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# The Eagle Ford Outcrops of West Texas: A Laboratory for Understanding Heterogeneities within Unconventional Mudstone Reservoirs

**Arthur D. Donovan[1], T. Scott Staerker[1], Aris Pramudito[1], Weiguo Li[1], Matthew J. Corbett[2], Christopher M. Lowery[3], Andrea Miceli Romero[4], and Rand D. Gardner[5]**

*[1]BP, 501 Westlake Park Blvd., Houston, Texas 77079, U.S.A.*

*[2]Department of Earth and Atmospheric Sciences, University of Nebraska–Lincoln,*
*214 Bessey Hall, P.O. Box 880340, Lincoln, Nebraska 68588, U.S.A.*

*[3]Department of Geosciences, University of Massachusetts, 611 North Pleasant St.,*
*233 Morrill Science Center, Amherst, Massachusetts 01003, U.S.A.*

*[4]ConocoPhillips School of Geology and Geophysics, University of Oklahoma,*
*Sarkeys Energy Center, 100 E. Boyd St., Norman, Oklahoma 73019, U.S.A.*

*[5]Department of Geology and Geophysics, Texas A&M University,*
*MS 3115, College Station, Texas 77843, U.S.A.*

## ABSTRACT

**The Eagle Ford outcrops in West Texas provide a unique opportunity to examine strata equivalent to the Eagle Ford unconventional mudstone reservoirs of South Texas in excellent vertically and laterally continuous exposures. Whereas unconventional mudstone reservoirs are commonly portrayed as homogenous, our work to date reveals a vertically heterogeneous facies and total-organic-carbon (TOC) succession in the Eagle Ford Group, with variability at the bed-, parasequence-, sequence-, and sequence-set scale. This heterogeneity suggests the potential for distinct vertical variability in the unconventional reservoirs that would affect well performance. Understanding and predicting those variations is essential to enable effective horizontal-well placement in the subsurface.**

**Outcrops of the Eagle Ford Group in West Texas consist of a vertical succession of five distinct facies, each of which contains a vertical succession of sub-facies. These facies and sub-facies were used to divide the Eagle Ford Group into the Lower Eagle Ford Formation and Upper Eagle Ford Formation. Within the Lower Eagle Ford Formation a (lower) unnamed member and (upper) Middle Shale Member were defined, whereas in the Upper Eagle Ford Formation a (lower) unnamed member and the (upper) Langtry Member are proposed. Each of the four Eagle Ford members, which can be correlated from the outcrops of West Texas into the subsurface of South Texas, have distinct lithologic characteristics, geochemical signatures, geographic distributions, and chronostratigraphic significance. Because the four proposed lithostratigraphic members within the Eagle Ford Group are bounded by regionally mappable unconformities, they are also chronostratigraphic units that are not coeval to (1) each other, (2) the underlying Buda Limestone, or (3) the overlying Austin Chalk.**

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## INTRODUCTION

The Upper Cretaceous (Cenomanian to Coniacian) Eagle Ford Group is a prolific unconventional mudstone reservoir in the Gulf of Mexico coastal plain of South Texas that is adding considerably to the hydrocarbon resources and reserves of the United States. Unconventional reservoirs like those in the Eagle Ford Group are typically described as monotonously uniform and homogenous mudstones, with the connotation being that these units represent simple "resource plays," that require limited geologic analysis beyond predicting product type. This perception quickly changes, however, when resource exploitation reveals a range of well-production rates across a play fairway, suggesting underlying geologic variability. This study builds upon previous efforts (Donovan and Staerker, 2010) to characterize, correlate, and interpret the key stratal surfaces and depositional nuances of the Eagle Ford mudstone play in outcrop, and to apply these findings to the subsurface of South Texas (Fig. 1).

The arid climate of West Texas provides a unique opportunity to study unconventional mudstone reservoirs that crop out in excellent road cuts and stunning canyon exposures along and adjacent to U.S. Hwy. 90 in Val Verde and Terrell counties, Texas (Fig. 2). This paper is a summary of some of our initial geologic findings from one of the BP-leased, private-property sites located in Lozier Canyon. This locality is an impressive northeast facing cut-bank exposure (Fig. 2C) located approximately 1 mi south of the Lozier Creek Bridge, which crosses U.S. Hwy. 90. As the digital image of the locality illustrates (Fig. 2C), this exposure is approximately 3000 ft long, almost 300 ft high, and is capped by the Austin Chalk. At this locality, almost every stratigraphic portion of the Eagle Ford could be accessed, and a 175 ft thick Eagle Ford section was measured on the northwest portion of the exposure.

The new data from the Lozier Canyon research site include geochemical, paleontological, and petrographic information. These new data are incorporated into revised sequence stratigraphic and depositional interpretations for Lozier Canyon,

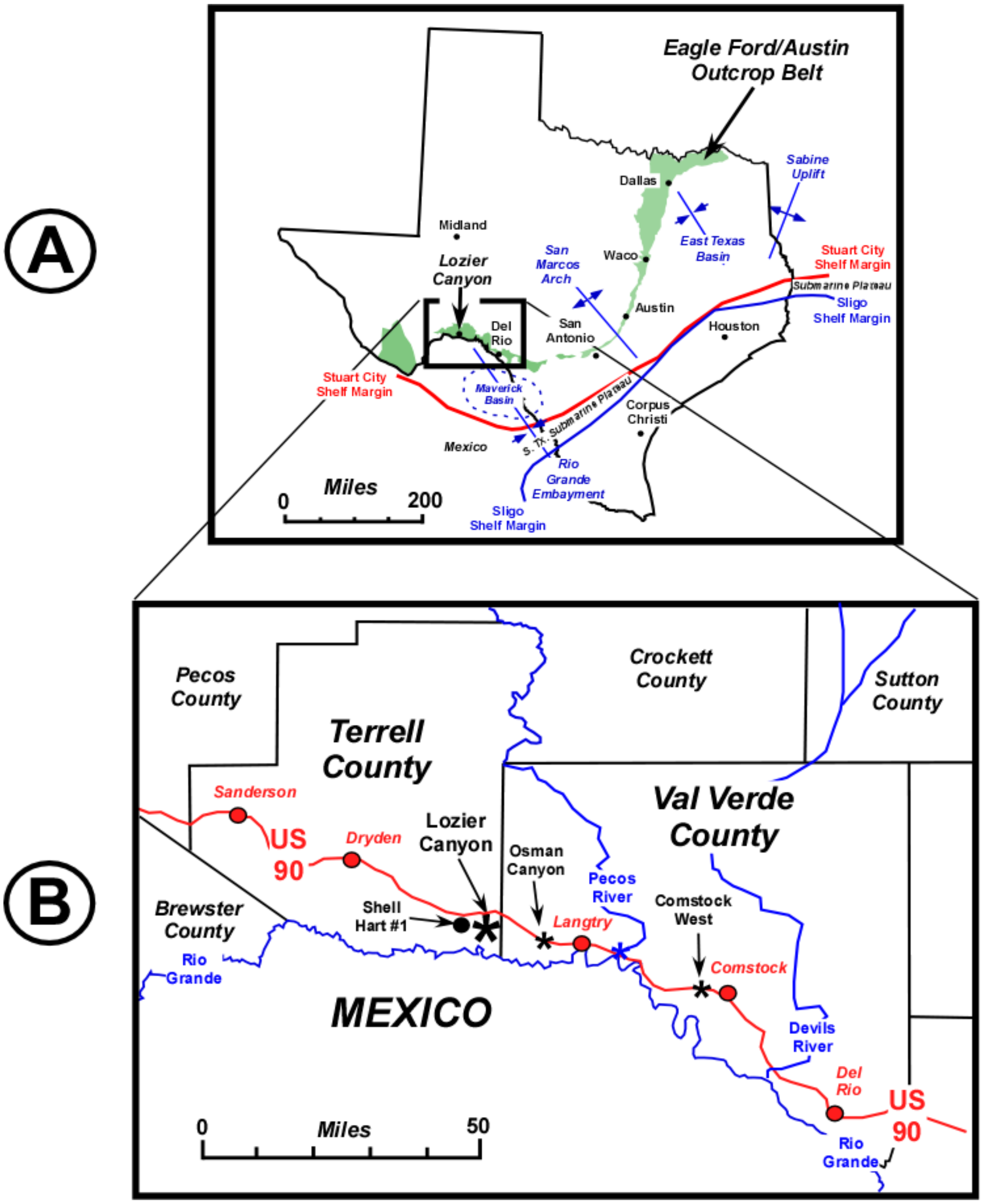


**Figure 1. (A) Map of Texas illustrating the major structural and physiographic features affecting the Gulf of Mexico coastal plain succession. (B) Location of key localities along and/or adjacent to U.S. Hwy. 90 in Val Verde and Terrell counties, Texas.**

which then serves as the basis for an improved stratigraphic correlations into the Eagle Ford oil and gas play of subsurface, South Texas.

## REGIONAL CONTEXT

The major structural features of the Gulf of Mexico Coastal Plain in Texas consist from east to west of the Sabine Uplift, East Texas Basin, San Marcos Arch, and Rio Grande Embayment (Fig. 1). Presently, the Eagle Ford unconventional mudstone play extends from the San Marcos Arch south into the Rio Grande Embayment in South Texas. In this region, Hill (1887a, 1887b) defined a carbonate-dominated Comanche Series overlain by a more siliciclastic-dominated Gulfian Series. As illustrated on Figure 3, the major formations within Hill's Comanche Series, from the base up, includes the Sligo, Pearsall, Glen Rose, Edwards, Georgetown, Del Rio, and Buda formations. Comanche reef build-ups in the Edwards through the Buda are also referred to as the Stuart City Reef Trend. Hill's Gulfian Series in South Texas includes the Eagle Ford, Austin, Anacacho, San Miguel, Olmos, and Escondido formations (Fig. 3). It should be noted, however, that the Woodbine Group, positioned between the Buda and Eagle Ford and defines the base of the Gulfian Series in northeast Texas, is absent in South Texas due either to (1) truncation by an unconformity at the base of the Eagle Ford (Hazard et al., 1949) or (2) more likely, a facies change in the Upper Cretaceous succession south of the San Marcos Arch (Hentz and Ruppel, 2010).

In a sequence stratigraphic context, the Cretaceous succession of South Texas falls within Sloss's (1963) first-order Zuni Sequence, which extends from the mid-Jurassic to the end of the Cretaceous (Fig. 3). The Eagle Ford Formation, which is also a major source rock across the Gulf of Mexico Basin, was deposited at or near the maximum flooding surface of the Zuni Sequence (Sloss, 1963). Hill's (1887a, 1887b) Comanche and Gulfian units can be used to define the major second-order sequences within the Cretaceous portion of Sloss's (1963) Zuni Sequence. Within this context, the Eagle Ford Group occurs at or near the interpreted maximum flooding surface of the Gulfian Series.

Our regional work within the Lower Cretaceous Comanche Series suggests that the Sligo and Stuart City intervals represent two major prograding reef-building episodes. These reef trends formed major relict physiographic features that affected subsequent Upper Cretaceous accommodation patterns across South

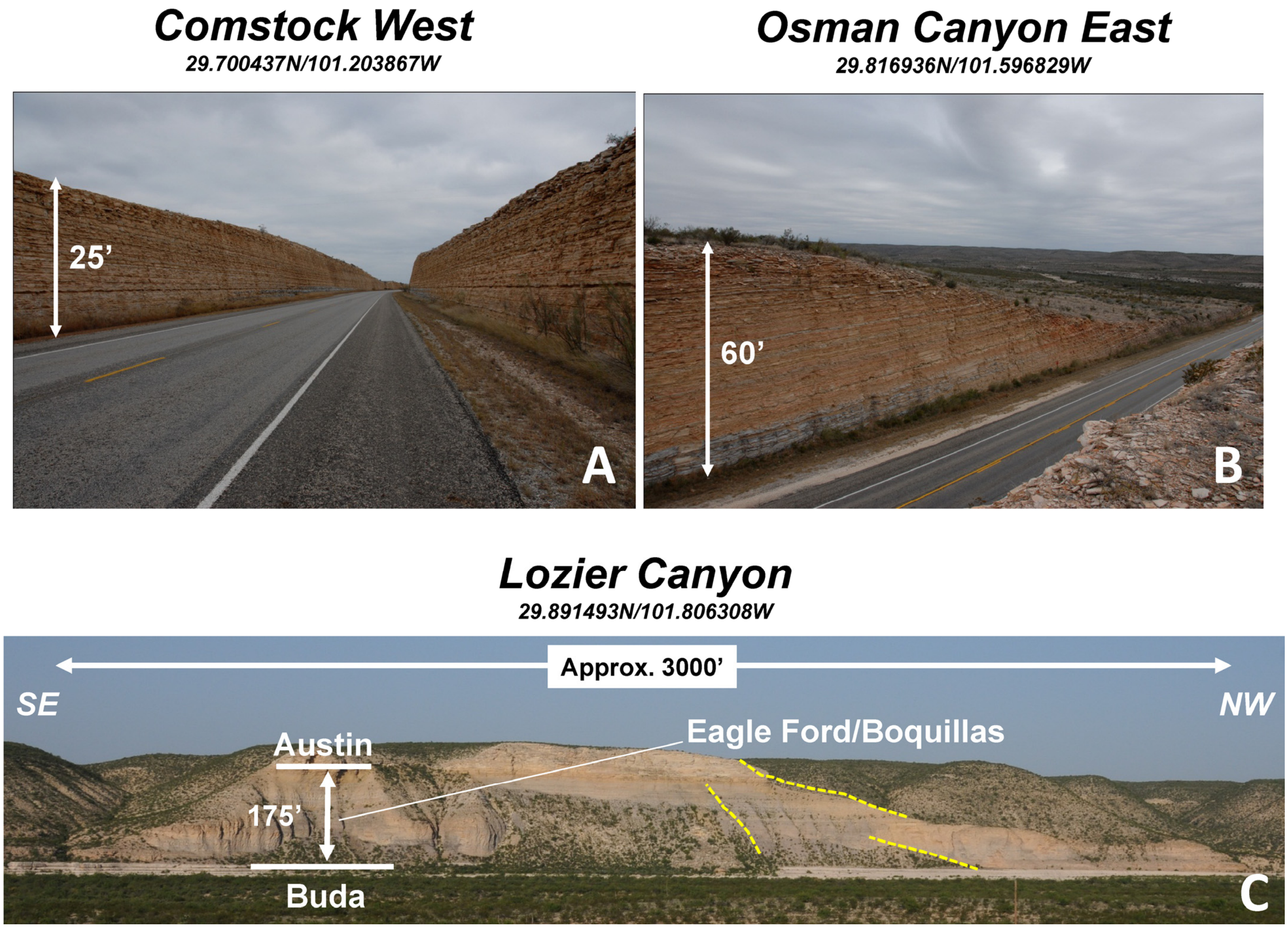

Comstock West
29.700437N/101.203867W
Osman Canyon East
29.816936N/101.596829W
Lozier Canyon
29.891493N/101.806308W

**Figure 2. Eagle Ford outcrops along and/or adjacent to U.S. Hwy. 90 at (A) Comstock West, (B) Osman Canyon East, and (C) Lozier Canyon. Along U.S. Hwy. 90, the Eagle Ford exposures tend to weather reddish brown; in these road cuts, the original gray-to-black color remains only at the central core of the exposures. In Lozier Canyon, however, the bulk of the Eagle Ford exposures are black to gray in color. Yellow dashed lines in 2C indicate locations of measured sections in Lozier Canyon.**

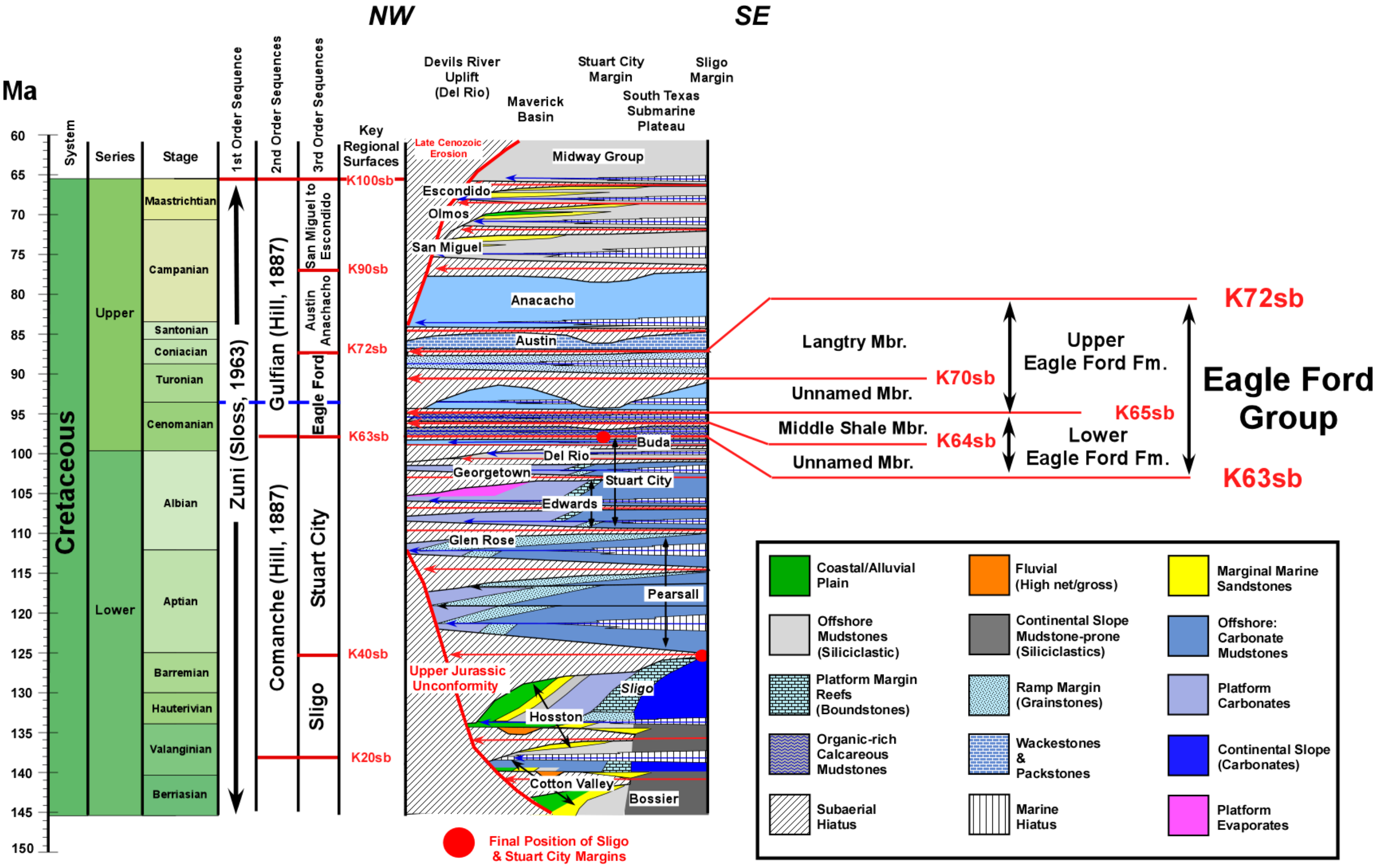


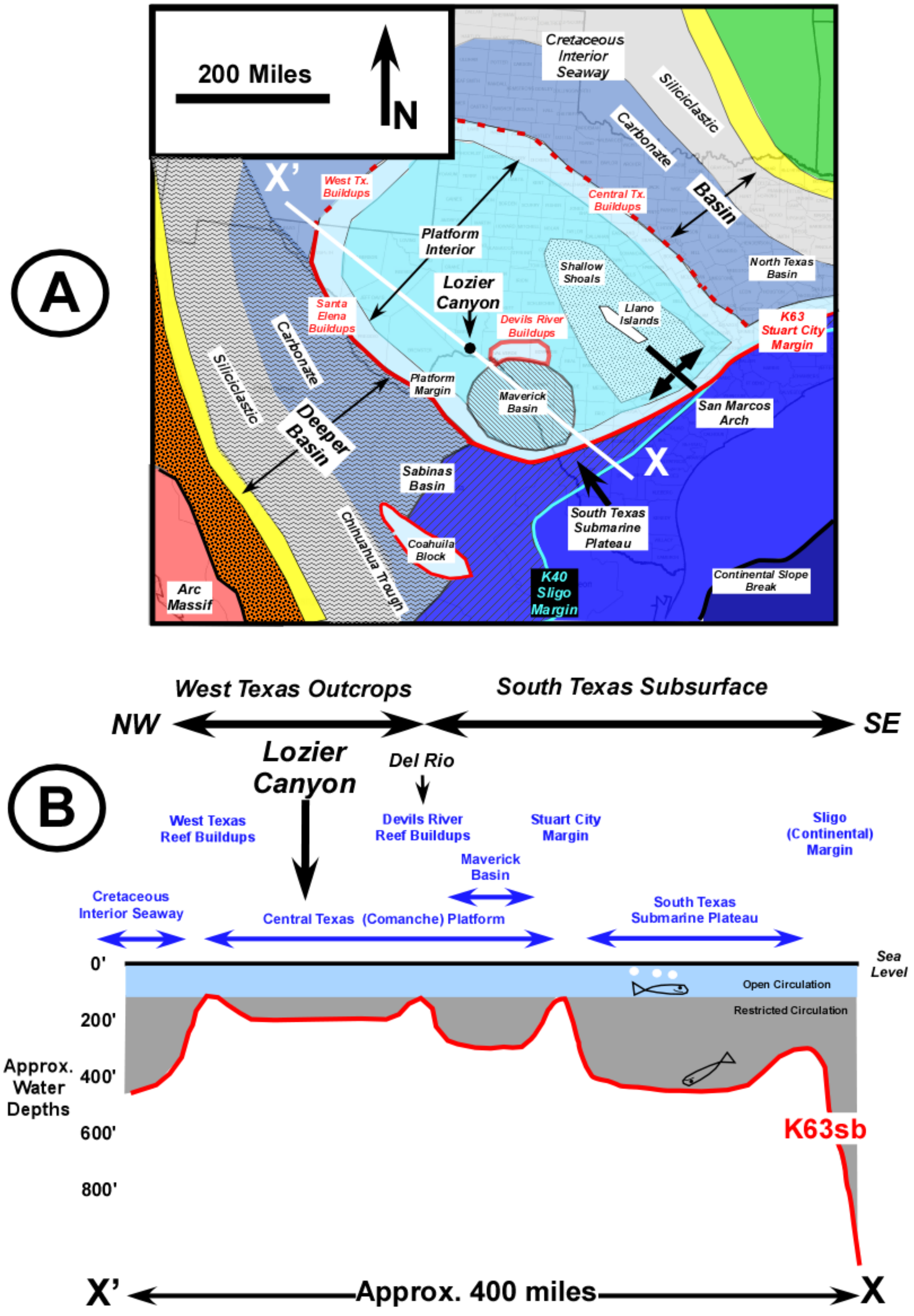
**Figure 3. Generalized Cretaceous chronostratigraphy of South Texas (modified after Donovan and Staerker, 2010).**

Texas. The Stuart City reef buildups rimmed the Comanche Platform, which was centered on the San Marcos Arch (Fig. 4A). This platform faced the Gulf of Mexico to the southwest, the North Texas Basin to the east, and into the Rio Grande Embayment (Sabinas Basin) to the southwest. In South Texas, the younger Stuart City Reef Trend failed to prograde as far basinward as the older Sligo Reef margin. In this region, a submarine plateau, herein termed the South Texas Submarine Plateau, formed. Along this submarine plateau, sufficient accommodation developed to allow thicker accumulations of Eagle Ford mudstones (Fig. 4). At the southwestern edge of the Comanche Platform, a structurally low area, the Maverick Basin developed (Goldhammer and Johnson, 1999). This structural feature is likely related to the deep-seated tectonic movement that formed the Rio Grande Embayment (Goldhammer and Johnson, 1999). This basin also effected Eagle Ford accommodation and the consequent deposition and preservation of organic-rich, calcareous, mudstones in the region. An idealized transect across the Comanche Platform is offered as a summary diagram to illustrate the inherited seafloor paleo-bathymetry at the onset of Eagle Ford deposition (Fig. 4B). Although water depths are difficult to estimate in the absence of direct water-depth indicators from benthic foraminifer biozones, we envision moderate (400–600 ft) water depths in the deeper portions of the seaway toward the South Texas Submarine Plateau, Rio Grande Embayment, and East Texas Basin and shallower (100–200 ft) water depths across most of the flooded Comanche Platform, including the Eagle Ford study area in Val Verde and Terrell counties, in West Texas (Fig. 4B).

## PREVIOUS WORK

Any discussion of the mudstone-prone strata stratigraphically situated between the Buda and Austin formations in West Texas would be remiss without first defining the stratigraphic terminology used and its relation to previous studies. For the sake of stratigraphic nomenclatural clarity, the discussion of the terms used in the region must go back to the original naming of the largely coeval Eagle Ford and Boquillas formations in different parts of Texas. In 1887, Hill defined the Eagle Ford Shale at the town of Eagle Ford just west of Dallas, Texas, and Udden (1907) named age-equivalent, organic-rich carbonates in Brewster County, near present day Big Bend National Park, as the Ernst Member of the Boquillas Formation. U.S. Geological Survey mapping in Brewster, Terrell, and Val Verde counties (Freeman, 1968), field-based sedimentological studies in Val Verde County (Lock et al., 2010), and paleontological work in the Big Bend area (Cooper et al., 2007a, 2007b) used “Boquillas” to identify these same strata. In contrast, Adkin’s (1932) monumental work on the Mesozoic Systems of Texas, as well as the classic work by Hazard (1959) on the Cretaceous strata of the Val Verde Basin referred to these strata in West Texas as “Eagle Ford.” This dual terminology also occurs on the geologic map of the Del Rio two-degree sheet (Barnes, 1977) where the Devils River was used as the geographically definable, but geologically arbitrary, boundary between the Boquillas Formation to the west and the Eagle Ford Formation to the east. Because there is minimal, if any, lithologic difference between the Eagle Ford and Boquillas strata on either side of the Devils River, a single strati-

**Figure 4. Generalized (A) paleogeographic map and (B) reconstructed transect across the Late Cenomanian Comanche Platform (modified after Donovan and Staerker, 2010).**



graphic name should be used. The term “Eagle Ford” predates the use of “Boquillas,” and therefore precedence supports use of the term Eagle Ford Group to define these strata across Texas.

Donovan and Staerker (2010) summarized, compared, and contrasted the various vertical zonation schemes that have been proposed by previous workers for the internal stratigraphy of the Eagle Ford succession of West Texas (Fig. 5). These works include Hazard’s measured sections from the 1959 West Texas Geological Society Guidebook; Freeman’s (1961, 1968) maps and unit descriptions; Pessagno’s (1969) and Smith’s (1981) regional micropaleontological (foraminifera and nannofossil) work and stratigraphic revisions; Trevino’s (1988) detailed measured sections along U.S. Hwy. 90; and recent work by researchers at the University of Louisiana–Lafayette (Peschier, 2006; Lock and Peschier, 2006; Lock et al., 2010).

Building upon the foundation of the prior investigations, Donovan and Staerker (2010) proposed a simple five-fold (A to E) vertical facies succession for the West Texas Eagle Ford outcrops that integrated the key observations of previous researchers. This vertical facies succession in Lozier Canyon is illustrated in Figure 5, and a photograph of the same succession is in Figure 6. From the base up, this vertical succession consists of (1) Facies A: light gray cross-stratified limestones (grainstones/packstones) separated by thin calcareous mudstone beds; (2) Fa-

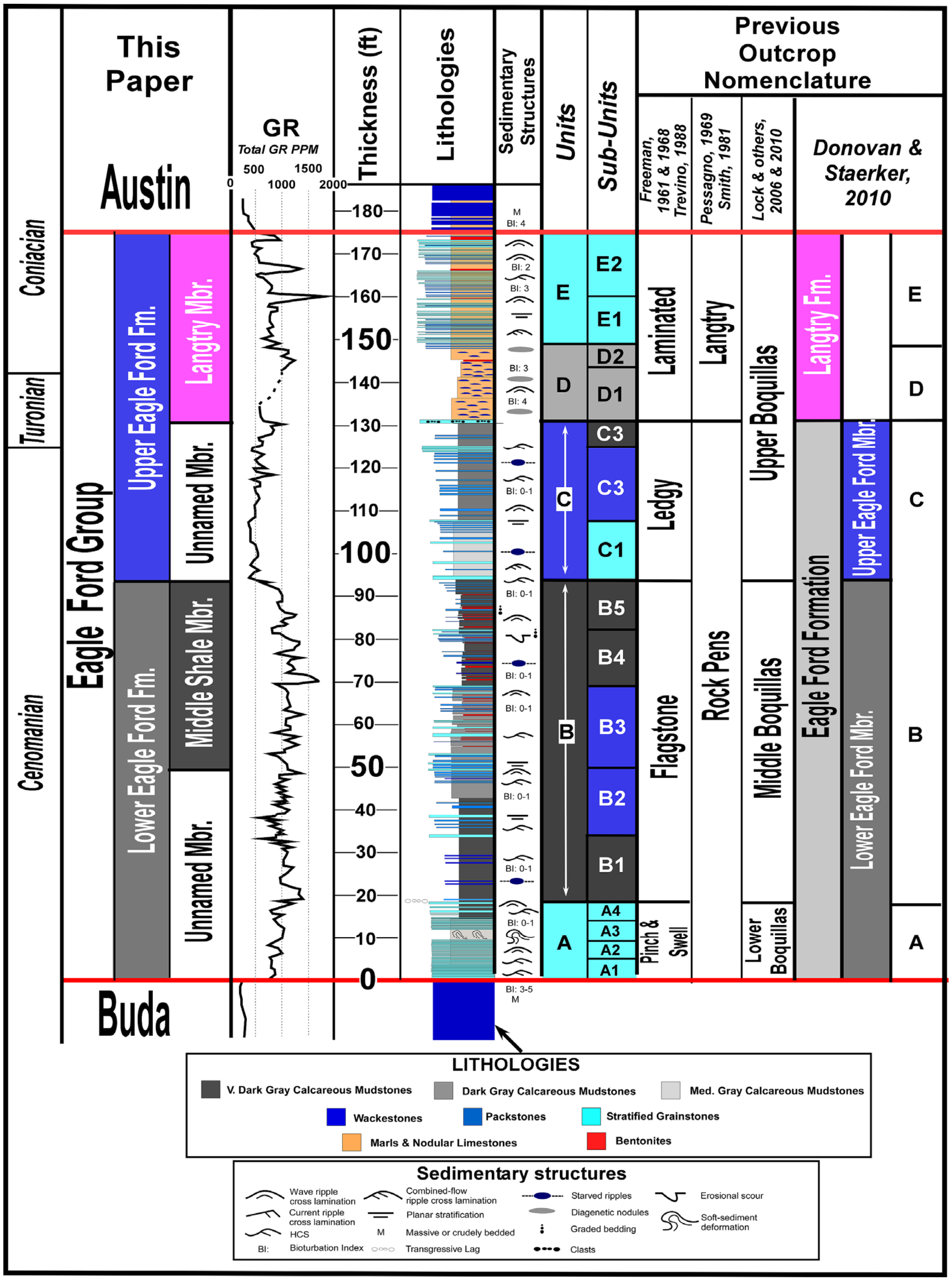


**Figure 5.** Comparison of the nomenclature used by previous researchers studying the Eagle Ford (Boquillas) outcrops of West Texas.

cies B: black organic-rich calcareous mudstones with scattered limestone (grainstone-prone) interbeds; (3) Facies C: medium-gray thick-bedded limestones (packstones and grainstones) with mudstone interbeds; (4) Facies D: pale-yellow ochre, echinoid-bearing marls and nodular limestones; and (5) Facies E: yellow ochre, thin-bedded limestones (grainstones) interbedded with calcareous mudstones. Donovan and Staerker (2010) used the contact between facies B and C to define a Lower Eagle Ford Member (below) and Upper Eagle Ford Member (above). Furthermore, they used the contact between facies C and D to separate the Eagle Ford Formation (below) from a proposed Langtry Formation (above). Their rationale to restrict the limits of the Eagle Ford succession at the time was based on (1) correlations of the Langtry into the subsurface where a major angular unconformity truncates underlying Eagle Ford strata; (2) a distinct (intra-Turonian) biostratigraphic break at the Eagle Ford/Langtry contact; and (3) the absence of a clear unconformity at the base of the overlying Austin Chalk, suggesting that the Langtry was more genetically related to the overlying Austin Chalk than to the underlying Eagle Ford Group. In terms of sequence stratigraphy, Donovan and Staerker (2010) interpreted facies A, B, and C as one depositional sequence and facies D and E as a second depositional sequence that continued upward into the overlying Austin Chalk.

## PROPOSED EAGLE FORD NOMENCLATURE

In this paper, a more traditional approach to Eagle Ford nomenclature is taken to more effectively tie the outcrops of West Texas to the subsurface of South Texas. Contrary to Donovan

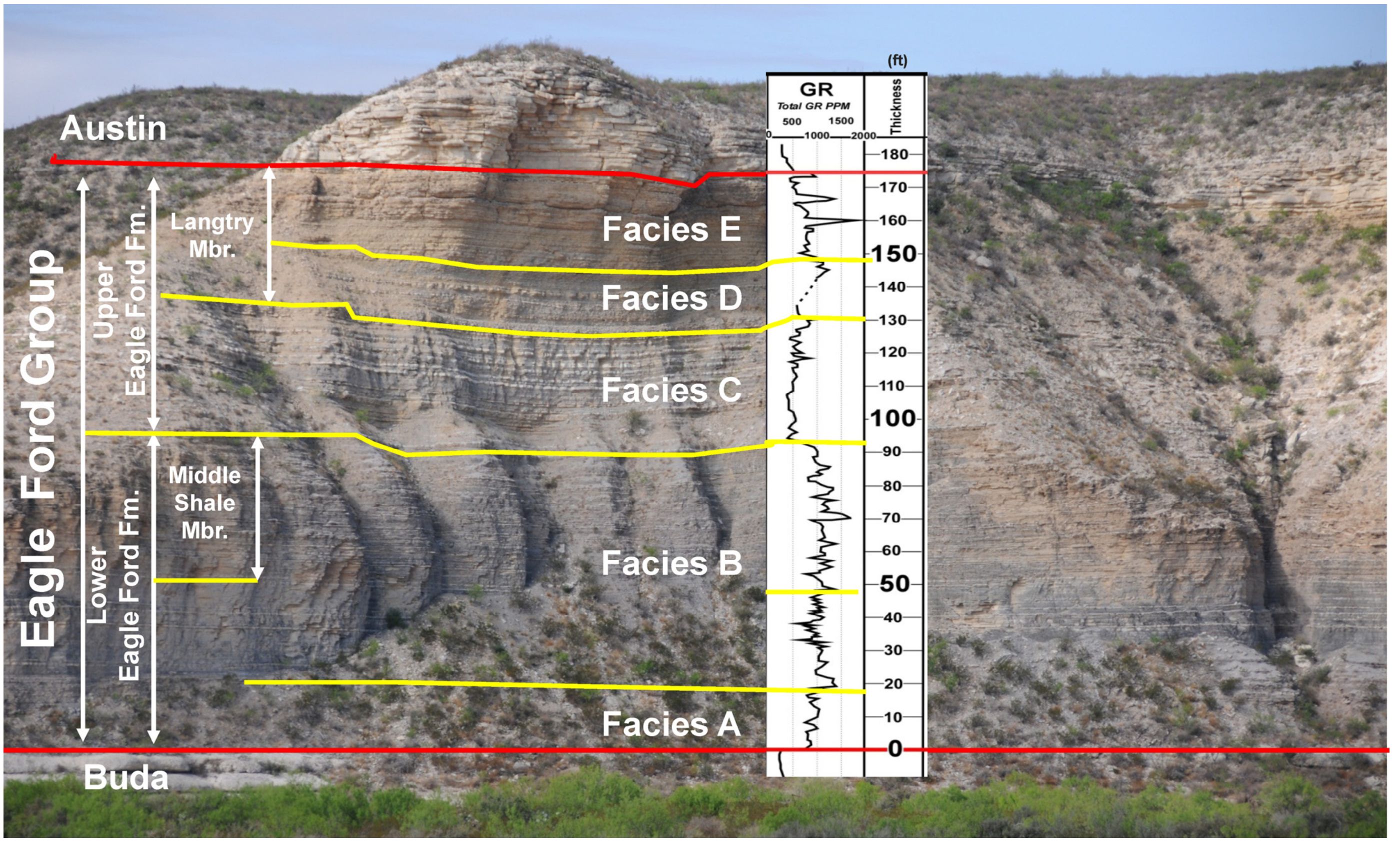


**Figure 6. West portion of the Lozier Canyon outcrop face and associated total gamma ray (GR) profile of the measured section. Note the five basic facies identified and the lithostratigraphic units proposed. On the outcrop photo, the Middle Shale Member is more difficult to define, but on the GR profile a change from decreasing to increasing GR values, which occurs at about 48 ft, marks the base of this unit.**

and Staerker's (2010) proposal that the Langtry unit be elevated to formation status, all of the strata situated between the Buda and Austin intervals in the West Texas outcrops are herein referred to as the Eagle Ford Group (Figs. 5 and 6). This is the same stratigraphic rank used by Adkins (1932) in his classic work on the Mesozoic systems of Texas, where the term Eagle Ford Group was used to map and define Eagle Ford strata across the state of Texas. The same approach was taken by Atkins and Lozo (1951), who correlated the Eagle Ford Group from Dallas County to Travis County.

A similar group status is also proposed for the Eagle Ford strata in the subsurface of South Texas (Fig. 7). Here, the Eagle Ford interval is commonly divided into an informal lower and upper units based primarily on geophysical log character (Grabowski, 1995; Hentz and Ruppel, 2010; Harbor, 2011). We herein propose to recognize formally this division and define a Lower Eagle Ford Formation and an Upper Eagle Ford Formation (Fig. 7). As illustrated on Figure 7, a distinct change in the gamma ray (GR) profile and changes that occur on other geophysical logs, spectral gamma ray (SGR) data, and geochemical data distinctly mark the Lower/Upper Eagle Ford contact. Notably, a distinct clay-rich/carbonate-poor marker bed, characterized by low GR, low resistivity, and unique density and neutron separation occurs at the base of the Upper Eagle Ford Formation (Fig. 7). Distinctive higher-GR zones at the top of the Lower Eagle Ford and Upper Eagle Ford are herein respectively termed the Middle Shale Member of the Lower Eagle Ford Formation and Langtry Member of the Upper Eagle Ford Formation (Fig. 7). As will be subsequently discussed, the same formations and members defined in the subsurface of South Texas can defined and mapped in the outcrops of West Texas.

## METHODS

The Big Bend area notwithstanding, most previous work on the exposed Eagle Ford Group over the past 30 years has focused on the outcrops along U.S. Hwy. 90 in Val Verde County, Texas (Trevino, 1988; Peschier 2006; Lock and Peschier, 2006; Lock et al., 2010; Donovan and Staerker, 2010). Although these roadside outcrops can be as much as 80 ft high and hundreds of feet in length, they have distinct limitations. These limitations include (1) extensive weathering with mildly weathered areas restricted to the center of only a few roadcuts, (2) limited vertical access to the sections, which prevents sampling without the use of specialized lift equipment, and (3) limited vertical continuity of the stratigraphic section (Fig. 2).

In addition to the exposures along U.S. Hwy. 90, there are also natural exposures in local canyons that drain into the Rio Grande in Val Verde County, Terrell, and Brewster counties. These canyon exposures, which commonly show the entire Eagle Ford succession, are less deeply weathered than the road cuts. The most investigated section among these natural outcrops is in Lozier Canyon (Fig. 2) in the eastern part of Terrell County (Fig. 1B). The Lozier exposures were studied by Hazard (1959), Freeman (1961, 1968), and Pessagno (1969), but are on private property unavailable to geoscientists for the past 40 yr. Fortunately,

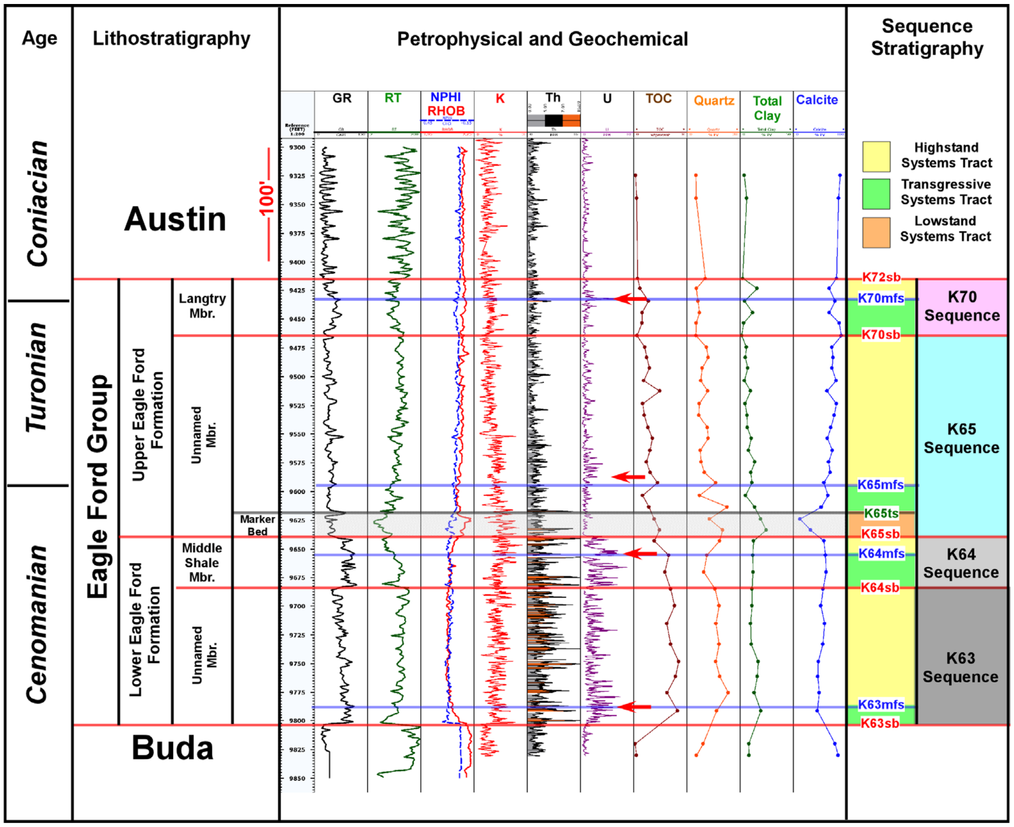


**Figure 7. Petrophysical and geochemical data from a well in Webb County (name and precise location are proprietary) support identification of the lithostratigraphic and sequence-stratigraphic units defined in this paper.**

BP's land department was able to gain controlled access for geologic research and field trips to these spectacular Eagle Ford outcrops. All of the data and interpretations reported herein come from work completed over the last 2 yr at one of the naturally occurring cliff exposures in Lozier Canyon (29.882648° North, 101.807563° West).

We used an integrated approach to studying the Eagle Ford succession in Lozier Canyon. This included study of the sedimentology (Li and Gardner), biostratigraphy (Staerker, Corbett, and Lowery), organic geochemistry (Miceli-Romero), inorganic geochemistry (Pramudito), and the chronostratigraphic and sequence stratigraphic framework (Donovan). Another key aspect of the study was to construct a GR outcrop profile using a hand-held device that also collected SGR data at the vertical spacing of 1 ft (Fig. 8). The SGR data allowed us to improve ties to nearby wells, as well as gain additional insights into bentonite, organics, and clay distributions through their associated thorium (Th), uranium (U), and potassium (K) enrichment profiles. It should be noted that there is an approximately 10-ft interval in the upper part of Facies D from which we obtained no SGR data because of limited access of the fresh (vertical) exposures in this interval. The results of the data collected for organic geochemistry are also plotted against the measured section and GR profile in Figure 8. A summary of geochemical and biostratigraphic data illustrates surfaces where changes occur consistently in both wells and outcrop (Fig. 9 and Table 1).

For biostratigraphy, samples were processed at approximately 2-ft spacing for nannofossils, foraminifers, and palynology. Although our focus was on microfossils, some macrofossil identifications were also made. The diverse paleontological data allowed for multiple proxies in assigning ages of units and surfaces in the Eagle Ford Group. Our age markers include the first and last occurrences of key nannofossils and foraminifers, and a palynological assemblage event (Table 1). These biostratigraphic markers were supplemented with Carbon-13 isotope ($\delta^{13}$C) analysis, which used both bulk and organic carbon separation methods. The $\delta^{13}$C analyses was particularly useful in interpreting the Cenomanian/Turonian (C/T) stage boundary though comparison of similar isotopic profiles from the Cenomanian-Turonian Global Stratotype Section and Point (GSSP) located near Pueblo, Colorado (Kennedy et al., 2005) (Fig. 10).

We used the chronostratigraphic-surface-naming convention used by BP, which numbers surfaces 1 to 100 for each of the systems in the Paleozoic and Mesozoic Eeras and for each of the series in the Cenozoic Era. The interval of interest covers the K63sb at the top of the Buda Limestone through the K72sb at the base of the Austin Chalk (Fig. 3). Genetically related surfaces of the same sequence (sequence boundary, sb; transgressive surface, ts; and maximum flooding surface, mfs) are assigned the same number and the appropriate surface type suffix (i.e., K63sb, K63ts, and K63mfs). This differs from an earlier Eagle Ford paper (Donovan and Staerker, 2010) where genetically related surfaces within the same sequence were given different numbers and suffixes in an effort to better signify the superposition of the surfaces (i.e., K63sb and K65mfs). This updated methodology also permits a unique sequence naming convention based on the basal bounding surface (e.g., K63 Sequence). Therefore, four sequences identified as K63, K64, K65, and K70 are defined within the Eagle Ford outcrops (Fig. 8), as well as in the subsurface of South Texas (Fig. 7).

Finally, we considered the suggestion that any vertical succession of lithologic units that are also chronostratigraphic in nature be termed members (K. Bohacs, 2012, pers. comm.). Whereas some unit boundaries defined by Donovan and Staerker (2010) are time-significant surfaces (B/C and C/D), others (A/B and D/E) are characterized by facies-related changes that occur

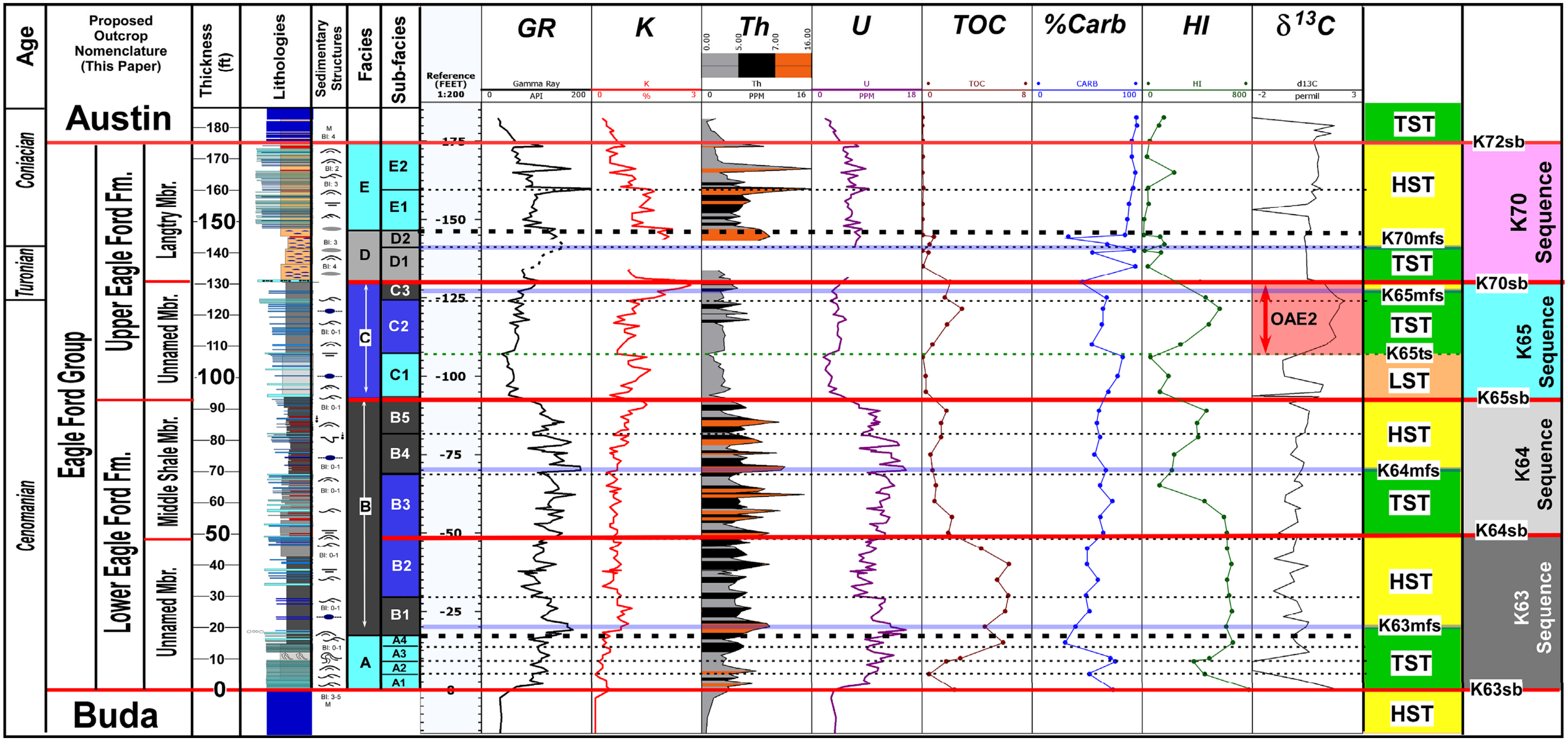


Figure 8. Summary of the lithologic, petrophysical, and geochemical data collected in Lozier Canyon in Terrell County, Texas. Comparison with Figure 7 indicates that the same lithostratigraphic and sequence stratigraphic units defined in the West Texas outcrops can be carried into the subsurface of South Texas. Legend for “Lithologies” column found in Figure 5. LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract, GR = gamma ray, K = potassium, Th = thorium, U = uranium, TOC = total organic carbon, %Carb = percent carbonate, HI = hydrogen index, and $\delta^{13}C$ = carbon isotopic signature.

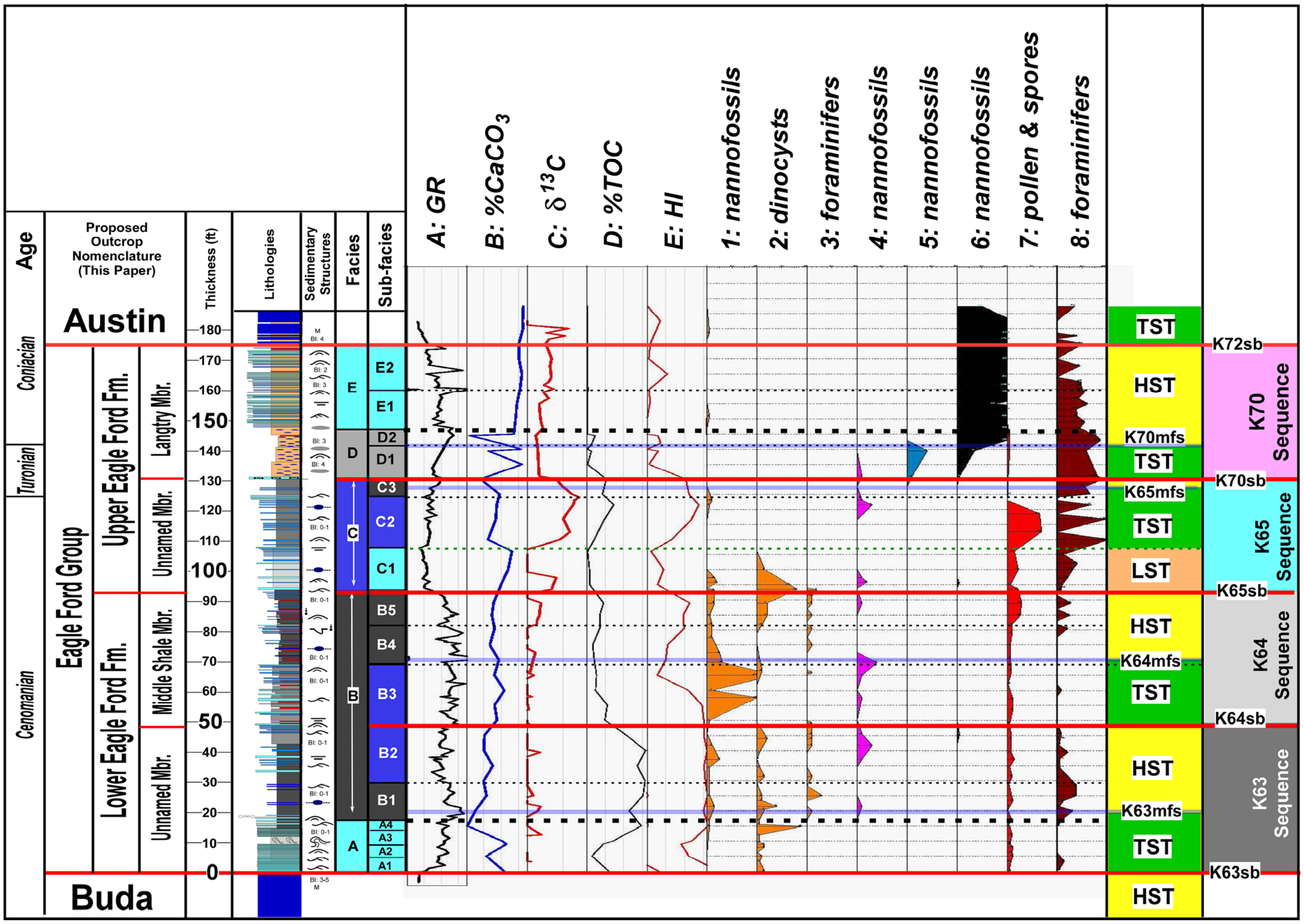


**Figure 9. Key biostratigraphic zones posted relative to the geochemical, petrophysical, and lithofacies interpretations from Lozier Canyon. The zones help define and reinforce our correlated surfaces and sequence interpretations. Key fossil changes occur at K70mfs, K70sb, just below the $\delta^{13}$C, and at two surfaces at and just above the K65sb. The criteria for fossil groupings in curves 1–8 are detailed in Table 1. There is currently poor age control in the interpreted Lower Eagle Ford.**

near, but not exactly at, interpreted maximum-flooding surfaces (Figs. 8 and 9). This fact, coupled with our basic operational procedure to use the facies and sub-facies defined in outcrop to define mappable members that can be correlated into the subsurface, led us to keep our facies and member terminologies separate.

## LOZIER CANYON OBSERVATIONS

### Overview

Observations made from the detailed measured section of the first locality studied at Lozier Canyon, coupled with the data generated from the samples collected (Figs. 8 and 10), reveal that all five of the Eagle Ford facies (A to E) defined by Donovan and Staerker (2010), can be further divided vertically. These new sub-facies increase the fidelity of the stratigraphic succession as shown on Figure 8. Details of the stratification observed within the various Eagle Ford facies of West Texas will be the focus of future publications.

The primary lithostratigraphic boundary within the Eagle Ford outcrops in Lozier Canyon is the contact between facies B and C, which occurs at approximately 95 ft on the measured section (Fig. 8). The contact is clearly discernible at the outcrop (Fig. 6). Dark gray, organic-rich carbonate mudstones with scattered packstone bedsets (Facies B) are abruptly overlain by medium-gray mudstones with abundant packstone/grainstone bedsets (Fig. 6). As illustrated on Figure 8, this boundary corresponds to a prominent decrease in GR values driven by decease in the U and Th components. Total organic carbon (TOC) and hydrogen index (HI) values also decease at this boundary (Fig. 8). Comparison of the GR profile, SGR profile, and geochemical data of this locality (Fig. 8), with our type well in Webb County (Fig. 7) indicates that this facies boundary corresponds to the contact between the Lower and Upper Eagle Ford formations in the subsurface.

The boundary between facies C and D is also distinct on the outcrops and is used to define the base of the Langtry Member of the Upper Eagle Ford Formation. In outcrop (Fig. 6), this break corresponds to a change from light gray mudstones interstratified with white grainstone/packstone bedsets (Facies C) to yellowish gray bioturbated marls (Facies D). At this boundary, the geochemical data record a decrease in TOC, HI, and $\delta^{13}$C as well as the end of the interpreted OAE2 (Fig. 8). An increase in carbonate and Th (bentonite) content also occurs across this boundary. The characteristics of the changes between facies D and E in the outcrop were used to define the base of the Langtry Member of the Upper Eagle Ford Formation (Fig. 8), which in turn can be used to define this member in the subsurface (Fig. 7).

**Table 1. Key taxa collected from Lozier Canyon used to define biozones graphically displayed in Figure 9.**

| Column number (Fig. 9) | |
|---|---|
| 1 | Composite abundance of nannofossils: *Helenia chiastia*, *Corrolithion kennedyi*, *Grantarhabdus coronadventis*, *Staurolithus aenigma*, *Rhagodiscus asper*, and *Axopodorhabdus albianus* |
| 2 | Composite abundance dinoflagellates: *Adnatosphaeridium tutulosum*, *Circulodinium colliveri*, *Dapsilidinium ambiguum pertusum*, *Diplofusa gearlensis*, *Epelidosphaeridium* cf. *spinosa*, *Heterosphaeridium? heteracanthum*, *Hystrichosphaeridium recurvatum*, *Litosphaeridium siphonophorum*, *Pervosphaeridium paucispinum*, *Valensiella reticulata*, and *Xiphophoridium alatum* |
| 3 | Composite abundance of foraminifera: *Rotalipora* spp., *Rotalipora cushmani*, and *Rotalipora greenhornensis* |
| 4 | Composite abundance of nannofossils: *Chiastozygus spissus* and *Helicolithus turonicus* |
| 5 | Abundance of *Eprolithus eptapetalus* |
| 6 | Composite abundance of nannofossils: *Eiffellithus eximius*, *Lithastrinus moratus*, *Lucianorhabdus maleformis*, *Marthasterites furcatus*, *Microrhabdulus decoratus*, *Miravetesina ficula*, and *Rhagodiscus splendens* |
| 7 | Composite of all pollen and spores identified (approximately 16 taxa) |
| 8 | Composite abundance of *Heterohelix plexus* |

The last lithostratigraphic unit of note is the proposed Middle Shale Member at the top of the Lower Eagle Ford Formation (Figs. 7 and 8). In the subsurface, the base of this unit is characterized by the sharp change from a decreasing to increasing total GR profile that also corresponds to a distinct change in the U profile (Fig. 7). At approximately 48 ft in the outcrop a boundary between sub-facies B2 and B3 was identified based on the occurrence of abundant 0.5–4 inch thick bentonite beds in the measured section, which also corresponded to an increase in U and Th content, as well as the onset of an increasing total GR profile on the SGR data. The overlying B3/B4/B5 interval is characterized by high U and Th content, in addition to elevated TOC and HI enrichment near the top. These inorganic and organic changes are interpreted as the outcrop equivalent of the Middle Shale Member located at the top of the Lower Eagle Ford (Fig. 8).

## Updated Characteristics of the Eagle Ford Outcrop Facies

### Facies (Unit) A

The basal facies of the Eagle Ford Group in West Texas was termed Facies A by Donovan and Staerker (2010). As outlined on Figure 5, this interval corresponds to the Pinch and Swell Unit of the Eagle Ford (Boquillas) identified by Freeman (1961, 1968). This facies, which in the section measured at Lozier Canyon, is approximately 18 ft thick (Figs. 8 and 11), consists of light grey interbedded grainstones and mudstones. The grainstone bedsets in this member contain individual stacked beds of hummocks and wave ripples (Fig. 12A). However, locally zones of contorted and deformed bedding also occur (Figs. 11 and 12B). Donovan and Staerker (2010) also observed that the grainstone bedsets dominate toward the base of this facies, whereas the mudstones become more dominant upward (Fig. 11). Figure 8 illustrates that the TOC content increases upward in this unit, whereas the GR profile shows an overall incremental upward GR increase as well.

In order to gain more detail, Facies A is now divided into four sub-facies labelled A1 to A4 from the base upward (Fig. 11). Overall, each successive sub-facies displays an incremental increase in the number and thickness of mudstone beds, and incremental decrease in number and thickness of grainstone bedsets (Figs. 8 and 11). Sub-member A1 is dominated by 4 to 8 inch-thick hummocky stratified grainstone bedsets separated by thin (<1 in) mudstone beds, whereas sub-facies A4 is dominated by 2 to 4 inch thick mudstone beds separated by 1–2 inch thick grainstone bedsets containing beds of wave ripples and small hummocks. The mudstones in sub-facies A2, A3, and A4 contain planktonic foraminifera. Within sub-facies A1 disarticulated bivalves of the genus *Ostrea* occur along some bedding planes (Fig. 12C), and fragments of both bivalves and echinoids were observed in thin-section. Interestingly, oyster shells are common allochems throughout Facies A and are especially common in the grainstone bedsets at the top of sub-facies A4. Also observed near the base of sub-facies A1 is a 6 inch thick grainstone bedset that appears to be burrowed (Fig. 12D). In Lozier Canyon, the base of sub-facies A3 is marked by an approximately 3 ft thick bedset with highly contorted and disrupted stratification, which locally appears to contain matrix-supported pebble- to cobble-size clasts (Fig. 12B). This interval has been interpreted as an "event bed," formed by depositional slope failure due potentially to major storms or seismic events (Lock and Peschier, 2006) and was observed at multiple locations in Val Verde and Terrill Counties. It should be noted, however, that the deformed event beds are both more common and stratigraphically lower in the roadcuts along U.S. Hwy. 90.

### Facies (Unit) B

Donovan and Staerker (2010) referred to the second distinct lithologic unit from the base up within the Eagle Ford in West Texas as Facies B. As outlined on Figure 5, this zone corresponds to the Flagstone Unit of the Eagle Ford (Boquillas) identified by Freeman (1961, 1968). At Lozier Canyon, this member consists of approximately 77 ft of black organic-rich carbonate mudstones with varying amounts of grainstone-dominated bedsets. As illustrated on Figures 5 and 8, both the base and top of Facies B are fairly distinct, but internally distinct variability occurs. Our recent work suggests that Facies B can be subdivided into five sub-facies termed B1 to B5 from the base up (Fig. 8).

Sub-facies B1 consists of approximately 12 ft of black organic rich mudstones (Figs. 8 and 11) containing only a few (inch-scale) limestone (grainstone/packstone) bedsets. As illustrated on Figure 8, a relative GR high occurs near the base of this

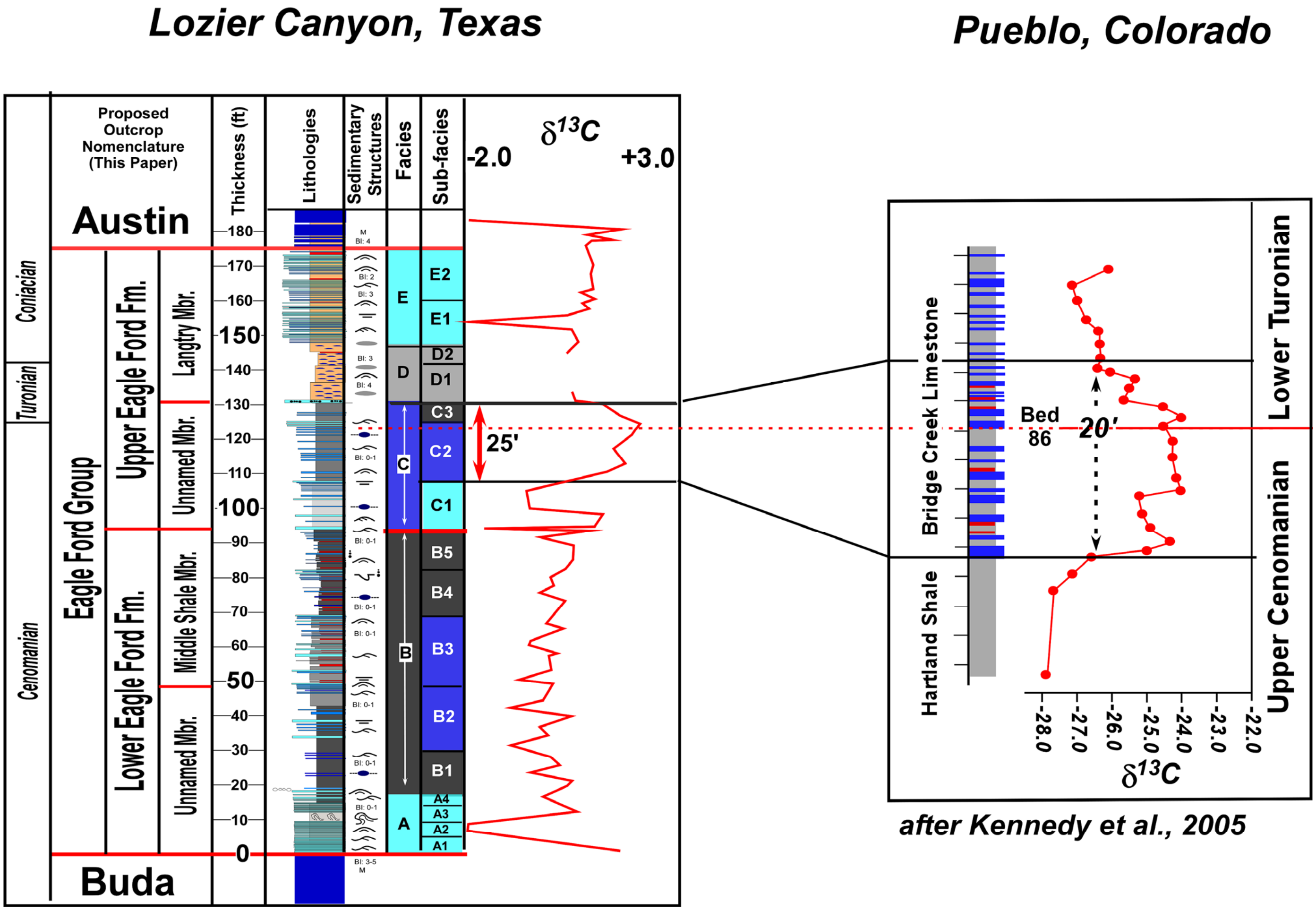


**Figure 10. The positive carbon isotope (δ$^{13}$C) associated with the C/T boundary globally associated with OAE2. The δ$^{13}$C excursion at the Lozier Canyon section is similar to what occurs at the C/T type locality in Pueblo, Colorado.**

unit, and overall this interval contains some of the highest TOC values (>6%) recorded at this site. The U content is also high. Just beneath the zone associated with the highest GR within this interval, and interpreted maximum flooding surface, there exists a grainstone bedset that contains oyster shells, as well as allochems which are phosphatized (Fig. 13). This assemblage suggests that anoxic water conditions at this locality existed fairly close to storm wave base within even the deepest water facies of the Eagle Ford succession.

Sub-facies B2 is approximately 20 ft thick. This sub-facies consists of 6–12 inch thick beds of black organic-rich carbonate mudstones alternating with 2–6 inch thick limestone (grainstone-prone) bedsets containing stacked beds of hummocky to swaley cross-laminations (Figs. 11 and 14A). Overall, thickness and frequency of the grainstone-prone bedsets increase upward in Facies B2, and the GR profile and carbonate content of sub-facies B1 and B2 incrementally decreases and increases upward, respectively (Fig. 8). The TOC profile remains high throughout most of this interval, decreasing only near the top (Fig. 8). This sub-facies appears to correlate to the primary completion target of some operators in the subsurface of South Texas.

Sub-facies B3, which is approximately 25 ft thick, also consists of carbonate mudstones alternating with stratified grainstone-prone bedsets (Fig. 14B). However, this sub-facies differs from the underlying sub-facies B2 mainly by the presence of distinct and abundant 0.5–3 inch thick bentonite beds, the occurrence of which appears to start abruptly at the base of this unit (Figs. 8 and 15). The abrupt appearance of bentonite beds at the base of the unit are typified by an increase in Th and U values, as well as a decrease in TOC values (Fig. 8). From base to top, sub-facies B3 displays an overall increase in GR values, suggesting it records an overall retrogradational succession (Fig. 8).

Overlying sub-facies B3 is sub-facies B4, which is approximately 13 ft thick, and B5, which is approximately 12 ft thick (Fig. 8). Both of these sub-facies are dominated by black organic-rich mudstones (Figs. 5 and 9) that contain abundant 1–4 inch thick bentonite beds (Fig. 16) and scattered grainstone-prone bedsets. Sub-facies B5 differs mainly from sub-facies B4 by containing fewer grainstone-prone bedsets, but overall the B4/B5 interval is characterized by an upward-decreasing GR profile due to upward-decreasing U content (Fig. 8). Interestingly, TOC and HI values increase upward within these intervals as does the K values, suggesting that siliciclastic (clay) content is also increasing upward (Fig. 8).

### Facies (Unit) C

The third distinct lithologic unit within the vertical succession of facies in the Eagle Ford of West Texas is Facies C. As outlined on Figure 5, this interval corresponds to Freeman's (1961/1968) Ledgy Unit of the Eagle Ford (Boquillas) succession. As Freeman's (1968) name implies, Facies C consists of

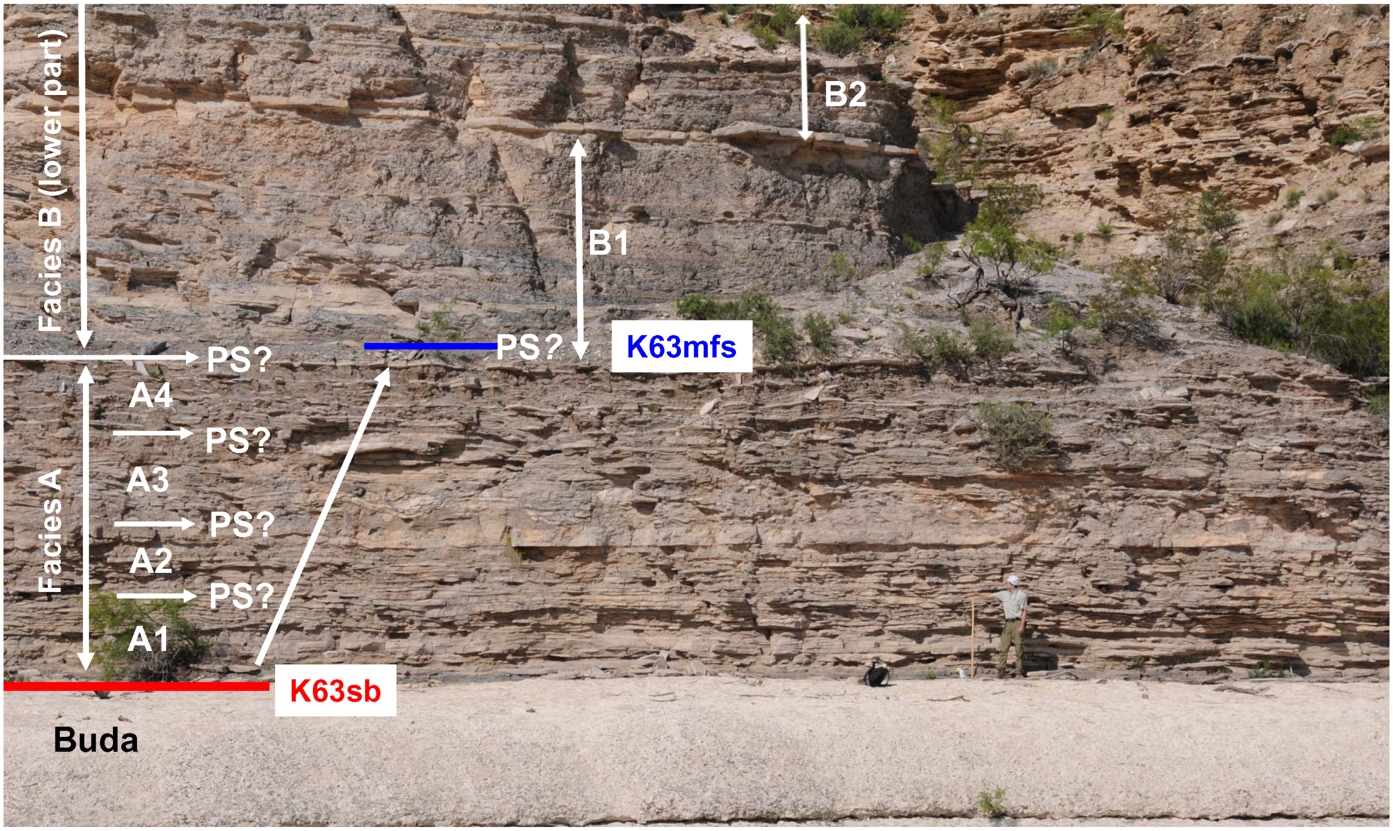


**Figure 11. Buda/Eagle Ford contact and the basal portions of the Eagle Ford Formation at Lozier Canyon. A six-ft tall micropaleontologist is holding 5-ft Jacob staff for scale. Note: (1) characteristics of sub-facies A1, A2, A3, A4, B1, and B2 and (2) the undulatory surface at the top of the Buda Limestone. PS = parasequence.**

grainstone/packstone bedsets, which are 8–24 inches thick, alternating with medium-gray carbonate mudstones (Fig. 17). Similar to Facies B, the more grainstone-prone bedsets in Facies C contains individual beds of hummocks, swales, and wave ripples (Fig. 18A). However, unlike the grainstone-prone bedsets in Facies B, burrows are common in the bedsets of Facies C (Fig. 18B), suggesting that oxygenated bottom conditions occasionally occurred within this unit.

Facies C, which is approximately 35 ft thick at site measured in Lozier Canyon, is characterized by a distinct change in color and lithologic character relative to underlying Facies B (Fig. 6). The base of member C is sharp and abrupt in outcrop and on the GR profile of the outcrop (Fig. 8). From the SGR data, it becomes clear that the overall GR decrease is due to an abrupt drop in Th, as well as U, content across this boundary. Moreover, the TOC and HI values drop at this contact, whereas the carbonate content increases. On the measured section, the presence of bentonite beds abruptly ends at his contact, marked by the dramatic decrease in the Th values. Thus the B/C facies boundary is also inferred to represent a distinct chronostratigraphic break, which marks the end of a period of bentonite deposition within the Eagle Ford Group. As mentioned previously, the facies B/C boundary in the outcrops of West Texas (Fig. 8) also corresponds to the Lower/Upper Eagle Ford Formation contact as carried into the subsurface in South Texas (Fig. 7).

Facies C can be divided into three distinct sub-facies, which from the base up are designated as C1, C2, and C3. In the Lozier Canyon outcrops, sub-facies C1, which is approximately 12 ft thick (Figs. 5 and 8), is characterized by alternating carbonate mudstones and grainstone/packstone bedsets that are yellowish gray in color (Fig. 17). The GR profile of this sub-facies has a blockier profile than the underlying facies and has some of the lowest GR values within the Eagle Ford Group (Fig. 8). This interval is characterized by low Th, U, TOC, and HI values but a higher carbonate content than underlying sub-facies B5 and overlying sub-facies C2 (Fig. 8).

The outcrop of sub-facies C2, which is approximately 17 ft thick, is similar to that of sub-facies C1 except that the mudstones in this sub-facies are more distinctly medium gray in color (Fig. 17). The geochemical and SGR data highlight the differences between the two sub-facies even more dramatically and record an increase in U, TOC, HI, and a corresponding decrease in carbonate content (Fig. 8). Overall, the total GR values for the C2 interval increase upward, suggesting an overall retrogradational stacking pattern for this interval (Fig. 8). A prominent positive excursion in the $\delta^{13}C$ profile also occurs within sub-facies C2, with the peak value located at 125 ft, which is the boundary with C3 (Fig. 8). Similarly, the highest TOC values from Facies C occur near the top of sub-facies C2 (Fig. 8).

The uppermost sub-facies C3 (Figs. 8 and 17), which is approximately 6 ft thick, is dominated by gray mudstones with higher GR values produced by increasing K enrichment upward (Fig. 8). Conversely, the $\delta^{13}C$ profile shows a decrease in values in C3 starting from the peak at the C2/C3 boundary.

### Facies (Unit) D

The fourth distinct lithologic unit of the Eagle Ford Group is Facies D (Donovan and Staerker, 2010). As outlined on Figure 5, the base of Facies D is equated to the base of Freeman's (1961,

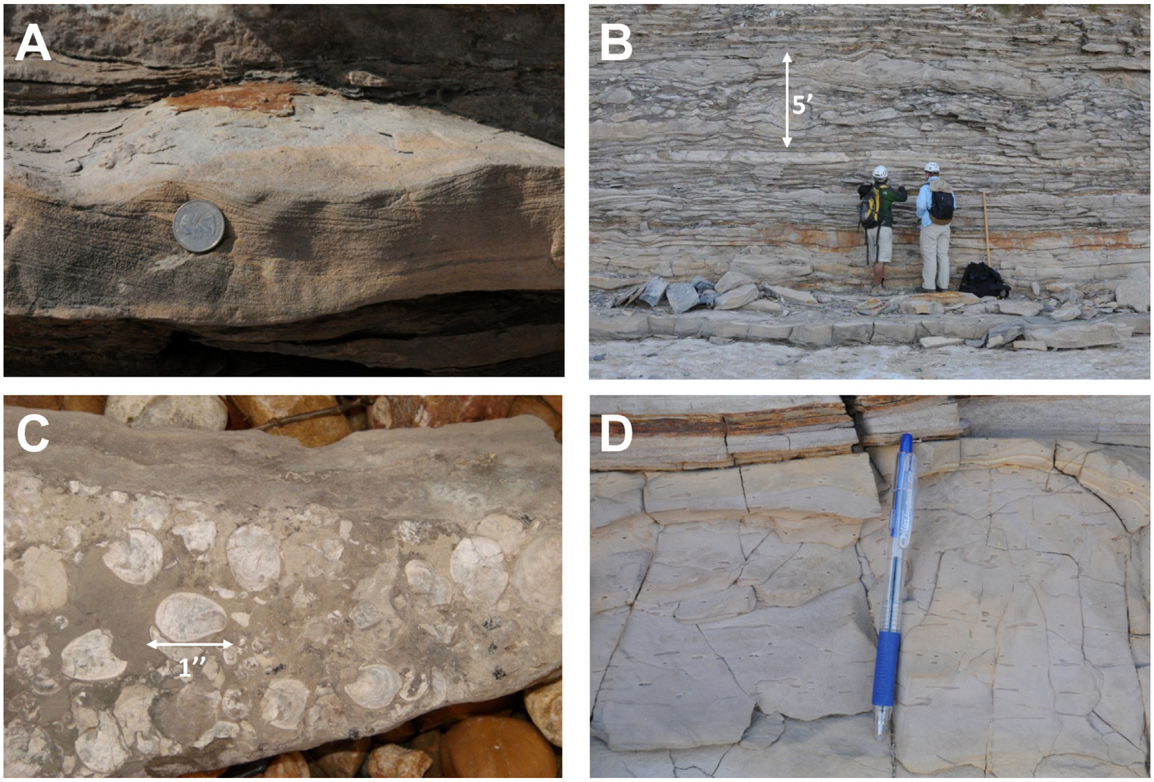


**Figure 12. (A) Interpreted small hummocks to wave ripples in sub-facies A1. (B) Sub-facies A3 with contorted bedding and apparent matrix-supported conglomerates. (C) Oyster bed within sub-facies A1. (D) Possible burrow fabric in one bed in the middle of sub-facies A1.**

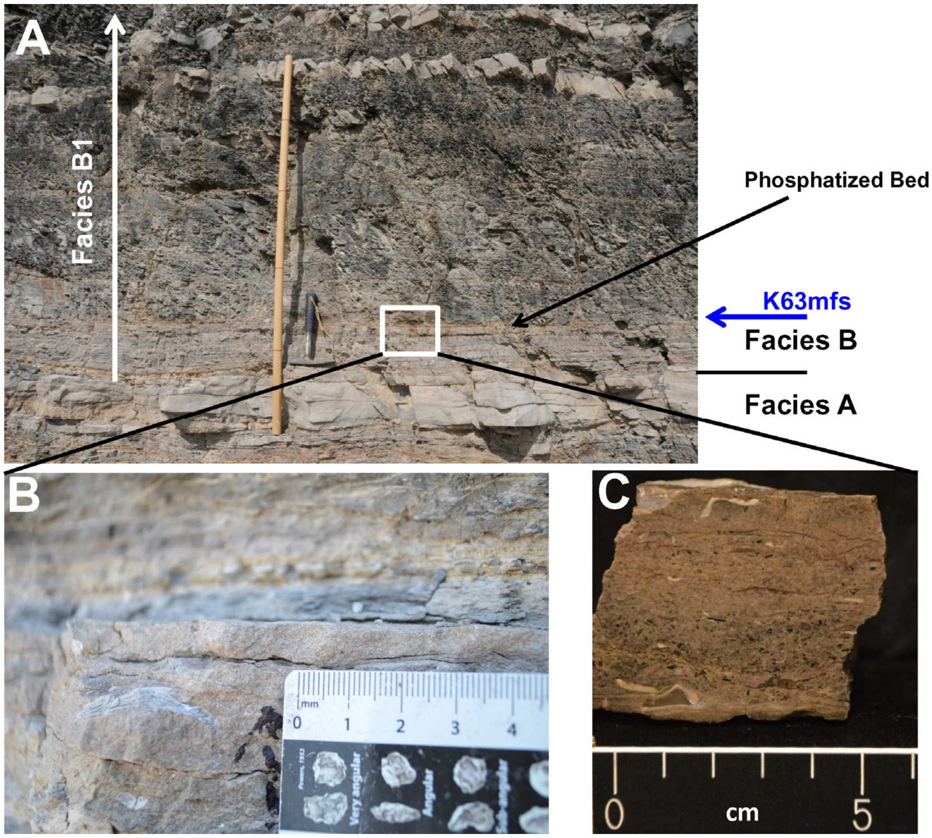


**Figure 13. (a) Contact between facies A and B at Lozier Canyon. (b) Grainstone bed in the basal portions of Facies B that contains oyster shells as allochems. (c) Slabbed cross-section of bed illustrated in (b) that also contains oyster shells and abundant allochems replaced by phosphate. This bed occurs just below the interpreted K63mfs.**

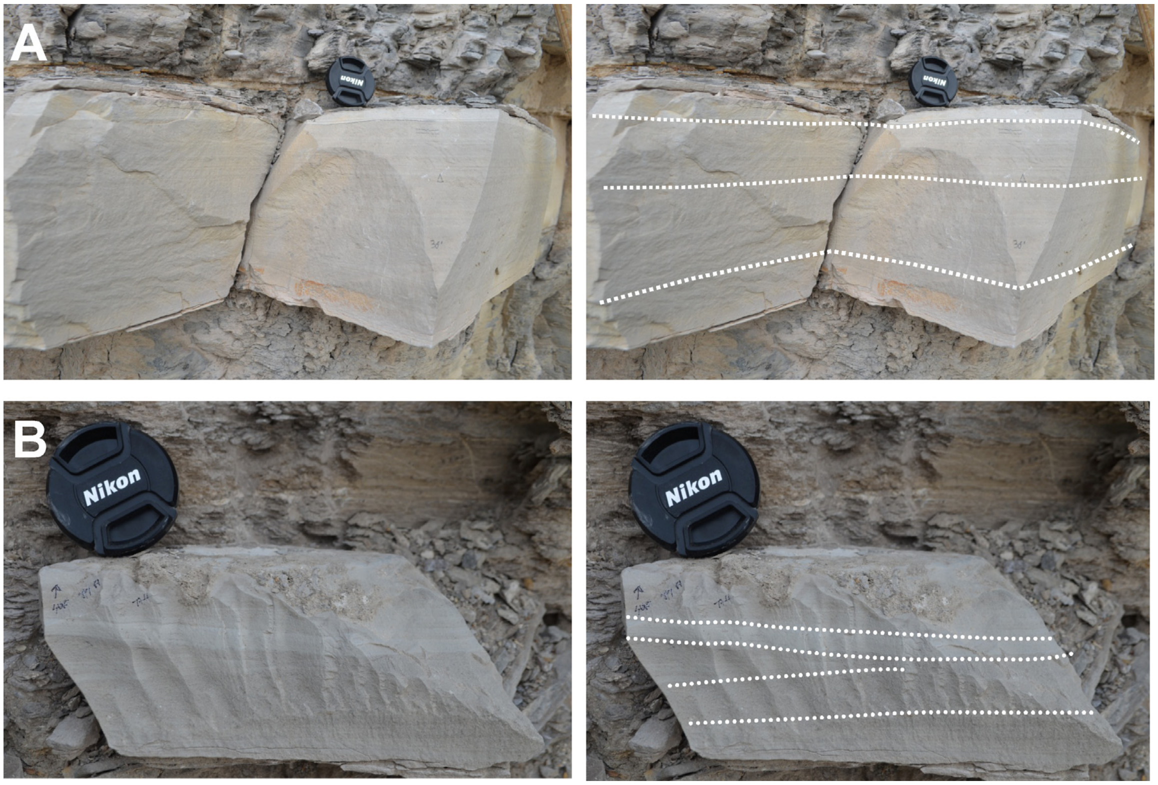


**Figure 14.** Uninterpreted and interpreted photos of low-angle inclined stratification at 36 ft in sub-facies B2 (A) and at 77 ft in sub-facies B4 (B).

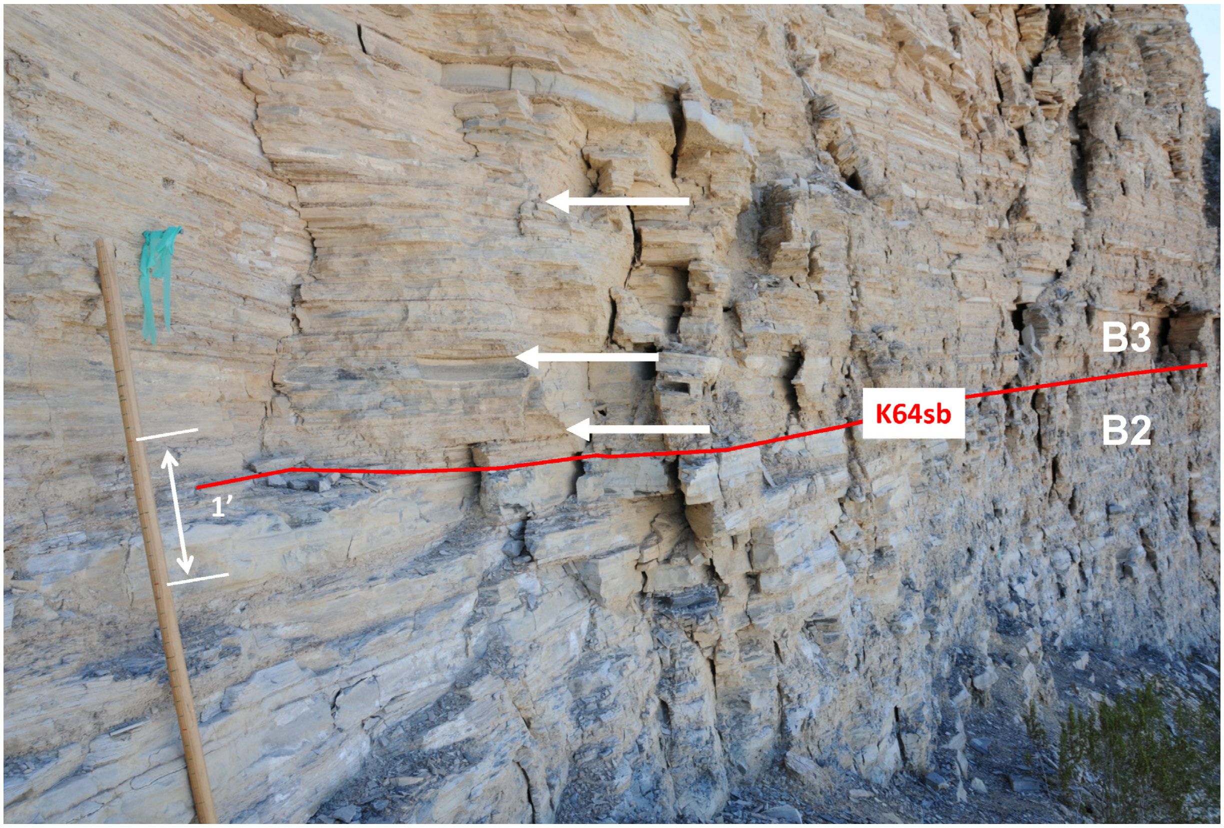


**Figure 15.** Boundary between sub-facies B2 and B3 at approximately 48 ft on the measured section. At this boundary, a slight color change occurs, which is associated with the onset of abundant 0.5–4.0 inch thick bentonite beds (white arrows). This boundary is interpreted as the K64sb.

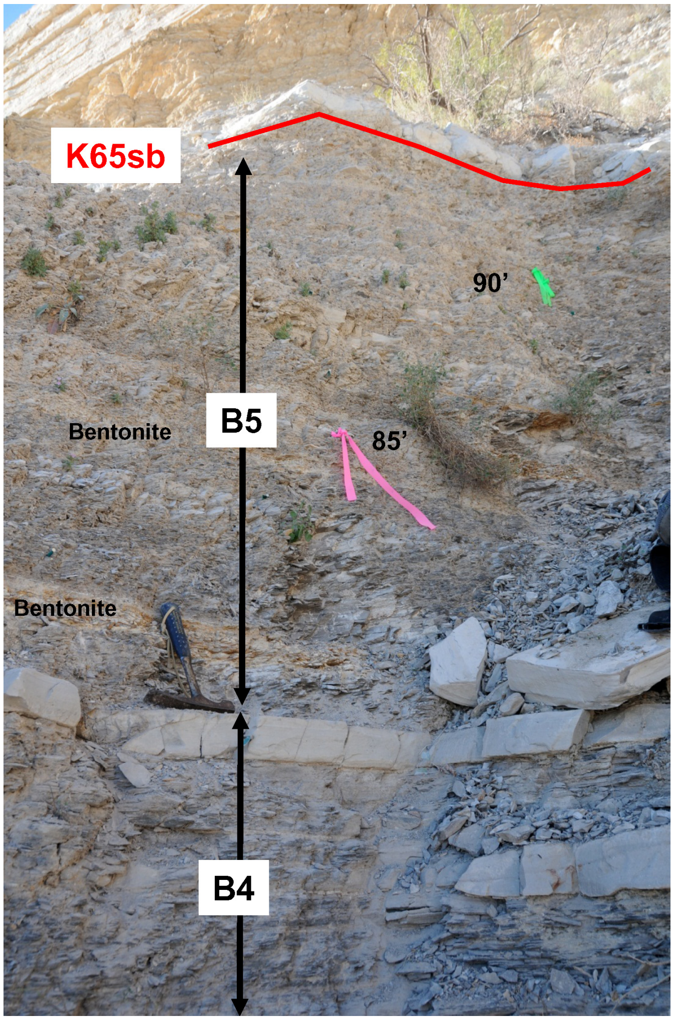


**Figure 16. Interbedded mudstones and grainstones at the top of sub-facies B4 give way to mudstones with scattered bentonite beds in sub-facies B5.**

1968) Laminated Unit of the Eagle Ford (Boquillas) unit and the base of Pessagno's (1969) Langtry Member of the Eagle Ford (Boquillas) succession. In this paper, facies D and E comprise the Langtry Member of the Upper Eagle Ford Formation (Fig. 5).

In lithologic character, the difference between Facies C and Facies D is dramatic and marked from a change from interbedded grainstones and gray mudstone in Facies C to highly burrowed yellowish-gray marls in Facies D (Figs. 19A and 20). Furthermore, in outcrop, the base of Facies D consists of an indurated massive packstone containing pebble-sized clasts of tan mudstones and bored internal fossil molds (Fig. 19B). Besides the abundance of burrows, Facies D is characterized by the presence of abundant echinoids, the most common of which is *Hemiaster jacksonii* (Fig. 19C).

From the elemental data, this boundary corresponds to a distinct decrease in K and TOC, as well as an increased carbonate, U and Th content (Fig. 8), making facies D and E appear distinctly different in elemental character from the underlying Facies C. The occurrence of thick 4–6-ft thick bentonite beds identified on the measured section and also recorded as distinct Th spikes on the SGR data is a distinctive aspect of facies D and E (Langtry Member).

Our recent work (Fig. 8) suggests that Facies D, which is about 17 ft thick, can be divided into a lower sub-facies (D1) that increases in mud-size content upward and an upper sub-facies (D2) that decreases in mud content and increases in carbonate content upward. Thus, the boundary between sub-facies D1 and D2 is marked by the interpreted inflection point (relative high) on the GR profile of the measured section (Fig. 8), which corresponds to the most recessive, clay-rich portion of the weathering profile (Fig. 20).

### Facies (Unit) E

The fifth and uppermost unit of the Eagle Ford Group is termed Facies E. As outlined by Donovan and Staerker (2010), Facies E consists of distinct yellowish-ochre-colored grainstones alternating with carbonate mudstones and bentonite beds. The grainstones consist of bedsets that are 2–4 inches thick containing wave ripples and small hummocks. Our recent work suggests that Facies E, which is about 27 ft thick, can be divided into a lower sub-facies (E1), which appears to be more bioturbated, and an upper sub-facies (E2) that is more distinctly stratified (Figs. 8 and 20). The top of Facies E is marked by the contact with the Austin Chalk (Fig. 20). As illustrated on Figure 21, this boundary is locally marked by the presence of 1–5 inch thick Eagle Ford rip-up clasts at the base of the Austin Chalk. This boundary is also distinct on the GR profile of the outcrop with a uniform decrease in Th, U, and K values (Fig. 8).

## Biostratigraphy and Stable Isotope Geochemistry

Biostratigraphic interpretations complement sedimentological and geochemical observations to define key stratal surfaces and establish empirical ties to the geologic time scale for the Eagle Ford units. Generalized population trends for key taxa or groups of taxa are reported herein as simple biozones and displayed as curves (Fig. 9 and Table 1). Many of the boundaries separating biozones occur at key stratal surfaces and represent either erosion along depositional sequence boundaries or extreme time and sediment condensation within marine condensed sections. Biostratigraphic changes are particularly prominent at or near the base of the Upper Eagle Ford Formation, at the base of the Langtry Member of the Upper Eagle Ford succession, and at or near the D1/D2 boundary within the Langtry Member.

At Lozier Canyon, a combination of the top ranges of *Rotalipora greenhornensis*, *Globigerinelloides bentonensis*, *Corollithion kennedyi*, and *Helenea chiastia* indicate that the basal 97.25 ft of the Eagle Ford Group (facies A to C1) is definitively Cenomanian in age. Similarly, the interval from 132 ft to approximately 145 ft (sub-facies D1) is definitively Turonian in age based on the presence of *Quadrum gartneri*. Unfortunately, the age of the interval between 97.25 ft and 132 ft is unresolvable at the section analysed from Lozier Canyon using only microfossil biostratigraphy, necessitating the use of either macrofossils or $\delta^{13}$C data.

At the GSSP, the Cenomanian/Turonian boundary is defined at an ammonite appearance located in Bed 86 of the Bridge Creek Limestone in Pueblo, Colorado (Pratt and Threlkeld, 1984; Kennedy et al., 2005). The stage boundary is bracketed by a succession of microfossil markers that include the lower Turonian first occurrence (FO) of the nannofossil *Q. gartneri* proposed by Watkins (1985); the upper Cenomanian last occurrence (LO) of nannofossil *H. chiastia* presented by Bralower (1988); and by the LO of the foraminifers *G. bentonensis* and keeled, *Rotalipora greenhornensis* as proposed by Leckie (1985). De-

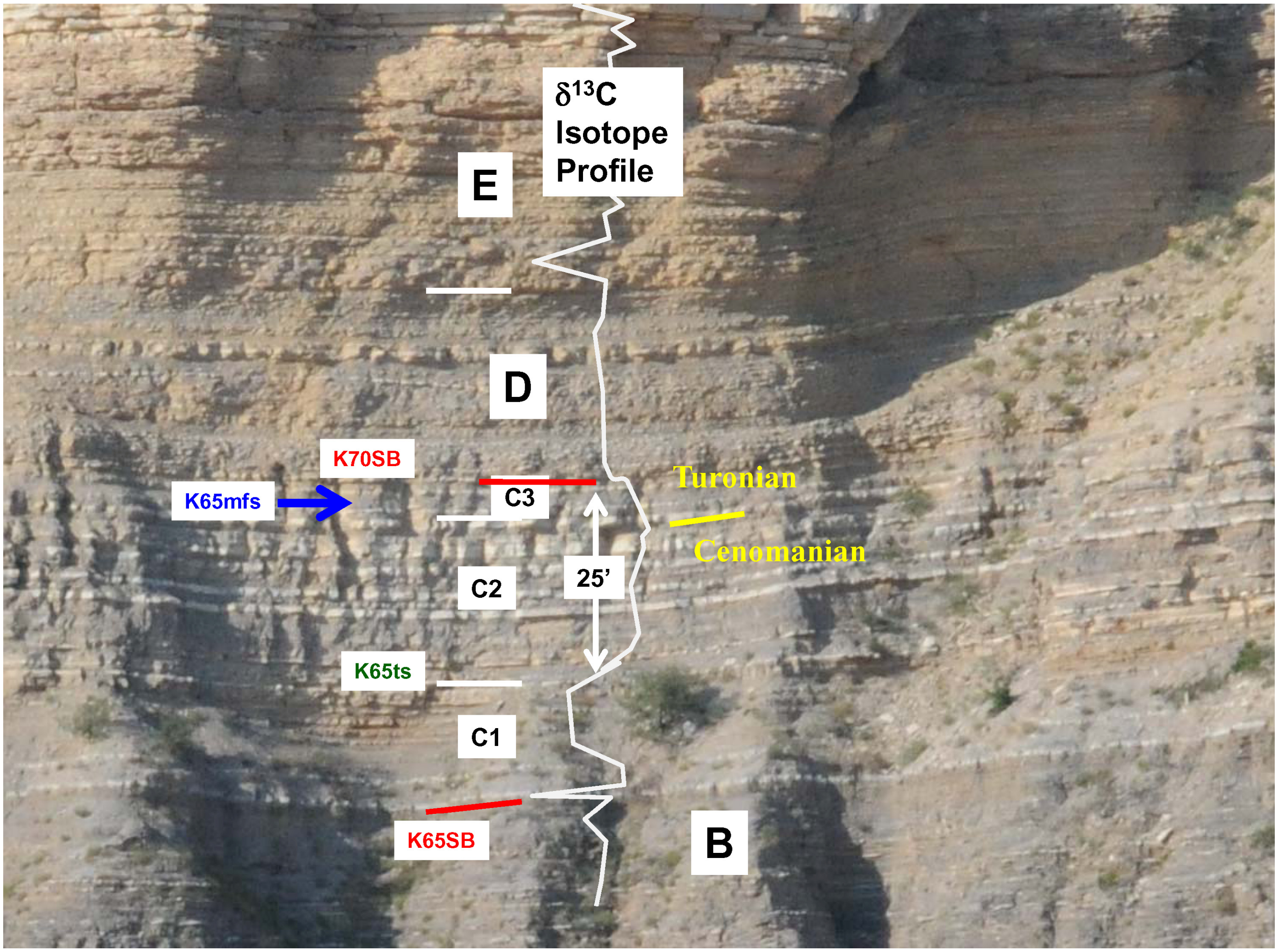


**Figure 17. Eagle Ford Group with superimposed $\delta^{13}C$ isotope profile. Note (1) onset of light gray packstone bedsets at the base of Facies C, (2) start of carbon isotope excursion at the base of sub-facies C2, (3) more mudstone-prone sub-facies C3, and (4) overall discontinuous (bioturbated) nature of Facies D.**

spite their presence in the Lozier section, these microfossil events do not provide sufficient fidelity to delineate the stage boundary at the bed-scale resolution needed for this study. In this rock section, the $\delta^{13}C$ profile is the better proxy for the Cenomanian/Turonian boundary.

The widespread burial of organic carbon during Oceanic Anoxic Event 2 (OAE2) (Schlanger and Jenkyns, 1976; Schlanger et al., 1987) caused a large positive excursion in the global ratio of $^{12}C$ to $^{13}C$ (expressed as $\delta^{13}C$), the termination of which falls just above the Cenomanian-Turonian boundary (Pratt and Threlkeld, 1984; Voigt, 2000; Sageman et al., 2006). Figure 10 illustrates the $\delta^{13}C$ profile from Lozier Canyon compared to the scaled $\delta^{13}C$ profile from the GSSP at Pueblo, Colorado (Kennedy et al., 2005). The isotopic profiles are quite similar and are inferred to represent the same anoxic event. By using the $\delta^{13}C$ signature as the preferred proxy criteria for the boundary, the base of the Turonian is at least as high as the top of sub-facies C2 at 124 ft and possibly as high as the facies C/D contact at 132 ft, depending on how one matches the $\delta^{13}C$ profiles (Fig. 10) Because we interpret a sequence boundary at the base of Facies D, the excursion is likely truncated to some extent. However, the close match of the $\delta^{13}C$ pattern from Lozier Canyon to that from the GSSP, coupled with the presence of lower Turonian microfossils in strata near the top of Facies C at the nearby Osman West locality as reported in Donovan and Staerker (2010), provides strong evidence for the Cenomanian-Turonian boundary occurring at the top of sub-facies C2 (Figs. 9 and 10). Furthermore, a significant change in total pollen and spores immediately below the Cenomanian/Turonian boundary in Lozier Canyon (Fig. 9, column 7) is similar to that which occurs in the Pueblo, Colorado, section (Dodsworth, 2000). The placement of the stage boundary within facies C is a revision from the earlier interpretation presented in Donovan and Staerker (2010), which placed the boundary at or near the facies B/C boundary.

We identified the Turonian/Coniacian boundary using the same criteria outlined in Donovan and Staerker (2010), which uses the extinction of *Eprolithus eptapetalus* as the proxy for the top of the Turonian. However, because there is no GSSP reference section for this boundary, it is likely that other biostratigraphers will disagree with our placement of this stage boundary. Nonetheless, we provisionally maintain that the surface at which the extinction of E. eptapetalus (Fig. 9, column 5) occurs and the coincident FOs of calcareous nannofossils *Marthasterites furcatus*, *Eiffellithus eximius*, and *Lithastrinus septenarius* in the overlying D2 sub-facies at Lozier Canyon (Fig. 9, column 6) collectively record the best approximation of the Turonian/Coniacian

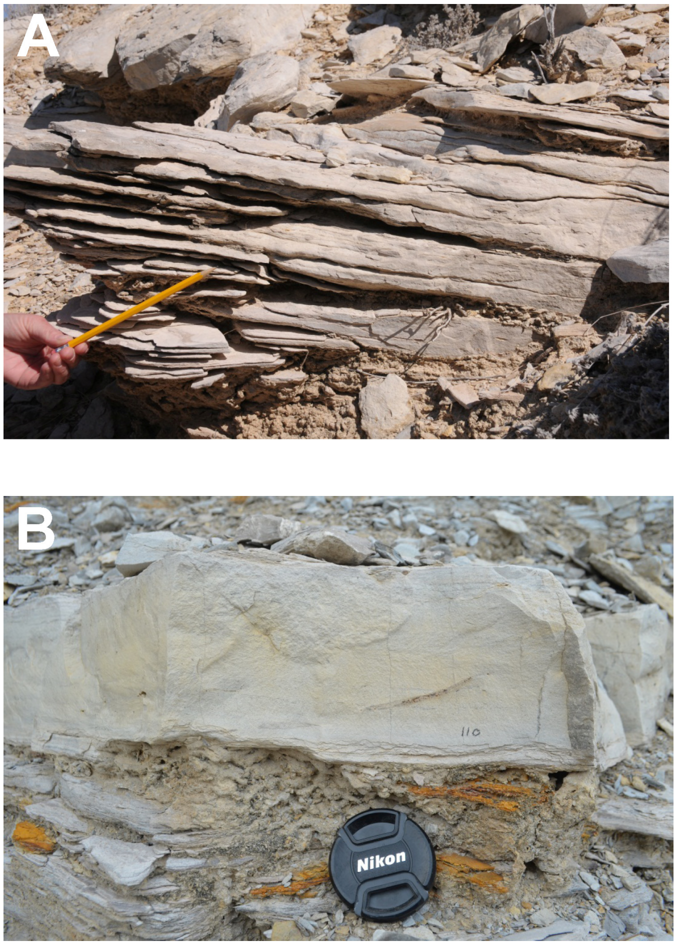


**Figure 18. Bedsets with (A) low-angle inclined stratification at 100 ft in sub-facies C1 and (B) sub-horizontal burrows at 110 ft in sub-facies C2.**

boundary at this locality. For comparison using the molluscan record, Cobban et al. (2008) approximated the stage boundary to occur between 25 ft and 100 ft above the base of the Austin Chalk based on the presence of the inoceramid bivalve *Cremnoceramus deformis erectus*. Given the paucity of macrofossils at Lozier Canyon, we were unable to reproduce the results of Cobban et al. (2008). Additionally, we could not find a site in Lozier Canyon where 100 ft of Austin Chalk exists to verify the presence of *C. deformis erectus* from the stratigraphic interval cited in Cobban et al. (2008). The paucity of published nannofossil data from inferred coeval units in the U.S. Western Interior also hinders determination of the nannofossil and macrofossil placements of the Turonian/Coniacian boundary.

In summary, over 70% of the Eagle Ford succession at Lozier Canyon is Cenomanian (facies A to C2), whereas the uppermost 30 ft (sub-facies D2 and Facies E) could be Coniacian, as defined using the presence of *E. eptapetalus*, *L. septenarius*, and *M. furcatus* under current conventions (Fig. 9). This interpretation suggests that much of the middle Turonian was eroded along the surface that separates sub-facies C3 from D1 at the base of the Langtry Member of the Upper Eagle Ford Formation (Figs. 8 and 9). Both sedimentology and stacking patterns cited earlier in this paper suggest that this surface is likely a sequence boundary (K70sb).

### Organic Geochemistry

Figure 8 contains plots of the TOC, percent carbonate, and HI at the Lozier Canyon. This plot reveals four zones of relative TOC enrichments. From the base up, the first enrichment zone includes the upper half of Facies A, all of sub-facies B1, and most of sub-facies B2. In this zone, TOC values of 4–6% are present, making it the most organic-rich portion of the entire Eagle Ford succession at this locality. The second enrichment zone includes sub-facies B4 and B5 where TOC values of 1–2% occur, especially within sub-facies B4. The third zone of enrichment, with TOC values of 1–3%, occurs within sub-facies C2 and C3. This zone directly corresponds to the $\delta^{13}C$ isotopic excursion interpreted to be associated with OAE2 that straddles the Cenomanian-Turonian stage boundary. The uppermost zone of relative enrichment, which is also the lowest in terms of absolute percent TOC, occurs around the boundary of sub-members D1 and D2, which also corresponds to our interpreted Turonian-Coniacian stage boundary (Fig. 8).

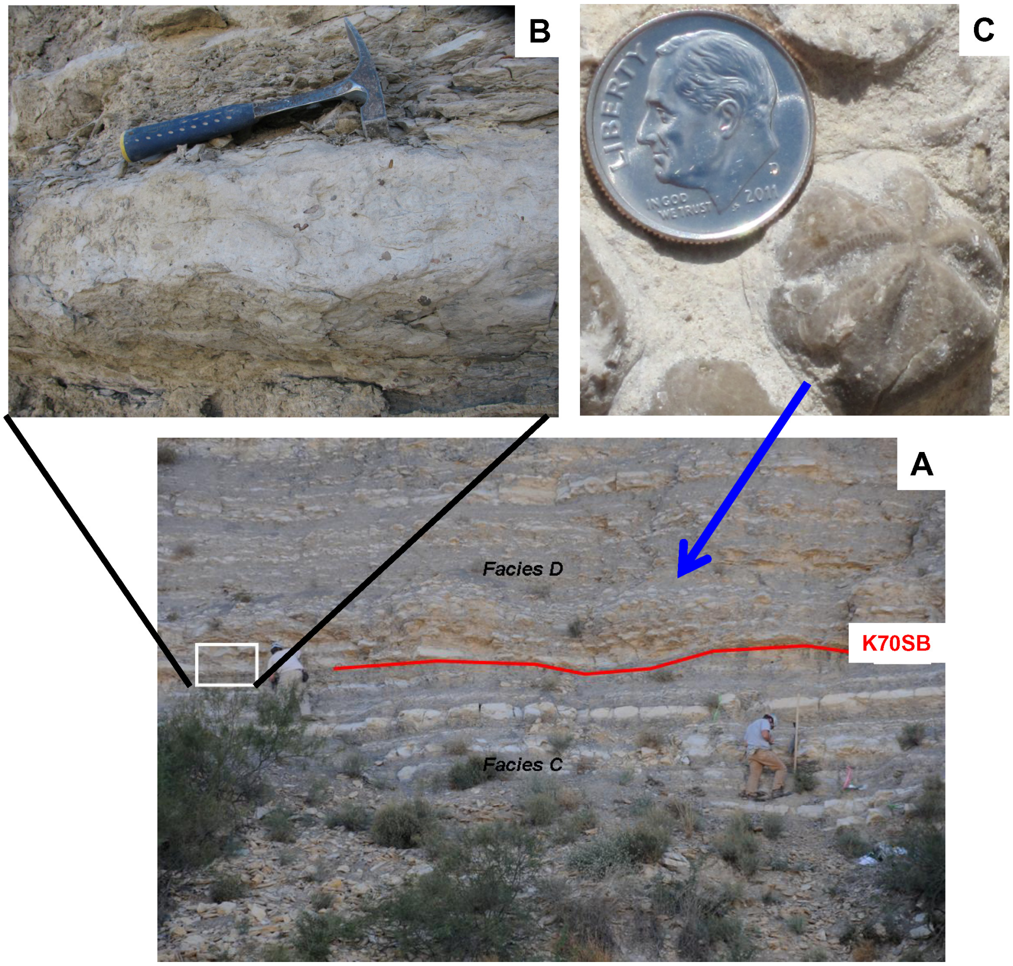
Figure 8 also contains a plot of the HI at this measured section. Enrichment zones similar to the TOC were noted, where HI values of 125 to almost 750 occur. The high HI values, however, should be put into the context of the low maturity of the Eagle Ford Group on this part of the Comanche Platform. At Lozier Canyon, pristine/phytane ratios from gas chromatography mass spectrometry (GCMS) analysis on several samples of the Lower Eagle Ford Formation range from 0.24 to 0.43, indicating strongly anoxic conditions during deposition. These values are also typical of organofacies A (Type IIS). It should also be noted that Ro values of the Lower Eagle Ford Formation ranging from 0.5 to 0.7 were calculated by Tmax from Rock-Eval pyrolysis.

## DATA INTEGRATION AND SEQUENCE STRATIGRAPHY

Based on the highway exposures in Val Verde County, and well-log correlations in South Texas, Donovan and Staerker (2010) proposed that the Eagle Ford consisted of two depositional sequences. However, our recent work in Lozier Canyon, as well as the incorporation of core and additional well-log data from the subsurface of South Texas, suggests that the Eagle Ford Group in West and South Texas comprises four depositional sequences, herein referred to as the K63, K64, K65, and K70 sequences. As illustrated in Figures 8 and 9, four distinct mudstone-prone zones, all of which correspond to TOC enrichments, relative U peaks, and in the case of the upper two, stage boundaries, occur at Lozier Canyon. Within these mudstone intervals, which are interpreted as marine condensed sections, we interpreted positions of maximum flooding surfaces, referred to as the K63mfs, K64mfs, K65mfs, and K70mfs. Based on the outcrop data, these marine condensed sections respectively occur near the base of sub-facies B2, near the base of sub-facies B5, at or near the base of sub-facies C3, and at the boundary between sub-facies D2 and D3.

Five sequence boundaries (sb) and coinciding transgressive surfaces (ts) bound and occur within the Eagle Ford Group. The K63sb/ts surface at the Buda/Eagle Ford contact corresponds to the boundary between Hill's (1887a, 1887b) Comanchean and Gulfian series in South and West Texas. In Lozier Canyon this contact is sharp, slightly undulatory, and marked by a change from Buda wackestones below to grainstones in Facies A of the Eagle Ford above (Figs. 8 and 11). In road cuts in Val Verde County, Lock and Peschier (2006) reported microkarst develop-

Figure 19. (A) Abrupt contact between facies C and D in Lozier Canyon. (B) Bed at the base of Facies D. Note abundant shale clasts and internal fossil molds. (c) Echinoid *Hemiaster jacksonii*, which is common in Facies D.



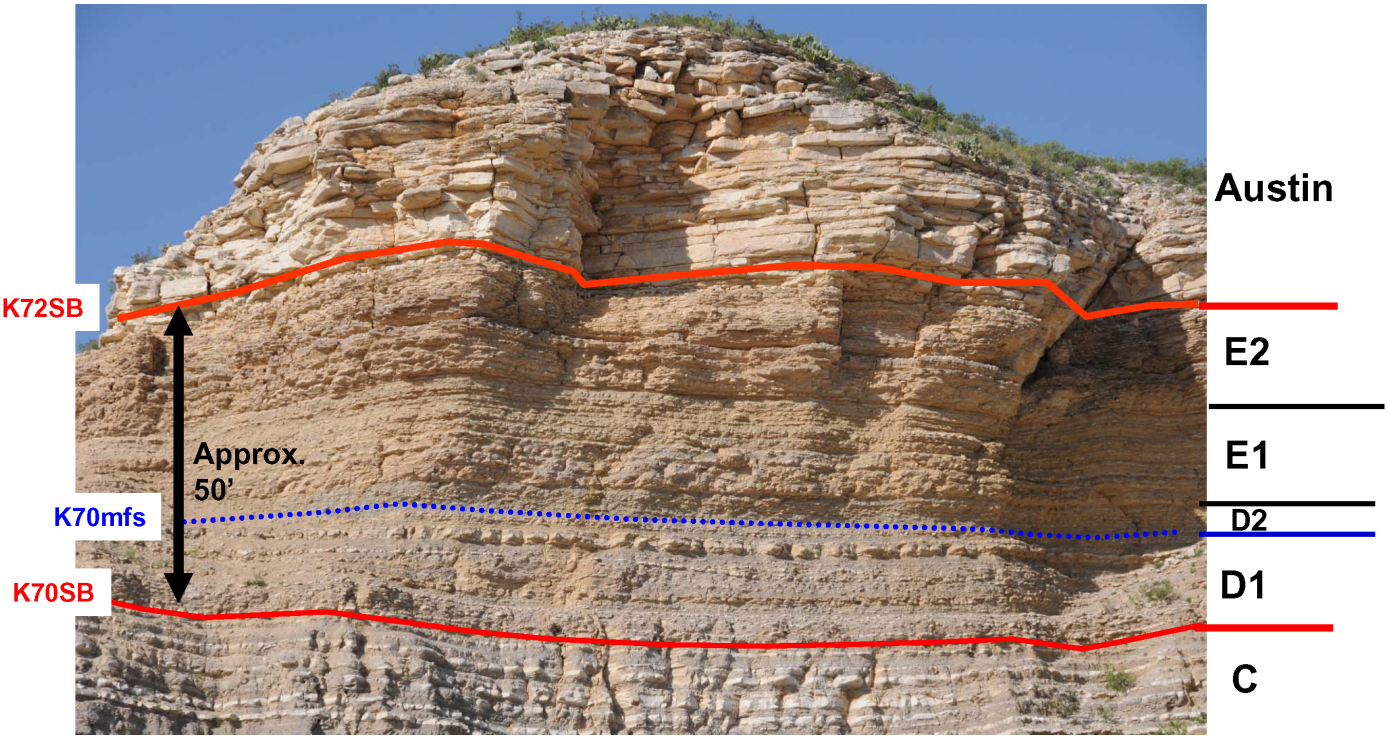


Figure 20. Outcrop character of sub-facies D1, D2, E1, and E2 in Lozier Canyon. Interpreted sequence stratigraphic surfaces are indicated.

ment at the top of the Buda Limestone. Freeman (1968, his p. 10) noted Buda thickness variation from 46 to 89 ft in his study area in southwest Val Verde, southern Terrell, and southeast Brewster counties. Thus, it is likely that the K63sb represents a subtle angular unconformity that is responsible for the observed thickness variations in the underlying Buda succession.

As noted in our description of Facies A, the presence of disarticulated oysters and hummocky cross-stratification (Fig. 12), suggests that shallow-marine conditions, near fair-weather wave base, existed during deposition of beds immediately above K63sb. The incremental upward increase in mudstone interbeds, coupled with the decreasing amounts of grainstone bedsets, within Facies A is interpreted as a transgressive systems tract that records gradual deepening from a middle shoreface to lower shoreface setting toward the top of Facies A, and culminates in an anoxic offshore setting during deposition of sub-facies B1. K63mfs is placed at the GR and TOC maxima that occur near the base of sub-facies B1 approximately 20 ft above the top of the Buda Limestone (Fig. 8). Thus, B1 strata overlying the interpreted K63mfs, along with the strata in sub-facies B2, represent inferred highstand deposits of the K63 Sequence. These highstand deposits display an overall upward increase in the number of limestone (grainstone-prone) bedsets, an overall upward-decreasing GR profile that also corresponds to a decrease in overall TOC content, and increase in weight percent carbonate.

The K64sb, placed at the contact between facies B2 and B3 at approximately 48 ft on the measured section (Fig. 8), coincides with the first occurrence of abundant bentonite beds and a slight color change (Fig. 15). Moreover, this surface marks the onset of a distinct increase in GR values, an increase in U, Th, and carbonate content, and a corresponding drop in TOC content (Fig. 8). The K64mfs occurs just above the base of subfacies B3, which is characterized by an overall upward-decreasing GR profile. Subfacies B4 and B5 are interpreted as deposits of a highstand systems tract (Fig. 8).

The K65sb, which occurs at the contact between facies B and C, is marked by an abrupt change in the physical and geochemical character of the Eagle Ford Group. Across this surface, the Eagle Ford lithology changes from black mudstone below to grainstone beds interbedded with grey mudstones above (Fig. 6). The boundary is also characterized by an abrupt decrease in the total GR values due to decrease in U and Th content, as well as a drop in TOC content and increase in carbonate content (Fig. 8). These strata probably record a change from highly anoxic conditions below the surface to a more oxygenated environment above. This change can better be explained by a chronostratigraphically significant surface than a simple time-transgressive facies change, and thus the K65sb is placed at this distinct lithologic contact. The K65ts coincides with the base of the isotopic excursion at the base of Facies C2, which also corresponds to an upward increase in TOC accumulation rate. The K65mfs is placed at the maximum GR peak within sub-facies C3. The distinct marker bed at the base of the Upper Eagle Ford Formation in South Texas (Fig. 7) is interpreted as siliciclastic-prone basal lowstand strata, which were deposited and preserved in deeper portions of the Comanche Platform.

The K70sb at the boundary between Facies C and Facies D, and at the base of the Langtry Member is characterized by a distinct change from grainstones with grey mudstone beds (below) to highly bioturbated yellowish marls (above) occurs (Fig. 8). A pronounced pebble lag with bored internal molds occurs along this surface at Lozier Canyon and elsewhere in West Texas, recording erosion and sediment reworking and bypass (Fig. 19). A prominent faunal change also marks this boundary, with earliest Turonian nannofossils occurring below it, and late Turonian nannofossils present above (Donovan and Staerker, 2010). Based on foraminifera data, Pessagno (1969) similarly placed the boundary between his Rock Pens (below) and Langtry (above) Members of the Boquillas Formation. The K70mfs is characterized by a strong floral and faunal increase and is placed at the boundary between sub-facies D1 and D2, which is at or very close to the interpreted Turonian-Coniacian stage boundary (Fig. 8).

Finally, the K72sb/ts occurs at the top of the Eagle Ford Group. The Eagle Ford/Austin contact corresponds to a change from wave-rippled grainstones interbedded with mudstones and bentonite beds (below) to wackestone beds interbedded with thin mudstone beds (above). Along U.S. Hwy. 90 adjacent to Lozier Canyon, distinct Eagle Ford rip-up clasts occur above this interpreted hiatal surface (Fig. 21).

It should be noted, that the attributes of stratal surfaces and systems tracts of the Eagle Ford Group are quite similar to those observed in other mudstone-dominated successions (e.g., Bohacs, 1990; Schieber, 1998; MacQuaker et al., 1998). These similarities with units of widely different ages and basin settings indicate the robustness of applying the sequence-stratigraphic approach to mudstone units.

## IMPLICATIONS TO SUBSURFACE CORRELATIONS

The primary purpose of our outcrop research is to apply observations and interpretations derived from inspection of the Eagle Ford exposures of West Texas to the equivalent strata of the subsurface where the Eagle Ford unconventional mudstone reservoirs are being exploited. Toward this end, analysis of the exposures at Lozier Canyon provides new insights into the lithostratigraphy and chronostratigraphy of the Eagle Ford Group. Although our original work (Donovan and Staerker, 2010) recognized some basic elements of our newly proposed framework, our detailed study of the Lozier Canyon exposures enabled us to add significant fidelity to our understanding of the geology of the Eagle Ford Group. Findings reported herein suggest that: (1) a regional unconformity separates the Lower and Upper Eagle Ford formations, and (2) the Lower and Upper Eagle Ford intervals each contain two distinct depositional sequences.

Using the geochemical and petrophysical signatures associated with the sequences defined in outcrop (Fig. 8), the same surfaces, systems tracts, and sequences can be defined in the subsurface of South Texas (Fig. 7). A fundamental difference between the stratigraphy of the Lozier Canyon area and of the type well in Webb County is the pronounce differences in the thicknesses of the interpreted K63 and K65 highstands (Fig. 22). We infer that conditions of greater accommodation creation existed during deposition and preservation of the K63 and K65 sequences in the South Texas Submarine Plateau area (Fig. 4) where the type well is located. Much lower rates of accommodation existed in the structurally shallower area of the Comanche Platform where Lozier Canyon occurs (Fig. 4). Interestingly, minimal accommodation variations occurred during deposition and preservation of the K64 and K70 sequences between these two areas, suggesting that the K64sb, at the base of the Middle Shale Member, and K70sb, at the base of the Langtry Member, are both tectonically enhanced angular unconformities and not just simple disconformities (Donovan, 2010).

**Figure 21.** (A) Eagle Ford/Austin contact along U.S. Hwy. 90 just east of Lozier Canyon. (B) Centimeter-scale rip-up clasts of Eagle Ford lithologies at base of the Austin Chalk just above the interpreted K72sb.

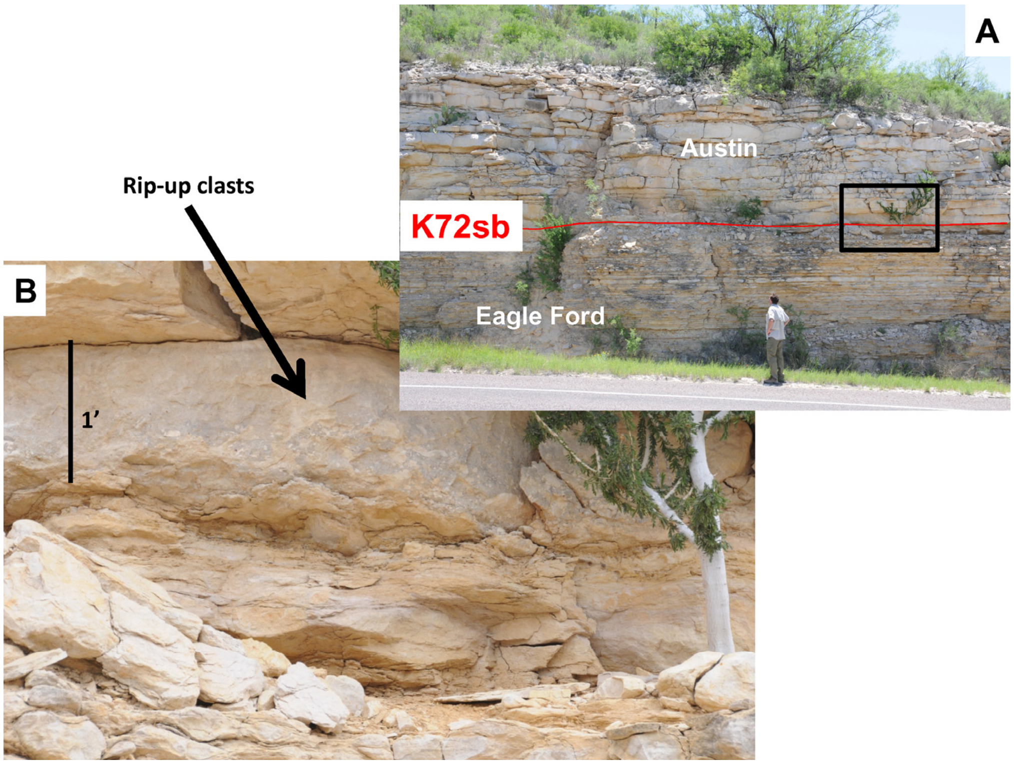
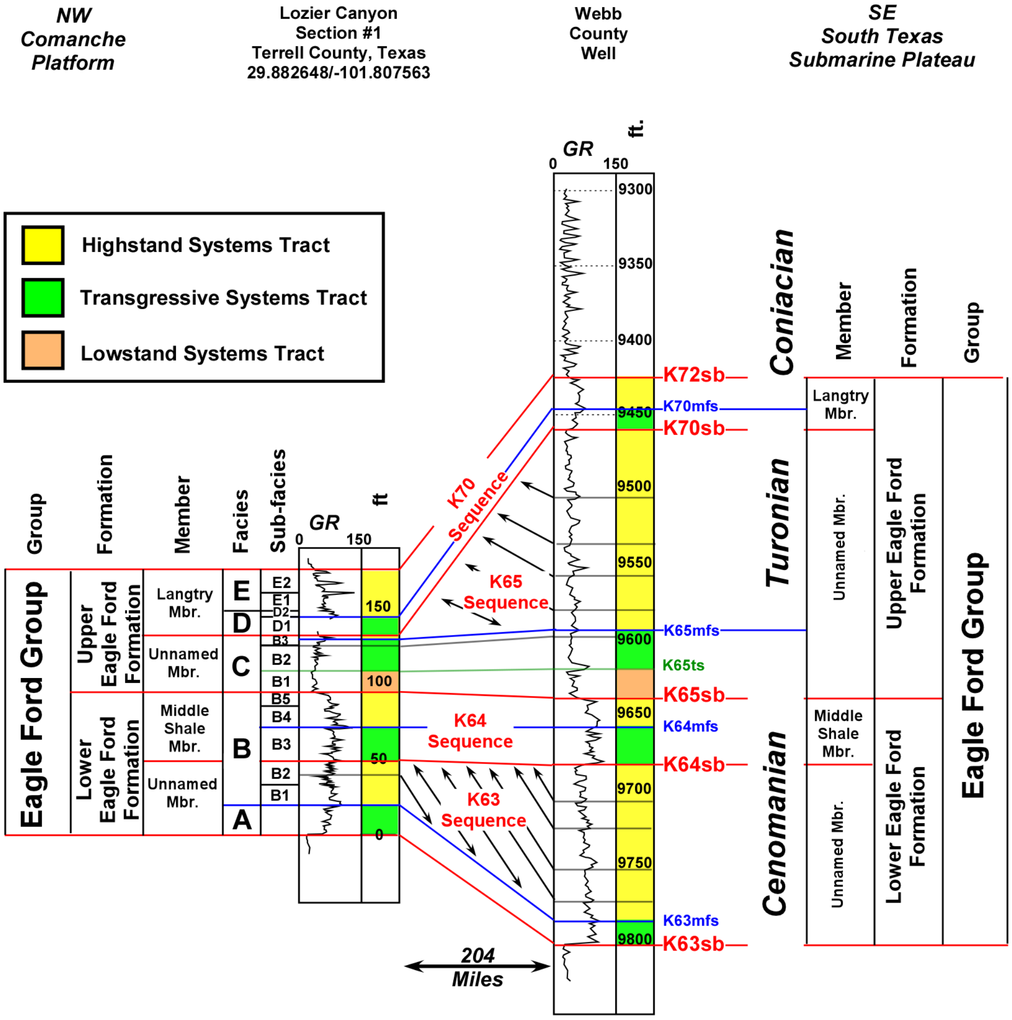


**Figure 22.** Correlations between the outcrop section in Lozier Canyon and well from the South Texas submarine plateau area of Webb County. Thickness variation appears mainly related to different accommodation conditions between the outcrop area in the structurally shallow Comanche Platform area and the deeper submarine plateau, which affected accumulation and preservation of highstand deposits in the K63 and K65 sequences. Datum is K64mfs. Arrowheads used to illustrate interpreted downlaps onto mfs's and toplap/truncation beneath sb's.



Regional truncation by angular discordance beneath the K64sb and K70sb is also inferred to occur between the deeper Maverick Basin and shallower San Marcos Arch (Fig. 23). Although the angular discordance beneath the Langtry Member (K70 Sequence) was noted by Donovan and Staerker (2010), thickness variations in the Lower Eagle Ford Formation, which Donovan and Staerker (2010) related to onlap, are now interpreted as the product of truncation and angular discordance beneath the K64 Sequence boundary at the base of the Middle Shale Member of the Lower Eagle Ford Formation. Finally, our correlations and biostratigraphic work suggest that both the Upper and Lower Eagle Ford formations, as well as portions of all four Eagle Ford members, can be mapped from the Maverick Basin toward the San Marcos Arch.

## SUMMARY AND CONCLUSIONS

Our work to date on the outcrops in Lozier Canyon suggests that the Eagle Ford Group can be divided into a Lower Ford Formation and Upper Eagle Ford Formation and that each of these formations consists of two distinct members. These formations and members defined in the outcrops of West Texas can be traced into the subsurface of South Texas. Moreover, we infer that these formations and members are bounded by regionally mappable unconformities and that the four members are also chronostratigraphic units or depositional sequences, each with distinct reservoir characteristics and unique geographic distributions. In this context, each of the four Eagle Ford sequences (members) is not coeval to (1) each other, (2) the underlying Buda Limestone, or (3) the overlying Austin Chalk. This conclusion is in sharp contrast to other interpretations that propose that the Lower and Upper Eagle Ford Formations, as well as the overlying Austin Chalk, are coeval, time-transgressive facies successions. Regional thickness variations of K63 Sequence, at the base of the Lower Eagle Ford Formation, and of the K65 Sequence, at the base of the Upper Eagle Ford Formation, suggest that the K64sb, at the base of the Middle Shale Member, and the K70sb, at the base of the Langtry Member, are also tectonically enhanced angular unconformities.

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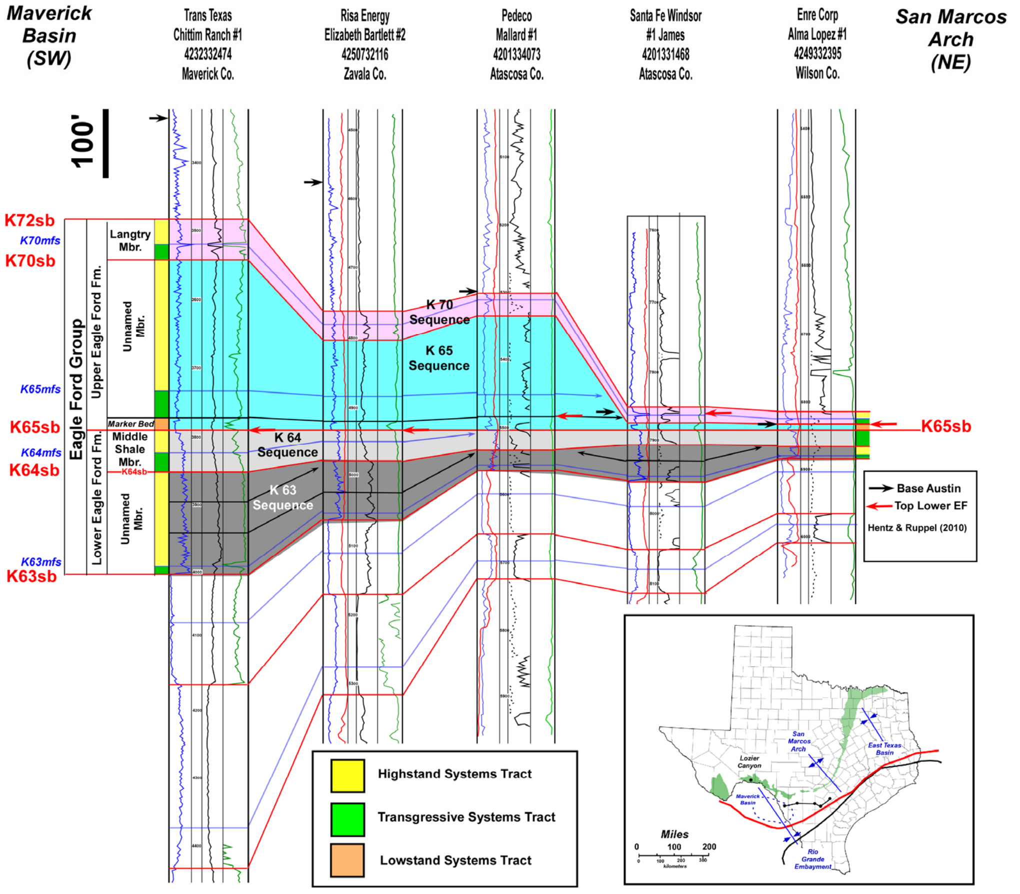

**Figure 23. Well-log correlations from the Maverick Basin to the San Marcos Arch. These correlations suggest that although portions of all four of the depositional sequences can be correlated across the area, the interpreted highstand deposits are preferentially preserved in areas of higher accommodation (Maverick Basin) and truncated in areas of lower accommodation (San Marcos Arch). The K70sb at the base of the Langtry Member is interpreted as a tectonically enhanced angular unconformity. The interpreted depositional sequence boundaries are red, the maximum flooding surfaces are blue, and miscellaneous parasequences are black.**

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