds.

Inferred Depositional History: Summary

Virgil and Wolfcamp rocks in North-central Texas have been interpreted as representing deposition within several depositional systems (Fig. 8). Fluvial-delta systems prograded rapidly westward across the slowly subsiding Eastern Shelf within shallow paleotopographic troughs resulting from differential compaction and localized differential subsidence. Within the region of investigation, sedimentation from the Ouachitas and adjacent piedmont supplied crevassing subdelta lobes until avulsion of over-extended systems occurred.

Fluvial-delta construction resulted in deposition of prodelta shales, delta front sandstones, distributary mouth bars, crevasse facies, and delta plain facies (channels, interdistributary marsh and coal). Lagoonal, mudflat, and embayment shales (containing crevasse facies) were complementary interdeltaic facies.

Marine destructional processes slowly modified fringes of abandoned compacting, subsiding deltas. Marsh environments (clay and coal) containing tidal channels occupied foundering delta plains and adjacent interdeltaic coastal plains. Thin, lenticular sands were deposited locally along subsiding delta margins; winnowed sediment was swept onto interdeltaic mud flats and strandplains. Local impure limestones and muds were deposited in lagoons and bay-sound areas on the inundated delta margin and interdelta coastline.

Widespread open shelf environments, in the absence of active local deltation, progressively occupied upslope areas. Shelf limestone environments, which coalesced over marsh-stabilized, subsiding deltas, and graded into destructional strandline facies, were eventually continuous with downslope shelf edge limestone environments.

Environments representing any depositional system could occur simultaneously along the coastline. Within the context of the inferred depositional model, repetitive sequences defined by deltation or by transgression are necessarily aperiodic and diachronous.

REPETITIVE DEPOSITION

Nature of Repetitive Sequences

The Cisco-Bowie depositional model attempts to explain or substantiate stratigraphic relationships, facies distribution, environmental interpretation, and the nature of repetitive facies. At present this is the only model that provides a guide to North-central Texas upper Pennsylvanian and lower Permian repetitive deposition (Fig. 4) which is based solely upon the local rock record and proposed Recent depositional analogs.

Basic sequence and local variants.–Thin, extensive, repetitive Cisco-Bowie rocks are interpreted to have been deposited through time and space by shifting fluvial and deltaic environments, which also controlled the location and principal sediment supply of associated interdeltaic and open shelf facies (Fig. 6). Bowie rocks are typified by alternating vertical sequences of fluvial channel and overbank facies with rare, intercalated marine nearshore facies. Additional component facies may eventually be delineated within Bowie rocks, but its repetitive nature will remain basically simple.

More complex Cisco repetitive facies comprise a sequence of two or more depositional systems (Fig. 7) including from bottom to top (1) open shelf; (2) interdeltaic; (3) deltaic or (4) fluvial and/or (2) interdeltaic; and (1) open shelf systems [shelf system arbitrarily selected the initial system in sequence]. Each depositional system contains component facies arranged in more or less homotaxial order. Jackson (1964, p. 318-319) applied the term cyclophase to this alternation of sand-shale clastic phases and carbonate phases without attempting to define specifically the depositional significance, except in terms of undo, clino, or fondo environments.

Variations of this basic depositional sequence are numerous and depend upon the interplay of depositional processes in the local area. Four common intergradational variations or variants occur within Cisco rocks (Fig. 7). Each is characterized by the dominant depositional system which developed at any time and place in response to shifting fluvial-delta sites. Fluvial variants developed in strandline areas; deltaic and interdeltaic variants dominated sequences in upslope marine areas; and shelf variants were deposited extensively in downslope areas (Fig. 8). Similar variants were recognized in coal-bearing deltaic rocks of the Donets Basin by Feofilova (1959).

Control of repetitive deposition.—Application of a fluvial-delta shelf model to these rocks makes it unnecessary to invoke an extrabasinal cyclic sediment supply, cyclic sea level changes, or cyclic shelf or basin subsidence, although none of these factors are necessarily precluded. The inferred model operates (and is self-regulating and self-perpetuating) under continuous but not necessarily uniform sediment supply and continuous but slow shelf subsidence. There is no necessity for absolute sea leavel changes to produce the vertical and lateral facies relationships which characterize Cisco-Bowie rocks.

Sea level changes? Yes, but principally relative, noneustatic changes in response to interplay of sediment supply rates, differential shelf stability, marine destruction, mud compaction, delta crevassing, and drainage avulsion. The distinctive nature of repetitive sequences in different regions (Illinois, Kansas, Ohio, Texas, Yorkshire, for example) undoubtedly reflects the unique interplay of these factors, one or more of which may override or dominate within a specific province during any time interval. Lesser differences (i.e., variants) within the same province reflect even more subtle local variations in processes which shaped the character and distribution of local depositional systems.

Repetitive units.—Genetically, Cisco-Bowie sequences resulted from the transient character of delta sites. The nature of repetitive sequences, defined from base to base of successive delta systems, therefore, depends upon the regularity or frequency with which delta (variant) systems developed within a local area. Stratigraphic evidence indicates that delta sequences within the Cisco-Bowie model are commonly local, aperiodic and diachronous along the paleostrandline, which limits the usefulness of these units in classical stratigraphic studies (Figs. 4, 6A).

Transgressive or format sequences (format, Forgotson, 1957) defined from base to base of successive, transgressive limestones are widespread packages of repetitive depositional systems, most useful in classic regional studies (Figs. 4, 6A, D). Limestone environments sometimes failed to encroach or occupy sites sufficiently far upslope to punctuate a "cycle" at the present outcrop or upslope limestone depositional sites failed to coalesce to provide extensive limestone facies. Within the context of the inferred Cisco-Bowie model, extensive shelf limestones were not only time transgressive upslope but also along the shelf (Fig. 6D). Diachronous, transgressive limestones, which bound format sequences, nevertheless, are useful stratigraphic markers.

In other basins where transgressive limestones are absent, coals are useful stratigraphic markers within repetitive sequences. Sequences without these extensive marine or nearshore facies are difficult to define. For example, transgressive limestones and other marine facies pinch out as predominantly marine Cisco rocks grade into nonmarine Bowie rocks, resulting in problems of delineating and mapping of repetitive fluvial sequences (Fig. 6C).

Chronology of Repetitive Sequences

Shifting modern delta sites, with corresponding changes in local rate of sediment supply, result from the interplay of various factors such as rates of local shelf subsidence, degree of mud compaction, intensity of marine destructional processes, volume of local sediment supply, and geomorphology of the drainage system (Coleman and Gagliano, 1964; Frazier, 1967). Similarly, these same factors should have been significant in controlling Virgil and Wolfcamp delta sites. When it can be demonstrated stratigraphically that delta systems are rarely time-equivalent along 50-75 miles of paleostrandline, it is obvious that any attempt to correlate them with world-wide cyclic control is impossible. It can be confidently inferred, therefore, that Cisco deltaic deposits are commonly aperiodic and diachronous (Fig. 6D).

Marine and nearshore destructional environments, which occupy Recent moribund delta sites, represent slow, coalescing deposition relative to delta constructional facies (Frazier, 1967, p. 306-310). Virgil and Wolfcamp marsh and limestone environments, at least, can be inferred to have developed somewhat like modern analogs. Contemporaneous delta, marsh and shelf deposition, which occurs in modern analogs, strongly points to a Cisco-Bowie depositional model in which shelf limestones (or any other facies) are not necessarily time-stratigraphic facies deposited in shelf-wide, uniform, contemporaneous environments.

Constructional facies within a single modern delta lobe represent relatively brief, discrete time intervals, while destructional, interdeltaic and transgressive facies involve greater time span (Frazier, idem). Rocks within each Cisco format sequence should, therefore, exhibit complex internal chronology. Such time and spatial relationships explain problems of attempted lithologic correlation of similar facies within homotaxial sequences of different deltas or interdelta areas, as well as between subdeltas of the same system. Homotaxis is a key to many perplexing Virgil-Wolfcamp faunal problems, and numerous long-standing arguments of correlation based on the layer-cake depositional model.

Distribution of Repetitive Sequences

Vertical and lateral facies relationships within Cisco-Bowie rocks, present a highly complex picture, but one which can be readily deciphered using the delta-controlled depositional model.

A section of Virgil and Wolfcamp strata at any arbitrary locality consists of a dozen or more superposed format sequences (Fig. 4). Each format is characterized at that locality by one of the four intergradational variants–fluvial, deltaic, interdeltaic and open shelf variants (Fig. 7).

An east-west profile of any format sequence parallel to paleoslope direction normally transects (in order) intergradational fluvial, deltaic or interdeltaic, and open shelf dominated facies or variants (Fig. 7). Southwestward migration of these depositional tracts from early Virgil to medial Wolfcamp resulted in a significant westward shift in average strandline (Fig. 6B). This basinward shift of 50-75 miles in average shoreline correlates closely with the rate of westward shifting shelf edges. It can be logically inferred that slope sequences beyond the shelf edge are also genetically related in time, space and origin to shelf sequences (Fig. 8).

GENESIS OF REPETITIVE SEQUENCES: SUMMARY

No evidence has been recognized within the region investigated which necessitates repetitive sea level changes or any other extrabasinal control to explain Cisco-Bowie deposition. Extensive shelf-wide erosion, commonly misinterpreted from excellent work by Lee (1938) in Young County, is not substantiated by detailed studies along 100 miles of outcrop. Significant erosion was restricted to localized channels within dominantly conformable sequences. (Fig. 1, 4). Maximum channel erosion (rarely more than 75 feet; average about 40 feet) occurred near the hinge between relatively stable alluvial plains and less stable deltation sites where more than 50 percent mud compaction and localized shelf subsidence increased the grade of fluvial systems (Fig. 6C). Filled channels 100 feet deep occur on modern deltas even under slightly rising sea level (Fisk, 1958, p. 193).

Eustatic sea level drop of more than 400 feet (Van Siclen, 1964, p. 537) on a shelf with less than one foot per mile paleoslope, for example, would expose the entire shelf. Depending upon the inclination of the slope from shelf to basin, the shoreline would have been located at least 150 miles west of the present outcrop of Cisco-Bowie facies. Dissected, regionally unconformable surfaces, possible strike valleys, and extensive terraces would be expected in the section-none of which have been recognized. The evidence presented by Van Siclen (1964, p. 537) for abrupt sea level drop (400 feet) is presently being reexamined in the light of an alternate model. Such a model involves slow subsidence, a large volume of fine-grained terrigenous clastic sediment supplied aperiodically to various downslope areas by westward to southward prograding dletas. Intermittent development of limestone environments occurred when terrigenous clastic sediment supply temporarily shifted elsewhere along the shelf edge. Many geologists may be reluctant to abandon the long-held belief that extensive limestones represent synchronous deposition. It is going to be increasingly difficult, however, in the light of growing documentation by both modern depositional processes and ancient facies models, for such workers to continue the widely held idea that "cyclic" sequences are necessarily time-stratigraphic. Diachronous, aperiodic sequences in modern analogs, plus increasing evidence from the rock record, undermines arguments that eustatic changes or cyclic tectonics are absolutely necessary. Intrabasinal processes best explain Cisco-Bowie repetitive deposition. It is even questionable whether deposition of Cisco-Bowie facies can be explained by modern sedimentary processes operative within a model dominated by repetitive sea level changes, especially changes approaching 400 feet.

Conclusions based on Eastern Shelf rocks studied to date are not intended to refute evidence cited for significant cyclic sea level changes by workers elsewhere in the basin. Such inconsistencies in interpretation within the same basin should, nevertheless, encourage workers to reevaluate critically and regularly that evidence which has long been the basis of interpretation. Above all, the search for answers should rely only upon full evaluation of the rock record and modern sedimentary processes.

A growing number of workers, who are investigating late Paleozoic cyclic sequences, have been proposing depositional models which closely resemble the Cisco-Bowie model. Derek Moore (1959) among others reached similar conclusions concerning the Yoredale Series of the British Isles. Swann's (1964, p. 654-655) late Mississippian cycles were similarly interpreted, although he stopped short of considering that carbonate and clastic depositional phases could be contemporaneous and, thus assumed time-stratigraphic cycles. Cocke's recent study (1968) of Missourian rocks on the Kansas Shelf resulted in a model identical to the Cisco-Bowie model for North-central Texas. Duff et al., who thoroughly reviewed cyclic or repetitive sedimentation throughout the world, generally agree with conclusions reached in this report on the Eastern Shelf-that is, studies to date indicate that:

(1) control is principally sedimentary and intrabasinal; (2) coal-bearing cyclothems or sequences were commonly deposited within a self-regulating delta model; (3) single, worldwide eustatic control is not justified by a thorough consideration of ancient sequences in the light of modern sedimentary data; (4) climatic controls are highly speculative; and (5) tectonic control, though locally important, has been overrated in importance (idem, p. 115-116, 148-156, 241-251).

CYCLICITY; A CRITIQUE

No effort has been made to recapitulate the wars, battles and sieges waged during the past 35 years in the name of cyclic deposition. Geologic literature is well stocked with debate ranging from sun spot cycles to vegetational control of cyclic deposition (Duff et al., 1967). Many combatants have battled for single universal factors. Some have fought under different flags when considering cyclicity in different geologic periods. Many have apparently fought for the fun of it; others have fought in self defense. Several, like sieged barons, have stubbornly clung to the parapet for decades, exchanging volleys occasionally to emphasize their readiness to battle for cyclothemic principles. Cycles by the score have been recognized-megacycles, normal cycles, paleolimnological cycles, baselevel transit cycles, trace element cycles, modal cycles, and even psychological cycles (Duff et. al., 1967). Others who have had more difficulty defining cycles, have resorted to Fourier analysis to delineate cycles, while some still search for the ideal cyclothem (idem).

Many geologic events and processes have been repetitive or perhaps even cyclic, but currently popular eustatic and diastrophic theories of cyclic sedimentation must be carefully reviewed. No one can deny that sea level changes and diastrophism have occurred. That most repetitive or "cyclic" sequences were controlled by single processes, however, is a concept deeply ingrained and too long looked upon as a fundamental geologic principal.

The prevalent concept that a cyclic sequence in the late Paleozoic resulted from unique phenomena caused by peculiar events operative only during that time should not be accepted until all possible factors are considered within the local rock section and the geologic history of the basin it represents. Is it not logical, for example, to assume that Pennsylvanian coal-bearing cyclothems, Cretaceous coal-bearing cycles, Tertiary lignite-bearing cycles, and Recent peat-bearing cycles developed within similar depositional process models? Perhaps intracratonic shelf stability, local source tectonics, vegetational characteristics, climatic variables or many other possible geologic variations caused Pennsylvanian cyclothems to vary,·not only from one area to another but to differ from Cretaceous, Tertiary, or Recent counterparts. What is of fundamental importance is that similar facies e.g. (coal, channel-fill sandstones, lagoonal muds, prodelta clays) displaying similar interrelationships point to similar origin despite differences in absolute facies geometry and scale. Pennsylvanian shoal-water delta facies may be but a few feet thick, hundreds of square miles in area, and highly modified by marine processes and delta-plain fluvial activity, but the ancient delta was deposited by the same sedimentary processes and within the same general sedimentary environments in which modern deltas were deposited.

Depositional environments, in which presently compacted and distorted late Paleozoic coal-bearing sequences (or any other for that matter) were deposited, are presently being reinterpreted by several workers using recently available and growing data from modern depositional models. The extensive areal distribution of some thin cyclic facies (e.g. marsh coals and transgressive limestones) is still, however, considered evidence by many workers of synchronous deposition of facies in widespread, uniform environments (Merriam, 1964; Duff et al., 1967). Such a layer-cake model demands abrupt sea level changes, according to these workers, which can be explained by eustatic sea level changes or sudden tectonic adjustments.

For many, abrupt vertical changes from coal to marine shale or limestone is evidence of sudden-ing deepening of water, and conversely, a change from limestone to deltaic-fluvial facies required a sudden drop in sea level. What is the difference in water depth at the depositional sites of a distributary-mouth bar on a shoal-water delta and a shelf limestone containing algal facies? Rapid vertical changes in facies such as marsh to shelf deposits without significant eustatic changes have been documented recently in several delta investigations (Coleman and Gagliano, 1964, p. 71; Kolb and van Lopik, 1966, p. 39-57; Frazier, 1967). Subsidence of a broad, predominantly marsh-stabilized mud coastline or foundering delta easily explains transgression or the development of marsh and open shelf environments directly over terrigenous clastics without resorting to sudden worldwide sea level variations. Likewise, deltaic deposits, prograding rapidly across a shallow shelf, should result in abrupt vertical chagnes (idem) from shelf deposits to terrigenous clastics without the necessity of lowering sea level.

The concepts of unique upper Paleozoic cyclic deposits, of standard or ideal cyclothems, and of worldwide sea level or diastrophic control should be kept open to question as data related to modern depositional processes are applied to these ancient facies. Reliance upon waxing and waning of distant glaciers or the universal control of sun cycles or other such phenomena are, perhaps, convenient and obviously comforting to Pleistocene-oriented geologists. Such factors must be placed in proper perspective, however, along with many other significant and perhaps locally overriding factors within a specific basin.

EPILOGUE

"To begin by asserting a world-wide synchroneity is clearly to pre-judge the question [eustatic sea level control] before the trial has begun. Lithologies in cyclic successions are obviously controlled by the environment of deposition. Our survey has shown that cycle types, irregularities and lateral changes in types are themselves largely a function of the environment. It is therefore manifestly ludicrous to attempt to find a single control for cyclic sedimentation" (Duff et al., 1967, p. 242).

"An argument over the origin of cyclothems is absurd; the argument must always deal with a particular cyclothem or a carefully defined class of cyclothems" (Beerbower, 1964, p. 41).

"Only if these [local mechanisms] fail to convince us of their adequacy is it permissible to go further afield into the more speculative realms of climate, regional earth-pulsations, planetary movements or cosmic influences" (Robertson, 1952, p. 515-516).

"The mechanism of cyclic advance of the delta is sufficient to account for all the observed features of the Yoredale Series cyclothems without recourse to more fanciful ideas" (D. Moore, 1959, p. 522).

"If one boggles at the idea that jumping continents, sunspot cycles or climatically controlled worldwide fluctuations in sea level may explain a 20-ft sequence of sedimentary rocks in southwestern Iowa, the fault would seem to lie in the state of the art rather than in a statement of its products" (Ferm, 1968, p. 30).

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