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Characteristics, stratigraphic architecture, and time framework of multi-order mixed siliciclastic and carbonate depositional sequences, outcropping Cisco Group (Late Pennsylvanian and Early Permian), Eastern Shelf, north-central Texas, USA

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Abstract

The Cisco Group on the Eastern Shelf of the Midland Basin is composed of fluvial, deltaic, shelf, shelf-margin, and slope-to-basin carbonate and siliciclastic rocks. Sedimentologic and stratigraphic analyses of 181 meter-to-decimeter-scale depositional sequences exposed in the up-dip shelf indicated that the siliciclastic and carbonate parasequences in the transgressive systems tracts (TST) are thin and upward deepening, whereas those in highstand systems tracts (HST) are thick and upward shallowing. The sequences can be subdivided into five types on the basis of principal lithofacies, and exhibit variable magnitude of facies shift corresponding to variable extents of marine transgression and regression on the shelf. The sequence stacking patterns and their regional persistence suggest a three-level sequence hierarchy controlled by eustasy, whereas local and regional changes in lithology, thickness, and sequence type, magnitude, and absence were controlled by interplay of eustasy, differential shelf subsidence, depositional topography, and pattern of siliciclastic supply. The outcropping Cisco Group is highly incomplete with an estimated 6–11% stratigraphic completeness. The average duration of deposition of the major (third-order) sequences is estimated as 67–102 ka on the up-dip shelf and increases down dip, while the average duration of the major sequence boundaries (SB) is estimated as 831–1066 ka and decreases down dip. The nondepositional and erosional hiatus on the up-dip shelf was represented by lowstand deltaic systems in the basin and slope.

Keywords: Sequence stratigraphy; Siliciclastics; Carbonates; Pennsylvanian; Texas

1. Introduction

Meter-to-decimeter-scale depositional cyclicity suggests spatial and temporal regularities of processes controlling accommodation space, sediment supply, and sedimentation (e.g., Gilbert, 1895; Barrell, 1917; Wanless and Shepard, 1936; Wilson, 1967; Goldhammer et al., 1994; cf. Drummond and Wilkinson, 1993). The upper Paleozoic cyclic successions of North America are commonly composed of mixed siliciclastic and carbonate rocks deposited in a variety of marine and nonmarine, shelf-to-basin environments (e.g., Wanless and Shepard, 1936; Merriam, 1964; Heckel, 1986; Boardman and Heckel, 1989). They are the building blocks of large-scale depositional sequen-

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ces (e.g., Brown et al., 1990; Goldhammer et al., 1994; Watney et al., 1995; Mazzullo, 1998). Investigation of multiple-order depositional sequences have provided insights into the genetic relationships among component depositional systems and on the interplay of geologic processes in cyclic sedimentation (Brown and Fisher, 1977; Van Wagoner et al., 1990; Mitchum and Van Wagoner, 1991; Vail et al., 1991; Goldhammer et al., 1994; Watney et al., 1995).

This study integrates detailed sedimentologic, petrographic, and stratigraphic observations of the mixed siliciclastic and carbonate rocks of the Cisco Group exposed on the up-dip Eastern Shelf, Texas, with a previously established shelf-to-basin large-scale (third-order) sequence stratigraphy (Brown et al., 1987, 1990). In addition, the time framework of sequence development is evaluated using the sedimentation rates derived from previous studies. The integration resulted in a better understanding of the mechanisms of major controls and stratigraphic responses at three levels of stratigraphic hierarchy in the study area. This paper presents (1) characteristics of 181 primary depositional sequences; (2) regional variations of sequence attributes; and (3) speculations on the roles of major geological processes in hierarchical cyclic sedimentation of the Cisco Group.

2. Geologic background

The Eastern Shelf in north-central Texas is bounded by structural highs to the north, east, and south, and dips ~ 0.5°W and WNW (Fig. 1A). It developed from the Late Mississippian and Early Pennsylvanian Concho Platform and was situated between the older Fort Worth foreland basin to the east and the rapidly subsiding Midland Basin to the west during Late Pennsylvanian and Early Permian time (Wermund and Jenkins, 1969; Yang and Dorobek, 1992). Approximately 370 m of nonmarine and marine siliciclastic and carbonate rocks of the Cisco Group were deposited on the up-dip shelf and ~ 900 m along the shelf margin (Fig. 1B; Brown et al., 1990).

The Cisco Group spans the Virgilian and early Wolfcampian epochs and was deposited during the late Paleozoic first-order sea-level fall caused by the formation of Pangea (Scotese and Denham, 1987). The shelf prograded ~ 200 km basinward by repeated progradation of lowstand deltaic systems and aggraded ~ 400 m mainly by the growth of shelf-edge carbonate banks (Fig. 1B; Brown et al., 1987). The siliciclastic sediments were derived from the Wichita Mountains and Arbuckle Uplift to the north, the Ouachita thrustbelts and the fluvial deposits exposed on the eastern flank of the Fort Worth Basin to the east (Brown et al., 1990), and some from the Llano Uplift to the south (Yang et al., 1998). Brown et al. (1990) identified five major depositional systems in the Cisco Group: up-dip fluvial–deltaic system, platform-shelf carbonate and siliciclastic systems, shelf-edge carbonate bank system, shelf-edge deltaic system, and basin–slope system (Fig. 1B). They also recognized 15 depositional sequences and attributed third-order eustasy as the dominant control on sequence formation (Fig. 2; cf. Galloway, 1971, 1989).

The Cisco Group in the up-dip Eastern Shelf is volumetrically dominated by fluvial–deltaic systems. The outcrop belt in the study area is ~ 300 by ~ 40 km, approximately parallel to the depositional strike (Fig. 3). Centimeter-scale description of 88 measured sections and petrographic studies of ~ 600 samples were conducted in this study (detailed petrographic data are in Yang, 1995). The sections are grouped into three traverses–the Colorado River valley traverse, the southern Brazos River valley traverse, and the Brazos River valley traverse (Fig. 3; Plates A–C (see back of this issue)).

3. Primary depositional sequences of the Cisco Group

3.1. Delineation and classification of primary sequences

Centimeter-scale field and petrographic observations on the lithologic and faunal composition, sedimentary texture and structure, and bedding geometry were used first to interpret lithofacies and associated depositional systems of individual strata. A group of lithofacies of the same depositional system (Brown and Fisher, 1977) defines a parasequence on a measured section. These facies and associated environments of individual parasequences, described in the next section, reveal diagnostic information on processes controlling sequence formation.

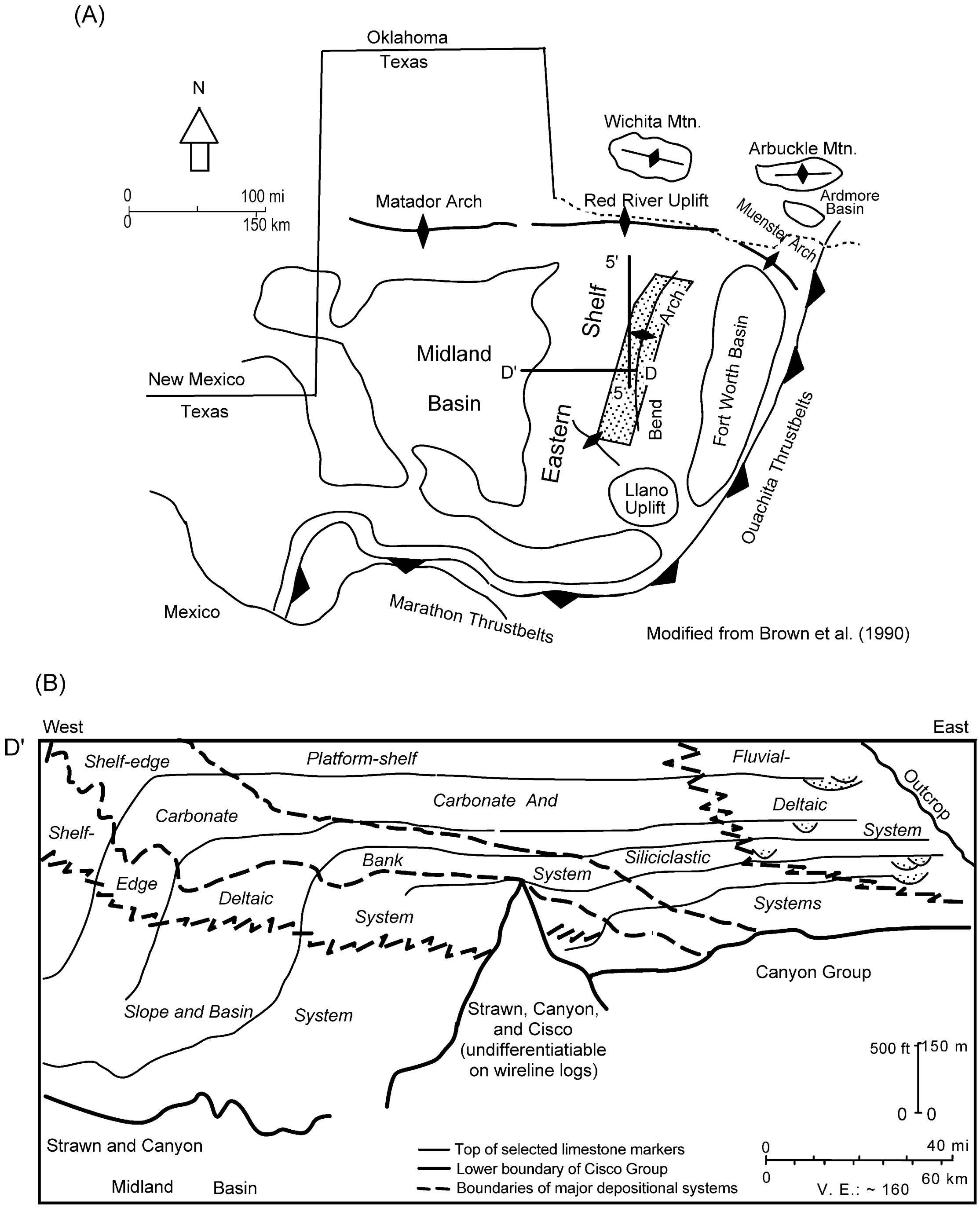
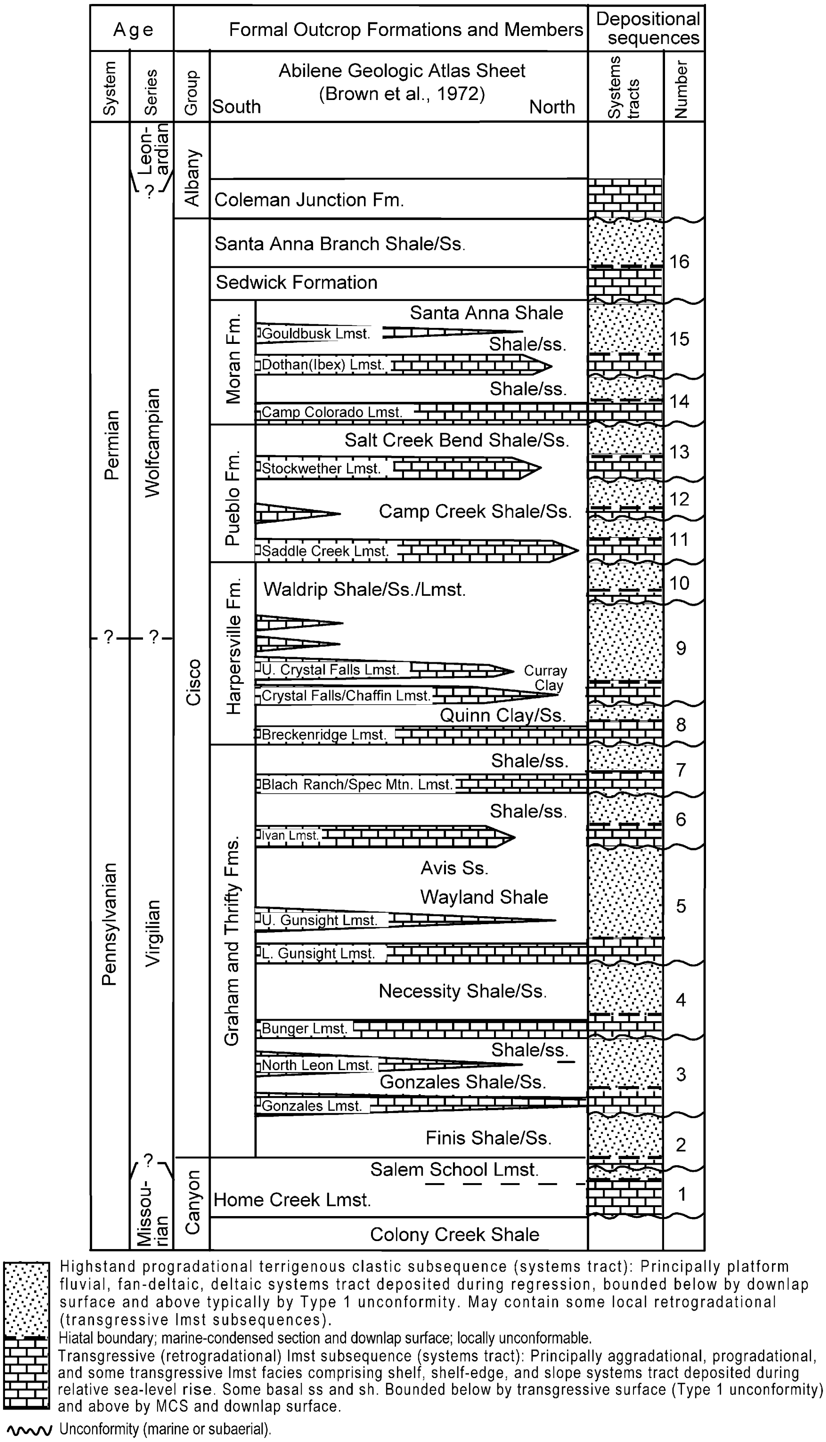


Fig. 1. (A) Tectonic elements surrounding Eastern Shelf in north-central Texas. Major sediment source areas were to north and northeast. Study area is stippled. (B) Simplified dip cross section of Cisco Group, showing major depositional systems and overall progradation and aggradation of Eastern Shelf during Cisco time. Modified from section D–D′ of Brown et al. (1990).


Age
Formal Outcrop Formations and Members
Depositional sequences
System
Series
Group
Abilene Geologic Atlas Sheet
(Brown et al., 1972)
South
North
Systems tracts
Number
Permian
Pennsylvanian
Leon-ardian
Wolfcampian
Virgilian
Missou-rian
Albany
Cisco
Canyon
Coleman Junction Fm.
Santa Anna Branch Shale/Ss.
Sedwick Formation
Moran Fm.
Santa Anna Shale
Gouldbusk Lmst.
Shale/ss.
Dothan(Ibex) Lmst.
Shale/ss.
Camp Colorado Lmst.
Pueblo Fm.
Salt Creek Bend Shale/Ss.
Stockwether Lmst.
Camp Creek Shale/Ss.
Saddle Creek Lmst.
Harpersville Fm.
Waldrip Shale/Ss./Lmst.
U. Crystal Falls Lmst.
Curray Clay
Crystal Falls/Chaffin Lmst.
Quinn Clay/Ss.
Breckenridge Lmst.
Graham and Thrifty Fms.
Shale/ss.
Blach Ranch/Spec Mtn. Lmst.
Shale/ss.
Ivan Lmst.
Avis Ss.
Wayland Shale
U. Gunsight Lmst.
L. Gunsight Lmst.
Necessity Shale/Ss.
Bunger Lmst.
Shale/ss.
North Leon Lmst.
Gonzales Shale/Ss.
Gonzales Lmst.
Finis Shale/Ss.
Salem School Lmst.
Home Creek Lmst.
Colony Creek Shale
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Highstand progradational terrigenous clastic subsequence (systems tract): Principally platform fluvial, fan-deltaic, deltaic systems tract deposited during regression, bounded below by downlap surface and above typically by Type 1 unconformity. May contain some local retrogradational (transgressive lmst subsequences).
Hiatal boundary; marine-condensed section and downlap surface; locally unconformable.
Transgressive (retrogradational) lmst subsequence (systems tract): Principally aggradational, progradational, and some transgressive lmst facies comprising shelf, shelf-edge, and slope systems tract deposited during relative sea-level rise. Some basal ss and sh. Bounded below by transgressive surface (Type 1 unconformity) and above by MCS and downlap surface.
Unconformity (marine or subaerial).

A set of parasequences showing a progressive upward-deepening or upward-shallowing trend defines a transgressive systems tract (TST) or a highstand systems tract (HST), respectively (Fig. 4A; Van Wagoner et al., 1988). In the study area, most TSTs and HSTs are composed of three parasequences, respectively (Table 1). Not all the parasequences are upward shallowing. In the TSTs, individual parasequences are upward deepening, whereas those in the HSTs are upward shallowing. A succession of upward-deepening and upward-shallowing parasequences indicates landward and seaward shoreline migration and relative sea-level rise and fall on the up-dip Eastern Shelf, respectively (Fig. 4A; Table 1; Wanless and Shepard, 1936; Van Wagoner et al., 1988, 1990).

The maximum-flooding marine condensed section (MCS) is commonly a thin interval of shale on the shelf with a maximum relative water depth in comparison to the underlying and overlying lithofacies. However, in some cases, the MCS is replaced by a surface, that is, maximum marine flooding surface (mfs), separating the underlying upward-deepening TST from the overlying upward-shallowing HST. Lowstand systems tracts (LST) were identified where fluvial channel deposits can be confidently interpreted as incised valley fill (ivf). In many cases, LST was not well developed, instead, nondeposition, erosion, and pedogenesis dominated. They are discussed in detail later.

Sharp and erosional boundaries at the bases of TSTs, or LSTs where present, are common, and juxtapose lithofacies of very different environments, indicating major reorganization of facies mosaic. They are identified as sequence boundaries (SB). Rare gradational sequence boundaries are present, suggesting gradual changes of environmental factors across the boundaries.

The TST, MCS or mfs, HST, and LST define the smallest depositional sequences (termed primary sequences) identifiable on the outcrop (Van Wagoner et al., 1990). One hundred and eighty-one meter-to-decimeter-scale primary sequences were delineated on all measured sections (Plates A–C). They are the basic stratigraphic entities of the Cisco Group and can be classified into five types on the basis of principal lithofacies in the TST, MCS, and HST of a sequence (Fig. 4).

Type A sequence: The principal lithofacies are transgressive platform limestone, maximum-flooding shelf shale (the core shale of Heckel, 1977 in the context of transgressive–regressive cycles), and highstand platform limestone. Transgressive and highstand nonmarine and marine siliciclastic deposits and calcareous paleosols are common.

Type B sequence: The principal lithofacies are coalesced transgressive and highstand platform limestones. Many limestones consist of a distinct upward-deepening system in the lower part and an upward-shallowing system in the upper part, separated by an mfs. The mfs, however, can only be inferred in very thin coalesced limestones.

Type C sequence: The principal lithofacies are transgressive shelf siliciclastics and highstand platform limestone. The maximum-flooding shale may or may not be present.

Type D sequence: The principal lithofacies are transgressive platform limestone and highstand marine shelf siliciclastics. The maximum-flooding shale may or may not be present.

Type E sequence: All component lithofacies are marine and nonmarine siliciclastics. The maximum-flooding shale may or may not be present. Carbonate deposition did not occur because of large siliciclastic influx at the depositional site.

About 70% of the primary sequences are Types A and B (Fig. 5A), indicating that environmental conditions on the up-dip shelf were conducive to carbonate deposition during late transgression and early highstand. The sequences are 80 cm to more than 20 m thick, and ~ 80% of them are thicker than 4 m (Fig. 5B). Some types C, D, and E sequences have distinctive maximum-flooding deposits and are probably aborted type A sequences when siliciclastic influx overwhelmed or retarded carbonate deposition (see later discussion). The lack of highstand limestones in some type D sequences was due to later fluvial channel erosion. The five types of primary sequences suggest

Fig. 2. Chrono-, litho-, and sequence stratigraphy of the Cisco Group. The north–south outcrop lithologic profile is highly simplified (Brown et al., 1987). The third-order depositional sequences were defined using both outcrop and subsurface data by Brown et al. (1990). The lowstand incised valley fills are scarce but locally abundant in outcrop on up-dip shelf. This study delineated numerous depositional sequences of higher frequency than the third-order sequences in the exposed Cisco Group.

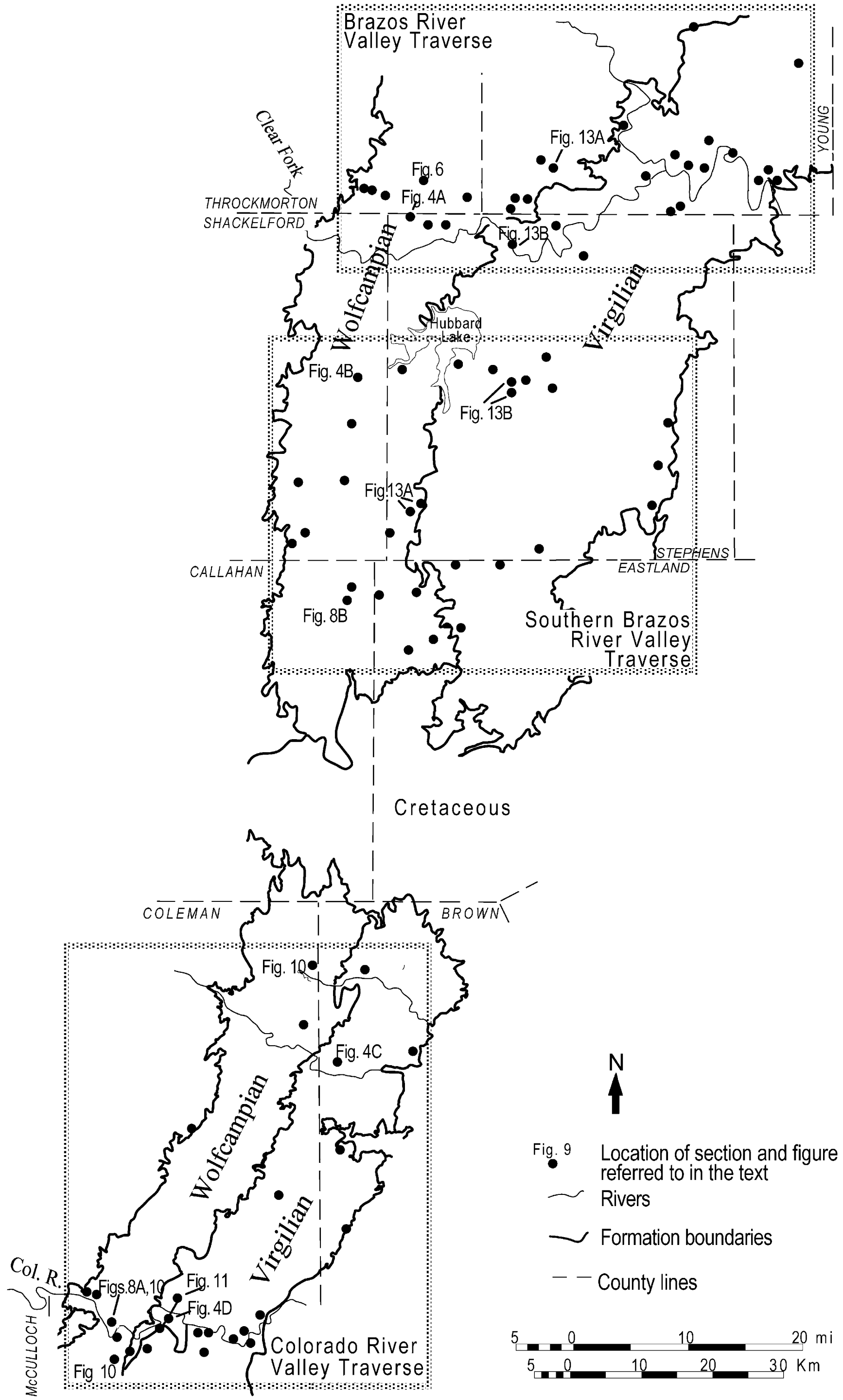


Fig. 3. Detailed map of outcrop study area showing major geologic contacts and location of measured sections. Measured sections are grouped into three traverses and are later used to construct composite sections for each traverse. Sections referred to in later figures are labeled.

variable dominance of major controlling processes on the up-dip Eastern Shelf during the Cisco time.

4. Lithofacies, depositional systems, and parasequences of primary sequences

Observation and interpretation of the characteristics of component lithofacies and depositional systems of individual parasequences are the first step in understanding the processes controlling the development of the five types of primary component sequences and the large-scale composite sequences (see later discussion). They are described in detail below (Table 1; see also Yang, 1995).

4.1. Parasequences in the lower parts of TSTs

The parasequences in the lower parts of TSTs are composed of vertically stacked coastal-plain and shorezone depositional systems. An upward-deepening trend is present in most parasequences. They are thin, commonly less than 2 m thick, and are composed of a succession of thin interbedded sandstone and shale, and carbonaceous shale or lignite, indicating progressive landward migration of environments. They are interpreted as coast plain systems. The basal contact is typically sharp or erosional and juxtaposes coastal-plain and marginal-marine facies with underlying lowstand fluvial deposits or calcareous paleosols of the underlying sequence. In some cases, a juxtaposition of the carbonaceous hydromorphic and leached soils with the underlying calcareous vertisols suggests a climate shift from a semi-arid climate of long-dry and short-wet seasonality to a subhumid climate of long-wet and short-dry seasonality (Schutter and Heckel, 1985; Cecil, 1990; Joeckel, 1994). The coincidental environmental and climatic shifts suggest seawater encroachment from the west and associated water-table rise (e.g., Heckel, 1995).

Overlying the coastal plain systems are shales, which are commonly calcareous and burrowed, some contain upward-increasing limestone nodules and open-marine fauna, indicating initiation of carbonate deposition on the shelf. Thin-walled brachiopods, crinoids, bryozoans, millimeter-size gastropods, fusulinids, and pelecypods are present. Sandstones are commonly calcareous and highly burrowed, some of which are conglomeratic with reworked clasts from the underlying deposits (Table 1). These deposits are interpreted as shale-rich strandline to shoreface facies of shorezone systems. In many sections where the coastal plain system was not deposited or was eroded during initial marine transgression, the shorezone system overlies directly the LST or the HST of the underlying sequences with sharp or erosional contacts. In this case, the basal contact of the shorezone system represents the transgressive ravinement surface when LST is present, or a merged sequence boundary and ravinement surface when LST is not present.

The thickness of the shorezone systems is 20–50 cm in types A, B, and D sequences containing transgressive limestones, but is 1–3 m in types C and E sequences without the limestones. In cases where the transgressive limestone pinches out into siliciclastics, the thickness and lithologic variations suggest that transgressive sedimentation along the depositional strike was reciprocal between carbonate and siliciclastic sediments. That is, where siliciclastic deposition filled the available accommodation space, transgressive carbonate deposition did not occur. Whether or not carbonate deposition took place at a location was determined by the availability of overwhelming siliciclastic influx, as supported by observations described below.

4.2. Parasequences in the upper parts of TSTs

Platform carbonate systems dominate in the upper TSTs of types A, B, and D sequences, but shelf siliciclastic systems dominate in types C and E sequences. The transgressive platform carbonate systems in types A, B, and D sequences are much more common than the shelf siliciclastic systems in types C and E sequences, and are complex. The limestones overlie the lower TSTs either gradationally or sharply and, in a few cases, directly overlie paleosols of the underlying sequences. They generally thin from 1–2 m in the lower Cisco to 20–50 cm in the upper Cisco, corresponding to the overall basinward shelf progradation during Cisco time (Galloway and Brown, 1972; Brown et al., 1987, 1990).

The lower part of the transgressive limestones commonly consist of current-laminated, arenaceous, skeletal grainstones and packstones with extra-clasts and, in some cases, basal conglomerates as winnowed lag deposits, reflecting a high-energy environment. The upper part consists of highly bioturbated, medium to thick packstones and wackestones deposited in a normal, low to moderate energy environment. Fossils are better preserved but less diverse upward (Table 1). In relatively thick limestones, the uppermost part consists of sparsely to moderately fossiliferous, highly burrowed, argillaceous and/or silty wackestones or lime mudstones, indicating a low-energy, relatively deep-water environment. The upward decrease in grain size, faunal diversity, and wave energy suggests that transgressive carbonate deposition did not keep up with sea-level rise and were eventually drowned. An upward-deepening trend is clearly discernible in many limestones, especially those thicker than 50 cm. The trend, combined with the overall limited thickness of transgressive limestones, suggests quick drowning of the carbonate systems, which prohibited parasequence-scale shallowing-upward progradation as observed in many thick and pure carbonate TSTs (James, 1979; Sarg, 1988; Jacquin et al., 1991).

Limestones in type B sequences are coalesced platform carbonate systems of the upper TST and the lower HST. The central parts of many coalesced limestones are bioturbated wackestones containing diverse normal marine fauna of crinoid, brachiopods, bryozoan, and fusulinid, whereas the outer parts are commonly current-laminated, arenaceous and/or argillaceous packstones or wackestones containing restricted fauna of mainly thick-walled pelecypod, gastropod, and ostracod, suggesting relatively deep water in the central parts (Boardman et al., 1984). The highstand carbonate systems are typically capped by intertidal and supratidal wackestones, which are not present in any transgressive systems. In comparison to the distinct transgressive limestones in types A and D sequences, most coalesced limestones are thinner, better current-laminated, more arenaceous, conglomeratic, and ferruginous. They also contain more micrite-coated and foram or worm tube-encrusted grains, suggesting a semi-restricted shallow subtidal to intertidal environment and, in few cases, supratidal environment as indicated by paleosols. These characteristics and the lack of marine condensed sections in the Type B sequences suggest a small sea-level rise and limited marine transgression in comparison with sequences with a distinct MCS.

The shelf siliciclastic systems in types C and E sequences are a continuation from the coastal plain and shorezone siliciclastic deposition. They indicate that, at a specific depositional site, siliciclastic influx was persistent during shelf deepening, suppressing carbonate deposition. The siliciclastic-rich sites must have been close to siliciclastic sources or a depocenter during marine transgression, whereas away from these sites, carbonate deposition became dominant. Local and regional sequence correlation described later demonstrate that a laterally persistent siliciclastic-rich interval along the depositional strike suggests regionally extensive siliciclastic sediment supply, probably produced by increased sediment yield in the upland source areas.

In general, siliciclastic and carbonate systems of the TSTs are thin and fine grained in comparison to those in the HSTs described below (Fig. 5C). The subsurface study of the Cisco Group immediately west of the outcrop belt by Yang et al. (1998) indicates that the upward-deepening parasequences are landward retrogradational, as are the TSTs as a whole (see also Galloway and Brown, 1972; Brown et al., 1990). Extensive marine transgression trapped most coarse siliciclastic sediments on land, and flooding of the shelf drowned the carbonate platform, hampering carbonate and siliciclastic progradation during marine transgressions (Heckel, 1977; Yang, 1996).

4.3. Marine condensed section (MCS)

Marine condensed sections commonly consist of mudstones with sharp basal and top contacts (Table 1; see also Boardman and Malinky, 1985; Boardman et al., 1984). Three lithologic varieties are present. The first type is common and consists of a lower dark gray, noncalcareous, and nonfossiliferous claystone or shale interval, and an upper calcareous, sparsely fossiliferous shale interval. They are similar to the core shales of the "Kansas-type" cyclothems (Heckel, 1977), although phosphatic nodules were not confirmed in this study (cf. Adlis et al., 1988). The lack of phosphatic nodules indicate that the Eastern Shelf was oxygenated, probably because the flooded up-dip Eastern Shelf was too shallow to be affected by oceanic upwelling as proposed by Heckel (1977, see also Rascoe and Adler, 1983) for the Kansas shelf of an inner epeiric sea during maximum marine flooding. The point of maximum flooding along the MCS is probably located in the lower interval with no macrofauna. This is supported by a detailed $\delta^{18}O$ profile of the Necessity Shale studied by Adlis et al. (1988) (Fig. 2).

The second type consists of calcareous and moderately fossiliferous shales with rare limestone nodules. A few shales even contain thin wackestone and packstone beds. The limestones are graded or current-laminated, arenaceous or argillaceous, and have a mixed normal and restricted marine fauna, suggesting minor regressions or offshore storm deposits. The presence of relatively abundant fossils and carbonates suggests that this type of MCS was deposited in more oxygenated and shallower waters than that of the first type, and may represent maximum flooding of a lesser extent. The last type of MCS includes shales in types C, D, and E sequences. The shales are silty or sandy and some have disseminated plant remains. They are interpreted as prodeltaic sediments as supported by overlying delta front or inter-deltaic embayment deposits. This interpretation suggests that the marine flooding was the most limited among the three types of MCS.

The thickness of all MCS' clusters around 40–70 and 1–4 m (Fig. 5C), and decreases upward in the Cisco Group, corresponding to the overall basinward shelf progradation and shoreline migration during Cisco time. Finally, all type B and many types C, D, and E primary sequences do not contain an MCS but an mfs, suggesting a limited extent of marine flooding. Since all measured sections have similar paleogeographic positions on the shelf, the variations in the extent of marine flooding on the up-dip Eastern Shelf suggest frequent marine floodings of varying extent during Cisco time. In addition, the extent of individual marine floodings also varied along depositional strike as indicated by local and regional sequence correlation. The complexity suggests multiple autogenic and allogenic controls on the extent of marine flooding on the up-dip shelf (see Discussion).

4.4. Parasequences in the lower parts of HSTs

Platform carbonate systems dominate in the lower HSTs of types A, B, and C sequences, whereas shelf siliciclastic systems dominate in types D and E sequences (Fig. 4). The siliciclastic systems are composed of marine shales with minor sandstones. The shales are commonly silty or sandy. Some are plant rich; some are fairly to sparsely fossiliferous, containing fragmentary or intact mollusks and brachiopods. Sandstones are fine grained, calcareous, thin, and commonly bioturbated. The inferred environments of the shale-rich successions include inner shelf, shoreface, and inter-deltaic embayment. In some localities, fine- to medium-grained sandstones dominate. They coarsen upward and display gradational contacts with the underlying prodeltaic shale. These sandstone-rich successions are interpreted as deltaic deposits. In general, the siliciclastic systems show a gradational upward-shallowing trend from the relatively deep-water environment of the MCS' to the marginal marine and nonmarine environments of the upper HSTs.

Platform carbonate systems are typically shallowing-upward wackestone, packstone, and grainstone successions deposited in diverse subtidal, intertidal, and supratidal environments (Table 1). The lower part consists of highly bioturbated packstone and wackestone with mixed deep and shallow-water fauna. The middle part consists of highly bioturbated packstones and minor wackestones. The upper part consists of muddy phylloid algal buildups in some cases and grainstone shoals in the other cases where skeletal grains are highly abraded, micrite-coated, and foram or worm tube-encrusted. Many grainstones become increasingly ferruginous and arenaceous upward, suggesting increasing oxidation and siliciclastic influx during progressive shoaling.

The cap layer contains abundant cryptalgal laminations, fenestrae, oncolites, bored surfaces, and thick-walled *Myalina*, indicative of restricted intertidal and supratidal environments. Spar-filled dissolution fissures and breccias in the upper part of some limestones indicate contemporary meteoric diagenesis and, in some cases, a thin layer of brown to cream colored, laminated, impure caliche formed. Thin ferruginous claystone or ironstone commonly overlies the limestones, suggesting a period of intense oxidation and supratidal sedimentation. The platform limestones grade into the overlying marginal-marine calcareous and fossiliferous shale or, in some cases, are partially or entirely eroded.

The highstand carbonate systems, unlike their transgressive counterparts, are shallowing upward and generally thick in outcrop (Fig. 5C; Table 1). They are also progradational on subsurface dip cross sections (Brown et al., 1990; Yang et al., 1998). The shallowing-upward and progradational architecture suggests that highstand carbonate systems kept up within or exceeded the maximum carbonate productivity window of ~ 10 m (Schlager, 1981; Adlis et al., 1988) during the slow sea-level fall.

4.5. Parasequences in the upper parts of HSTs

Two vertically stacking parasequences are common in the upper part of HST. The lower parasequences are upward-coarsening and upward-thickening succes-

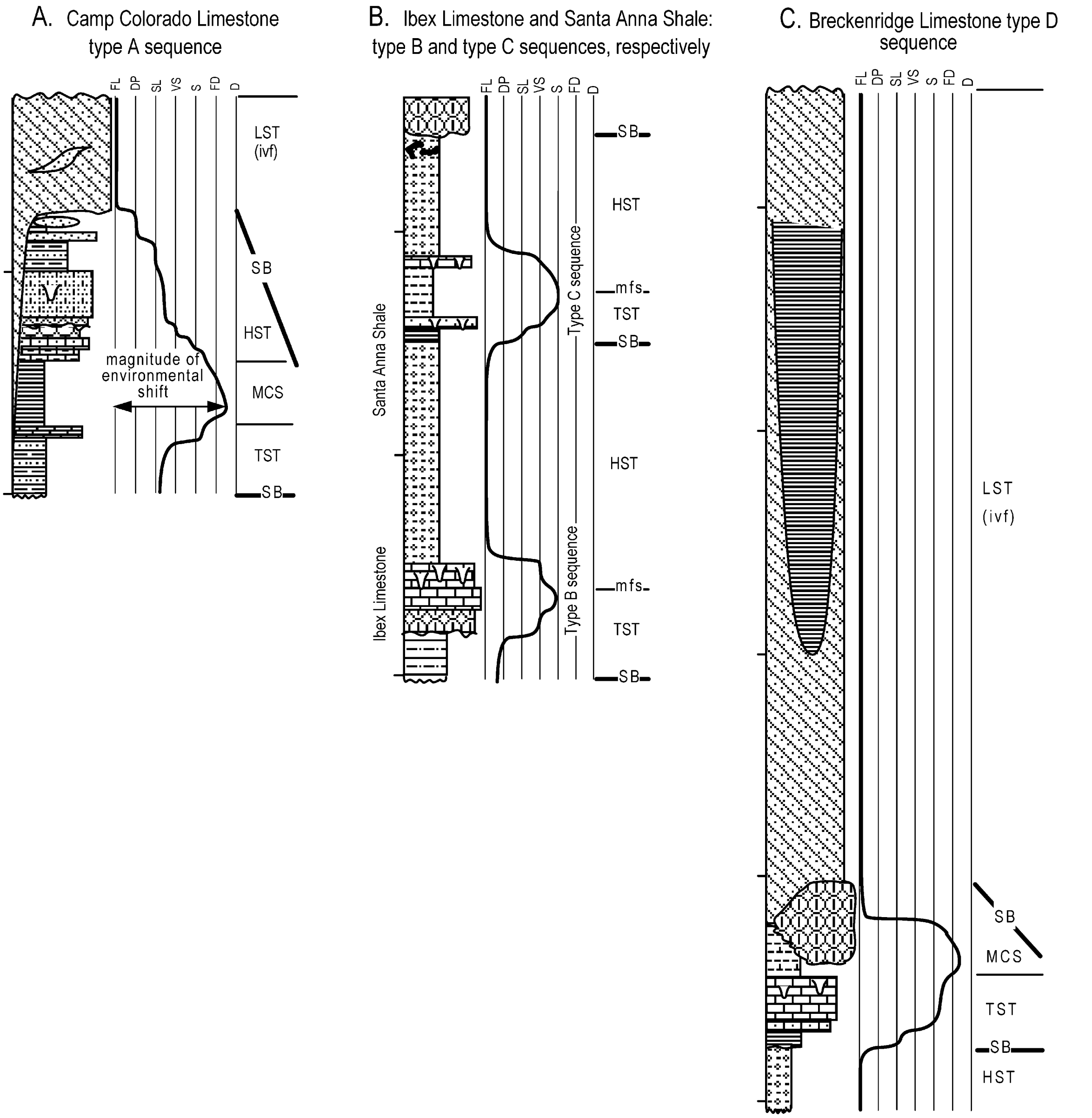


Fig. 4. Examples of five types of primary sequences identified in outcropping Cisco Group. Each section consists of a lithologic column, a facies curve showing depositional environmental interpretation, and sequence stratigraphic subdivisions. (A) Type A sequence. Sequence magnitude is also defined. (B) Type B sequence in lower part and type C sequence in upper part of section. (C) Type D sequence. The incised fluvial channel removed the lower and upper HST and contains a large mud plug. (D) Type E sequence.

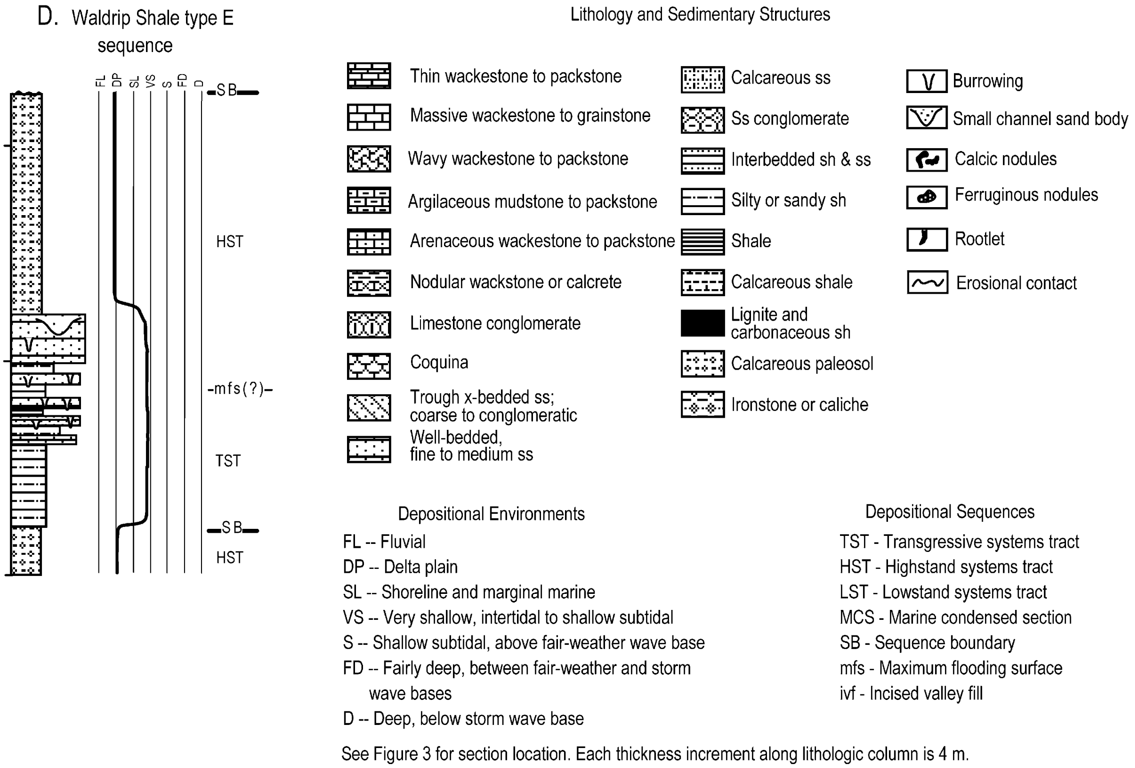


Fig. 4 (*continued*).

sions of shale, sandy shale, and sandstone. They are typically thicker than 80–90 cm. In some cases, medium-grained sandstones are massive or tabular cross-stratified with basinward offlapping geometry. The successions are progradational as documented in the subsurface immediately west of the outcrop by Galloway and Brown (1972) and Yang et al. (1998). In other cases, thin to medium thick, well sorted, fine to medium-grained tabular sandstones contain low-angle, multi-directional tabular cross stratifications. The successions are interpreted as distal and proximal delta-front facies. Some sand-filled shallow channels with shell lags are interpreted as tidal channels of the upper shoreface and strandplain environments.

The upper parasequences are mainly thick successions of sandy, nonfossiliferous, and rarely carbonaceous shales. Shales are commonly brownish gray and ferruginous. Locally abundant sandstones are large to medium trough and tabular cross-stratified and thicker than 1–2 m. They are commonly conglomeratic at base. Small channels are present. These shale-encased sandstones are probably fluvial and distributary channel fills and splay deposits. Lateral facies changes among channel-fills and overbank deposits are common on the outcrops. The successions are interpreted as coastal-plain deposits.

The upper HSTs differ from the lower TST counterparts. The HSTs are thick, ferruginous, sandstone rich and contain many erosional surfaces; the TSTs are thin, dominantly marginal-marine and marine shales, and lack fluvial and deltaic deposits. The differences resulted from increasing siliciclastic influx into a large but gradually decreasing accommodation space during late highstand on the up-dip shelf.

4.6. Parasequences of the LSTs

The parasequences of the LSTs consist of extensive paleosols and locally abundant fluvial channel-fills. Although paleosols are described in this section, the classification of paleosols as lowstand or highstand deposits is problematic, as discussed in the next sec-

Table 1
Sedimentary characteristics, depositional environments, and systems tracts of primary depositional sequences of the exposed Cisco Group

Systems tracts		Component lithology		Fossil assemblage	Sedimentary structures and textures	
Lowstand systems tracts[a]		Paleosol (>80%), variegated, red, or purple; 30% multistory; vertisol or inceptisol	Ss and conglomerate; minor sh in mud plugs	Rare plant remains	Root mold; calcic/clay nodule horizon; slickenside; soil ped; clay cutan	Coarse to medium, trough and planar x-beds; channel geometry
Highstand systems tracts	Upper	Ss and sh, sandy, rarely carbonaceous; ss hematitic; conglomerate at base		Rare plant remains	Large–medium trough and planar x-beddings	
		Sh and ss, sand-rich, commonly ferruginous; local thick deltaic ss		Rare; low-diversity marine fossils; some plant remains	Current-flow structures. Mostly noncalcareous	
	Lower	Grainstone and packstone, arenaceous and ferruginous, some algal bioherms; some as soils; capped by thin ferruginous claystone, ironstone, or *Myalina coquina*		Low-diversity fauna. Pelecypod, ostracode, fusulinid, crinoid, phylloida algae	Cryptalgal lamination; boring; fenestrae; abraded and altered, coated/encrusted grains; *Osagia*	
		Packstone and minor wackestone		Very fossiliferous	Highly burrowed	
		Packstone and wackestone		Mixed deep-shallow-water fauna	Highly burrowed	
Marine condensed section		Dark gray sh; some silty or phosphatic; 30% are calcareous with rare ls nodules, few thin, arenaceous and argillaceous wackestone tempestites		Disseminated plants in some cycles; sparse to fairly abundant mega-fossils; micro-fossils not studied. Mixed fauna in tempestites	Well-laminated to massive, blocky. Tempestites graded, well current-laminated	
Transgressive systems tracts	Upper	Argillaceous/arenaceous wackestone and mudstone. Skeletal packstone and wackestone Packstone, grainstone, arenaceous, common extra clasts; conglomerate lags		Thin-walled brachiopod, crinoid, fusulinid, millimeter-size gastropod, spicule, trilobite, phylloid algae, ostracode, bryozoan	Lower part common current laminated. Upper pat bioturbated or massive. Well bedded, medium-thick	
	Lower	Sh dominant, commonly calcareous; some sandy; some with upward-increasing ls nodule. Ss commonly calcareous; some conglomerates		Some (30%) sh fairly fossiliferous; thin-walled brachiopod crinoid, bryozoan, millimeter-size gastropod, fusulinid, pelecypod; some plant-rich. Fossils or molds in ss	Burrowed to highly burrowed; ripple marks and herring-bone x-bedding fairly common	
		Interbedded ss and sh; sheet ss; basal carboniferous sh and lignite		Plant remains, freshwater molluscs	Bioturbation; current-flow structures	

[a] (1) Paleosols (left) and fluvial incised valley fills (right) are described separately. (2) Paleosols capping the HST were developed coeval with the fluvial incised valley fills, but the parent sediments of the paleosols are upper HST deposits. See text for discussion on placement of sequence boundaries.

Boundary relations		Thickness		Depositional environments	
Diffusive or gradational	Erosional; relief <10 m	10 to ~20 m; 85% 1–15 m; 60% <4 m	<10 m	Semi-arid with a pronounced dry season; developed mostly on parent fluvial and deltaic sediments	Fluvial, incised valley
Sharp, erosional or gradational, common facies changes		>1–2 m; commonly >5 m; ss >1–2 m		Shoreline, delta plain, fluvial	
Sharp or gradational		>80–90 cm		Mudflat, tidal channel, beach, delta, prodelta	
Sharp or gradational		<10 cm to >10 m; most 20–50 cm, 60–80 cm, 1–4 m		Restricted to semi-restricted, episodically exposed tidal flat	
				Lower intertidal to shallow subtidal; some fairly deep	
Sharp		<10 cm–>10 m; most 40–70 cm and 1–4 m		80% deeper than fair-weather wavebase; very shallow to shallow in Types III, IV, and V cycles; most hemipelagic and prodeltaic	
Gradational or sharp; some sharp or erosional contacts with underlying cycle		<0.1–10 m; most 20–50 cm and 1–2 m		70% lower intertidal to subtidal; some fairly deep subtidal; few below fair weather wavebase; normal, open, low to high energy. Upward deepening	
Gradational or sharp. Some sharp/erosional with underlying cycle		<0.1 to >5 m; most 20–50 cm in types I, II, IV cycles; 1–3 m in types V, III cycles		Mudflat, tidal channel, barrier bar, back-barrier	
Sharp to erosional; rarely gradational		Usually <2 m		Delta plain, estuarine, strandplain	

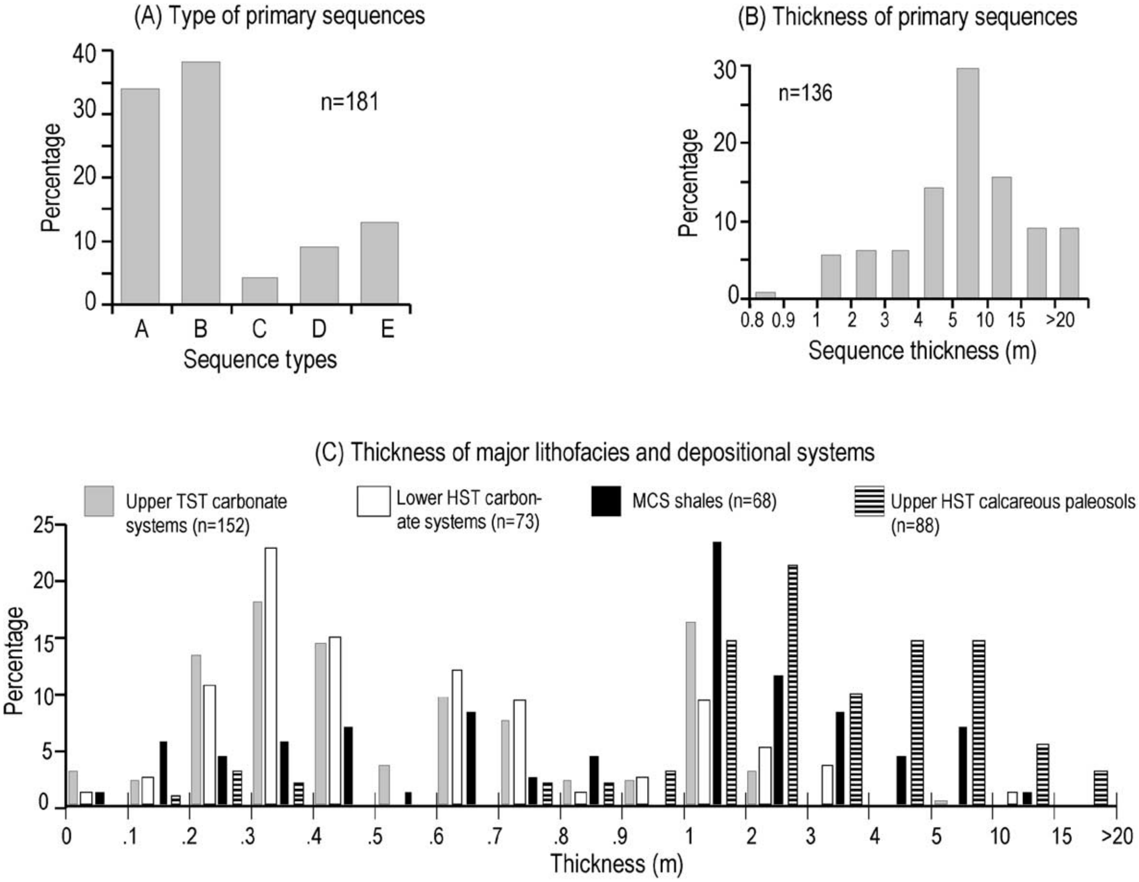


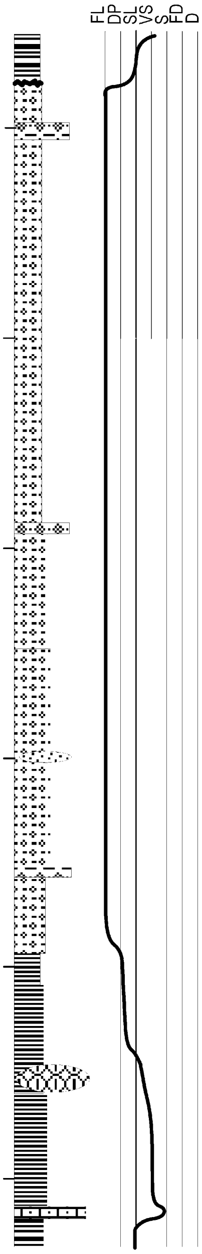
Fig. 5. (A) Type distribution of 181 primary sequences on all measured sections. (B) Thickness distribution of 136 primary sequences that are fully exposed on outcrop. (C) Thickness distribution of major depositional systems and lithofacies that are fully exposed on outcrop. The coalesced transgressive and regressive limestones in type B sequences were counted as transgressive limestones.

tion. The fluvial sandstones are thick, coarse to medium grained, containing large-scale trough or tabular cross-stratifications. The channels are as much as 10 m deep on the outcrops, eroding the upper HST shales and, in several cases, the lower HST limestones of the underlying sequences. Lee (1938), Brown (1960, 1962, 1969), Brown et al. (1972, 1990), Hentz and Brown (1987), and Hentz (1988) mapped individual fluvial channel systems, which are confined in deep valleys up to 30 m in depth and 5 km in width. Combined with extensive subsurface mapping, Brown et al. (1990) identified that these channel systems were transportation fairways for thick deltaic sediments deposited on the basin and slope, and are lowstand incised valleys of third-order depositional sequences (see also Galloway, 1971; Yang et al., 1998). The thick channel sandstones, however, are only found in primary sequences located in the basal part of the third-order sequences (see later section on orders of depositional sequences). In other primary sequences, fluvial sandstones in the LSTs are either not present or much thinner than the ivf's at the base of the third-order sequences.

Paleosols cap the upper HSTs in ~80% of the primary sequences where lowstand incised valleys

Fig. 6. Characteristics of a multi-story paleosol in a type B sequence. Pedogenesis during sea-level lowstand was interrupted by episodic fluvial sediment influx. The top paleosol surface is sharp whereas the lower surface is diffuse. Sequence boundary is placed at top of paleosol and, thus, the paleosol is not interpreted as LST, although at least some parent sediments of the paleosol were deposited and pedogenesis occurred during sea-level lowstand (Fig. 7).

Location 87. Stockwether Limestone Intermediate Sequence



Field and microscopic observations	Interpretations: Environment	Interpretations: Systems tract
Shale, silty, yellowish to greenish brown. Carbonaceous. L. boundary sharp and wavy.	Coastal swamp	TST
		SB
Mudstone, reddish purple, variegated. Slickensided, blocky. ~ 1 m below top paleosol surface, a layer (~10 cm) of reddish claystone nodules, each ~ 5 cm in diameter, hard, heavy, central part calcareous. A faint boundary ~ 5 m below top surface separating above mudstone from underlying vaguely bedded shale and mudstone that are reddish and variegated with few pale bluish thin clay layers (< 5 cm thick).	Paleosol #1 (Fluvial influx followed by pedogenesis)	HST
Caliche, ferruginous, resistant and persistent. Sample -- Calcrete, variegated, dense. Irregular to subrounded calcic nodules separated by clay and silty mudstone partings. No fossils. Uniform sparry calcite crystals, often as thin partings. Mudstone, pale bluish purple, variegated, locally carbonaceous. It forms a small bench in the area, because of the overlying resistant caliche.	Paleosol #2 (Fluvial influx followed by pedogenesis)	
Shale, purple, grading downward to buff-gray, with sandy partings. Upper 2 m yellowish purple to brown, variegated, with oblique veins of pale bluish purple mudstone. Limestone/calcrete, earthy. No fossils. Shale, bluish vivid color.	Paleosol #3 (Fluvial influx followed by pedogenesis)	
Shale, blue.	Coastal plain	
Shale, yellow with purple seams.	Mudflat	
Limestone conglomerate lens, a few hundred feet long, composed of rolled pebbles of limy shale; sandstone nearby at same horizon.	Tidal channel	
Shale, yellow and gray.	Mudflat	
Lmst., brown, fossiliferous, argillaceous & arenaceous.	Shallow subtidal	m f s
Shale, carbonaceous.	Lagoon/swamp	TST

See Figure 3 for section location and Figure 4 for lithologic, environmental, and sequence keys. Each thickness increment along lithologic column is 4 m.

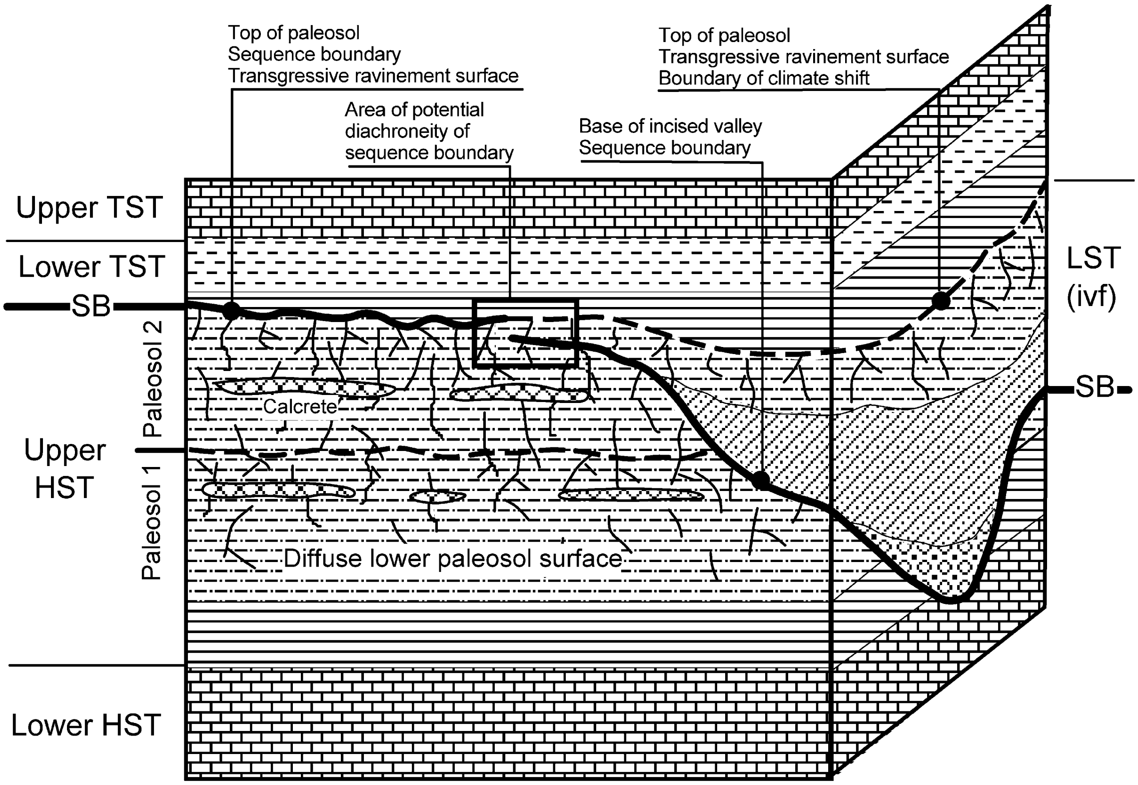
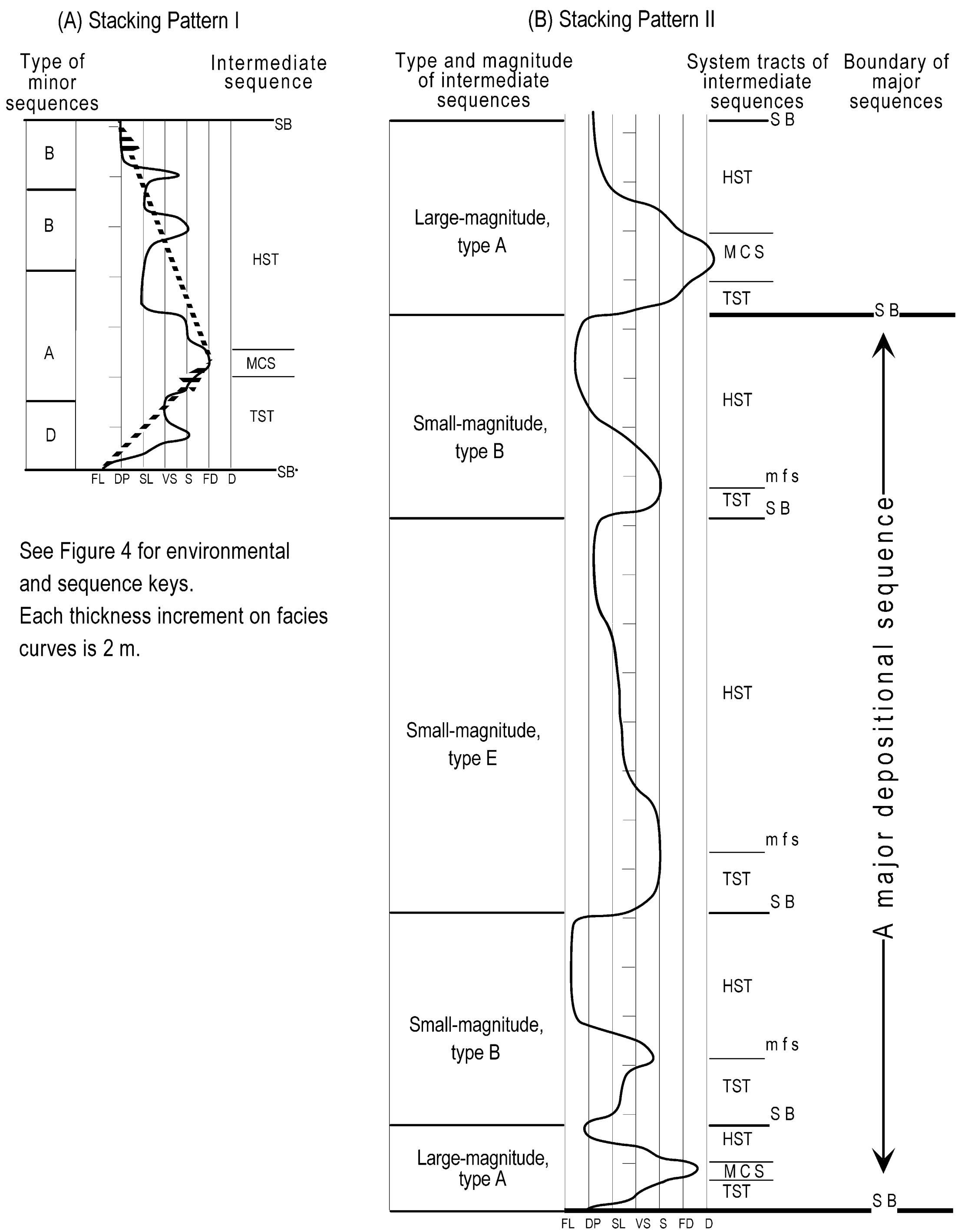


Fig. 7. Schematic diagram showing potential diachroneity between the top of paleosol developed in interfluves and the base of an incised valley, both of which formed during sea-level lowstand and are chosen as sequence boundaries in this study. The diachroneity will be exaggerated in case of multistoried paleosols formed during separate pedogenetic intervals (e.g., Fig. 6). In addition, the chosen sequence boundaries place the paleosols in the upper HST and incised valley fills in the LST of the overlying sequence, although both pedogenesis and cutting and filling of the incised valley are approximately coeval.

were not present. They are 10–20 m thick and mostly 1–15 m thick (Fig. 5C). Those thicker than 4 m were probably formed by multiple pedogenic events. Especially, the thick, multi-story paleosols indicate multiple episodes of siliciclastic deposition followed by pedogenesis (e.g., Fig. 6). The variegated, red, or purple paleosols contain oblique slickensides formed by swelling and shrinking of clay-rich sediments during dry and wet seasons (Schutter and Heckel, 1985; Retallack, 1990). Soil peds are tens of centimeter to less than 1 cm in diameter, commonly separated by clay cutans. Equant or elongate calcareous and/or clayey nodules are concentrated 1–2 m below the top paleosol surface. They are 3–10 cm in diameter, dense, with internal dendritic rootlets. Many clayey nodules are ferruginous, brecciated, and cemented by sparry calcite. Most paleosols are interpreted as vertisol and inceptisol formed in a semi-arid climate with a pronounced dry season (Schutter and Heckel, 1985; Retallack, 1990; Joeckel, 1994).

The paleosols developed on nonmarine shales and, in some cases, marine shales and limestones, and have diffuse lower boundaries and sharp or erosional upper boundaries. They indicate a period of subaerial expo-

Fig. 8. (A) Sequence stacking pattern I synthesized from the Camp Colorado intermediate sequence. An intermediate sequence consists of a deepening-upward succession of minor sequences and a shallowing-upward succession of minor sequences. The upper HSTs of minor sequences are typically marine to marginal marine deposits, whereas the upper HSTs of intermediate sequences are nonmarine. (B) Sequence stacking pattern II synthesized from the Santa Anna Branch sequences. Several small-magnitude intermediate sequences are bounded by two large-magnitude intermediate sequences. See Fig. 3 for section location.



See Figure 4 for environmental and sequence keys.
Each thickness increment on facies curves is 2 m.

sure and nondeposition after the deposition of parent sediments. Therefore, the top paleosol surfaces, which juxtapose paleosols with overlying TSTs, are significant stratigraphic discontinuities.

4.7. Boundaries of primary sequences

The bases of incised valley fills (ivf's), across which abrupt basinward shift of depositional systems occurs, are sequence boundaries (Brown et al., 1990; Van Wagoner et al., 1990; Vail et al., 1991). Where ivf's are not present, the top or the base of the paleosols on the interfluves is a potential sequence boundary (Fig. 7). Paleosol formed when the up-dip shelf was subaerially exposed and received no or minimal fluvial sediments, coeval with the deposition of LST on the basin and slope and development of incised valleys on the shelf. Hence, it is reasonable to choose the base of the paleosols as the sequence boundary (Fig. 7). If so, the parent sediments of the upper HSTs that the paleosols developed upon would be included as LST. This presents a dilemma that the paleosol interval belongs to both the upper HST and the LST. In addition, the base of paleosols is diffuse and its stratigraphic position varies depending on many factors, such as local topography, environment, and type of parent sediments (Fig. 7).

On the other hand, the top of paleosols indicates the termination of pedogenesis due to renewed nonmarine or marginal marine siliciclastic deposition. It is commonly sharp or erosional, and juxtaposes the underlying paleosols with overlying lower TST. It is also a boundary of climate transition from semi-arid to subhumid conditions (e.g., Tandon and Gibling, 1994; Yang, 1996). However, the surface may not be coeval with the base of an incised valley, especially where multi-story paleosols are present (Fig. 7). In addition, the top of paleosol, in some cases, is also the initial transgressive surfaces where the nonmarine and marginal marine deposits of the lower TST is missing, separating the HST of the underlying sequence from the overlying marine TSTs (Fig. 7; see also Tandon and Gibling, 1994). Nevertheless, the top paleosol surface is a distinct stratigraphic discontinuity and is correlative over large interfluves on the up-dip shelf. It represents a significant amount of depositional hiatus. Therefore, it is chosen as the sequence boundary in this study and the paleosols are classified as the upper HST deposits of the underlying sequence.

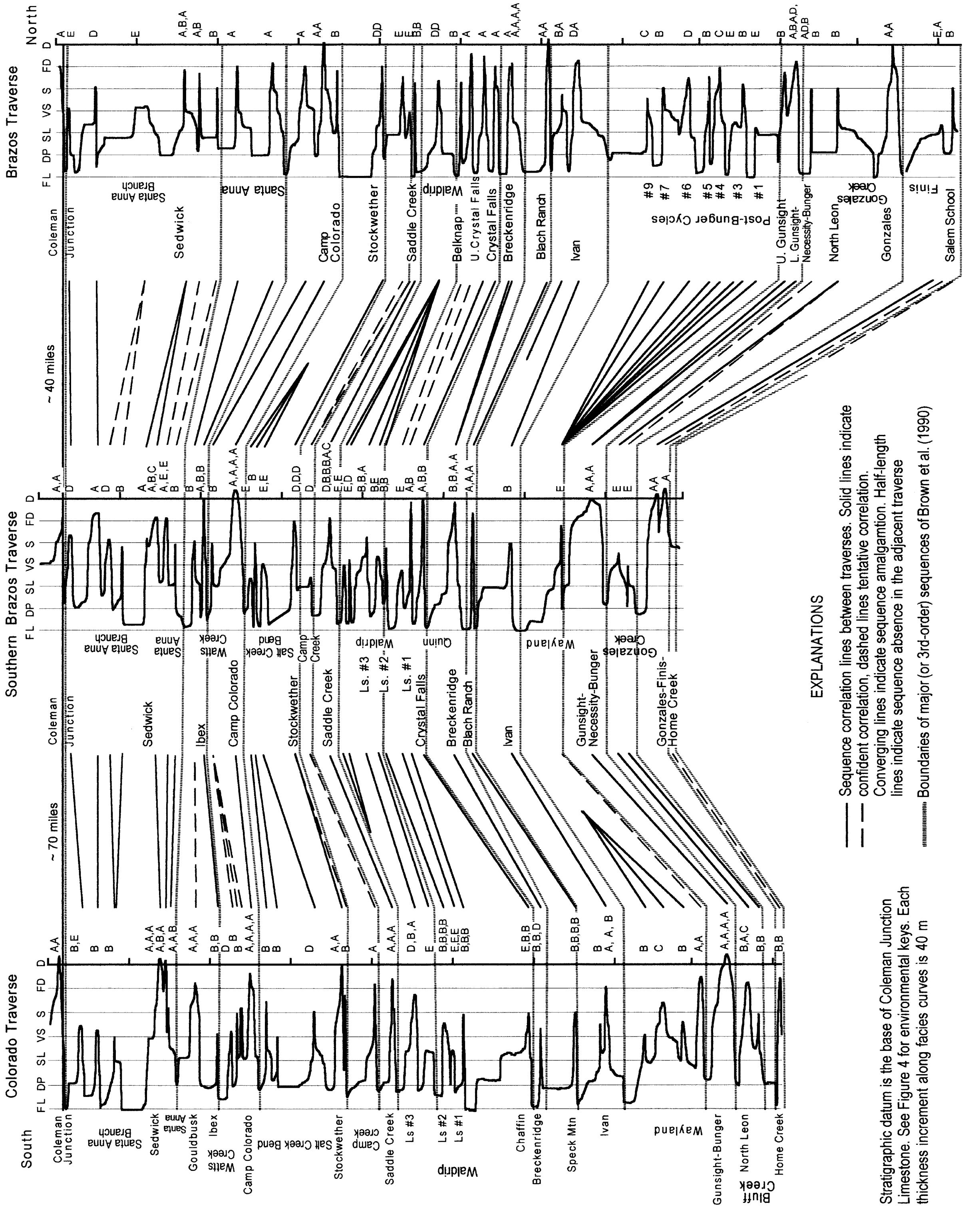
5. Sequence stacking patterns

The maximum environmental shift within a primary sequence, as interpreted from component lithofacies, defines the magnitude of the primary sequence (Fig. 4A). It is an indicator of the maximum shoreline movement relative to a site and can be used to characterize a sequence to aid in its correlation. Type A primary sequences typically show a large magnitude of facies shift between MCS shales and LST ivf's or mature paleosols (e.g., Fig. 4A). A sequence at two sites may differ in lithofacies, but its magnitude of environmental shift may remain the same. In addition, the magnitude of successive primary sequences commonly varies systematically. The magnitude variations among a succession of primary sequences define two types of stacking patterns.

5.1. Stacking pattern I

Stacking pattern I is defined by vertical stacking of a succession of upward-deepening primary sequences overlain by a succession of upward-shallowing primary sequences (Fig. 8A). The individual primary sequences are called *minor* sequences, and the bundle of minor primary sequences in stacking pattern I defines an *intermediate* sequence (Fig. 8A). An intermediate sequence has greater magnitude of facies shift, thick-

Fig. 9. Correlation of primary and major (or third-order) depositional sequences (Brown et al., 1990) among Colorado, southern Brazos, and Brazos traverses along depositional strike on up-dip Eastern Shelf. The composite section of a traverse includes all cycles on individual measured sections in the traverse (Plates A, B, and C). Each composite section consists of lithostratigraphic and primary sequence names at left, a facies curve in middle, and type(s) of a primary sequence at right. For a primary sequence studied in several locations within a traverse, the type of the sequence at each location is listed. A primary sequence may or may not change its type within a traverse, indicating the nonpersistence or persistence in sequence type. The magnitude and thickness of a primary sequence can be determined from the facies curves. The southern Brazos section is the shortest, suggesting a pre-Cisco topographic high along the southern Brazos traverse. A major sequence commonly contains several intermediate sequences.


South
North
Colorado Traverse
Southern Brazos Traverse
Brazos Traverse
FL DP SL VS S FD D
~ 70 miles
~ 40 miles
Coleman Junction
Santa Anna Branch
Sedwick
Santa Anna
Gouldbusk
Watts Creek
Ibex
Camp Colorado
Salt Creek Bend
Camp Creek
Stockwether
Saddle Creek
Ls #3
Ls #2
Ls #1
Waldrip
Chaffin
Breckenridge
Speck Mtn
Ivan
Wayland
Gunsight-Bunger
North Leon
Bluff Creek
Home Creek
Ls. #3
Ls. #2
Ls. #1
Crystal Falls
Quinn
Blach Ranch
Gunsight-Necessity-Bunger
Gonzales Creek
Gonzales-Finis-Home Creek
Belknap
U. Crystal Falls
Post-Bunger Cycles
#9
#7
#6
#5
#4
#3
#1
U. Gunsight
L. Gunsight-Necessity-Bunger
Gonzales
Finis
Salem School
EXPLANATIONS
Sequence correlation lines between traverses. Solid lines indicate confident correlation, dashed lines tentative correlation.
Converging lines indicate sequence amalgamtion. Half-length lines indicate sequence absence in the adjacent traverse
Boundaries of major (or 3rd-order) sequences of Brown et al. (1990)
Stratigraphic datum is the base of Coleman Junction Limestone. See Figure 4 for environmental keys. Each thickness increment along facies curves is 40 m

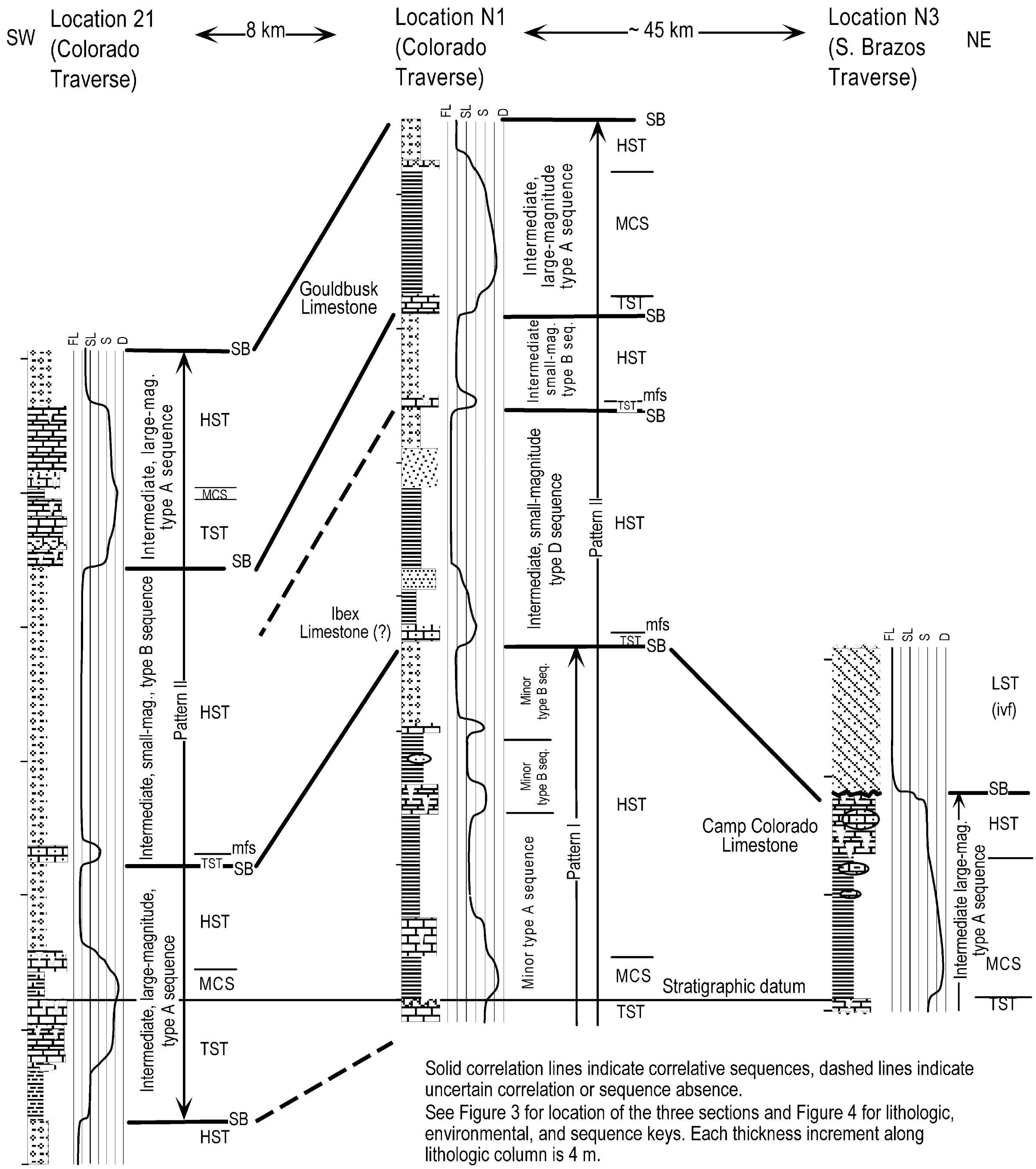


Fig. 10. Correlation of magnitude, thickness, type, and stacking patterns of minor and intermediate sequences in Camp Colorado to Gouldbusk interval in the Colorado traverse. The intermediate Camp Colorado sequence has persistent magnitude and type. It contains three minor sequences of stacking pattern I in location N1 and an ivf in location N3. The prominent intermediate Gouldbusk sequence is absent in the southern Brazos traverse (Fig. 9). Stacking pattern II from the Camp Colorado to Gouldbusk intermediate sequences correlates between locations 21 and N1, but has different number of intervening small-magnitude intermediate sequences at the two locations.

ness, and duration than its component minor sequences.

The middle part of an intermediate sequence is commonly occupied by a type A minor sequence, of which the MCS coincides with that of the intermediate sequence. The succession of upward-deepening minor sequences constitutes the TST of an intermediate sequence, and the succession of upward-shallowing minor sequences constitutes the HST of the intermediate sequence (Fig. 8A). The upward-deepening and upward-shallowing successions of minor sequences imply landward retrogradation and basinward progradation of minor sequences, respectively, during the formation of an intermediate sequence. The two-level sequence hierarchy suggests that the major controlling processes are ordered.

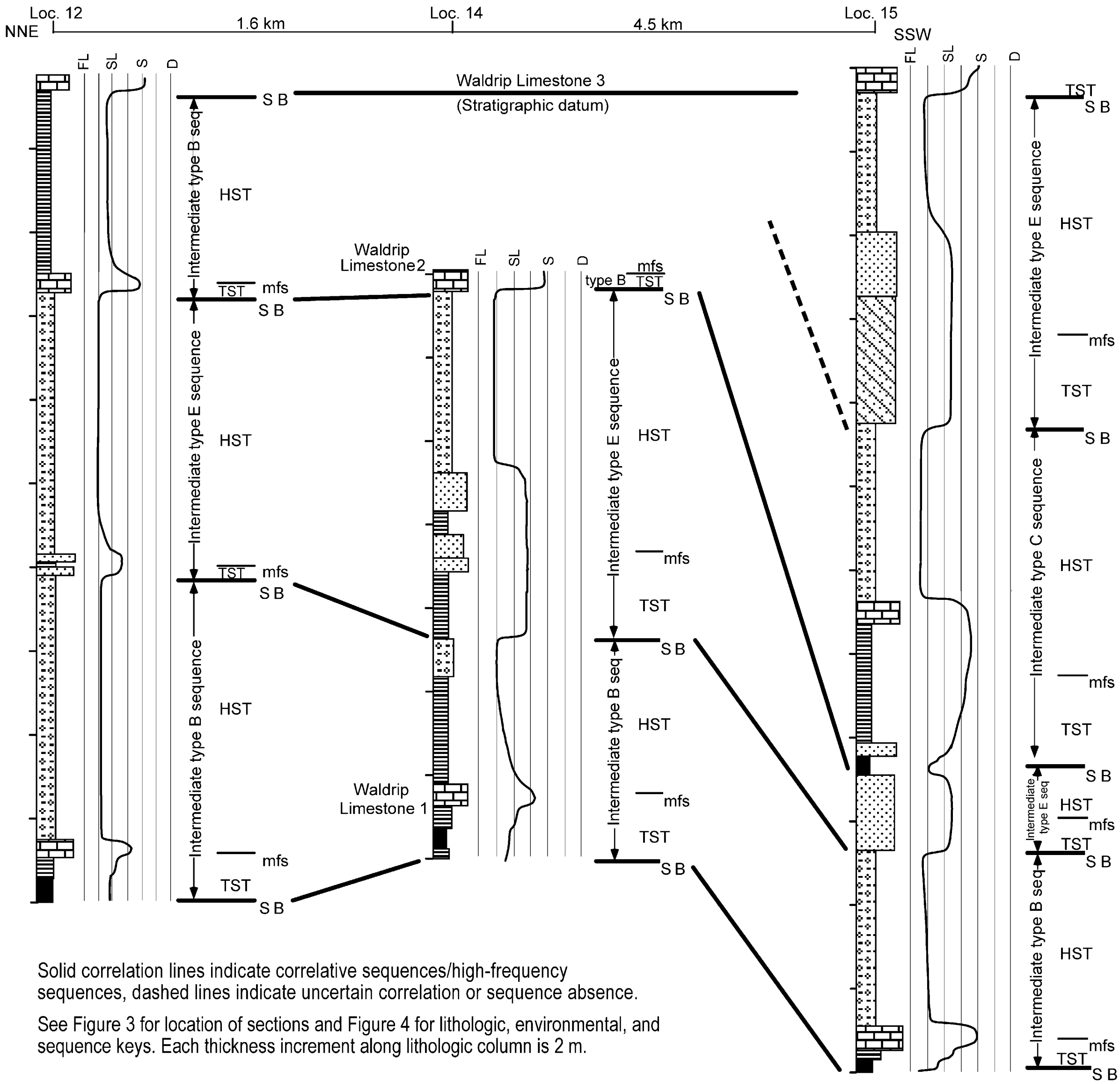


Fig. 11. Correlation of intermediate sequences in Waldrip interval in Colorado traverse. Local changes in thickness and sequence absence contrast with the persistence in sequence type, signifying interplay between autogenic and allogenic controls on cyclic sedimentation.

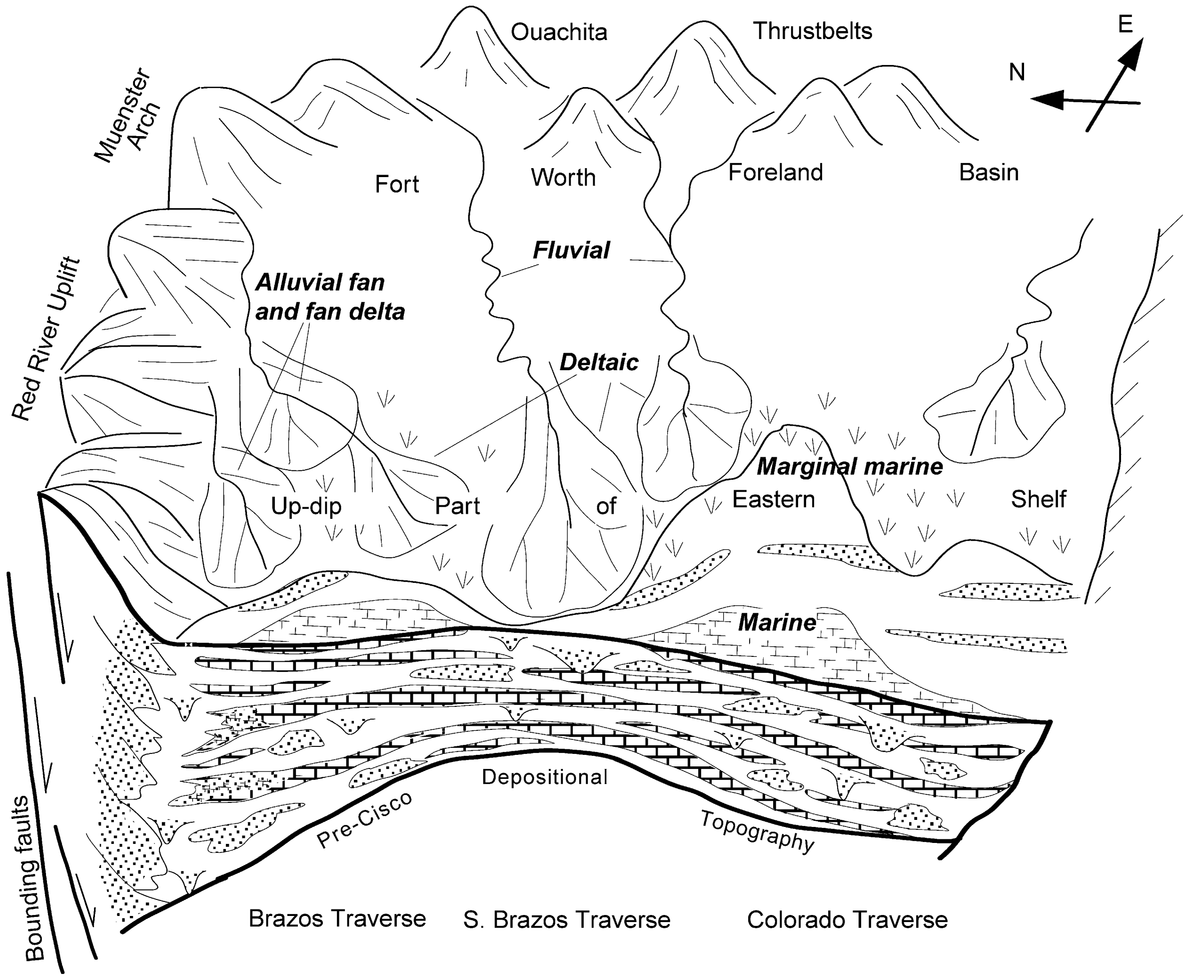
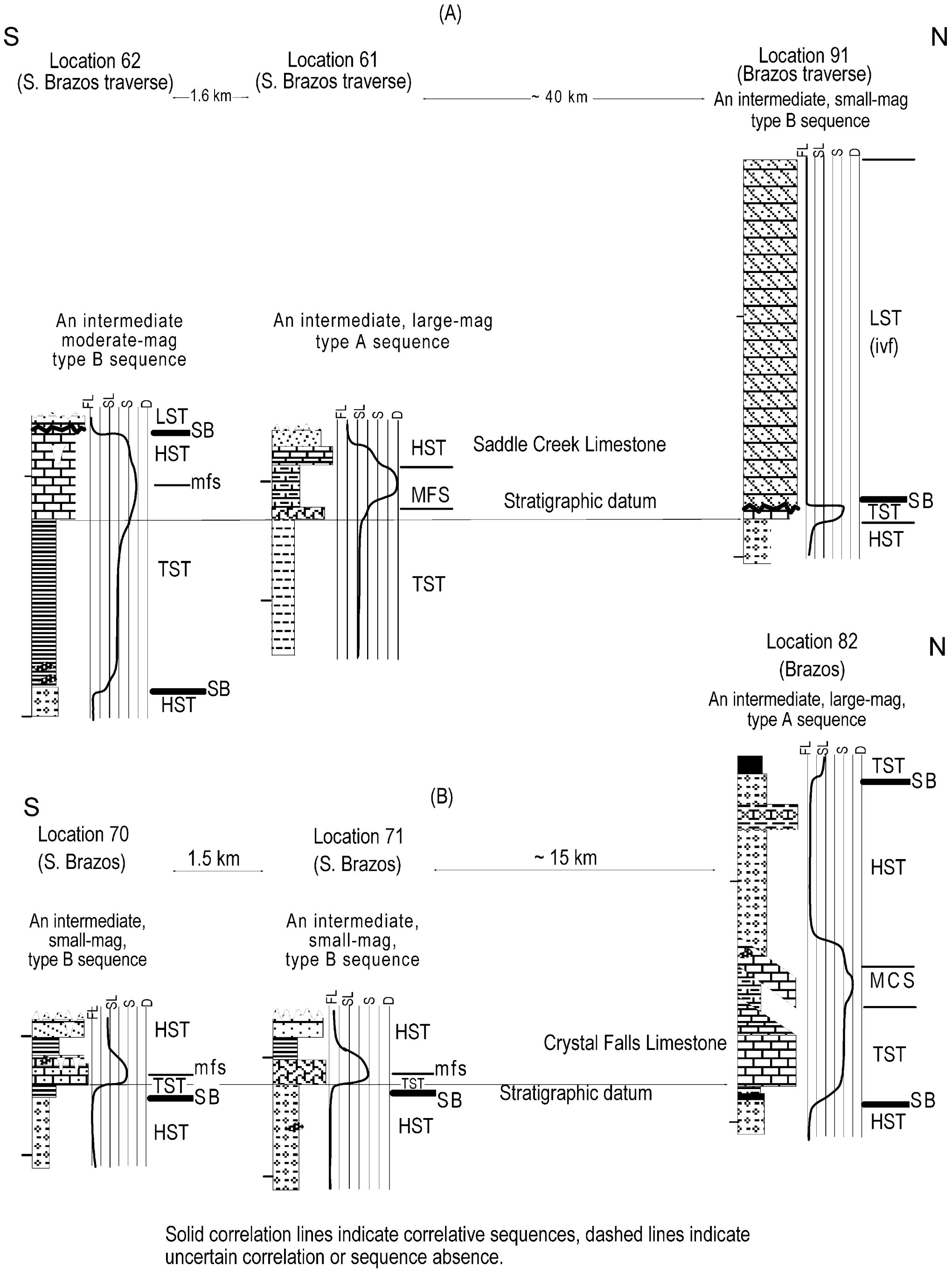


Fig. 12. Block diagram showing paleogeography in vicinity of up-dip Eastern Shelf during sea-level highstand. Reconstruction was based on observations in this study and tectonic and depositional environmental interpretations of previous workers (e.g., Lee, 1938; Wermund and Jenkins, 1969; Galloway, 1971; Brown et al., 1990; Yang, 1995; Yang et al., 1998 among many others).

5.2. Stacking pattern II

Stacking pattern II is defined by bundling of intermediate sequences of different magnitude of environmental shift. That is, several small-magnitude intermediate sequences are bounded stratigraphically above and below by two large-magnitude intermediate sequences (Fig. 8B). The primary sequences in pattern II are intermediate, not minor, sequences, because some of them are correlative to the intermediate sequences of pattern I on the outcrop. Pattern II reveals a nonhierarchical but systematic relationship among intermediate sequences. The recognition of the two stacking patterns and sequence correlation described

Fig. 13. (A) Correlation of the intermediate Saddle Creek sequence between southern Brazos and Brazos traverses, showing northward decrease in sequence magnitude. The sequence at location 91 may have had an MCS that was eroded later by the incised valley. Observations at other locations in Brazos traverse indicate that the sequence has a small magnitude in the traverse. (B) Correlation of the Crystal Falls intermediate sequence, showing northward increase in magnitude. Contrasting trends in sequence magnitude between (A) and (B) signify varying dominance of allogenic controls on Eastern Shelf during Cisco time.



Solid correlation lines indicate correlative sequences, dashed lines indicate uncertain correlation or sequence absence.

See Figure 3 for location of the three sections and Figure 4 for lithologic, environmental, and sequence keys. Each thickness increment along the lithologic column is 4 m on locations 62, 82, and 91, 2 m on locations 61, 70, and 71.

later indicate that most primary sequences on the Cisco outcrop are intermediate sequences.

Last, stacking patterns II are correlative with the third-order depositional sequences defined in both outcrop and subsurface over the entire Eastern Shelf by Brown et al. (1987, 1990; see also Yang et al., 1998 and later discussions) (Fig. 8B). Thus, the Cisco Group contains a three-level sequence hierarchy compose of minor, intermediate, and major (i.e., third-order of Brown et al., 1990) sequences.

6. Local and regional trends of cyclic sedimentation

Sequence correlation integrates sequence characteristics on 1-D sections to delineate trends of cyclic sedimentation along the outcrop belt. This task is challenging due to fragmentary outcrop exposures. But the sequence stratigraphic framework of Brown et al. (1990) and lithostratigraphic frameworks of previous workers (e.g., Lee, 1938; Brown, 1960, 1962; Galloway, 1971; Brown et al., 1972; Harrison, 1973; Hentz and Brown, 1987; and many other references in Yang, 1995) provided exceptional guidance. The correlation is essentially along depositional strike, where regionally persistent limestones serve as the best correlation markers (Plates A, B and C; Brown, 1969; Brown et al., 1987).

6.1. Local variations of sequence characteristics and sequence absence along a traverse

The magnitude and type of many intermediate sequences, especially the large-magnitude ones, are persistent for several tens of kilometer (Fig. 9). For example, the Camp Colorado Limestone sequence is correlative in type and magnitude for ~ 45 km along the Colorado traverse (Fig. 10). However, the small-magnitude sequences change their types erratically and some become absent within the traverse (e.g., the Ibex and overlying sequences in Fig. 10 and the Waldrip sequences in Fig. 11). Sequence correlation in the Brazos traverse, especially in the lower Cisco Group, is complicated by common facies changes, limestone pinch-outs into thick siliciclastic intervals, and fluvial channel erosion (Lee, 1938; Hentz and Brown, 1987).

Intermediate sequences showing stacking pattern I are rare in the study area: five in the Colorado traverse, two in the southern Brazos traverse, and three in the Brazos traverse. They are incomplete, containing two to three minor sequences of typically types A and B, and cannot be correlated between traverses. The rarity and incompleteness of pattern I intermediate sequences can be attributed to the limited accommodation space on the up-dip shelf. They become more complete and abundant down dip where accommodation space increases (Yang et al., 1998).

Stacking pattern II, however, is common in the outcrop (Fig. 9). The large-magnitude sequences are mostly type A, whereas the intervening small-magnitude sequences vary laterally in type and number (e.g., Fig. 10). First, the intervening sequences are commonly types B, E, and A in the Colorado traverse but increasingly types E, D, and C to the north, indicating a northward increase in siliciclastic deposition. Second, the number of intervening sequences decreases from two to four in the Colorado traverse, and one to three in the Southern Brazos traverse, to one to two in the Brazos traverse. The northward change in the type and number of the intervening sequences may be caused by: (1) larger siliciclastic influx in the north and northeast close to the source area suppressed some sequences; (2) some sequences were not recorded in the southern Brazos traverse because it is located on a pre-Cisco topographic high (see next section); and (3) local sequence absence obscured regional correlation. The first two causes are probable because the basic stacking patterns and many large-magnitude intermediate sequences correlate among the three traverses for ~ 180 km (Fig. 9).

6.2. Regional trends of depositional topography, number of sequences, and thickness of the Cisco Group along the outcrop belt

The Cisco Group thickens away from the southern Brazos traverse toward the south and north (Fig. 9), indicating a pre-Cisco topographic high along the southern Brazos traverse and two pre-Cisco lows along the Colorado and Brazos traverses, as also depicted on the structural map at the base of the Cisco Group (Wermund and Jenkins, 1969). The relief between the southern Brazos and the Brazos traverses was probably accentuated by the increased subsidence along the bounding faults to the north and the increased sediment loading due to the copious sediment supply in the Brazos traverse near the major sediment source (Fig. 12; Lee, 1938; Hentz and Brown, 1987).

In addition, the total number of primary sequences varies from 39 in the Colorado traverse, 36 in the southern Brazos traverse, to 43 in the Brazos traverse (Fig. 9). This indicates that sequences were better developed and preserved in the pre-Cisco lows. The patterns of accommodation space and siliciclastic supply (Fig. 12) exerted significant control on cyclic sedimentation of the Cisco Group on the up-dip shelf.

6.3. Regional trends of sequence magnitude, type, and absence between traverses

6.3.1. Trend 1—persistent sequence type and magnitude across the shelf

The magnitude and type of some intermediate sequences are remarkably persistent in the study area, such as the Saddle Creek and Bunger–Gunsight sequences between the Colorado and Southern Brazos traverses, and the Blach Ranch and the Stockwether sequences between the Southern Brazos and Brazos traverses (Fig. 9). Stacking pattern II is also laterally persistent in many intervals, such as the five intermediate sequences between Waldrip Limestone 1 and 3 between the Colorado and Southern Brazos traverses, and the small-magnitude intermediate sequences in the Camp Colorado to Coleman Junction interval (Fig. 9). In general, large-magnitude type A intermediate sequences are persistent from the outcrop to at least 100 km basinward of the outcrop (Yang et al., 1998; see also Galloway, 1971; Brown et al., 1987). The persistent intermediate sequences suggest a shelf-wide control, which overwhelmed intra-shelf variations in differential subsidence, depositional topography, and siliciclastic influx in the study area (see also Heckel et al. (1998) for examples in the mid continent). Sea-level change of a eustatic origin is likely the control, as supported by the Milankovitch signals detected in the Cisco Group (see Discussion).

6.3.2. Trend 2—sequence magnitude decrease and sequence absence toward the pre-Cisco high

Some intermediate sequences are absent or their magnitude decreases dramatically from the Colorado to the southern Brazos. Examples are the absence of the prominent Gouldbusk sequence and the absence of three small-magnitude intermediate sequences in the Wayland Shale from the Colorado to southern Brazos traverses (Figs. 9 and 10). This is because the marine accommodation space created by marine transgression was limited over the pre-Cisco high, especially when the sea-level rise was small.

6.3.3. Trend 3—sequence magnitude increase toward pre-Cisco high

Contrasting to Trend 2, some intermediate sequences increase in magnitude from the Colorado to the southern Brazos, such as the Spec Mountain/Blach Ranch sequence (Fig. 9). The increase suggests: (1) periods of increased accommodation space on the pre-Cisco high, probably caused by episodic acceleration of subsidence of the high due to its proximity to the northern bounding faults, and/or (2) periods of decreased subsidence in the Colorado traverse.

6.3.4. Trend 4—sequence magnitude decrease toward the siliciclastic-rich areas

The magnitude of some intermediate sequences, such as the Saddle Creek sequence, decreases from the southern Brazos to the siliciclastic-rich Brazos (e.g., Fig. 13A). The northward magnitude decrease coincides with northward increase in sandstone, quartz content in limestones, and erosion (Fig. 12; Lee, 1938; Hentz and Brown, 1987), which again coincides with the northward increase in siliciclastic influx due to the proximity of the major source areas. In the Brazos traverse, large siliciclastic influx could have overwhelmed some marine transgressions (e.g., Curray, 1964), and extensive fluvial channel erosion (Lee, 1938; Hentz and Brown, 1987) during sea-level lowstand could also have removed some sequences.

6.3.5. Trend 5—sequence magnitude increase toward the siliciclastics-rich areas

Contrasting to Trend 4, some intermediate sequences increase in magnitude from the southern Brazos to the Brazos, such as the Crystal Falls sequence (Fig. 13B). In addition, some intermediate sequences in the Brazos are absent in the southern Brazos, such as the prominent Upper Crystal Falls sequence and eight of the nine sequences between the Ivan sequence and the Gunsight–Necessity–Bunger sequence (Fig. 9). An increase in sequence magnitude and the formation and preservation of more intermediate sequences in an area require, first, a large accommodation space and, second, a limited siliciclastic influx so that carbonate deposition would not be overwhelmed (see discussion on Trend 4). The Brazos traverse had larger accommodation space due to the pre-Cisco low and greater subsidence (Fig. 12). Thus, periods of limited siliciclastic influx from the northern source area were critical to forming more sequences and to the magnitude increase of some sequences. Episodic faulting near the Brazos could have also induced local transgression and regression, forming local small-magnitude sequences.

Above all, local and regional sequence correlation demonstrates the dynamic nature of cyclic sedimentation along the depositional strike on the up-dip Eastern Shelf. Eustasy was probably instrumental to the shelf-wide persistence of some sequences and the cyclicity of the Cisco Group. Differential subsidence, pre-Cisco topography, and the timing, amount, and locus of siliciclastic influx interacted with evolving

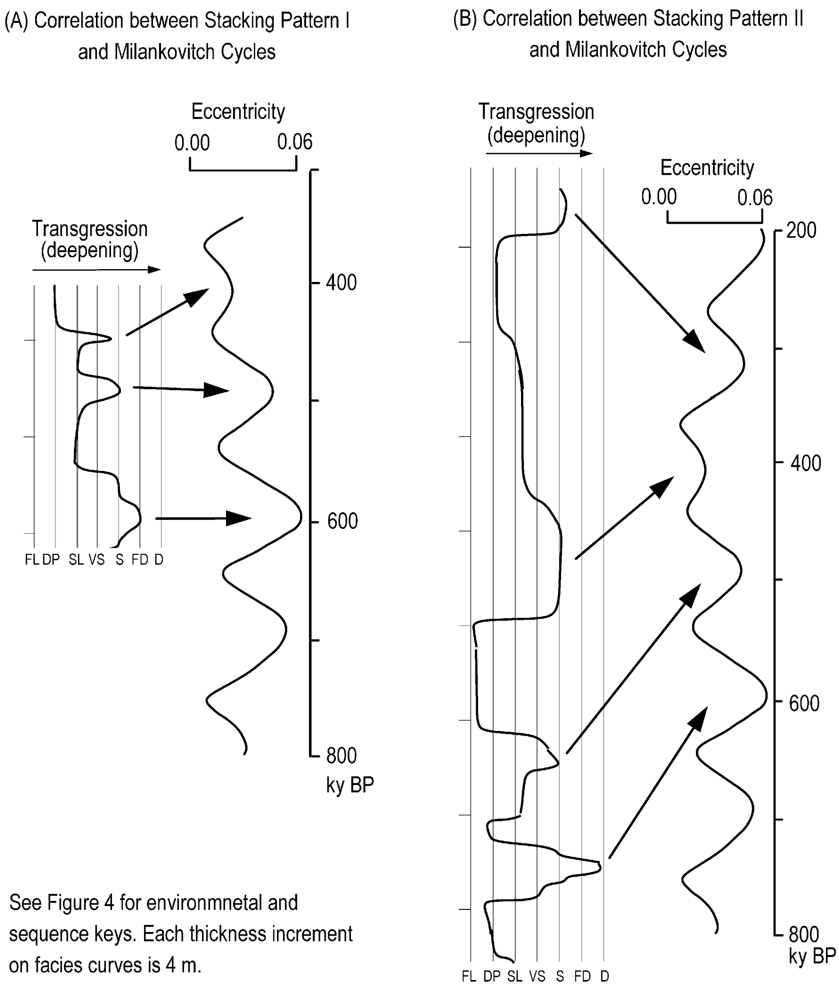


Fig. 14. Two possible schemes of correlation between sequence stacking patterns and Milankovitch orbital cycles (Imbrie and Imbrie, 1979). The intermediate Camp Colorado sequence in (A) is incomplete with only MCS and HST. Correlation in (A) suggests that the minor sequences may be 100-ka short-eccentricity cycle and the intermediate sequence 400-ka long-eccentricity cycle, whereas correlation in (B) suggests that the intermediate sequences may be 100-ka short-eccentricity cycle. The correlation is suggestive but uncertain. However, spectral results of Yang and Kominz (1999) supports the correlation in (B).

Table 2A
Average effective sedimentation rates and duration of deposition of outcrop composite sections, compiled from Yang and Kominz (1999)

Outcrop composite sections[a]		Average effective sedimentation rates (cm/ka)	Depositional duration of Cisco Group (ka)
Colorado traverse	Without cycle grouping	29.0	1247
	With cycle grouping	23.7	1532
S. Brazos traverse	Without cycle grouping	25.4	1211
	With cycle grouping	24.2	1274
Brazos traverse	Without cycle grouping	39.2	1111
	With cycle grouping	44.0	1007

[a] Yang and Kominz (1999) performed two spectral analyses for each composite section, one using the raw facies curve, the other using a facies curve where thin cycles are grouped.

depositional topography and fluctuating sea level on the up-dip shelf. The complex and contrasting trends of individual intermediate sequences indicate that the dominance of each factor varied in space and time.

7. Discussion

7.1. Possible Milankovitch origin and time framework of Cisco sequences

Many previous studies have suggested dominant Milankovitch-related eustatic and climatic controls on the Cisco depositional cyclicity (e.g., Lee, 1938; Galloway, 1971, 1989; Harrison, 1973; Boardman and Malinky, 1985; Boardman and Heckel, 1989; Brown et al., 1990; Yang, 1996; Yang et al., 1998; Yang and Kominz, 1999). A eustatic control on the three-level sequence hierarchy in the Cisco outcrop successions conforms with the continental glaciation and associated eustasy in the late Paleozoic (e.g., Crowell, 1978; Veevers and Powell, 1987).

The stacking patterns of the high and intermediate sequences were compared with that of the Milankovitch cycles. In pattern I, where an intermediate sequence contains four minor sequences, the intermediate sequence matches the 400-ka long-eccentricity cycle and the minor sequences match the 100-ka short-eccentricity cycles (Fig. 14A; Berger, 1988). Alternatively, in cases where an intermediate sequence contains three minor sequences, the ratio of 1:3 would match that between the short-eccentricity cycle (100 ka) and the obliquity cycle (34 ka) at 300 Ma (Berger et al., 1992). Stacking pattern II, which commonly contains three small-magnitude intermediate sequences bounded by two large-magnitude intermediate sequences, matches the pattern of four 100-ka eccentricity cycles in a 400-ka eccentricity cycle (Fig. 14B). The inferred matches are only tentative because pattern I is incomplete and pattern II contains a varying number of intervening sequences. Extensive spectral tests of the subsurface and outcrop Cisco successions by Yang and Kominz (1999) indicated that the short-eccentricity (100 ka) periodicity is the

Table 2B
Average total duration and average duration of deposition of major sequences, and average duration of major sequence boundaries of Cisco Group

	Average of total duration of major sequences (ka)[a]	Average depositional duration of major sequences (ka)[b]		Average duration of major SB (ka)[c]			
		Depositional duration of Cisco Group[d]		Total duration of Cisco Group			
				14 Ma		17 Ma	
		First estimate	Second estimate				
Colorado traverse	933 (14 Ma)	83	102	850	831	1050	1031
S. Brazos traverse	1133 (17 Ma)	81	85	853	848	1053	1048
Brazos traverse		74	67	859	866	1059	1066

[a] Calculated by dividing the chronostratigraphic durations of Cisco Group by the number (15) of major sequences. The chronostratigraphic durations of Cisco Group, 14 and 17 Ma were estimated based on Klein (1990) and Harland et al. (1989), respectively.

[b] Calculated by dividing depositional durations of Cisco Group by the number (15) of major sequences.

[c] Calculated by dividing the total hiatal time of Cisco Group by the number (15) of major sequence boundaries. The total hiatal time is (chronostratigraphic duration of Cisco Group – depositional duration of Cisco Group).

[d] From the first and second estimates of each traverse in the last column of Table 2A.

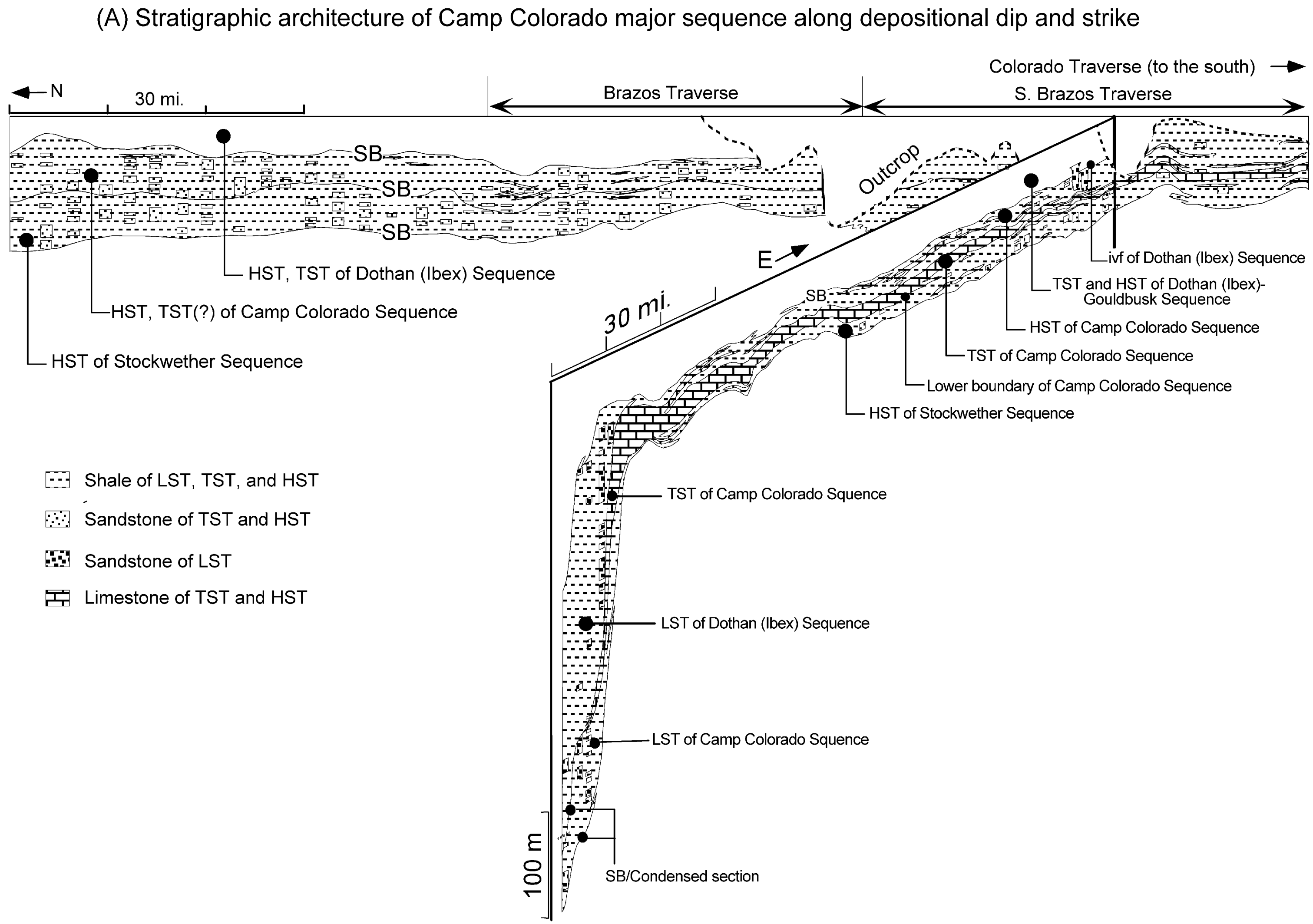


Fig. 15. (A) Stratigraphic architecture of Camp Colorado major sequence along depositional dip and strike on Eastern Shelf, showing regional reciprocal sedimentation from up-dip shelf to basin and slope, and thickness and lithologic variations along depositional strike on up-dip shelf. Modified from sections D–D′ and 5–5′ of Brown et al. (1990; see Fig. 1A for location). (B) Composite sections of Camp Colorado major sequence in Colorado, southern Brazos, and Brazos traverses, showing variations in thickness, lithology, and number of minor and intermediate sequences along depositional strike in the study area.

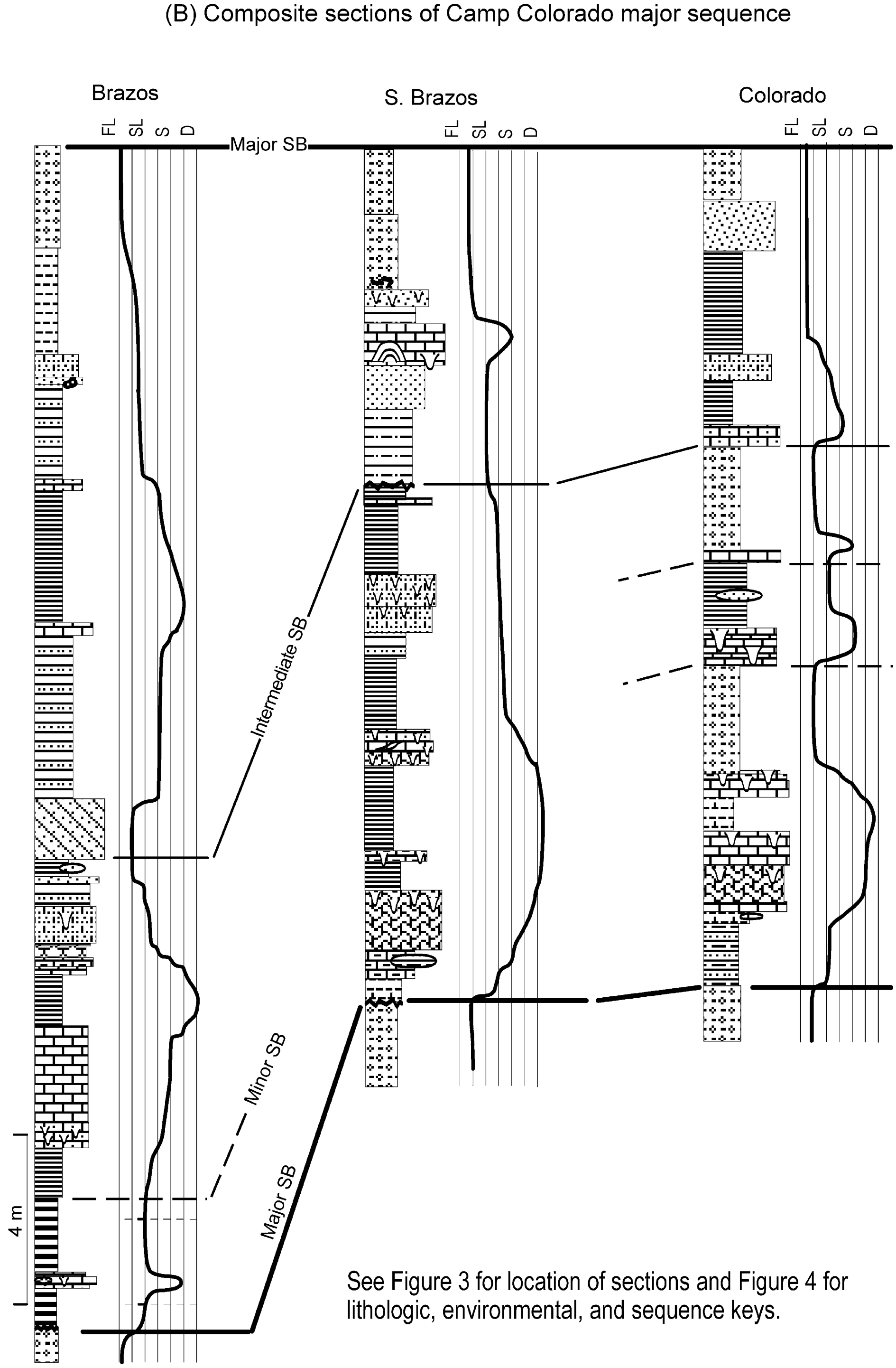


Fig. 15 (*continued*).

most prominent and persistent, and the long-eccentricity (400 ka) and obliquity (34–43 ka) periodicities are persistent in the Cisco records. The spectral result supports that the intermediate sequences are most likely related to the 100-ka short-eccentricity cycles, the major sequences related to the 400-ka long-eccentricity cycles, and the minor cycles probably related to the obliquity cycles.

The facies-dependent sedimentation rates of the Cisco deposits in Yang and Kominz (1999) were used to calculate the depositional durations of the composite sections along the three traverses (Fig. 9). The rates were derived on the basis of period calibration of spectra of 30 Cisco successions, including the three composite sections. The durations of deposition of the three composite sections range from 1 to 1.5 Ma (Table 2A). The average duration of deposition (not including the time represented by sequence boundaries) of the 15 major (or third-order) sequences of Brown et al. (1990) is 67–102 ka (Table 2B). The average total duration of a major sequence, including both depositional and hiatal time, ranges from 933 to 1133 ka, as calculated by dividing the chronostratigraphically estimated duration of the Cisco Group by the number of major sequences (Table 2B). Moreover, assuming the 15 sequence boundaries of the 15 major sequences represent all the hiatal time, the average duration of a major sequence boundary ranges from 831 to 1066 ka (Table 2B).

The average duration of the major sequence boundary is long on the up-dip Eastern Shelf. Well-developed incised valley systems (e.g., Brown et al., 1990) and extensive calcareous paleosols formed during the long periods of subaerial exposure associated with boundaries of major sequences. Thick deltaic systems were deposited basinward of the shelf margin during sea-level lowstand, when nondeposition and erosion dominated on the up-dip shelf (Galloway, 1971, 1989; Brown et al., 1987, 1990). The depositional duration of the lowstand deltaic systems of the 15 major sequences is approximately equal to the time represented by the 15 sequence boundaries on the up-dip shelf, as estimated using the progradational thicknesses of the lowstand deltaic systems and the average sedimentation rate of the upper shelf siliciclastic rocks. This supports the sequence stratigraphic interpretation that deposition of LSTs in basin and slope coincides with a long period of erosion and nondeposition on the up-dip shelf (e.g., Vail et al., 1977, 1991; Brown et al., 1990).

The depositional duration of major sequences must increase down dip, where deposition was more continuous and accommodation space was larger than those on the up-dip shelf (Galloway, 1971; Brown et al., 1990; Yang et al., 1998). Yang and Kominz (1999) confirmed that the depositional duration of the Cisco Group increases gradually from 1 to 1.5 Ma in the outcrop to 3.4 Ma ∼ 100 km basinward from the outcrop. Correspondingly, the average depositional duration of a major (i.e. third-order) sequence increases to 227 ka, and the average duration of the boundary of a major sequence decreases to 707–907 ka.

7.2. Hierarchical depositional sequences of the Cisco Group

In the three-level hierarchy of the Cisco sequences, the major sequences are the largest in thickness and duration, developed during the long-term progradational and aggradational infilling of the Midland Basin and Eastern Shelf (Galloway, 1989; Brown et al., 1990). A major sequence typically contains two to five intermediate sequences, each of which may contain up to four minor sequences in the outcrop (e.g., Figs. 9 and 15A,B). The number of high and intermediate sequences in a major sequence nearly double in the subsurface ∼ 100 km basinward of the outcrop belt (Yang et al., 1998). Rare local noncorrelative sequences do not fit in the hierarchy and are simple sequences of Vail et al. (1991). The minor sequences in stacking pattern I are rare, thin, and have typical gradational boundaries in the outcrop, but many thicken significantly and become type A sequences in the down-dip direction (Yang et al., 1998). The abundant intermediate sequences on the outcrop are the basic building blocks of major sequences on the up-dip shelf. The retrogradational or progradational pattern of a set of intermediate sequences within a major sequence cannot be adequately addressed in this study because of the limited down-dip extent of the outcrop belt, but were interpreted in the near-outcrop subsurface by Yang et al. (1998).

The sequence hierarchy conforms with the significant Milankovitch signals in the Cisco spectra (Yang and Kominz, 1999). A Milankovitch orbitally driven glacio-eustasy exhibits a hierarchy of high- and lowamplitude sea-level fluctuations (Berger, 1988; see also Boardman and Heckel, 1989). The up-dip Eastern Shelf could be flooded only by extremely large sea-level rises. As a result, first, deposition would be very limited and erosion and nondeposition would be extensive on the up-dip shelf. Yang and Kominz (1999) estimated that only 6–11% of the Cisco time is represented by the rocks in the outcrop. Second, the depositional durations of the primary sequences on the up-dip shelf would be generally short and vary over a

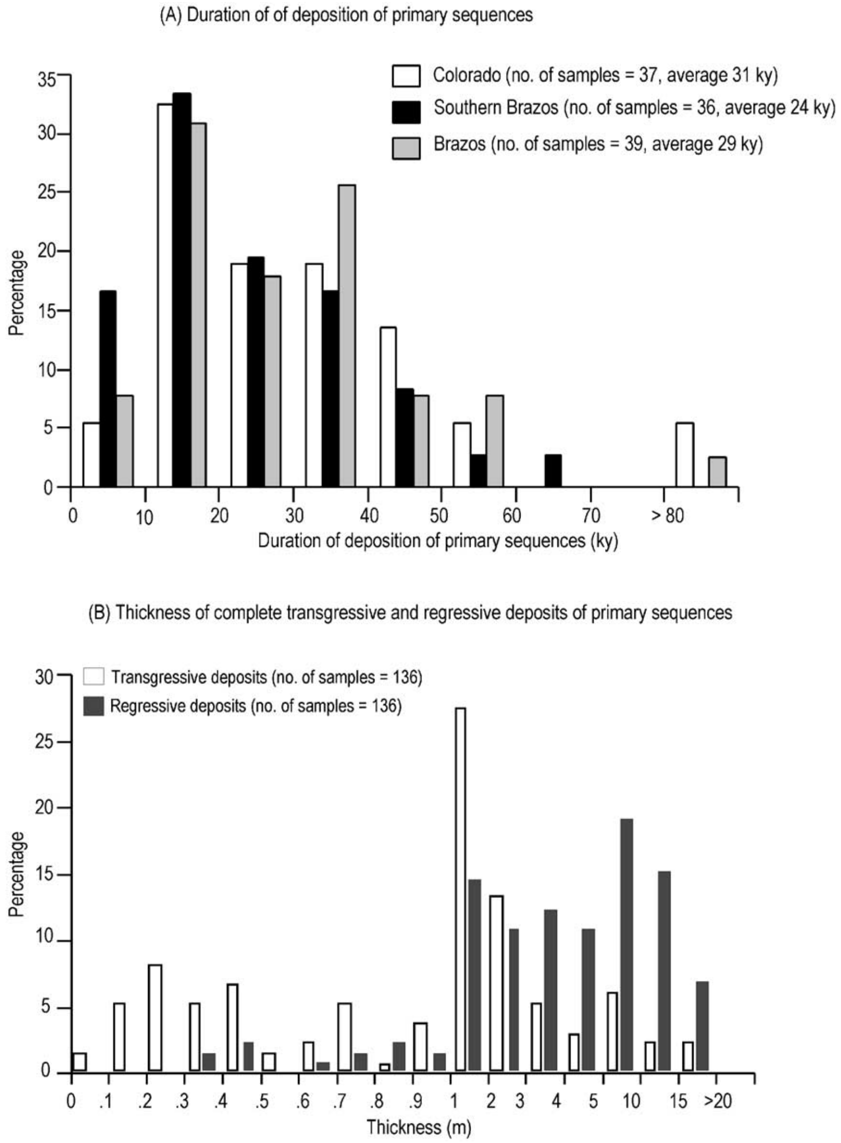


Fig. 16. (A) Distribution of depositional duration of Cisco primary sequences observed in this study. The durations were calculated using facies-dependent sedimentation rates in Yang and Kominz (1999). The southern Brazos sequences have the shortest average duration and the narrowest range. The distribution of the Brazos sequences is slightly bimodal. (B) Thickness distribution of transgressive and regressive deposits of the Cisco primary sequences that are fully exposed on outcrop. Transgressive deposits include TSTs and MCS shales, if present. Regressive deposits include HSTs and ivf's of LST, if present. Assuming a constant sedimentation rate for both transgressive and regressive deposits, the duration of transgressive and regressive deposits should have the same distribution as the thickness.

wide range. They are 6–107 ka (average 31 ka) in the Colorado traverse, 3–67 ka (average 24 ka) in the southern Brazos traverse, and 6–83 ka (average 29 ka) in the Brazos traverse (Fig. 16A), as calculated using facies-dependent sedimentation rates in Yang and Kominz (1999). The primary sequences of the southern Brazos have the shortest average duration with the narrowest range among the three traverses, resulting from the small accommodation space over the pre-Cisco high.

7.3. Stratigraphic architecture on the up-dip shelf

The major Cisco sequences display a reciprocal sedimentation pattern, in which marine and nonmarine carbonate and siliciclastic rocks of TSTs and HSTs dominated on the shelf and coarse deltaic deposits of LSTs dominated in the basin and slope (Galloway, 1971, 1989; Brown et al., 1987, 1990; see also Wilson, 1967; Fig. 15A). The pattern is also manifested by the pattern that shelf deposition was coeval with basin–slope starvation during sea-level rise and highstand, and shelf bypassing and erosion were coeval with basin–slope deposition during sea-level lowstand.

In the intermediate sequences on outcrop, the succession of depositional systems of the TST, which stack upward from nonmarine to marginal marine siliciclastic facies to marine limestones, is similar to that of the HST in a reverse order (i.e., upward from marine limestones to marginal marine to nonmarine siliciclastic deposits) (Fig. 4A–D; Table 1). However, the parasequences in TSTs are thin, and deepen and fine upward, whereas those in HSTs are thick, and shallow and coarsen upward (Fig. 5C). The TSTs as a whole, in comparison to the HSTs, are also thinner (Fig. 16B) and have shorter duration if assuming a constant sedimentation rate for both TST and HST.

Thin and deepening-upward parasequences in TSTs formed because siliciclastic influx on the shelf was minimal and the carbonate system was quickly drowned during transgression. Transgressive sedimentation was limited by sediment supply because accommodation space was ample but carbonate and siliciclastic sediment supply was limited during transgression on the up-dip shelf. Thick, shallowing-upward, and in many cases, coarsening-upward, parasequences in HSTs formed because a large, gradually decreasing, shelf accommodation space during slow sea-level rise and fall allowed keep-up carbonate deposition and progradation of a large amount of siliciclastic sediments. Highstand sedimentation was limited by accommodation space because sediment supply was copious while accommodation space was decreasing.

The characteristics of TSTs and HSTs also vary along depositional strike in the study area due to a variety of allogenic and autogenic controls (Fig. 15A; see also Lee, 1938; Brown, 1969; Brown et al., 1990; Yang et al., 1998). Regional allogenic controls include pre-Cisco topography, location of siliciclastic sediment sources and delivery systems, and eustasy (Fig. 12). Sequence absence due to local erosion, nondeposition, differential shelf subsidence, and lateral facies change manifests autogenic controls (e.g., Fig. 11). Interestingly, the Brazos traverse, which is the thickest and has the largest number of intermediate sequences, has the shortest depositional duration among the three traverses (Fig. 16A). The discrepancy can be explained by (1) the rarity of thick limestones and MCS shales that represent more time than nonmarine siliciclastic facies and, (2) the abundant erosional surfaces in the deposits of the Brazos traverse, which may represent significant hiatal time (Fig. 15A,B). In general, allogenic processes control regional stratigraphic architecture of parasequences and systems tracts and autogenic processes control the internal lithologic and stratal patterns.

8. Conclusions

(1) The mixed carbonate and siliciclastic depositional sequences of Cisco Group on the up-dip Eastern Shelf show a three-level hierarchy consisting of major (third-order), intermediate, and minor sequences. Noncorrelative simple sequences are rare. Most primary sequences in the outcrop are intermediate. Parasequences in TSTs of primary sequences consist of deepening-upward, thin carbonate and siliciclastic systems, whereas those in HSTs consist of shallowing-upward, thick carbonate and siliciclastic systems.

(2) Correlation of magnitude, type, and stacking pattern of minor and intermediate sequences revealed a variety of allogenic controls, such as pre-Cisco topography, location of sediment source areas and sediment delivery systems, and eustasy, and autogenic

controls, such as differential subsidence and lateral facies changes, on sequence formation. The former determined the stratigraphic architecture of parasequences and systems tracts; the latter determined the internal lithologic and stratal patterns.

(3) Based on the spectral calibration of the Cisco Group from Yang and Kominz (1999), the depositional duration of a major sequence is 67–102 ka and that of a third-order sequence boundary is 831–1066 ka on the up-dip shelf. The former increases and the latter decreases in the down-dip direction. The depositional durations of primary sequences range from 3 to 107 ka. Cyclic sedimentation on the up-dip Eastern Shelf was dominated by nondeposition and erosion, with only a 6–11% stratigraphic completeness.

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References

Adlis, D.S., Grossman, E.L., Yancey, T.E., McLerran, R.D., 1988. Isotope stratigraphy and paleodepth changes of Pennsylvanian sedimentary deposits. Palaios 3, 487–506.

Barrell, J., 1917. Rhythms and the measurements of geologic time. Geological Society of America Bulletin 28, 745–904.

Berger, A., 1988. Milankovitch theory and climate. Review of Geophysics 26, 624–657.

Berger, A., Loutre, M.F., Laskar, J., 1992. Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science 255, 560–566.

Boardman II, D.R., Heckel, P.H., 1989. Glacial–eustatic sea-level curve for early Late Pennsylvanian sequence in north-central Texas and biostratigraphic correlation with curve for midcontinent North America. Geology 17, 802–805.

Boardman II, D.R., Malinky, J.M., 1985. Glacial-eustatic control of Virgilian cyclothems in north-central Texas. In: McNulty, C.L., McPherson, J.G. (Eds.), Transactions, American Association of Petroleum Geologists. Southwest Section, Fort Worth Geological Society, Fort Worth, USA, pp. 13–23.

Boardman II, D.R., Maples, R.H., Yancey, T.E., Malinky, J.M., 1984. A new model for the depth-related allogenic community succession within North American Pennsylvanian cyclothems and implications on black shale problem. In: Hyne, N. (Ed.), Limestones of the Midcontinent. Special Publication 2. Tulsa Geological Society, Tulsa, USA, pp. 141–182.

Brown Jr., L.F., 1960. Stratigraphy of the Blach Ranch–Crystal Falls section (Upper Pennsylvanian), northern Stephens County, Texas. University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 41, Austin, USA.

Brown Jr., L.F., 1962. A stratigraphic datum, Cisco Group (Upper Pennsylvanian), Brazos and Trinity Valleys, north-central Texas. University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 46, Austin, USA.

Brown Jr., L.F., 1969. Virgil-lower Wolfcamp repetitive depositional environments in north-central Texas. In: Elam, J.G., Chuber, S. (Eds.), Cyclic Sedimentation in the Permian Basin. West Texas Geologic Society, Midland, USA, pp. 115–134.

Brown Jr., L.F., Fisher, W.L., 1977. Seismic-stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull-apart basins. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration Memoir 26 American Association of Petroleum Geologists, Tulsa, USA, pp. 213–248.

Brown Jr., L.F., Goodson, J.L., Harwood, P., 1972. Abilene sheet. The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000, Austin, USA.

Brown Jr., L.F., Iriarte, R.F.S., Johns, D.A., 1987. Regional stratigraphic cross sections, Upper Pennsylvanian and Lower Permian strata (Virgilian and Wolfcampian Series), north-central Texas. The University of Texas at Austin, Bureau of Economic Geology Cross Sections, Austin, USA, 27 plates.

Brown Jr., L.F., Iriarte, R.F.S., Johns, D.A., 1990. Regional depositional systems tracts, paleogeography, and sequence stratigraphy, Upper Pennsylvanian and Lower Permian strata, north-central Texas. The University of Texas at Austin, Bureau of Economic Geology Reports of Investigations 197, Austin, USA, 27 plates.

Cecil, C.B., 1990. Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks. Geology 18, 533–536.

Crowell, J.C., 1978. Gondwanan glaciation, cyclothems, continental positioning, and climate change. American Journal of Science 278, 1345–1372.

Curray, J.R., 1964. Transgressions and regressions. In: Miller, R.L. (Ed.), Papers in Marine Geology. Macmillan, New York, pp. 175–203.

Drummond, C.N., Wilkinson, B.H., 1993. Aperiodic accumulation of cyclic peritidal carbonate. Geology 21, 1023–1026.

Galloway, W.E., 1971. Depositional systems and shelf-slope relationships in uppermost Pennsylvanian rocks of the Eastern

Shelf, north-central Texas. PhD Thesis, The University of Texas at Austin, Austin, USA.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis: I. Architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists Bulletin 73, 125–142.

Galloway, W.E., Brown Jr., L.F., 1972. Depositional systems and shelf-slope relationships in Upper Pennsylvanian rocks, north-central Texas. The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 75, Austin, USA.

Gilbert, G.K., 1895. Sedimentary measurement of geologic time. Journal of Geology 3, 121–127.

Goldhammer, R.K., Oswald, E.J., Dunn, P.A., 1994. High-frequency, glacio-eustatic cyclicity in the middle Pennsylvanian of the Paradox Basin: an evaluation of Milankovitch forcing. In: de Boer, P.L., Smith, D.G. (Eds.), Orbital Forcing and Cyclic Sequences. International Association of Sedimentologists, Special Publications 19, 243–283.

Harland, W.D., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1989. A geologic time scale. Cambridge Earth Science Series. Cambridge Univ. Press, Cambridge, UK.

Harrison, E.P., 1973. Depositional history of Cisco–Wolfcamp strata, Bend Arch, north-central Texas. PhD Thesis, Texas Tech University, Lubbock, USA.

Heckel, P.H., 1977. Origin of phosphatic black shale facies in Pennsylvanian cyclothems of Midcontinent North America. American Association of Petroleum Geologists Bulletin 61, 1045–1068.

Heckel, P.H., 1986. Sea-level for Pennsylvanian eustatic marine transgressive–regressive depositional cycles along midcontinent outcrop belt, North America. Geology 14, 330–334.

Heckel, P.H., 1995. Glacial–eustatic base-level—climatic model for late middle to Late Pennsylvanian coal-bed formation in the Appalachian Basin. Journal of Sedimentary Research B65, 348–356.

Heckel, P.H., Gibling, M.R., King, N.R., 1998. Stratigraphic model for glacial-eustatic Pennsylvanian cyclothems in highstand nearshore detrital regime. Journal of Geology 106, 373–383.

Hentz, T.F., 1988. Lithostratigraphy and paleoenvironments of Upper Paleozoic continental red beds, north-central Texas: Bowie (new) and Wichita (revised) Groups. Bureau of Economic Geology, Report of Investigations No. 170, The University of Texas at Austin, Austin, USA.

Hentz, T.F., Brown Jr., L.F., 1987. Wichita Falls-Lawton Sheet. The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, Austin, USA, scale 1:250,000.

Imbrie, J., Imbrie, K.P., 1979. Ice Ages, Solving the Mystery Enslow, Hillside, NJ.

Jacquin, T., Arnaud-Vanneau, A., Arnaud, H., Ravenne, C., Vail, P.R., 1991. Systems tracts and depositional sequences in a carbonate setting: a study of continuous outcrops from platform to basin at the scale of seismic lines. Marine and Petroleum Geology 8, 122–138.

James, N.P., 1979. Shallowing-upward sequences in carbonates. In: Walker, R.G. (Ed.), Facies Models, Geoscience Canada Reprint Series 1: Geoscience Canada. The Geological Association of Canada, Calgary, pp. 109–120.

Joeckel, R.M., 1994. Virgilian (Upper Pennsylvanian) paleosols in the upper Lawrence Formation (Douglas Group) and in the Snyderville Shale Member (Oread Formation, Shawnee Group) of the northern Mid-Continent, USA: pedologic contrasts in a cyclothem sequence. Journal of Sedimentary Research A64, 853–866.

Klein, G.deV., 1990. Pennsylvanian time scales and cycle periods. Geology 18, 455–457.

Lee, W., 1938. Stratigraphy of the Cisco Group of the Brazos Basin. University of Texas Publication 3801. Univ. of Texas, Austin, USA, pp. 11–90.

Mazzullo, S.M., 1998. Stratigraphic architecture of Lower Permian, cyclic carbonate reservoirs (Chase Group) in the Mid-continent USA, based on outcrop studies. American Association of Petroleum Geologists Bulletin 82, 464–483.

Merriam, D. 1964. Symposium on Cyclic Sedimentation. Kansas Geological Survey, Bulletin, vol. 169. Kansas Geol. Survey, Lawrence, USA.

Mitchum Jr., R.M., Van Wagoner, J.C., 1991. High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency cycles. Sedimentary Geology 70, 131–160.

Rascoe Jr., B., Adler, F.J., 1983. Permo-Carboniferous hydrocarbon accumulations, mid-continent, USA. American Association of Petroleum Geologists Bulletin 67, 979–1001.

Retallack, G.J., 1990. Soils of the Past, an Introduction of Paleopedology Unwin Hyman, Boston.

Sarg, J.F., 1988. Carbonate sequence stratigraphy. In: Wilgus, C.K., Hastings, B.S., Kendal, C.G.St.G., Posamentier, H.W., Ross, J.C., Van Wagoner, J.C. (Eds.), Sea-level Changes: An Integrated Approach. Special Publication 42. Society of Sedimentary Geology, Tulsa, USA, pp. 155–182.

Schlager, W., 1981. The paradox of drowned reefs and carbonate platforms. Geological Society of America Bulletin 92, 197–211.

Scotese, C.R., Denham, C.R., 1987. User's Guide to Terra Mobilis: A Plate Tectonics Program for the Macintosh Earth in Motion Technologies, Houston, USA.

Schutter, S.R., Heckel, P.H., 1985. Missourian (early Late Pennsylvanian) climate in midcontinent North America. International Journal of Coal Geology 5, 111–138.

Tandon, S.K., Gibling, M.R., 1994. Calcrete and coal in late Carboniferous cyclothems of Nova Scotia, Canada: climate and sea level changes linked. Geology 22, 755–758.

Vail, P.R., Mitchum, R.M., Thompson III, S., 1977. Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. In: Payton, C.E. (Ed.), Seismic Stratigraphy Applications to Hydrocarbon Exploration. Memoir 26. American Association of Petroleum Geologists, Tulsa, USA, pp. 63–82.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., Perez-Cruz, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. In: Einsele, E., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer-Verlag, Berlin, pp. 617–659.

Van Wagoner, J.C., Mitchum, R.M., Posamentier, H.W., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendal, C.G.St.G., Posamentier, H.W., Ross, C.A.,Van Wagoner, J.C. (Eds.), Sea Level Changes: An Integrated Approach. Special Publication 42. Society of Sedimentary Geology, Tulsa, USA, pp. 39–45.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high resolution correlation of time and facies. Methods in Exploration No. 7. American Association of Petroleum Geologists, Tulsa, USA.

Veevers, J.J., Powell, C.McA., 1987. Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive–regressive depositional sequences in Euramerica. Geological Society of America Bulletin 98, 475–487.

Wanless, H.R., Shepard, F.P., 1936. Sea level and climatic changes related to late Paleozoic cycles. Geological Society of America Bulletin 38, 1177–1206.

Watney, W.L., French, J.A., Doveton, J.H., Youle, J.C., Guy, W.J., 1995. Cycle hierarchy and genetic stratigraphy of middle and upper Pennsylvanian strata in the upper mid-continent. In: Hyne, N.J. (Ed.), Sequence Stratigraphy of the Mid-Continent. Tulsa Geological Society, Tulsa, USA, pp. 141–192.

Wermund, E.G., Jenkins Jr., W.A., 1969. Late Pennsylvanian series in north-central Texas. In: Wermund, E.G., Brown, L.F. (Eds.), A Guidebook to the Late Pennsylvanian Shelf Sediments, north-central Texas. Dallas Geological Society, American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists Annual Meeting, Dallas, USA., SEPM, Tulsa, pp. 1–11.

Wilson, J.L., 1967. Cyclic and reciprocal sedimentation in Virgilian strata of Southern New Mexico. Geological Society of America Bulletin 78, 805–818.

Yang, K.-M., Dorobek, S.L., 1992. Mechanisms for Late Paleozoic Synorogenic Subsidence of the Midland and Delaware basins, Permian Basin, Texas and New Mexico. West Texas Geological Society, Midland, USA, pp. 45–60.

Yang, W., 1995. Depositional cyclicity of the Cisco Group (Virgilian and Wolfcampian), north-central Texas. PhD Thesis, The University of Texas, Austin, USA.

Yang, W., 1996. Cycle symmetry and its causes, Cisco Group (Virgilian and Wolfcampian), Texas. Journal of Sedimentary Research B66, 1102–1121.

Yang, W., Kominz, M.A., 1999. Testing periodicity of depositional cyclicity, Cisco Group (Virgilian and Wolfcampian), Texas. Journal of Sedimentary Research 69, 1209–1231.

Yang, W., Kominz, M.A., Major, R.P., 1998. Distinguishing the roles of autogenic versus allogenic processes in cyclic sedimentation, Cisco Group (Virgilian and Wolfcampian), north-central Texas. Geological Society of America Bulletin 110, 1333–1353.

Plate A. Measured Stratigraphic Sections, Transgressive-Regressive Cycles, and Local Stratigraphic Correlation, Cisco Group (Virgilian and Wolfcampian), Colorado River Valley Traverse, North-Central Texas.

Plate B. Measured Stratigraphic Sections, Transgressive-Regressive Cycles, and Local Stratigraphic Correlation, Cisco Group (Virgilian and Wolfcampian), Southern Brazos River Valley Traverse, North-Central Texas.

Plate C. Measured Stratigraphic Sections, Transgressive-Regressive Cycles, and Local Stratigraphic Correlation, Cisco Group (Virgilian and Wolfcampian), Brazos River Valley Traverse, North-Central Texas.