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In the paper by Oboh-Ikuenobe et al., Table 1 (p. 206) is missing part B, as follows:

Anatomy of epicontinental flooding: Late Albian-Early Cenomanian of the southern U.S. Western Interior Basin

8	Thick to very thick-bedded fine-grained sandstone	Medium-scale planar cross bedded with subdominant current and oscillation ripple lamination; herringbone cross-bedding common; ripple-bounded planar foresets common; bound by shallow, wide channel scours; scours amalgamated	Plant fragment impression common; burrows rare, and mostly *Arenicolites*	Tidal channel
9	"Wavy bedded " thin to medium tabular-to-slightly lenticular beds of fine-grained sandstone interbedded with thin to very thin beds of silty shale	Sandstone - mixed current and oscillation ripples grading laterally locally to small-scale planar cross bedding in thicker beds; ripple foresets are commonly clay-draped; load casts common Silty shale - blue to dark gray, thickly laminated to rippled; siderite concretions present locally	Plant fragment and log impressions; rare bivalve molds; one ankylosaur track site; bioturbation minimal, but burrows and trails are common and include *Teredolites, Skolithos, Planolites, Arenicolites,* and rare	Subtidal bar/sheet
10a	Blue-gray muddy siltstone with rare widely dispersed very thin beds of very fine-grained sandstone	Mudstone/siltstone - massive to locally thickly laminated Sandstone - current and oscillation rippled occurring in lenticular units floored by channel scours Locally capped by rooted horizons	Very minor burrowing local (*Arenicolites and Planolites)* in sandstone; root casts present, local root fragments; spores common	Brackish to fresh water estuary Fill
10b	Dark gray to dark blue-gray siltstone	Thickly laminated, moderately indurated, fine silty mudstone, occurring in lenticular units floored by channel scours; interfingers laterally with lithofacies assemblage 6 locally and commonly grades to assemblage 10a	Locally bioturbated burrowing consists of *Teredolites, Skolithos, Planolites,* and *Arenicolites*, logs noted locally; spores and dinoflagellates common	Brackish to marine estuary fill
11	Siltstone/mudstone coarsening up to fine-grained medium bedded sandstone	Blue-gray to dark gray rippled to thinly laminated thin-bedded siltstone and mudstone transitioning up into ripple, parallel, and locally planar to hummocky cross-bedded medium bedded sandstone	Rooted horizons and dinosaur tracks on top surfaces locally; commonly bioturbated; burrows are common and include: Skolithos, Arenicolites, Thalassinoides, Planolites, Ophiomorpha, and Rhizocorallium	Prograding shoreface
12a	Shale	Thickly to thinly laminated dark gray very fissile shale, jarosite found locally; tabular	*Skolithos, Arenicolites, Planolites* and *Thalassinoides*, dinoflagellates common	Restricted basinal marine
12b	Shale	Thickly to thinly laminated dark gray, very fissile shale; abundant jarosite; tabular	*Skolithos, Arenicolites, Planolites* and *Thalassinoides*, dinoflagellates common; abundant foraminifers	Open marine

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ANATOMY OF EPICONTINENTAL FLOODING: LATE ALBIAN–EARLY CENOMANIAN OF THE SOUTHERN U.S. WESTERN INTERIOR BASIN

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ABSTRACT

The mid-Cretaceous (Late Albian–Early Cenomanian) sedimentary succession between Wyoming and Texas, which is generally attributed to transgression during the early part of the third-order Greenhorn cycle, reveals three thin sequences of unusually large, regional extent, deposited during three higher order marine cycles. These three sequences are preserved in outcrop sections and wells in central and southeastern Colorado, northeastern New Mexico and northwestern Oklahoma. We conducted an integrated study utilizing sedimentology, micropaleontology, palynology and organic geochemistry in order to understand the environmental details of the marine–terrestrial transitions during a continental flooding event and how they fit into the larger picture of the first-order Zuni Sequence. Each of the three sequences (referred to as sequences 3.1, 3.2 and 4) records biofacies shifts of over 200 km within vertical sections of less than 20 m that mark ephemeral Tethyan flooding into southeastern Colorado. In each sequence, basal fluvial–paralic sandstone with non-marine fossil assemblages and isotopic and palynofacies signals passes vertically into marine-influenced shale and sandstone. Marine fossils, mainly as moderately diverse agglutinate foraminiferal biotas, nearshore dinoflagellate cysts and acritarchs, and *Skolithos* ichnofauna, become progressively poorer up-dip until only brackish-tolerant ichnofauna, sparse agglutinate foraminifers and non-marine palynomorphs remain. Two of the three thin sequences record previously unrecognized transgressions that appear to have lasted no more than a million years each, accompanied by high amount of freshwater input. Therefore, the regional scale of this database covering as it does a considerable portion of the southern Western Interior Basin, provides an instructive example of the sedimentary and biotic response to transgressions across low-relief margins of epeiric seas.

RESUME

La succession sédimentaire du Crétacé moyen (Albien Supérieur–Cénomanien Inférieur) entre le Wyoming et le Texas, qu'on attribue généralement à la transgression pendant la première partie du cycle de Greenhorn de troisième ordre, révèle trois séquences minces d'une très grande étendue régionale, qui se sont mises en place pendant trois cycles marins de plus haut ordre. Ces trois séquences sont conservées dans des sections d'affleurement et dans des puits au centre et au sud-est du Colorado, au nord-est du Nouveau-Mexique et au nord-ouest de l'Oklahoma. Nous avons mené une étude intégrée, dans laquelle nous avons utilisé la sédimentologie, la micropaléontologie, la palynologie et la géochimie organique pour comprendre les détails environnementaux des transitions terrestres marines durant un événement d'inondation continentale, et comment ceux-ci prennent place dans le plus grand cadre de la Séquence Zuni du premier ordre. Chacune des trois séquences (appelées séquences 3.1, 3.2 et 4) enregistre des mouvements de biofaciès de plus de 200 km dans des sections verticales de moins de 20 km, qui marquent une inondation téthysienne éphémère au sud-est du Colorado. Dans chaque séquence, du grès basal fluvial–paralique avec des assemblages de fossiles non-marins et des signaux isotopiques et de palynofaciès, passe verticalement dans du schiste d'influence marine et du grès. Des fossiles marins, pour la plupart dans la forme de biotes foraminifères agglutinés assez diverses, de cystes dinoflagellates et d'acritarches littoraux, et de l'ichnofaune *Skolithos,* deviennent de plus en plus pauvres jusqu'à ce qu'il n'y reste que de l'ichnofaune tolérante d'eau saumâtre, quelques forminafères agglutinés épars et des palynomorphes non-marins. Deux des trois séquences minces enregistrent des transgressions qu'on n'a pas jusqu'ici reconnues, et dont chacune ne semble pas avoir duré plus d'un million d'années, accompagnées d'un grand flux d'eau douce. Par conséquent, puisque cette base de données couvre une si grande partie du Bassin Intérieur de l'Ouest, elle fournit un exemple instructif de la réponse sédimentaire et biotique à des transgressions à travers des marges bas-relief de mers épicontinentales.

INTRODUCTION

The northward encroachment of the Tethys from the Gulf of Mexico during the middle part of the Cretaceous has long been recognized as the first stage of the larger Zuni flooding event that submerged most of the North American Western Interior during Late Cretaceous time (Sloss, 1963). Traditional sequence models of mid-Cretaceous Western Interior Basin suggest that the Zuni flooding occurred in two advances and retreats. The first north–south connection between the Boreal and Tethyan biotic provinces (the Kiowa–Skull Creek cycle) was made during the early part of the Late Albian (approximately 103–99 Ma) (Williams and Stelck, 1975; Kauffman, 1977, 1984; Kauffman and Caldwell, 1993; Scott et al., 1998). These provinces became separated during the latest Albian and earliest Cenomanian but the fully connected seaway that spanned Late Cretaceous time was reestablished about 95.8 Ma (date 25—Obradovich, 1993) in the Middle Cenomanian (Greenhorn cycle), when the Thatcher Limestone Member of the Graneros Formation was deposited.

However, depositional events are poorly known during this important time of separation between continent-wide flooding episodes because of the absence of marine marker

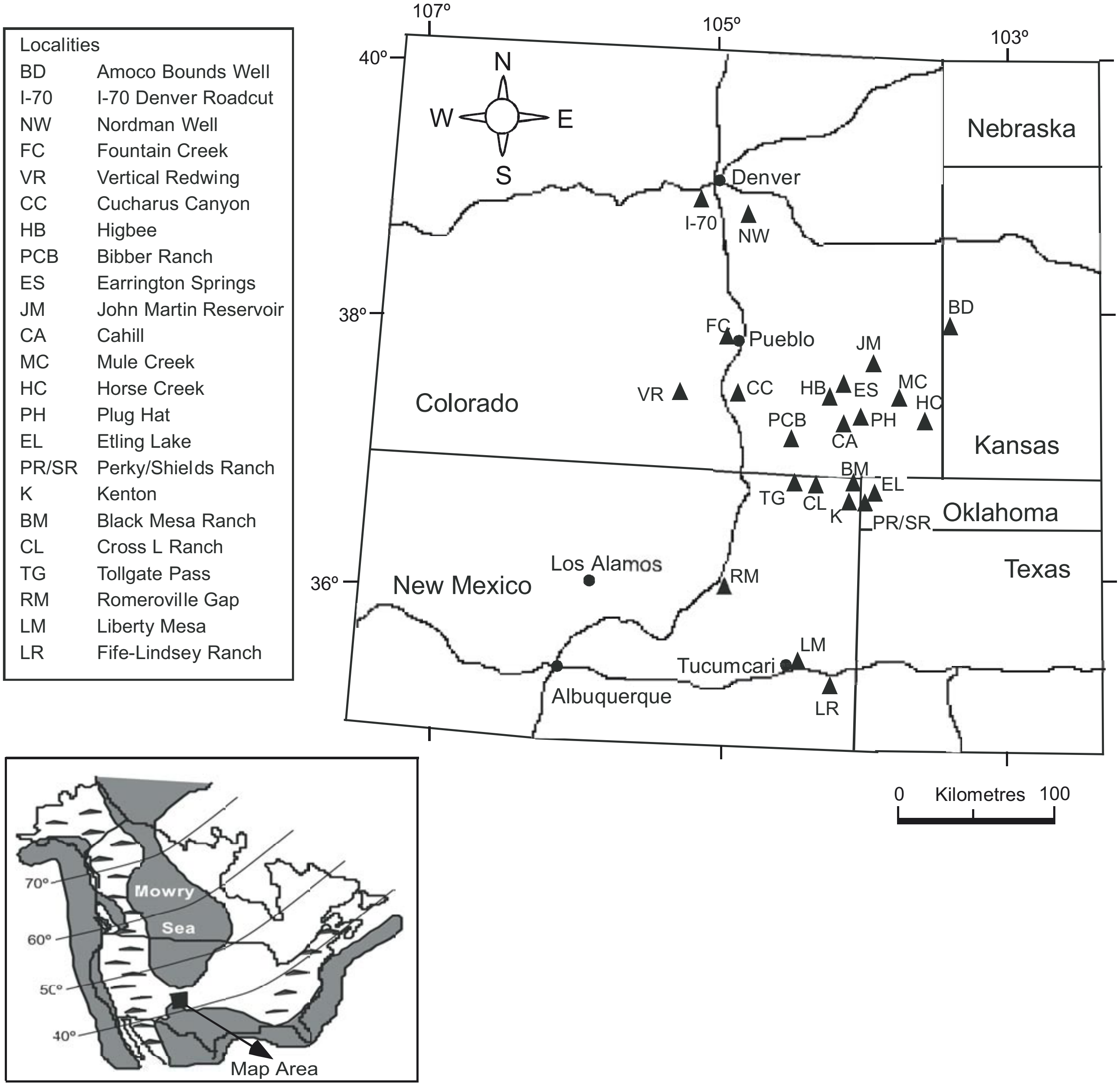

Figure 1. Map showing the locations of the stratigraphic sections studied in the southern Western Interior Basin. Inset paleogeographic map is modified from Williams and Stelck (1975).

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beds and post-Cretaceous erosion in the southern Western Interior Basin. Several key questions about the flooding of the basin have not been fully addressed: (1) When and where did the southern Tethyan Sea connect with the northern Boreal Sea?; (2) Were there significant short-term transgressions associated with Zuni flooding of the basin?; (3) What were the conditions of the marine basin in the incipient southern Western Interior Cretaceous seas, and how did the flooding interact with the terrestrial environment? and; (4) What is the regional expression of terrestrial versus marine environments during transgressions across the low-gradient continental interior? In order to fill critical gaps that help answer the above questions, we undertook a multi-proxy investigation of Upper Albian to Lower Cenomanian strata utilizing sedimentology, micropaleontology, palynology and organic geochemistry. Our study area encompassed central and southeastern Colorado northwestern New Mexico and northwestern Oklahoma (Fig. 1). It appears that during the lowstand following the Kiowa–Skull Creek cycle, two short-term partial floodings invaded the southern and northern ends of the Western Interior prior to full connection of the Greenhorn cycle. By integrating our data with existing information on the south-central Western Interior Basin, new details have emerged about the Greenhorn flooding event that may serve as a model of marine-terrestrial transitions during flooding of low-gradient epicontinental seaways.

SEQUENCE STRATIGRAPHIC FRAMEWORK

The Kiowa-Skull Creek cycle in our study area is composed of, in ascending order, the Lytle Sandstone, the Plainview Formation, the Skull Creek Shale and equivalent Glencairn Formation in southeastern Colorado, the Tucumcari Shale in New Mexico, and the Kiowa Formation in Kansas (Fig. 2). This megacycle is bounded at its base and top by regional unconformities SB1 and SB3.1, and within the megacycle SB2 separates the Lytle from the overlying Plainview or equivalent shale (Holbrook and Wright Dunbar, 1992; Holbrook, 1996, 2001; Scott et al., 2004a; Holbrook et al., 2006). The age of the Kiowa, Glencairn, Tucumcari and Skull Creek is narrowly constrained to the lower part of the Upper Albian by ammonites, dinoflagellates, and foraminifers (Hancock et al., 1993; Scott et al., 2004a).

The succeeding Greenhorn megacycle in the southern part of the Western Interior consists of the Muddy Sandstone, which includes the Dry Creek Canyon Formation (Waage, 1953) and the Mowry Shale in Colorado, and the Mesa Rica Sandstone, the Pajarito Formation, and the Romeroville Sandstone in New Mexico (Figs. 2, 3). A regional sequence boundary SB 3.1 occurs at the base of the Mesa Rica Sandstone (Scott et al., 2004a). The age of the lower part of the Greenhorn cycle is constrained by a new radiometric date of 98.7 ± 0.31 Ma and by a radiometric date of 95.78 ± 0.61 Ma just below the Thatcher Limestone Member of the Graneros Shale (Obradovich, 1993).

In the south-central part of the basin at Etling Lake, Black Mesa State Park in Oklahoma, the Mesa Rica Sandstone is differentiated into three members, the Lower, Middle and Upper members (Fig. 4A). The Lower Member is thick-bedded sandstone bounded by SB 3.1 at the base and above by TS 3.1, a sharp transgressive contact. The overlying Middle Member of the Mesa Rica is composed of two coarsening-upward siltstone–sandstone cycles representing floodplain and deltaic deposition. In comparison with the amalgamated channel-belt sandstone Lower Member, the Middle Mesa Rica member has a higher ratio of fine-grained flood-basin strata to sandy channel-belt strata. This is typical of the fluvial response to base-level rise during marine transgression in areas landward of the shoreline (Wright and Marriott, 1994; Shanley and McCabe, 1994; Holbrook et al., 2006). The top of the Middle Mesa Rica is marked by incised surface SB 3.2. We note that the minor transgression of the Middle Mesa Rica and surface SB 3.2 have not yet been correlated into the Boreal realm, although there are cycles in the equivalent Muddy (Weimer, 1984, 1990; Sonnenburg, 1987; Scott et al., 1998) and Viking sandstones (e.g., Walker and Wiseman, 1995) that may be correlative. The overlying Upper Mesa Rica Member is a fluvial channel-fill sandstone, the top of which is another sharp transgressive contact TS 3.2 that is overlain by multiple coarsening-upward mudstone-sandstone cycles. Roots and dinosaur footprints occur in the lower parasequences, while trace fossils of the *Skolithos* assemblage are preserved in the upper cycles, which grade into the Graneros Shale. The Romeroville Sandstone is not developed in this area. However, a few kilometres west at the Perky/Shields Ranch section a 3 m thick fluvial sandstone occurs in the position of the Romeroville.

About 70 km north at the Higbee, Colorado section (Fig. 4B) the three members of the fluvial Mesa Rica Sandstone overlie the marine Skull Creek/Glencairn at SB 3.1. This is as far up-dip as the Mesa Rica members can be recognized before merging into one unit, and the Dry Creek Canyon Formation overlies them. The contact is transgressive surface TS 3.2 and above is blue-gray siltstone and rippled sandstone with a diverse trace fossil assemblage. The overlying thick-bedded fluvial sandstone is identified as the Romeroville Sandstone. The base is a sharp erosional contact SB 4 but the top is eroded and the Graneros Shale has been removed here as is typical in the region. In the Cucharus/Huerfano Canyon area, the fluvial Mesa Rica and the Romeroville sandstones form prominent cliffs and are separated by the Dry Creek Canyon Formation (Fig. 4C). The *Arenicolites* trace fossil assemblage with dinosaur footprints indicates local marine influence in the Dry Creek Canyon Formation. The top of the Romeroville is eroded here, but locally throughout the canyon paralic facies less than 1 m thick separate the Romeroville from the Graneros Shale.

A key section at Fountain Creek (Fig. 4D) north of Pueblo is located near the type area where Waage (1953) defined the Dry Creek Canyon Formation as a member of the Dakota Sandstone. The Mesa Rica Sandstone (Lower Sandstone unit of Waage, 1953) is in contact with the marine Glencairn Formation at SB 3.1. This sandstone interval and a thin interval of dark gray shale of the Dry Creek Canyon are repeated by faulting. The top of the Mesa Rica is a sharp contact represented by TS 3.1, which is overlain by siltstone and shale with marine dinoflagellates (*Apteodinium* sp. cf. *A. deflandrei* Clarke and Verdier, *Chlamydophorella nyei* Cookson and Eisenack, *Oligosphaeridium complex* White, *Subtilisphaerea deformans* Davey and Verdier), the acritarchs *Fromea amphora* Cookson and Eisenack and *F. fragilis* Cookson and Eisenack, spores, pollen and leaves.

The Dry Creek Canyon Formation is a lithologically complex interval about 16.5 m thick (Fig. 3). It is overlain at a sharp contact (SB 4) by a 5-m thick sandstone, which corresponds to the basal bed of Waage's Upper Sandstone unit. We interpret this unit as the Romeroville Sandstone, which was named for strata near its terminus in northernmost New Mexico (Lucas and Kues, 1985; Kues and Lucas, 1987). Here the Romeroville passes into coastal deposits, including sandstone with marine trace fossils (Bejanar and Lessard, 1972; Kues and Lucas, 1987; Lucas, 1990) that are locally incised by fluvial units interpretable as either valley fills above sequence boundary SB 4 or distributary channels above surfaces equivalent to SB 4. Farther north, the Romeroville becomes more clearly terrestrial, occurring as prominent, cliff-forming fluvial sandstone 0 -16 m thick and incised into older terrestrial and paralic Dry Creek Canyon strata. Like the Mesa Rica, Holbrook et al. (2006) extended the Romeroville into southeastern Colorado to replace the informal, upper sandstone member of the Dakota Sandstone (cf. Long, 1966), thereby raising the Dakota to group status there, as it is in New Mexico (Kues and Lucas, 1987).

The lower part of the Dry Canyon correlates with the Middle Shale Member of the Mesa Rica Sandstone to the southeast. Near the middle of the Dry Creek Canyon is a prominent sandstone bed about 3 m thick that we correlate with the Upper Member of the Mesa Rica Sandstone to the southeast. The underlying shale and siltstone interval is correlated with the Middle Member of the Mesa Rica, and the overlying siltstone and shale are correlated with the Pajarito Formation in eastern New Mexico.

MATERIAL AND METHODS

We measured and sampled twenty-one outcrop sections and one cored well in central and southeastern Colorado, northeastern New Mexico, and northwestern Oklahoma (Fig. 1). The stratigraphic sections in the Front Range in central Colorado (e.g., Rocky Mountain Production Company Nordman Trust No. 44-20 well, I-70 Denver section) act as controls for reconstructing depositional paleoenvironments. Samples spanned the Kiowa-Skull Creek transgression/regression (T5–R5) and uppermost Dakota-Greenhorn transgression (T6) cycles (Kauffman, 1984), which have previously been subdivided into two sequences separated by regional unconformities (Weimer, 1984, 1990; Mateer, 1987; Lucas and Kisucky, 1988; Lucas, 1990; Lucas et al., 1998; Holbrook and Wright Dunbar, 1992; Scott et al., 2004a). Sampling was designed to test for additional, intervening north to south flooding events in the study area. We augmented facies information from outcrop sections with photomosaics of adjacent rock exposures to catalogue facies architecture and interrelationship of discontinuity surfaces in order to put key sections into lateral context. In total, 138 samples (mostly siltstone and shale) were processed and analyzed for foraminifers, palynomorphs (spores, pollen, dinoflagellates, acritarchs) and kerogen or dispersed organic matter; macrofossils were collected and identified. Samples were processed and microfossils identified using standard techniques for each fossil group (Traverse 1988; Lipps 1994). A subset of 102 samples from 17 outcrops were used to measure total organic carbon (TOC) and total sulfur using a LECO® C/S 244 induction furnace at the Biogeochemical Laboratory at Indiana University. A Finnigan MAT 252 mass spectrometer was used for isotopic analysis.

Kerogen slides were processed from 130 of the 138 paleontological samples collected and used for palynofacies interpretation. We identified the following eight types of palynomorph groups and dispersed organic matter: (1) spores and pollen; (2) fungal remains; (3) marine palynomorphs (dinoflagellates, acritarchs, foraminiferal linings); (4) freshwater algae (*Botryococcus*, *Pediastrum*); (5) structured phytoclasts (wood, cuticles, parenchyma); (6) unstructured and comminuted phytoclasts (including resins and highly degraded wood); (7) black debris; and (8) amorphous organic matter (AOM). Three hundred particles per slide were point-counted, and interpreted with minimum variance Euclidean cluster analysis on transformed percentage data (Appendices 1–3). The octave scale used is a weighting function that converts percentage counts into ten relative abundance classes based on modified $\log_2$ scale (Beck and Strother, 2004). Kovach (2002) wrote the program used for cluster analysis, and the theory behind its use can be found in Gauch (1982) and Kent and Coker (1992). In this study, palynofacies assemblages were defined by cluster analyses of the kerogen properties (Figs. 5–7; Table 2). The data were subdivided into four groups to aid interpretation of facies variations across the study area. Just six samples were processed from Sequence 2, i.e. the Glencairn and Tucumcari formations, and they were not subjected to cluster analysis. All groups of organic components were considered, but it appears that fungal remains and freshwater algae had the least effect on the sample clusters (labelled A, B, etc.) used to identify palynofacies assemblages (see also Appendices 1–3 for samples represented in each assemblage).

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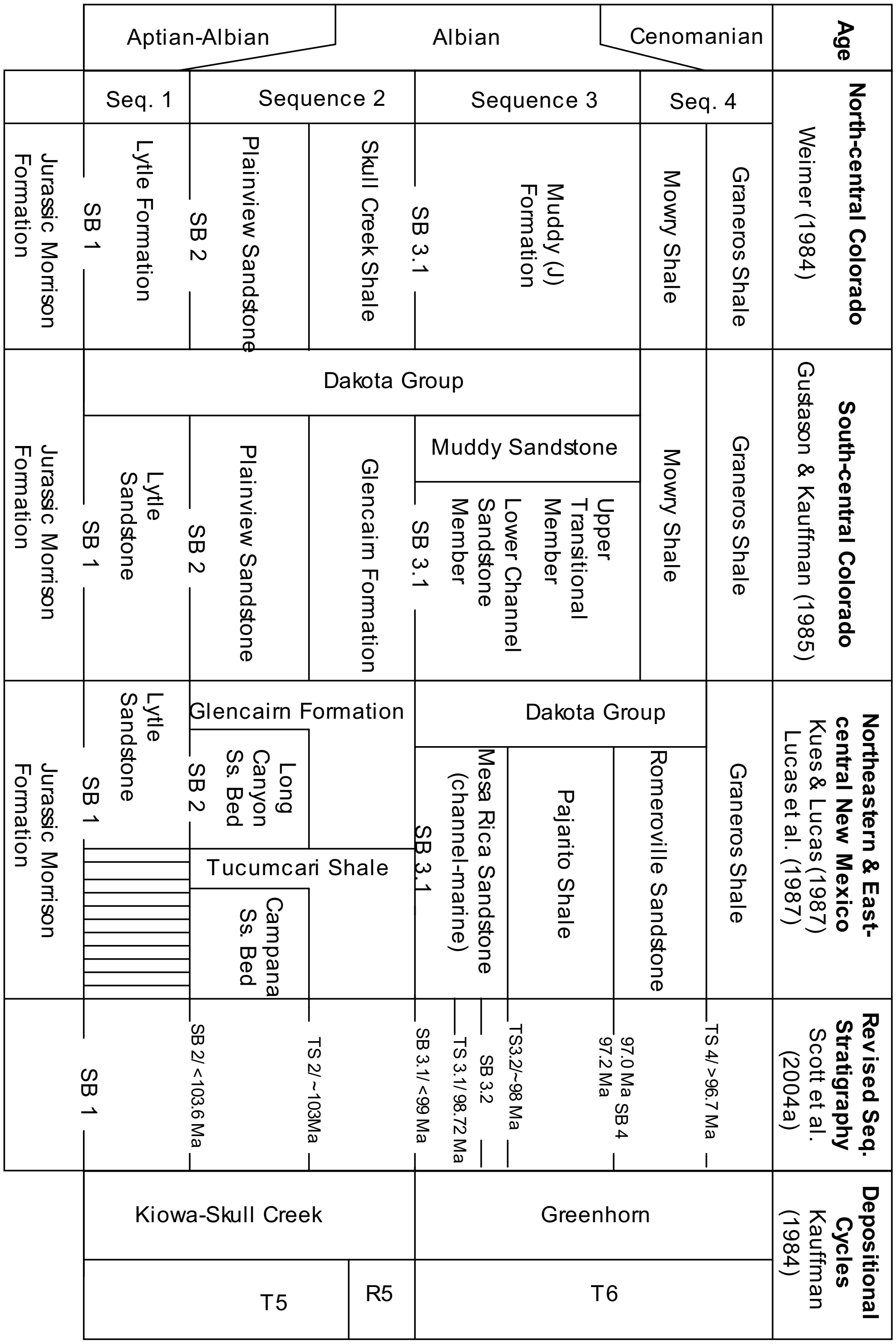
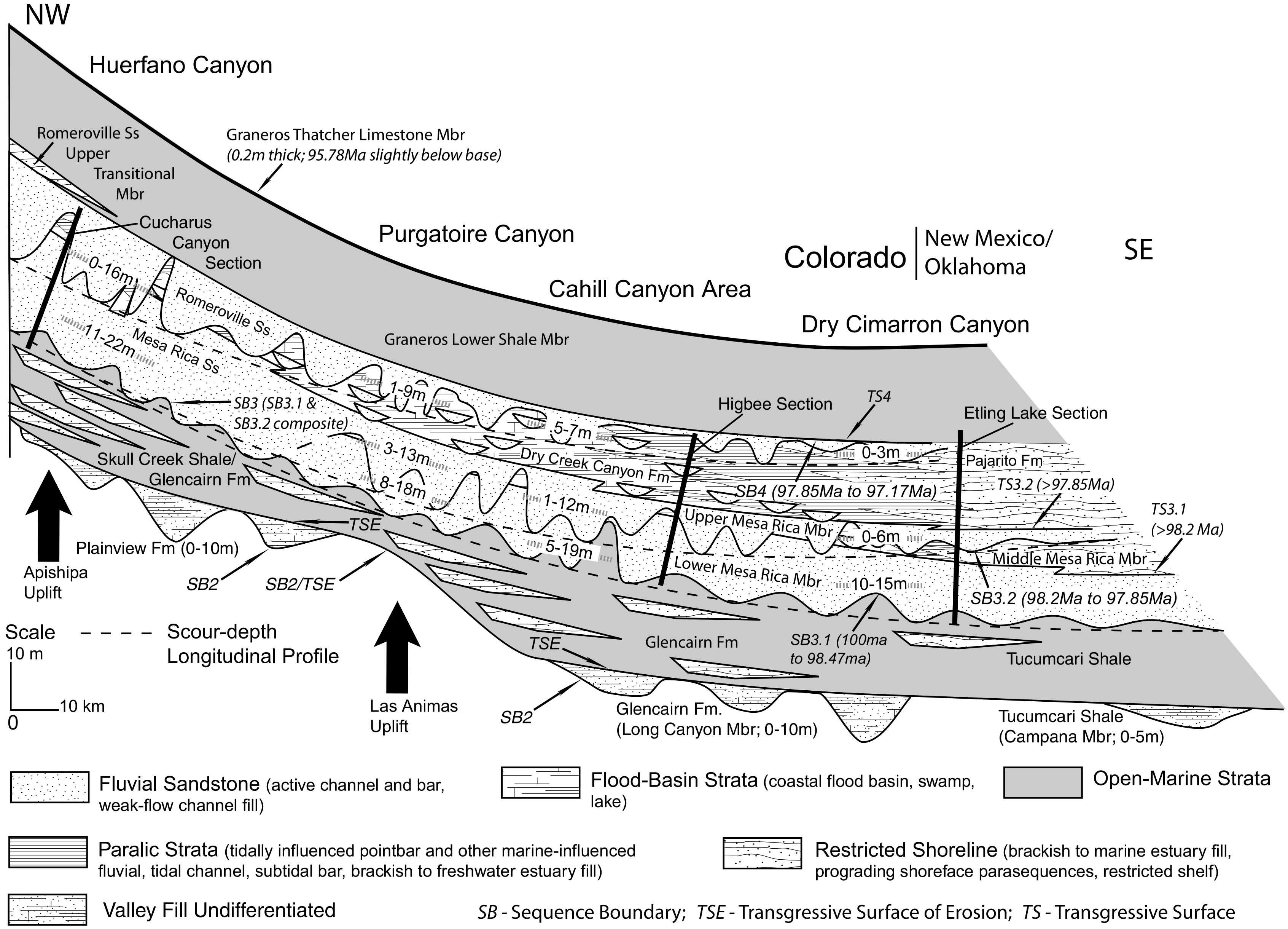


Figure 2. Stratigraphic framework of the middle Cretaceous succession in the southern Western Interior Basin.

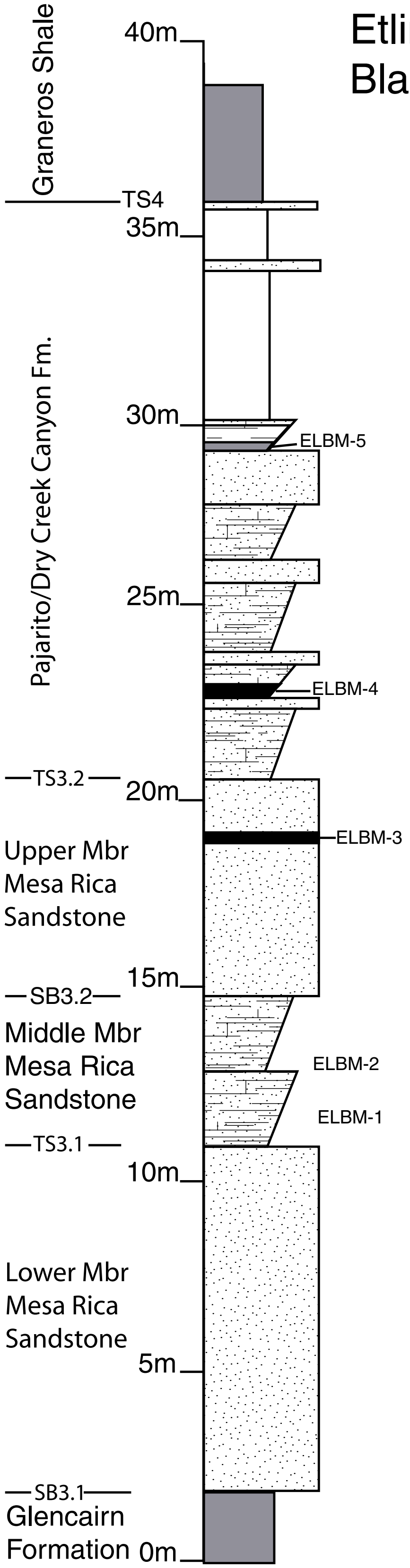
Lithofacies assemblage	Lithology	Characteristics	Typical Biota	Environment
1	Fine to medium grained sandstone	Medium-scale trough and planar cross bedding; channel scours common and locally lined with mud rip-ups and pebble lags	Abundant plant fragment impressions; rare dinosaur tracks; minimal burrowing	Fluvial (active channel deposition)
2	Medium to thick bedded fine-grained sandstone interbedded with thin-to very thin siltstone and mudstone beds	Sandstone - current rippled or small-scale planar cross bedded; Siltstone/mudstone - thickly laminated to rippled, blue-gray to pale yellow; exposures are bounded and internally portioned by channel scours	Abundant plant fragment impressions; no significant burrowing	Fluvial (weak flow channel fill)
3	Dark fissile shale/muddy siltstone	Dark gray to black, fissile, thin to thickly laminated, carbonaceous to coaly, jarosite streaks locally, locally rippled	Intensely rooted; minimal to no animal traces present	Swamp
4	Alternating clay and silty clay	Commonly varved with alternating light and dark thinly laminated clay and silty clay; thin-bedded rippled to parallel silt partings locally, tabular geometry	Some small burrows locally; abundant plant fragments and spores	Lake
5	Muddy siltstone with rare, widely dispersed and very thin beds of very fine-grained sandstone	Blue-gray; blocky structure, rippled and parallel laminated but locally but typically massive, local well-developed paleosols with red to pink alteration halos present, tabular geometry; siderite concretions found locally	Rooted horizons locally; very minor burrowing locally (*Arenicolites, Skolithos*, and *Planolites)* in sandstone	Coastal and non-coastal fluvial flood basin
6	Medium to very thick-bedded fine-grained sandstone interbedded with blue-gray muddy siltstone	Sandstone - current and oscillation rippled and small-to medium-scale planar and trough cross bedding; clay draped ripples rare; herringbone cross bedding and clay-draped planar cross-bed foresets locally in thickest beds; Siltstone - rippled-to-thickly laminated	Abundant plant fragment impressions; local rooted horizons; abundant dinosaur tracks; burrows uncommon *Teredolites, Skolithos, Planolites, Arenicolites*, and rare *Thalassinoides*	Marine-influenced fluvial
7	Medium to very thickly-bedded fine-grained sandstone interbedded with thin to very thin-bedded silty mudstone	Sandstone - current and oscillation rippled or small-scale planar cross bedded; channel scours locally that are commonly lined with clay rip-ups; clay-draped ripples common Mudstone - dark gray, thickly laminated-to-rippled Beds are parallel, and have depositional dip of approximately 10 degrees and constitute "inclined heterolithic strata"	Lignite fragments and plant fragment molds common; burrowing is minimal overall and comprise *Teredolites, Skolithos, Planolites, Arenicolites,* and rare *Thalassinoides*	Tidally influenced point bar

Table 1. Principal lithofacies in Upper Albian–Lower Cenomanian strata of the southern Western Interior Basin (modified after Holbrook, 2001; Akins, 2003). Distribution of lithofacies assemblages is depicted in Figure 3 as follows: assemblages 1–2 (fluvial sandstone); 3–5 (flood basin strata); 6–10a (paralic strata); 10b–12a (restricted shoreline); 12b (open marine strata); and 1–10 (valley-fill undifferentiated).

Figure 3 (right). Longitudinal cross section of Upper Albian–Lower Cenomanian strata in the southern Western Interior Basisn from the Huerfano Canyon area of southeastern Colorado down paleo-depositional dip to east-central New Mexico (Locations shown in Fig. 1); modified from Holbrook et al., 2006).


NW
Huerfano Canyon
Purgatoire Canyon
Cahill Canyon Area
Dry Cimarron Canyon
Colorado
New Mexico/
Oklahoma
SE
Romeroville Ss
Upper
Transitional
Mbr
Graneros Thatcher Limestone Mbr
(0.2m thick; 95.78Ma slightly below base)
Cucharus
Canyon
Section
0-16m
Romeroville Ss
11-22m
Mesa Rica Ss
Graneros Lower Shale Mbr
1-9m
5-7m
SB3 (SB3.1 &
SB3.2 composite)
3-13m
8-18m
Skull Creek Shale/
Glencairn Fm
Dry Creek Canyon Fm
1-12m
5-19m
Higbee Section
TS4
0-3m
Etling Lake Section
Pajarito Fm
TS3.2 (>97.85Ma)
SB4 (97.85Ma to 97.17Ma)
TS3.1
(>98.2 Ma)
Upper Mesa Rica Mbr
0-6m
Middle Mesa Rica Mbr
Lower Mesa Rica Mbr
10-15m
SB3.2 (98.2Ma to 97.85Ma)
TSE
Plainview Fm (0-10m)
Apishipa
Uplift
SB2
SB2/TSE
Scale
10 m
0
10 km
Scour-depth
Longitudinal Profile
Las Animas
Uplift
TSE
Glencairn Fm
SB3.1 (100ma
to 98.47ma)
Tucumcari Shale
SB2
Glencairn Fm.
(Long Canyon Mbr; 0-10m)
Tucumcari Shale
(Campana Mbr; 0-5m)
Fluvial Sandstone (active channel and bar, weak-flow channel fill)
Flood-Basin Strata (coastal flood basin, swamp, lake)
Open-Marine Strata
Paralic Strata (tidally influenced pointbar and other marine-influenced fluvial, tidal channel, subtidal bar, brackish to freshwater estuary fill)
Restricted Shoreline (brackish to marine estuary fill, prograding shoreface parasequences, restricted shelf)
Valley Fill Undifferentiated
SB - Sequence Boundary; TSE - Transgressive Surface of Erosion; TS - Transgressive Surface

Etling Lake, Oklahoma (EL)
Black Mesa State Park



Marine shale (L.A. 12).

Covered slope of siltstone and silty sandstone capped by thin-bedded fine-grained rippled sandstone with abundant siderite (L.A. ?).

Covered slope of siltstone and silty sandstone capped by thin-bedded fine-grained rippled sandstone with abundant *Skolithos* and *Planolites* (L.A. ?).

(L.A. 11; 20.7-30m)
Coarsening up interval, dark-gray fissile shale grading up to thin-bedded silty sandstone, capped by thin-bedded hummocky cross-stratified, fine sandstone.

Coarsening up interval, rippled siltstone grading up to thin-medium-bedded wave-rippled fine-to-medium-grained sandstone, top intensively rooted, dinosaur tracks, *Thalassinoides, Planolites, Arenicolites*, and *Skolithos* in upper sandstone.

Coarsening up interval, rippled siltstone grading up to thin-medium-bedded wave-rippled fine-to-medium-grained sandstone, top intensively rooted, dinosaur tracks, *Thalassinoides* and *Planolites* in upper sandstone.

Coarsening up interval, dark-gray fissile carbonaceous shale grading up to thin-bedded silty sandstone, capped by rooted medium-bedded fine sandstone, well developed *Arenicolites* in top.

Intensively rooted rippled fine sandstone above very-thin bedded rippled to parallel laminated orange to pale yellow silty mudstone.

Medium-scale trough and planar cross bedded sandstone with channel scours and layer of carbonaceous shale (L.A. 1 and 3).

Partly covered, two upward-coarsening cycles, each cycle is basal blue-gray siltstone grading up to rippled sandstone (L.A. 11).

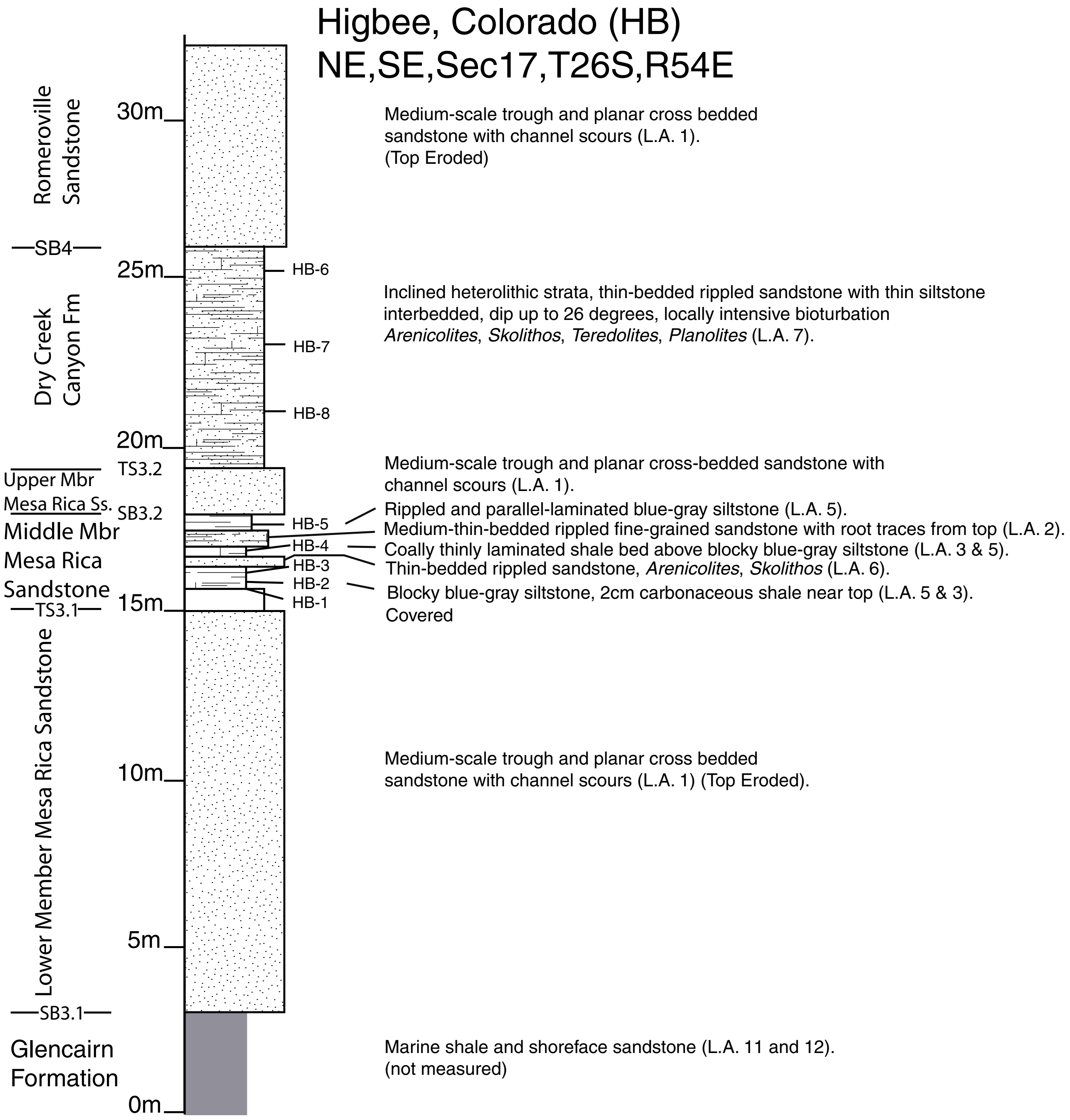
Medium-scale trough and planar cross bedded sandstone with channel scours (L.A. 1).

Marine shale and shoreface sandstone (L.A. 11 and 12) (not measured).

Sequence/ Cluster	Characteristics of palynomorph groups and dispersed organic matter	Marine influence	Palynofacies
3.1A	Rare marine palynomorphs present; all but one sample have amorphous organic matter (AOM); also has highest percentages of sporomorphs; variable percentages of other palynomorphs and organic matter components.	Strongly brackish/ Marginal marine	II
3.1B	No marine palynomorphs in all samples; some AOM in only three samples of lacustrine origin; variable percentages of other palynomorph and organic matter components, including very high percentages of unstructured and comminuted phytoclasts in three samples (>89%), and fairly high percentages of black debris in three other samples (~25-40%; evidence of recycling?).	Non-marine (Freshwater)	I
3.2A	Highest percentages (3-14%) and diversity of marine palynomorphs; also has highest percentages (mostly 20-33%) of AOM; moderate percentages (12-20%) of structured and high percentages (30-70%) of unstructured phytoclasts.	Shallow marine	III
3.2B	Less than 2% to 7% of marine palynomorphs in all but six samples; rare to moderate percentages of AOM (1-20%); fairly high percentages of unstructured and comminuted phytoclasts (40-60%); variable but moderate to high percentages of structured and unstructured phytoclasts (18-60%); black debris generally between 6% and 19% in several samples; persistent but low percentages of fungal remains in Earrington Springs samples.	Weakly-strongly brackish/ Marginal marine	II
3.2C	No marine palynomorphs (except rare occurrence in two samples); all but four samples do not have AOM; rare but persistent occurrence of fungal remains and freshwater algae in samples with AOM (lacustrine); very high percentages of structured phytoclasts (mostly 50-90%); seven samples with moderate to high percentages of black debris (mostly 17-40%).	Non-marine (Freshwater/ Lake)	I
3.2D	No marine palynomorphs or AOM, high to very high percentages of unstructured phytoclasts (31-88%); black debris prominent (13-38%) in eight samples.	Non-marine (Freshwater/ Swamp)	I
4A	Samples have few marine palynomorphs; some AOM (3-7%); and moderate to high percentages of structured phytoclasts (>45%).	Strongly brackish/ Marginal marine	II
4B	Moderate to high percentages of AOM (11-29%) and some marine palynomorphs (<1-7%); and high percentages of unstructured phytoclasts (47-81%).	Shallow marine	III
4C	Highest percentages of AOM (19-29%), the most marine palynomorphs in interval (2-7%), and subequal percentages of structured and unstructured phytoclasts.	Shallow Marine	III

Table 2. Summary of palynofacies data for sequences 3.1, 3.2 and 4, and correlation with inferred depositional conditions. Figures 5–7 show sample clusters.

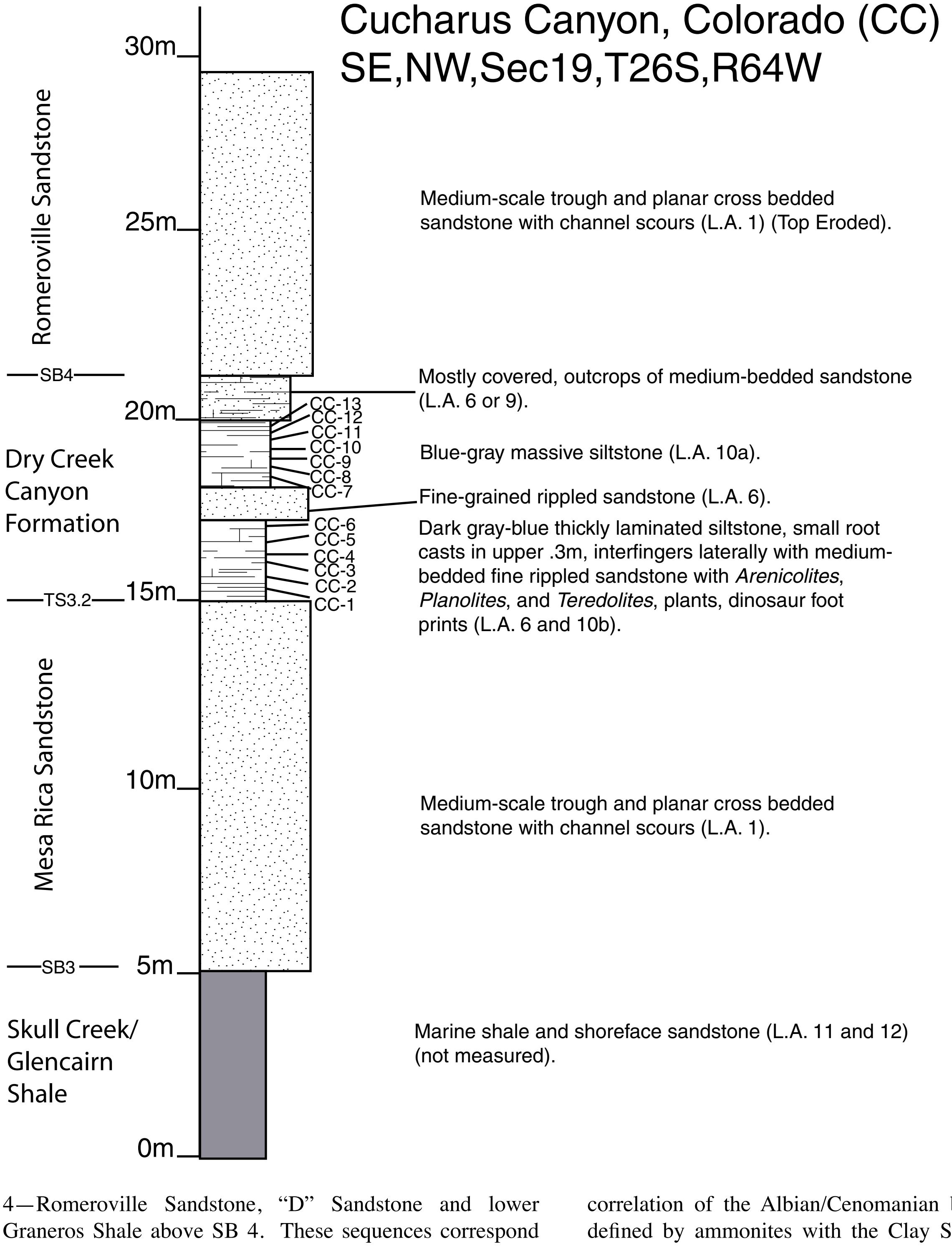
Figure 4 (left and next three figures). Representative sections illustrating lithofacies and sequence stratigraphy in the southern Western Interior Basin. See Figure 1 for locations of sections. (A) Etling Lake section at Black Mesa State Park, Cimarron County, Oklahoma. (B) Section near Higbee, Colorado. (C) Section at the Cucharus/Huerfano Canyon. (D) Fountain Creek section.



RESULTS

SEQUENCE SUBDIVISIONS

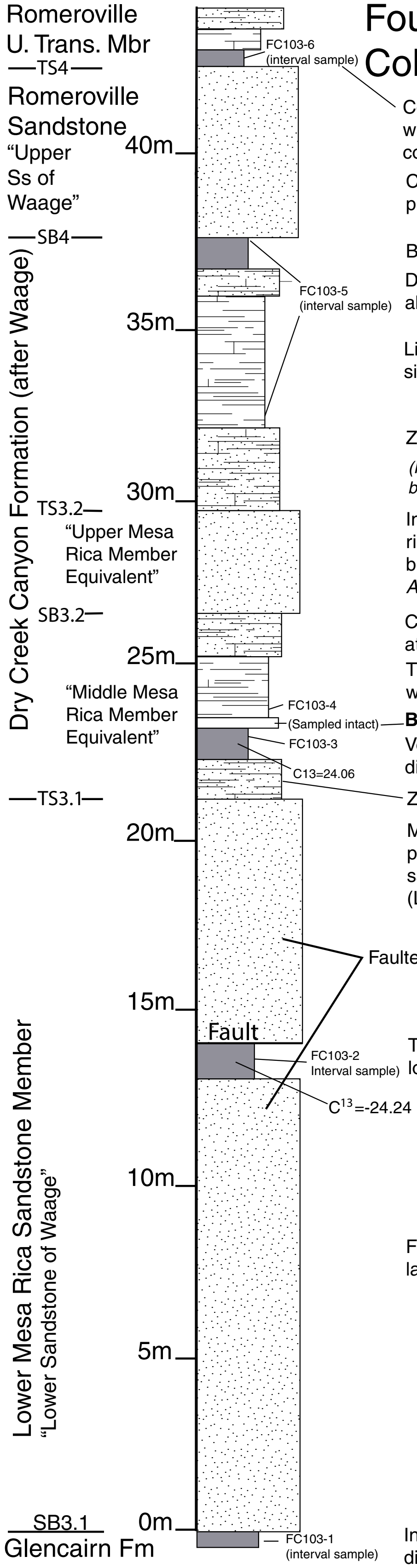
Stratigraphic units are divided into four sequences: (1) Sequence 2—Glencairn Formation and Tucumcari Shale, below sequence boundary SB 3.1; (2) Sequence 3.1—Lower and Middle members of the Mesa Rica Sandstone, between SB 3.1 and SB 3.2 [SB 3.1 separates marine sandstone of the Tucumcari Formation from fluvial sandstone of the Mesa Rica Sandstone (Scott et al., 2004a), which were grouped into the Mesa Rica by some previous workers (Gilbert and Asquith, 1976; Gage and Asquith, 1977)]; (3) Sequence 3.2—Upper Member of the Mesa Rica Sandstone, Dry Creek Canyon Formation, Pajarito Formation, Huntsman Shale and Van Bibber Shale, between SB 3.2 and SB 4; and (4) Sequence



4—Romeroville Sandstone, "D" Sandstone and lower Graneros Shale above SB 4. These sequences correspond to the four-step series of transgressive/regressive events identified in the study area that collectively culminated in the Late Cretaceous Zuni flooding (see discussion of cycles below).

The sequences are dated by integration of biostratigraphy and radiometric dates (Scott et al., 2004a). The time scale for the Albian and Cenomanian in this report is based on correlation of the Albian/Cenomanian boundary in Texas defined by ammonites with the Clay Spur Bentonite Bed of the Mowry Shale (Scott et al., 2004b), which is dated at 97.17 ± 0.69 Ma (Obradovich, 1993). Discussion of the departure from the most recent scale in which the age of this boundary is 99.6 ± 0.9 Ma (Gradstein et al., 2004) is beyond our objectives; it is discussed more fully by Oboh-Ikuenobe et al. (2007). Obradovich analyzed argon isotope ratios of single crystals from the white bentonite bed at 50.2 m in the

Fountain Creek Section of Waage, 1953 (FC) Colorado, Lat N38 40.361' Long W104 51.293'



Coarsening upward interval 5m thick starting with dark-gray shale, and ending with fine-grained sandstone. Sparse spore and pollen. Entire interval is completely bioturbated (L.A. 11 and 12).

Cross-bedded and rippled fine-grained sandstone with local mudstone partings (L.A. 1 and 2).

Blocky laminated dark-to-medium-gray shale (<10%silt) (L.A. 5 or 12).

Dark-red-brown thinly rippled fine-to-very-fine-grained sandstone with abundant and disseminated charcoal fragments (L.A. 6).

Light-to-medium gray brown slightly fissile thickly laminated to slightly rippled siltstone with very-fine sandstone locally. Sparse spore and pollen (L.A. ?).

Zone of interfingering of units above and below.

(Note: Waage (1953) recorded shark teeth and bivalves in Dry Creek Canyon section here, but the unit could not be verified.)

Interval of inclined heterolithic strata with thin-to-medium beds of fine-grained rippled to cross-bedded sandstone interbedded conformably with very-thin-medium-bedded rippled siltstone and mudstone. Present are abundant *Planolites*, *Arenicolites*, *Lockia*, and cf. *Rhizocorallium*. Charcoal abundant in lower 0.7m (L.A. 7).

Coarsening upward interval with medium-thin fine-very-fine sandstone beds at top (L.A. 11).

Thinly laminated light-to-medium-gray clay to silty clay fissile shale. Interfingers with beds above (L.A. 12).

Bentonite layer 10cm thick, white with yellow mottles, clay (98.72+/-0.31Ma).

Very-dark-gray thinly laminated shale (<20% silt) and concoidal fracture, dinoflagellates. Diverse spore and pollen and leaves (L.A. 12).

Zone of intertonguing for units above and below

Mixed thin-medium-bedded rippled sandstone with thin-to-very-thin mudstone partings and wedges/lenses of planar and trough cross-bedded fine-grained sandstone. Abundant *Planolites* and *Skolithos* burrows in top 1m only (L.A. 1 and 2, capped by 6).

Faulted/duplicated section

Thinly laminated medium-to-dark-gray very fissile shale. Locally nodular and locally rippled. Some white and yellow staining, diverse spore and pollen (L.A. 12a).

Fine-medium-grained planar and trough cross-bedded sandstone with local conglomeratic layers and wood impressions (L.A. 1 and 2).

Incomplete section; (24m+) of dark-gray shale and bioturbated sandstone, dinoflagellates, spores, and pollen (L.A. 11 and 12).

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Fountain Creek section (Fig. 4D) (Table 5; for methodology see Obradovich et al., 2002). This bentonite is 10 cm thick and overlies a dark gray shale 24 m above the base of Waage's (1953) Lower Sandstone unit of the Dakota Sandstone. We correlate the derived age of 98.72 ± 0.31 Ma to the Middle Shale Member of the Mesa Rica Sandstone to the southeast.

LITHOFACIES

Mid-Cretaceous rocks spanning the Plainview through Graneros strata are subdivided into twelve lithofacies assemblages (Table 1). The Plainview and equivalent strata constitute valley-fill deposits with an erosional basal contact and locally include a wide range of lithofacies. These strata, however, are dominated by terrestrial/fluvial channel lithofacies assemblages 1–2 and, to a lesser degree, paralic assemblages 6 and 9–10a. One distinction between this unit and higher Mesa Rica and Romeroville units is that fluvial units are commonly bioturbated. This bioturbation is attributed to both marine influence on fluvial systems (assemblage 6) and downward burrowing of fluvial strata from above during marine transgression. Marine units of the Skull Creek and equivalent strata (lithofacies assemblages 11 and 12) disconformably overlie the Plainview and equivalent strata. The relative proportions of assemblage 11 and 12 are variable, with a tendency for more (up to 3–5) intervals of assemblage 11 in up-dip regions and fewer (0–2) assemblage 11 intervals in down-dip extremes of the Tucumcari Shale. Assemblage 12a is present among deposits of 12b but is not differentiated in Figure 3.

The Lower and Upper members of the Mesa Rica Sandstone and the Romeroville Sandstone are dominated by lithofacies assemblage 1, and, to a lesser degree, lithofacies assemblage 2. The basal contact of each of these units is an erosive unconformity, but lithofacies assemblage 6 in down-dip areas characterizes their upper surfaces. These units record a high degree of vertical and lateral reworking by fluvial channels, which winnowed finer-grained flood-basin deposits and preserved sheets of sandy, amalgamated channel-fill and bar deposits (Holbrook, 2001; Holbrook et al., 2006). The Lower and Upper members of the Mesa Rica generally interfinger with overlying lithofacies of the Middle Mesa Rica Member and Dry Creek Canyon Formation, respectively. The contact between the Romeroville and overlying Graneros Shale, however, is generally sharp.

Strata of the Middle Mesa Rica and the Dry Creek Canyon Formation may contain all twelve assemblages listed in Table 1. These assemblages are not equally represented, and their geographic distribution is not uniform (Fig. 3). Up-dip areas of both Middle Mesa Rica and Dry Creek Canyon are dominated by finer-grained assemblages 3–5, recording environments typical of fluvial floodplains. These floodplain strata encase subequal amounts of fluvial channel assemblages 1 and 2. Volumetrically, lithofacies assemblages 1, 2 and 5 are the most significant in these areas. The fluvial strata record a generally aggrading fluvial system. Some minor degree of marine influence is locally apparent in the form of scattered marine trace fossils, and is expressed in the sandstone layers as lithofacies assemblage 6. This trend is more apparent both up-section and down-dip in both units. These dominantly fluvial units grade down-dip into paralic deposits of assemblages 6–10a, which also wedge in from the top of each section. Estuary fill (10a) and subtidal bar (9) deposits appear to be the most dominant assemblages, but fluvial (1, 2) and marine-influenced fluvial (6) assemblages are also common, illustrating the intertonguing nature of the fluvial and paralic deposits. Some paralic deposits are apparent in the Dry Creek Canyon Formation in the up-dip areas of Huerfano Canyon (Fig. 4C). These strata likely record a tongue of the Boreal sea which intruded south along the relatively lower west flank of the Las Animas arch during maximum transgression at this time (see Discussion section below). Paralic units of the Middle Mesa Rica member and Dry Creek Canyon Formation pass down-dip into restricted shoreline deposits of lithofacies assemblages 10b, 11 and 12a. These assemblages are common in these areas. Locally (e.g., John Martin Reservoir, Perky/Shields Ranch, Fife Ranch), deposits of assemblage 12b interfinger with paralic deposits of the Dry Creek Canyon/Pajarito formation, suggesting local and ephemeral intrusion of open-marine waters into the extreme down-dip areas during deposition.

The Graneros Shale is dominated by lithofacies assemblage 12b (although assemblage 12a does occur, particularly in the lower part of the section). Shoreface deposits of assemblage 11 are also not found in the Graneros Shale over most of the area. The upper transitional member of the Dakota Sandstone in the Rocky Mountain exposures (e.g., Vertical Red Wing), however, may record transgressive shoreface sand of this lithofacies (Odien, 1997).

PALYNOFACIES

Palynofacies assemblages represent non-marine (freshwater/weakly brackish; I), strongly brackish/marginal marine (II) and open/shallow marine (III) conditions. These interpretations are confirmed by chemofacies data (Appendix 4). The Pajarito Formation in northern New Mexico contains a non-marine assemblage of fifteen spore and pollen taxa (R.H. Tschudy *in* Baltz, 1990).

Samples from shallow marine-facies III (e.g., Huntsman Shale in the Nordman well and the Graneros Shale) have an abundant and diverse assemblage of dinoflagellate cysts and acritarchs, in addition to high percentages of AOM and >50% terrestrial components, such as spores, pollen, phytoclasts and black debris. The average $\delta^{13}C$ value for the marine samples is –25.56, and the organic carbon/sulfur (C/S) ratio is 0.16. Samples from the facies of the brackish/marginal marine paleoenvironments II have rare occurrences

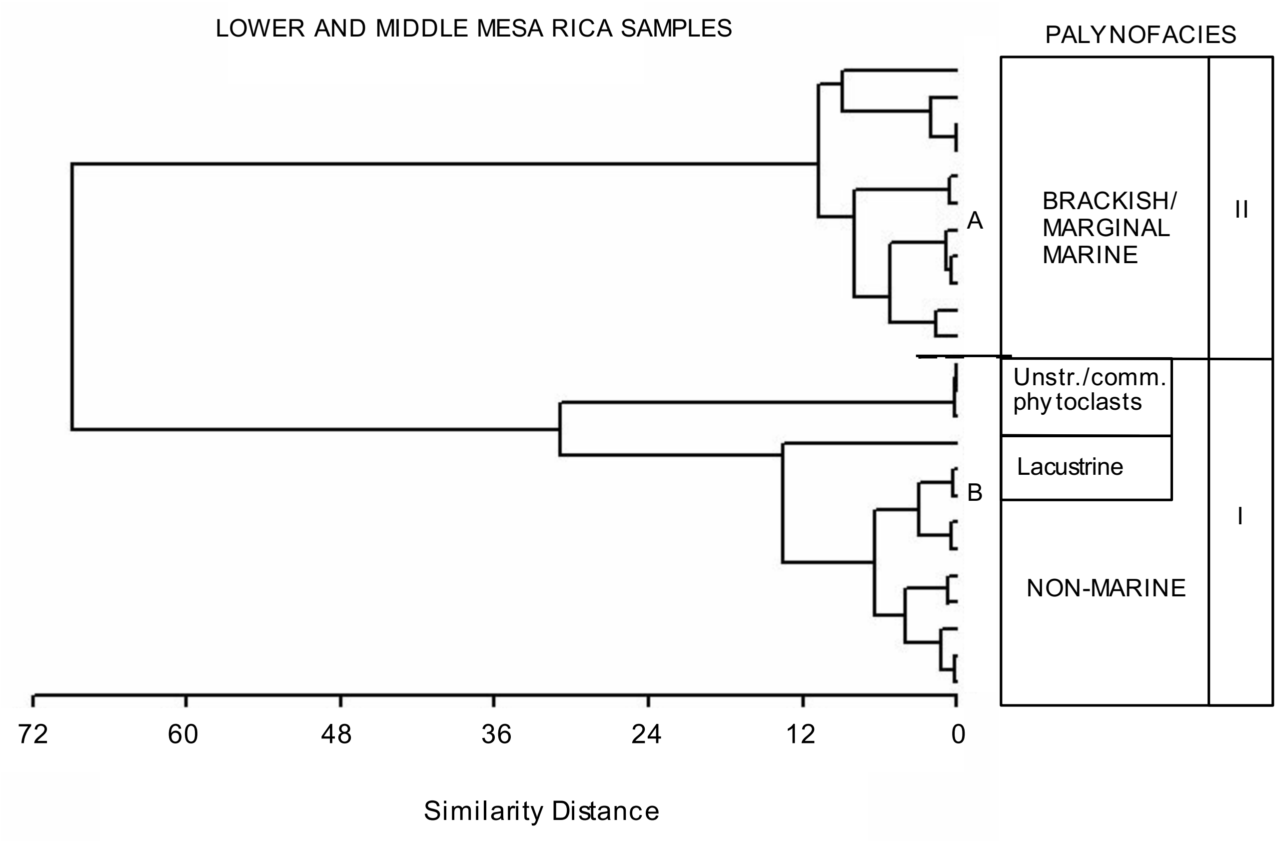

Figure 5. Dendrograms for the average linkage cluster analysis of palynological samples (Q-mode) and inferred depositional environments of sequence 3.1.

of marine palynomorphs and AOM, whereas non-marine samples (I) lack these two components. The C/S ratios for these latter two assemblages are low, ranging from 0.02 to 1.64 and averaging 0.20. They also have low $\delta^{13}C$ values <–25.0. The palynofacies assemblages appear to be similar in each stratigraphic interval. Angiosperm and less commonly conifer foliage is also present in sandstones of the Glencairn and Mesa Rica formations (Kues and Lucas, 1987).

FORAMINIFERAL ASSEMBLAGES

Two assemblages of the *Ammobaculites* biofacies support the environmental interpretations (Table 3). A low-diversity assemblage consists of seven species and suggests a marginal-marine environment (biofacies 2). A moderately diverse assemblage is composed of nine species that supports a shallow marine environment (biofacies 3). The low-diversity *Ammobaculites* biofacies is present above TS 3.2 in the Pajarito Shale and the Dry Creek Canyon Formation (lithofacies assemblages 1–6) in most sections in southeastern Colorado, the Oklahoma Panhandle sections and northeastern New Mexico. The most common taxa are *Ammobaculites obliquus, A. subcretaceus, Miliammina ischnia* and *Verneuilinoides perplexus* (Long, 1966; Scott et al., 2004a), and less common are *Trochammina rutherfordi* and *Trochammina* sp. These species are generally present in the Graneros Shale and rarely in the Pajarito/Dry Creek Canyon. This assemblage indicates a marginal-marine paleoenvironment with a mixed Boreal/Tethyan provenance. The *Ammobaculites* species are most indicative of the southern provenance, and *M. ischnia* and *T. rutherfordi* are characteristic of northern provenance in the Mowry Shale, Huntsman Shale and the pre-*M. mellariolum* interval of the Graneros Shale (Loeblich and Tappan, 1950; Eicher, 1960, 1965). No foraminifers were recovered from the mudrock interval in the Middle Member of the Mesa Rica Sandstone above TS 3.1 and below SB 3.2.

The Dry Creek Canyon Formation at Fountain Creek, and elsewhere in the Colorado Springs area (locality 32 of Long, 1966), yielded siliceous sponge spicules probably representing a shallow- or marginal-marine fauna. It also yielded a single specimen of *Ammodiscus kiowensis*, a marine species that is widespread in the Skull Creek Shale and equivalents in the Western Interior of the U.S.A. and Canada. This foraminiferal species, however, may be reworked from the underlying Glencairn Formation because it occurs in the Glencairn at several other localities in southeastern Colorado (Long, 1966, pl. 12).

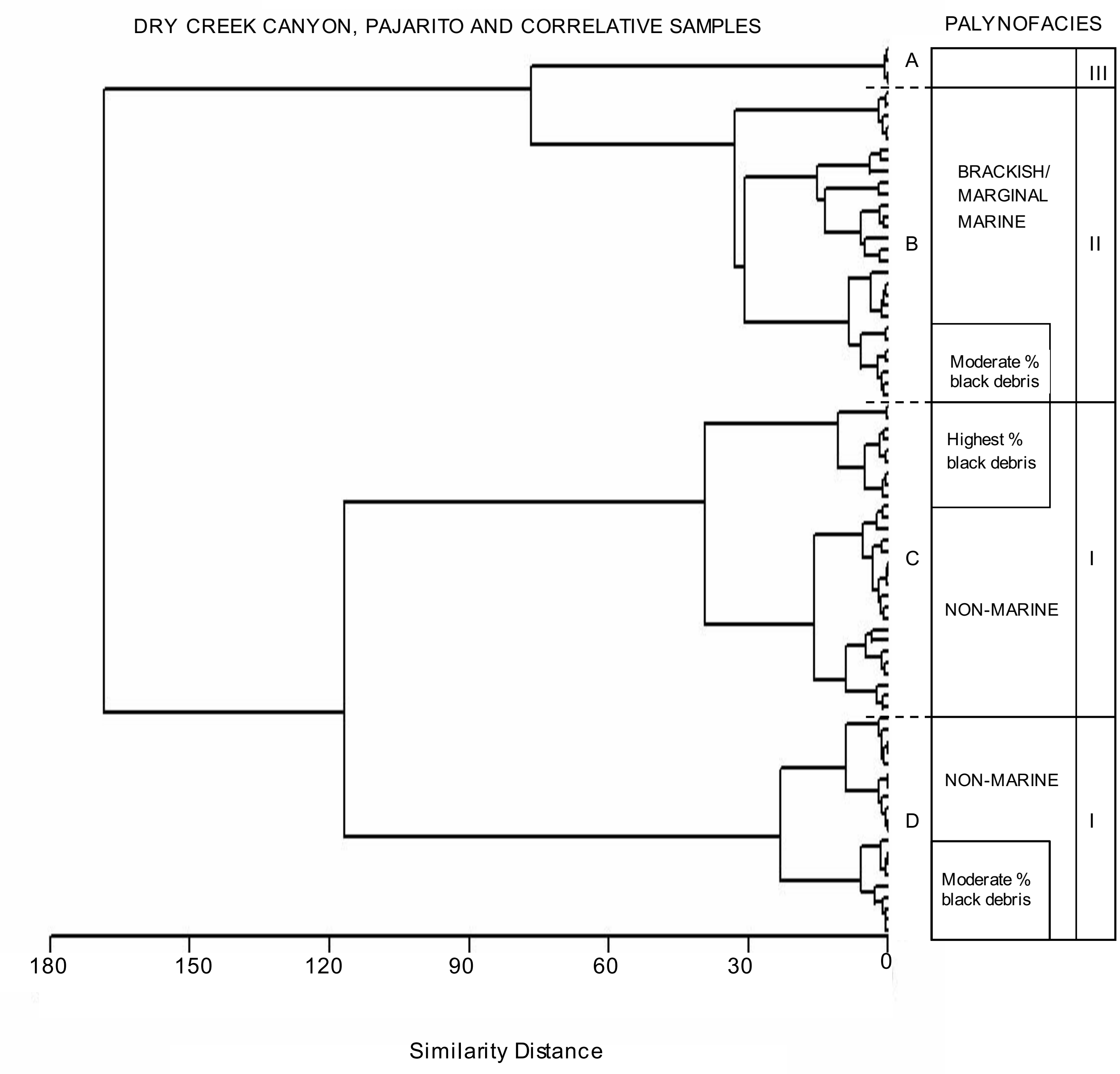

Figure 6. Dendrograms for the average linkage cluster analysis of palynological samples (Q-mode) and inferred depositional environments of sequence 3.2.

ICHNOFACIES AND MACROFOSSILS

Three ichnofossil assemblages are recognized (Table 3). The progressive addition of ichnotaxa and the reduction of dinosaur tracks reflect the change from non-marine to shallow-marine. Ichnofossils are uncommon and of low diversity in the Middle Member of the Mesa Rica Sandstone above TS 3.1 (biofacies 1). Locally the paralic (brackish) *Arenicolites*, *Planolites*, and *Skolithos* are present with rare dinosaur footprints (biofacies 2); marine *Thalassinoides* and *Rhizocorallium* are rare and localized. At Clayton Lake, New Mexico, dinosaur footprints (Hunt and Lucas, 1998) occur on the top bed at the boundary between the Lower and Middle Mesa Rica members.

The Upper Member of the Mesa Rica Sandstone was deposited in a fluvial channel system that was transgressed by paralic environments (Gilbert and Asquith, 1976; Gage and Asquith, 1977; Lucas, 1990; Holbrook, 2001; Scott et al., 2004a). Locally the uppermost bed (TS 3.2) has *Planolites, Thalassinoides* and *Rhizocorallium* (biofacies 3). This facies is similar to the Channel Complex (CH) sandstone facies of the Viking Formation in western Canada (MacEachern and

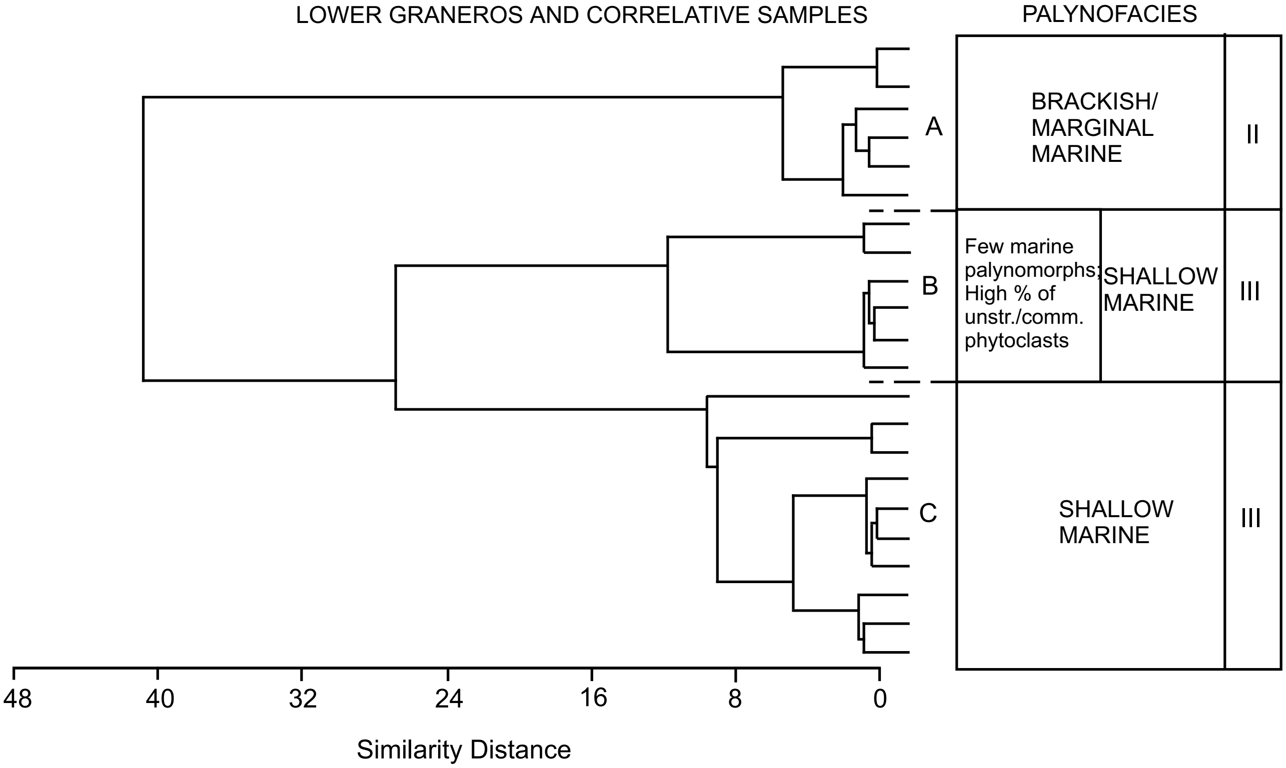

Figure 7. Dendrograms for the average linkage cluster analysis of palynological samples (Q-mode) and inferred depositional environments of sequence 4.

Pemberton, 1994; Buatois et al., 2005). *Rhizocorallium* is also characteristic of shoreface and estuarine deposits of the upper Glencairn Formation (Basan and Scott, 1979).

Above TS 3.2 tracks, trails and burrows are relatively common in sandstones of the Pajarito Formation in the southeastern area, but to the northwest trace fossils are absent in the Pajarito interval at the Romeroville Gap section. Up-section ichnofossil assemblages are indicative of the following depositional conditions: paralic for the Pajarito Formation, non-marine for the Romeroville Sandstone, and marine for the Graneros Shale. The homogeneous sandstone beds in the Pajarito contain root casts up to one metre long as well as plant debris. Wood with *Teredolites* occurs at the Tollgate Pass section. Imprints of a three-toed ornithopod dinosaur, belonging to *Amblydactylus*, are also present in some Pajarito horizons (Kues and Lucas, 1987; Lucas et al., 1987; Hunt and Lucas, 1998), and the base of some beds with footprints have casts of *Thalassinoides*. The succeeding thin-bedded sandstones have *Arenicolites, Skolithos, Planolites* and rare *Rhizocorallium* burrow fills and bedding plane casts of varying diameters, which are reminiscent of the Estuary Mouth Complex (EM) assemblage of MacEachern and Pemberton (1994) and Buatois et al. (2005). But northwestward the Pajarito comprises delta plain and meander-belt facies (in the Dakota Sandstone—Gilbert and Asquith, 1976; in the Mesa Rica Sandstone—Gage and Asquith, 1977).

Bivalves are unknown in the incipient flooding intervals above either TS 3.1 or TS 3.2 north of Tucumcari, New Mexico. South of Tucumcari at the Fife–Lindsey Ranch section, however, the oyster *Peilinia levicostata* Kues (Lucas et al., 2001) is abundant in a thin interval of transported shells, and a single mould of a corbulid clam was recovered from a sandstone bed above. Four species of infaunal bivalves and a gastropod occur rarely in the Pajarito Formation in the Oklahoma panhandle (Kues et al., 1985; Kues and Lucas, 1987). Evidently, fully marine salinity did not develop north of these localities in east-central New Mexico and northwestern Oklahoma.

INTEGRATED BIOFACIES

Assemblages of palynomorphs and foraminifers, and ichnofacies have been used to define integrated biofacies (Table 3). Dominantly non-marine biofacies 1 is characterized by abundant plant and wood fragments, root casts, scattered *Skolithos*, *Planolites* and dinosaur footprints, diverse and abundant spores and pollen, and is found in the Middle Shale Member of the Mesa Rica Sandstone comprising sequence 3.1. Freshwater algae *Botryococcus*

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and *Pediastrum* were more prominent in a lacustrine paleoenvironment (lithofacies assemblage 4) in parts of southeastern Colorado. Marginal Marine biofacies 2 has dinosaur tracks, *Planolites*, *Arenicolites*, *Teredolites* and *Skolithos*, rare *Thalassinoides* and *Rhizocorallium*, a low-diversity assemblage of agglutinate foraminifers, a low-diversity assemblage of dinoflagellates cysts and acritarchs, and abundant spores and pollen. Biofacies 2 is present in parts of the Dry Creek Canyon Formation, the Pajarito Formation, and lower Graneros Shale comprising sequence 3.2. Shallow-marine biofacies 3 consists of abundant trace fossils (similar types as in biofacies 2 with the exception of dinosaur tracks), oysters, moderately diverse agglutinate foraminifers (*Ammobaculites* assemblage), diverse and abundant dinoflagellates cysts and acritarchs, a low-diversity spore assemblage, and abundant AOM. Biofacies 3 is found

Biofacies	Palynomorphs	Foraminifera	Ichnofossils	Macrofossils	Interpretation
1	Diverse and abundant spores and pollen (sporomorphs), including *Alisporites bilateralis, Camarozonosporites insignis, Cicatricosisporites hallei*, *Corollina jardinei, Cyathidites australis*, *Gleichinidites circinidites*, *Gleichiniidites senonicus*, and *Liliacidites* spp.; the freshwater algae *Botryococcus* and *Pediastrum* are preserved in lake sediments.	None	Rare burrows	Abundant plant fragments and impressions, some lignite fragments, root casts	Freshwater/ Non-marine
2	Abundant sporomorphs but slightly less diverse than Biofacies 1; low diversity assemblage of dinoflagellate cysts and acritarchs (mainly *Ovoidinium verrucosum, Palaeoperidinium cretaceum, Pseudoceratium interiorense,* and *Pterosperma* spp); few chitinous inner linings of foraminifera.	Low diversity agglutinated benthic fauna (*Ammobaculites euides, Ammobaculites obliquus, A. subcretaceus, Haplophragmoides* sp., *Haplophragmoides* sp. aff. *H. gilberti, Haplophragmoides* sp. cf. *H. linki, Pseudobolivina variana, Reophax* sp. indet., *Verneuilinoides perplexus*).	Rare dinosaur tracks, few to common burrows of *Teredolites, Planolites, Arenicolities,* and rare *Thallassinoides.*	Root casts and plant fragments; few logs; rare bivalve molds	Brackish/ Marginal marine
3	Diverse and abundant dinoflagellate cysts and acritarchs including *Aptea polymorphum, Apteodinium grande, Circulodinium hystrix, Florentinia resex, F. radiculata, Fromea amphora*, *Leiosphaeridia* spp., *Odontochitina operculata, Oligosphaeridium complex, Oligosphaeridium pulcherrimum, Ovoidinium scabrosum*, *O. verrucosum, Palaeohystrichophora infusorioides, Palaeoperidinium cretaceum, Pterosperma* spp., *Spiniferites multibrevis, Subtilisphaera perlucida*); low diversity assemblage of sporomorphs, and chitinous inner linings of foraminifera.	Moderately diverse agglutinated benthic fauna of the *Ammobaculites euides* "biofacies": *Ammobaculites euides, A. obliquus, A. subcretaceous, Ammobaculoides phaulus, Ammobaculoides plummerae, Ammomarginulina cragini, Haplophragmoides* sp. cf. *H. linki, Lituotuba sp., Pseudobolivina variana, Verneuilinoides perplexus.* Low diversity agglutinated benthic fauna of the *Miliammina manitobensis* Zone of Eicher (1965) in central Colorado: *Miliammina ischnia, M. manitobensis, Psamminopelta bowsheri, Pseudobolivina variana, Reophax* sp. cf. *R. incompta, Spirolocammina* sp. cf. *S. planula, Trochammina rutherfordi, Verneuilina Canadensis, Verneuilinoides hectori*, *V. perplexus*.	*Skolithos* ichnofacies (burrows of *Skolithos, Arenicolities, Planolites, Thalassinoides,* and *Rhizocorallum*).	Oysters	Shallow marine

Table 3. Characteristics of biofacies identified in the study area.

in the lower Graneros Shale (sequence 4) and the Huntsman Shale (sequence 3.2). Locally, oysters are present in the Pajarito Formation. In addition to providing biostratigraphic control for the Late Albian to Early Cenomanian interval (particularly via dinoflagellate cysts—Scott et al., 2004b; Oboh-Ikuenobe et al., 2007), biofacies confirm depositional environments inferred from lithofacies (Table 4) and are integrated with other data to delineate the extent of marine influence in the study area (Figs. 8–10).

MAJOR MID-CRETACEOUS TRANSGRESSIVE–REGRESSIVE CYCLES

The strata studied have been assigned to the Kiowa–Skull Creek Cycle and the beginning of the Greenhorn Cycle (Kauffman, 1977, 1984; Gustason and Kauffman, 1985; Fig. 2). These are third-order cycles. The two maximum transgressive marine marker units of these two cycles, the Kiowa–Skull Creek shales and the Thatcher Member of the Graneros Shale, correlate with strata in northern Texas and the Boreal region of the Western Interior Basin (Scott et al., 2003) and serve as chronostratigraphic anchor points for defining the timing of intervening incomplete cycles. The Kiowa–Skull Creek cycle correlates on the basis of ammonites with the lower Upper Albian Kiamichi-Fort Worth formations in northern Texas, and the Thatcher Member correlates with the Middle Cenomanian Tarrant Formation of the Woodbine Group. The beginning of the Kiowa transgression is dated at 104 Ma (Scott et al., 1998, 2004a) and the Thatcher is 0.9 m above a bentonite dated at 95.78 ± 0.61 Ma (Obradovich, 1993).

This study presents evidence for two additional fourth-order transgressive/regressive episodes between these two major flooding events. These new cycles span the Lower/Upper Cretaceous boundary as defined by ammonites and dinoflagellates (Scott et al., 2001, 2004b; Oboh-Ikuenobe et al., 2007). The studied stratigraphic interval is divided into four shorter-term cycles beginning at the bases of the Kiowa and Glencairn formations (SB 2), the Lower Member of the Mesa Rica Sandstone (SB 3.1), the Upper Member of the Mesa Rica Sandstone (SB 3.2), and the Romeroville Sandstone (SB 4), respectively.

SEQUENCE 2: KIOWA-SKULL CREEK CYCLE

Early Late Albian flooding is represented by the Kiamichi–Duck Creek transgressive cycle in the Gulf Coast about 104 Ma to 100 Ma (Scott et al., 1998, 2001, 2003, 2004a) and rapidly inundated the Western Interior. The base of these units is a sharp transgressive surface of erosion (TS 2) that can be traced continuously from the southernmost exposures in east-central New Mexico north into the central Western Interior near Denver (Holbrook and Wright Dunbar, 1992). Portions of a preceding valley network that was buried by this transgression are preserved under this surface as the Long Canyon and Campana sandstone beds, and the sandstones of the Plainview Formation (Fig. 2). Interestingly these valley fills are not compound and do not reflect multiple filling events during transgressive/regressive cycles. On the other hand, in South Dakota, the equivalent Fall River Sandstone deposited as the Boreal Sea experienced Kiowa–Skull Creek transgression has evidence of multiple filling events and stepwise transgression (Willis, 1998). If, indeed, any such stepwise transgression took place in the south, its evidence was wiped out by the transgressive surface of erosion. The only indication of Cretaceous sedimentation over the southern Western Interior prior to this transgression is a fluvial drainage network preserved by the Lytle and Cheyenne sandstones (e.g., Long, 1966; Holbrook and Wright Dunbar, 1992). The flooding linked the Boreal and Tethyan seas and resulted in the first continuous north-to-south seaway (Kauffman, 1977; Kauffman and Caldwell, 1993).

Regression (recorded by SB 3.1) then split the sea and resulted in Tethyan retreat into east-central New Mexico and the Texas panhandle area (Holbrook and Wright Dunbar, 1992; Holbrook, 1996). Movements on the Las Animas Arch, part of what is traditionally considered the Transcontinental Arch (e.g., Weimer, 1984), apparently contributed to this split between the seaways (Holbrook, 2001).

SEQUENCE 3.1: RENEWAL OF TRANSGRESSION

After the sea retreated, a new, geographically limited transgression took place across a low-gradient coastal alluvial plain into southeastern Colorado about 99 Ma to 98 Ma (Fig. 10A). This event was the first of two steps preceding the more widespread Greenhorn transgression. Streams that formed in the coastal plain during regression were straightened by low gradients as they flowed into the coastal sea, and deposited on the alluvial plain a thoroughly laterally reworked sand unit (Lower Mesa Rica—Holbrook, 1996; Holbrook et al., 2006). Although sinuosity is also dependent upon discharge, bed load and other factors, such non-braided straight alluvial systems are unlikely on slopes greater than about 10^{-3} (Schumm and Khan, 1972). The straight sandy alluvial channels with widths (~ 200 m) and depths (~ 12 m) typical in the study area should have slopes $\leq 10^{-4}$ (Chang, 1985). Considering that the median grain size of these deposits is fine sand and applying the width/depth ratio of 200:12 for the these channels (Holbrook, 1996), we calculate the minimum slope needed to generate the bed shear stress required to transport the preserved bedload using the Shield's method (Bridge, 2003). This slope would be approximately 2×10^{-6}, and would constitute a minimum slope estimate for these channels. Because the thickness of this sand is relatively uniform and only about one channel-storey thick over the area of transgression, we assume that the surface across which the transgression continued had an extremely low gradient within this 10^{-4} to 10^{-6} range.

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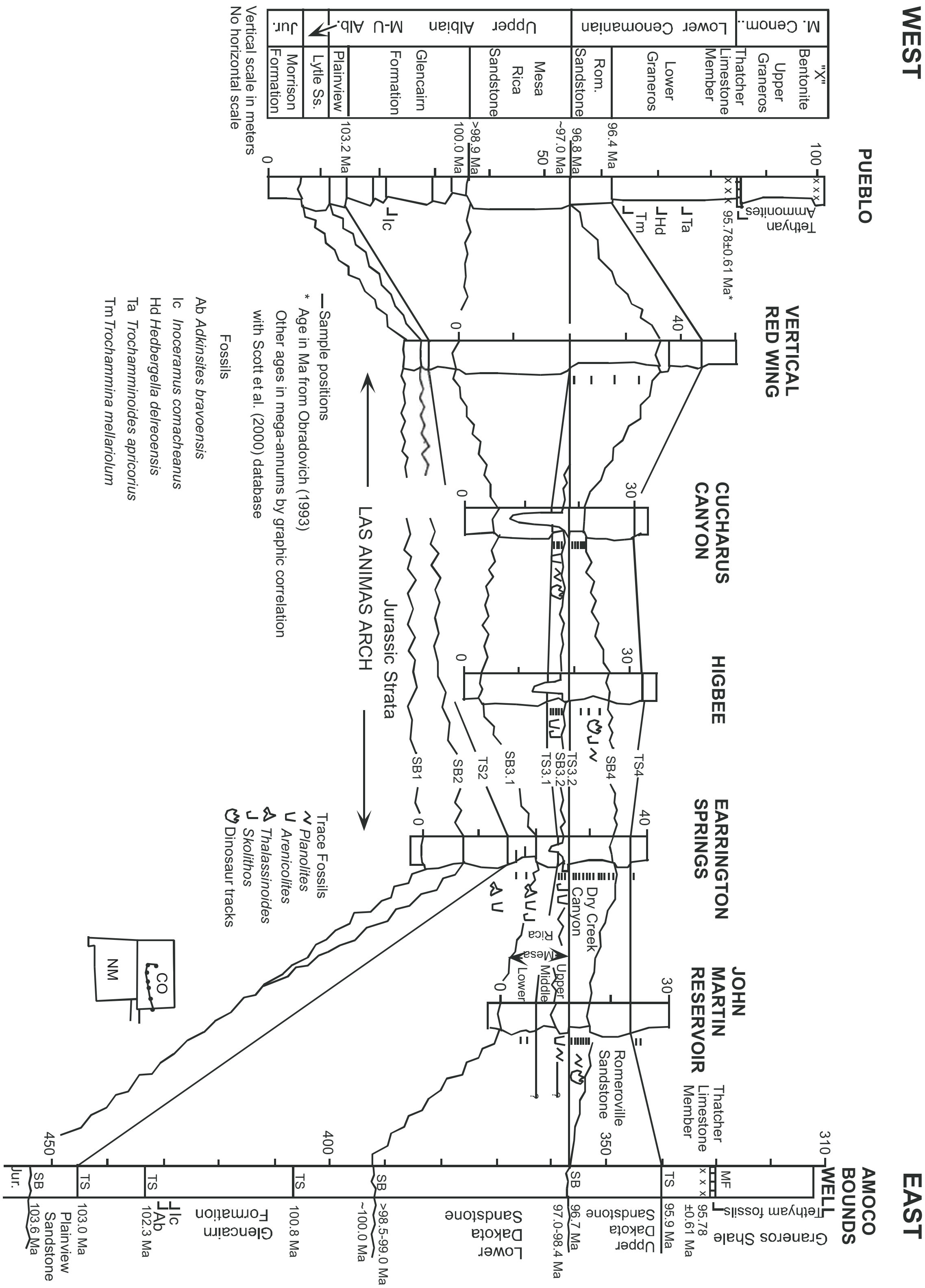

Figure 8. West to east correlation of the Pueblo section in Colorado to the Amoco Bounds Core in western Kansas, showing continuity of depositional sequences and sequence stratigraphic architecture. Sedimentary units consist of sandstone, siltstone and shale, wavy lines are eros□

Depositional Condition	**Lithofacies & environments**	**Chemofacies (δC^{13})**	**Palynofacies/ Cluster**	**Biofacies**
Non-marine (Freshwater/ Weakly brackish)	1,2: Fluvial channel/channel fill 3,5: Swamp/flood basin 4: Lake (lacustrine) 6-8: Tidally influenced fluvial 9: Subtidal bar/sheet 10a: Estuary fill with freshwater influence	< -23.63	I/3.1B I/3.2D I/3.2C I/3.1B - II/3.2B No data I/3.1B	1
Strongly brackish/ Marginal marine	10b: Estuary fill with marine influence 11: Prograding shoreface 12a: Restricted marine	-23.63 to -24.84	II/3.1A II/3.2B II/4A	2
Marine	12b: Open/shallow marine	> -24.84	III/3.2A, 4B, 4C	3

Table 4. Summary of facies data and inferred depositional environments in Tables 1– 3 and Figures 5–7.

This transgression of sequence 3.1 differed from the Kiowa–Skull Creek transgression in that no significant transgressive surface of erosion formed over most of the area. A very low-relief transgressive surface (TS 3.1) developed in the southern parts of the study area near the Perky/Shields Ranch and Etling Lake sections in western Oklahoma (Fig. 4A) where restricted-marine strata (Middle Mesa Rica) overlie the fluvial Lower Mesa Rica. However, this surface everywhere else is transitional between conformable fluvial and overlying fluvial/paralic units (Fig. 4B). This brief transgressive event that deposited the Middle Mesa Rica was followed by a regression that formed a regional sequence boundary (SB 3.2) and produced another overlying sheet of reworked fluvial sand (Upper Mesa Rica). Sandstones of the Upper and Lower Mesa Rica members merge to the west and north into a single sandstone layer, where the intervening sequence boundary SB 3.2 (and the regression it records) is indistinguishable (Fig. 4C) (Scott et al., 2004a; Holbrook et al., 2006).

SEQUENCE 3.2: THE DRY CREEK/PAJARITO TRANSGRESSION

The third cycle comprises the Upper Mesa Rica Sandstone and the Pajarito Formation and the upper part of the Dry Creek Canyon Member deposited about 98 Ma to 97 Ma. The Upper Mesa Rica sands were laid down by low sinuosity, non-braided channels that produced local valleys (Holbrook et al., 2006). Although these channels were generally much smaller in size than those of the Lower Mesa Rica, they likely produced a similar constructional surface with similar shallow gradients. The deposition of the Upper Mesa Rica was succeeded by a transgression that extended considerably farther north than the transgression of sequence 3.1 (Fig. 10B). A discrete transgressive surface is observed only locally in areas where delta plain (Kues and Lucas, 1987) and restricted-marine strata (Dry Creek Canyon in Colorado and Pajarito Formation in New Mexico; Scott et al., 2004a) overlie fluvial units (Fig. 4A). Otherwise, the boundary is transitional and forms above a constructional low-gradient

Lab No.	Grains	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	K/Ca	% Rad	$^{40}Ar/^{39}Ar$	Age Ma	±δ
7JDO35-1	1	7.313709	0.009092	0.000074	53.89	99.63	7.286985	98.87	0.20
7JDO35-2	2	12.511037	0.006880	0.000288	71.22	99.28	12.420879	165.41	*0.32*
7JDO35-3	1	7.356687	0.003246	-0.000077	150.96	100.24	7.374325	100.02	*0.25*
7JDO35-4	1	7.306420	0.007719	0.000132	63.48	99.40	7.262532	98.58	0.21
7JDO35-5	1	7.307972	0.006706	0.000165	73.09	99.26	7.254044	98.44	0.20
7JDO35-6	2	7.301054	0.006852	0.000066	71.51	99.66	7.276607	98.73	0.21
7JDO35-7	1	7.376010	0.006676	0.000246	73.40	98.94	7.298048	99.02	0.21
7JDO35-8	1	8.707203	0.007379	0.000292	66.41	98.64	6.615769	89.99	0.19

Table 5. $^{40}Ar/^{39}Ar$ analytical data for the bentonite in the lower shale of the Dry Creek Canyon Formation (field sample FC103-157; bentonite bed is 24 m above the base of Waage's [1953] Lower Sandstone Unit of the Dakota Sandstone); this interval is correlated with the Middle Shale Member of the Mesa Rica Sandstone. The unweighted mean age is 98.72 Ma and the error of the mean at the 95% confidence level is 0.31. Italicized values were not used to generate the mean age. Reactor corrections: $(^{36}/^{37})Ca = 2.64x10^{-4}$; $(^{39}/^{37})Ca = 6.73x10^{-4}$; $(^{40}/^{39})K = 5.68x10^{-3}$. (Modified from J.D. Obradovich, written comm. 2003).

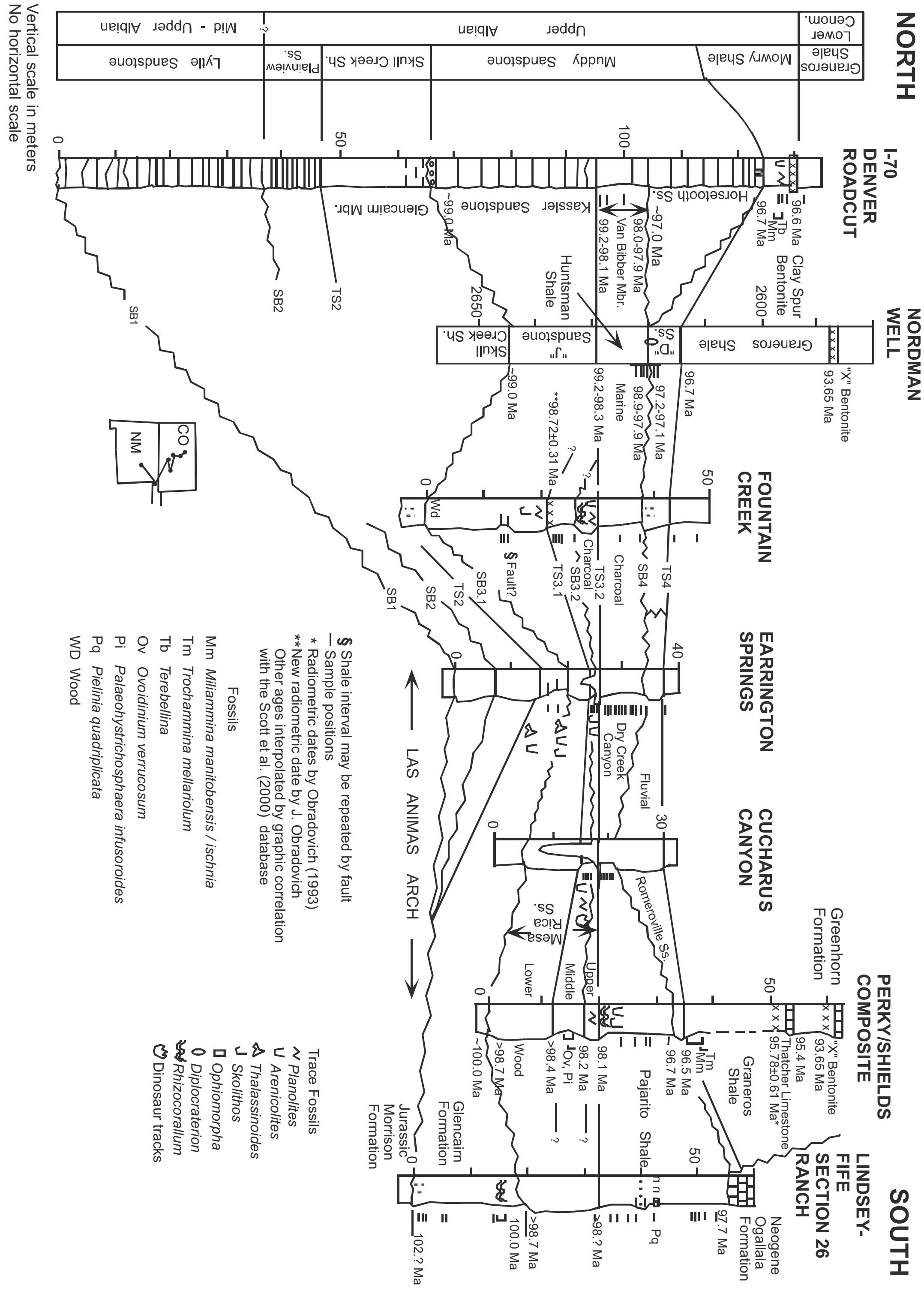

Figure 9. North-to-south correlation of the I-70 Denver Roadcut section in Colorado through the Perky/Shields composite section in Oklahoma to the Lindsey–Fife Section 26 Ranch in New Mexico, showing continuity of depositional sequences and sequence stratigraphic architecture. Sedimentary units consist of sandstone, siltstone and shale, wavy lines are erosive contacts, and inset map shows position of the cross section. Horizons that yielded key fossils and trace fossils are shown.

alluvial surface (Fig. 4C). The transgression, however, brought restricted-marine waters up the axis of the basin for a considerable distance in order to form an ephemeral link with the Boreal Sea to the north (see Sequence 4 below). This event was followed by a regression that produced sequence boundary SB 4 after which fluvial strata of the Romeroville Sandstone were deposited (Fig. 4B) (Holbrook et al., 2006).

SEQUENCE 4: GRANEROS TRANSGRESSION OF THE LONG-TERM GREENHORN CYCLE

The fluvial Romeroville Sandstone consists of amalgamated low-sinuosity fluvial channel fills. The Romeroville was flooded abruptly and experienced little aggradation before being overlain by open-marine strata (Holbrook, 2001; Holbrook and Oboh-Ikuenobe, 2002). The transgressive surface has no widespread pebble lag or intensive truncation of underlying units over this area and probably records minimal removal of aggradational material by transgressive erosion. Consequently, the restricted marine strata of the lower Graneros Shale overstep sharply onto the surface of amalgamated fluvial sandstone beds that were deposited during falling stage, lowstand, and early transgression (Holbrook, 2001; Holbrook and Oboh-Ikuenobe, 2002; Fig. 10C). During the subsequent transgression, the Las Animas Arch was inundated, and the Middle Cenomanian connection between the Boreal and Tethyan seas was re-established. The two biotas became mixed in southeastern Colorado and the Oklahoma panhandle. The Thatcher Limestone Member marks a full connection of the Boreal and Tethyan seas. Although transgressive/regressive events continued (e.g., Niobrara, Bearpaw and Claggett formations), this connection remained unbroken and persisted until the earliest Maastrichtian (Kauffman, 1977; Kauffman and Caldwell, 1993).

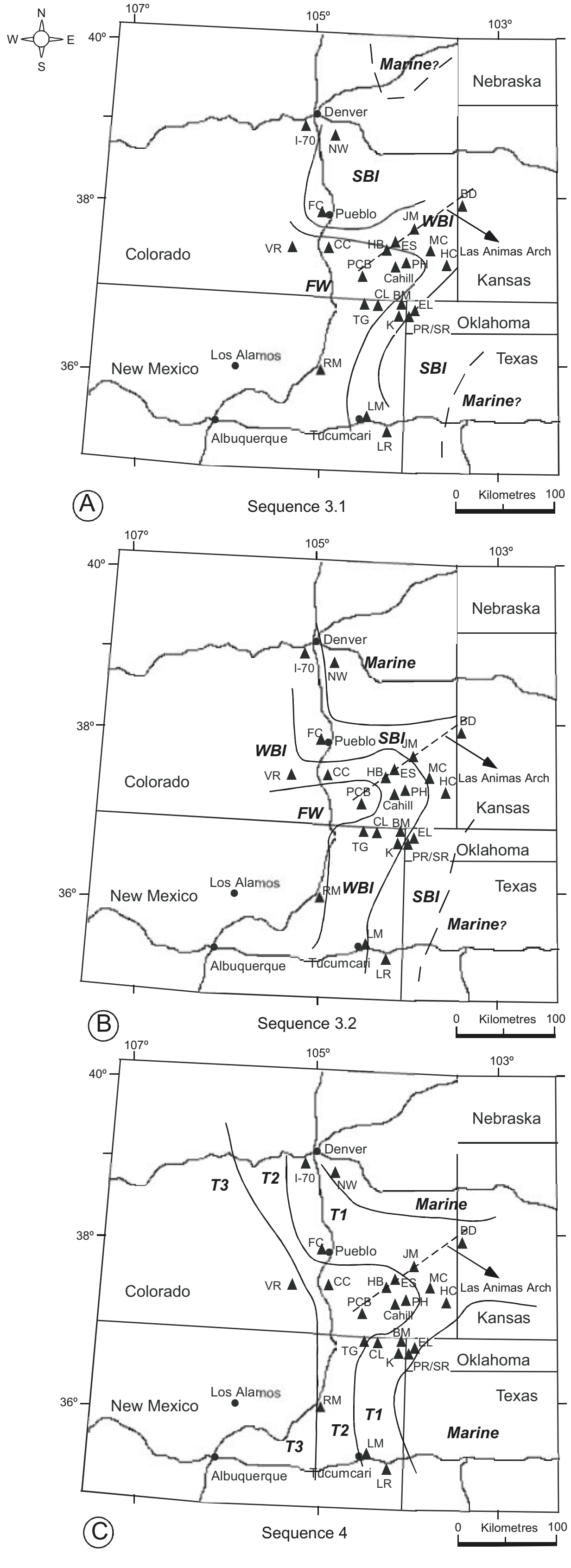

Figure 10. Reconstructions of lateral extent of marine influence in the Southern Western Interior Basin. Locality names are in Figure 1. (A) Middle Mesa Rica sequence 3.1 maximum transgression. (B) Dry Creek/Pajarito maximum transgression of sequence 3.2. (C) Graneros transgression (T1–T3) above transgressive surface 4 on the Romeroville Sandstone during the early stage of the long-term Greenhorn cycle. Basal sediments of the lower Graneros Shale are characterized by brackish features. Criteria for reconstructions are as follow: FW (freshwater) = dominated by lithofacies assemblages 1–5, integrated biofacies 1, palynofacies I and non-marine chemofacies; WBI (weak brackish influence) = lithofacies assemblages 5–10a, integrated biofacies 2, palynofacies I and II, and non-marine to brackish chemofacies; SBI (strong brackish influence) = lithofacies assemblages 10b–12a, integrated biofacies 2 and 3, palynofacies II, and brackish chemofacies; Marine = dominated by lithofacies assemblage 12b, integrated biofacies 3, palynofacies III, and marine chemofacies.

CHARACTERISTICS OF THE COASTAL SYSTEMS DURING A FOUR-STEP FLOODING EVENT

Four Late Albian and Early Cenomanian transgressions took place across a low-gradient alluvial plain, and it appears that only a modest increase in relative sea level was required. For example, transgression that deposited the Middle Mesa Rica Member from eastern New Mexico to southern Colorado covered a distance of roughly 200 km. The estimated maximum slope value for the flooded channels of approximately 1×10^{-3} would have required a relative sea level rise of 200 m to cause this flooding. If these rivers had a lower gradient more typical of the modern Mississippi River alluvial coastal plain (10^{-4}; Saucier, 1994), flooding over this distance would have required only a 20 m sea level rise. A minimum estimated slope of 2×10^{-6} would probably have required a rise of only 4 m to cause flooding. While aggradation of contemporary coastal fluvial systems during this rise would have worked against flooding, such aggradation would have been mostly confined to the lower channel reaches (Holbrook et al., 2006). This would have lowered gradients of coastal rivers in conjunction with rising relative sea level. If sediment supply was sufficient for aggradation to maintain pace with the rise of sea level, this would only delay the eventual flooding event. Although fluvial aggradation did not prove sufficient to prevent eventual transgressive flooding, it likely did influence the relative distribution of brackish versus marine coastal environments by influencing the topography across which transgression eventually occurred.

Rivers up to 12 m deep feeding this marginal sea from the retreating alluvial plain transported fresh water and sediment into the low-gradient coastal areas during transgression (Holbrook, 2001). The restricted nature of this shallow-water, low-gradient region would have made mixing of these fresh waters with marine Tethyan waters difficult. This explains why shale, otherwise characteristic of marine shelf or marine coastal deposition, have brackish/marginal marine indicators of high woody debris and other plant fragments and are poor in marine foraminifers and dinoflagellates (zone SBI and, to a lesser degree, the marine region; Figs. 10A–10C). Likewise, carbon-isotope values of shallow-marine facies are close to values from terrestrial units, and increase toward more marine values offshore. These seawaters were likely somewhat brackish nearshore. Furthermore, slight fluctuations in sea level, local sediment supply, or storm-surge activity likely resulted in marine influence penetrating well inland of the coast. This apparently resulted in broad coastal wetlands that experienced local and periodic marine inundation. Cretaceous data reveal a broad transition between terrestrial fluvial systems and marine systems characterized by wide coastal wetlands (zone WBI) through a brackish coast and shelf complex (zone SBI), instead of a sharp terrestrial to marine transition.

Plint and Wadsworth (2003) identified similar broad transgressive effects arising from minimal sea-level rise occurring over low gradients in the Cretaceous Western Interior Basin of Canada, in the Dunvegan Formation which is roughly equivalent to the Graneros/Greenhorn interval. Although the transgressive/regressive cycles they identified were of slightly shorter duration, ten within 2 m.y. rather than our three cycles in 1.3 m.y., they defined up to 50 km of marine transgression per cycle caused by about 24 m of sea-level rise. Similarly, they recorded up to 30 km of marine influence beyond the 50 km limit of the marine transgressive shoreline.

EVIDENCE FOR EPHEMERAL OCEANIC CONNECTIONS

Although we focus on correlation and extent of inundation by Tethys during the latest Albian in the southern margin of the Western Interior Basin, the Pueblo section, I-70 Denver section and the Nordman well constrain correlation to the Front Range area.

The Tethys Ocean very briefly inundated the southern Western Interior twice during a two million year period of the latest Albian following the early Late Albian Kiowa–Skull Creek flooding (Figs. 3, 8, 9). The Early Cenomanian flooding that deposited the basal Graneros Shale culminated in the Middle Cenomanian connection that lasted for the remainder of the Cretaceous. The first transgression deposited the Middle Shale Member of the Mesa Rica Sandstone (sequence 3.1), and the second deposited the Dry Creek Canyon, Pajarito and their correlative formations (sequence 3.2). The Middle Mesa Rica transgression was less than a million years in duration and fully marine conditions did not become established in the study area. The Dry Creek Canyon/Pajarito transgression, however, appears slightly more aerially extensive and lasted more than a million years. Brackish to marine flooding enabled Tethyan and Boreal marine waters to mix and generate a low-diversity flora of dinoflagellates and acritarchs. This mixed assemblage suggests that flooding was more substantial than when the Middle Mesa Rica was deposited. Thus, the second brief transgression was an ephemeral and never fully realized connection between the Boreal and Tethyan seas as part of the protracted first-order Zuni transgression. A similar stressed connection would likely be typical of conditions early in the long-term Greenhorn transgression as well, when the lower part of the Graneros Shale was deposited.

Facies in the Middle Mesa Rica suggest that freshwater environments (including lacustrine lithofacies 4 in parts of southeastern Colorado) were widespread in the study area. Brackish/marginal-marine conditions existed in the Oklahoma panhandle and the extreme southeastern corner of Colorado (Fig. 10). Later, during the Dry Creek/Pajarito transgression, the Huntsman Shale in the Nordman well recorded shallow-marine conditions, the evidence being a diverse assemblage of near-shore dinoflagellate cysts and acritarchs, as well as a moderately diverse agglutinate foraminiferal assemblage. Brackish/marginal-marine conditions existed in the Front Range west of Denver and in southeastern Colorado, the Oklahoma panhandle and locally in northeastern New Mexico; only the broad area around in southeastern Colorado and the Oklahoma panhandle record an ephemeral Tethys/Boreal connection.

The Romeroville Sandstone, lower Graneros Shale (including the "D" Sandstone of east-central and northeast Colorado and equivalent strata mark the onset of the long-term Greenhorn transgression during the earliest Cenomanian, and were dominated by non-marine and coastal fauna and flora. While shallow-marine conditions existed in northern Colorado and northeastern New Mexico, brackish/marginal marine conditions dominated southeastern Colorado and north to Denver (Fig. 10). However, the basal Graneros Shale west of Denver contains the Boreal foraminifer *Miliammina manitobensis*. Thus, faunal and facies trends suggest that connection probably existed around the Las Animas Arch, which acted as a barrier across which Boreal and Tethyan arms linked.

CONCLUSIONS

The unique contribution of this study is the delineation of marginal depositional environments by integrated data sets in the very shallow part of an alternately expanding and shrinking epeiric seaway. The study area was the site of mixing of waters from two contrasting seas: Boreal and Tethys. Lithofacies, palynological attributes, benthic foraminifers, trace fossils and carbon isotopes together define brackish/marginal to non-marine paleoenvironments that document these water-level fluctuations and migration of coastlines over broad areas of low slopes. Carbon-isotopic data in particular show that short-term transgressions resulted in brackish/marginal marine areas rather than fully marine conditions. The most important outcomes of this study are:

1. The details of two previously unrecorded transgressions are documented in the south-central Western Interior Basin. These short-term events during latest Albian time deposited the Middle Shale Member of the Mesa Rica Sandstone (sequence 3.1), and the Dry Creek Canyon, the Pajarito and correlative formations (sequence 3.2).
2. Minimal sea-level rise (10^0-10^1 m) of at least 4 m but less than 200 m would be required to generate the broad transgressive conditions observed if relative rise was abrupt compared to sediment supply.
3. Transgression across low-gradient coastal plains similar to the ones identified in the study area should be characterized by broad transitions from non-marine (freshwater) to marine conditions typified by wide wetland and shallow brackish belts. These freshwater conditions were likely common once transgression crossed the hinge line marking the tectonic boundary between the shelf and continental interior.
4. The marine flooding events appear to have been gradual across the shelf and had high fresh water input. Ephemeral Tethys/Boreal connection occurred during the Dry Creek/ Pajarito transgression.
5. The Las Animas Arch was an active high during mid-Cretaceous time and influenced shoreline positions. The arch was the primary barrier between the Boreal Sea and Tethys within what has been traditionally called the Transcontinental Arch.
6. The levels of transgressive connection in sequences 3.1, 3.2 and 4 allow for glimpses of what the transgression and biotic exchange would have looked like during the early stages of the transgression.

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