A Publication of the Gulf Coast Association of Geological Societies
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The Eagle Ford Group Returns to Big Bend National Park, Brewster County, Texas

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ABSTRACT

The Upper Cretaceous succession in the Big Bend Region of West Texas is plagued by the continued use of provincial lithostratigraphic terms not used elsewhere in the state of Texas. These provincial terms greatly limit: (1) correlating these strata to coeval units in outcrops, as well as the subsurface, elsewhere in Texas; and (2) utilizing these outcrops as windows to examine strata coeval to economically important unconventional reservoirs within the Eagle Ford Group in the subsurface of South Texas. However, with the use of petrophysical and geochemical techniques (handheld spectrometer, X–ray fluorescence [XRF], and stable isotopes), it is possible to identify and define the Eagle Ford and Austin groups, as well as potentially a remnant of the older Woodbine Group, within Big Bend National Park, Brewster County, Texas. Because the Hot Springs section is west of the classic Eagle Ford and Austin outcrops in the Lozier Canyon region of Terrell County (West Texas), the Big Bend outcrops also provide insights into lateral facies changes within these units.

As historically defined, within the Big Bend region, the Boquillas Formation overlies the Buda Formation and is overlain by the Pen Formation. Futhermore, the Boquillas Formation is divided into a lower Ernst Member and an upper San Vincente Member, while the Ernst Member is divided into four informal sub-members referred to as units 1 to 4 from the base upwards. Correlations from Lozier Canyon revealed that the Boquillas Formation at Hot Springs is equivalent to both the Eagle Ford and Austin groups in the Lozier Canyon region of West Texas. The Eagle Ford Group defined in Lozier Canyon is equivalent to units 1 to 3 of the Ernst Member at Hot Springs. Our work also suggests that unit 1 of the Ernst Member at Hot Springs is equivalent to the Lower Eagle Ford in Lozier Canyon, while units 2 and 3 of the Ernst Member at Hot Springs is equivalent to the Upper Eagle Ford at Lozier Canyon.

INTRODUCTION

Geographically, Big Bend National Park is in West Texas along the Rio Grande, the natural boundary between the United States and Mexico (Fig. 1). In the Upper Cretaceous, however, the Big Bend region was positioned between the Gulf of Mexico and the Western Interior Seaway (Fig. 2). Tectonically, this region was positioned along the collision front of Gondwana and Laurasia in the Late Paleozoic marked by the Ouachita Tectonic Front (Fig. 3), underwent foreland deformation in the Mesozoic and Paleogene (Fig. 3), and then Neogene extension with the Rio Grande Rift.

From a stratigraphic standpoint, the Upper Jurassic and Cretaceous succession of the region is part of Sloss' (1963) 1st-order Zuni Megasequence. The maximum flooding event of this cycle, which is marked by the maximum incursion of the Western Interior Seaway, occurs in the latest Cenomanian and early Turonian.

Manuscript received March 15, 2017; revised manuscript received June 21, 2017; manuscript accepted July 13, 2017.

GCAGS Journal, v. 6 (2017), p. 161–176.

In general, this maximum flooding event coincides with a geochemical event referred to as the Ocean Anoxic Event 2 (OAE2), which is marked by a major positive $\delta^{13}C$ isotope excursion (Fig. 4). This is a half to one million-year duration anoxic period that lead that leads to the extinction of approximately 27% of marine invertebrates, and in particular up to 70% of the ammonite species (Elder, 1989). Works by Donovan et al. (2015a, 2015b) and Donovan (2016) has documented that in the subsurface of South Texas and outcrops of West Texas the OAE2 event occurs within the Eagle Ford Group, specifically at the base of the Upper Eagle Ford Formation (Figs. 5 and 6).

Figure 7 is a chronostratigrahic summary of the Cenomanian through Coniacian stratigraphy of Texas. In general, the succession from the base up consists of the Del Rio/Grayson, Buda, Woodbine, Eagle Ford, and Austin. The Woodbine Group is lower Cenomanian and is identified in the East Texas Basin and not generally defined in South or West Texas. The Eagle Ford Group is middle Cenomanian to upper Turonian. Classically, the base of the Coniacian was placed at the base of the Austin. However, a recent published geologic time scale (Ogg et al., 2012) has moved the Turonian/Coniacian boundary up three ammonite zones higher, which now places this boundary well within the Austin Group.

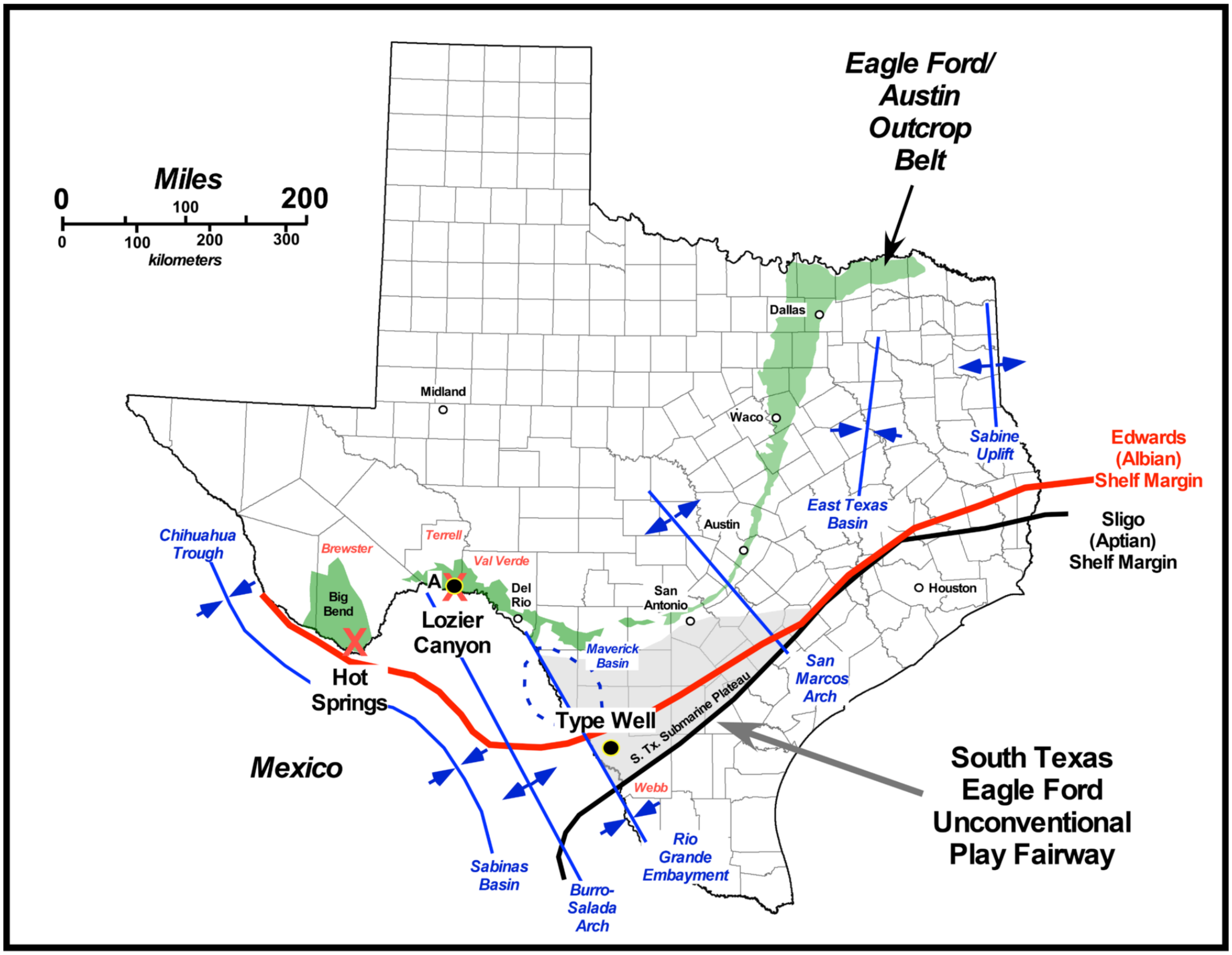


Figure 1. Texas map showing the location of Hot Springs in Big Bend National Park (BBNP) along with the locations of the wells used for comparison: BP/SLB Lozier Canyon #1 in Terrell County and a well in Webb County (near the Eagle Ford production trend). The green areas represent the outcrop belt of Eagle Ford and Austin groups in Texas. The blue lines mark the axes of prominent archs/uplifts and basins/troughs during the Late Cretaceous. The red line marks the edge of the Edwards (Albian age) shelf margin and the black one is the older Aptian Sligo reef margin. This map is based on maps in Donovan et al. (2015a, 2015b) and Donovan (2016).

PREVIOUS WORK: BIG BEND

Lithostratigraphy

Udden (1907) published the first geologic descriptions of Big Bend National Park and Brewster County. He divided the Upper Cretaceous (post-Buda) succession into three units: Boquillas Flags, Terlingua Beds, and Tornillo Clays (Fig. 8). For his Boquillas Flags, he measured a 585 ft (178 m) thickness, and for the overlying Teringua Beds, an estimated 1250 ft (380 m) thickness. It should be noted that Udden (1907) identified a three-ft thick siliceous bed containing ammonites about half way up his Boquillas Flags. This ammonite-rich bed is now commonly referred to as the *Allocrioceras hazzardi* beds (Cooper and Cooper, 2014). Udden (1907) suggested that the Boquillas Flags correlated with Eagle Ford Group and Terlingua Beds with Austin Group.

Adkins (1932) used what is now referred to as *Allocrioceras hazzardi* beds as the base of the Austin Group in the Big Bend region and interpreted the 289 ft (88 m) section between it and the top of the underlying Buda as his Boquillas Flags facies of the Eagle Ford Group. Maxwell et al. (1967), however, rejected Adkins (1932) proposed (Eagle Ford/Austin) nomenclature for the Big Bend Region and named Udden's (1907) Boquillas Flags, the Boquillas Formation. He also divided his Boquillas Formation into a lower Ernst Member and an upper San Vicente Member. The contacts of these formations, however, differed from Eagle Ford/Austin contact proposed by Adkins (1932). Cooper et al. (2007), however, redefined the San Vicente Formation, and used the *Allocrioceras hazzardi* beds to define its base (Fig. 8). In this updated framework, Adkins' (1932) Eagle Ford and Austin groups equated respectively to the new Ernst and San Vicente members of Cooper et al.'s (2007) Boquillas Formation.

PREVIOUS WORK: SOUTH AND WEST TEXAS

In the subsurface of South Texas, strata between the Buda and Austin are referred to as the Eagle Ford Group (e.g., Fig. 5). The base of the Eagle Ford is marked by a distinct gamma ray (GR) increase driven by an increase in U, as well as Th and K content, along with an increase in total organic content (TOC)

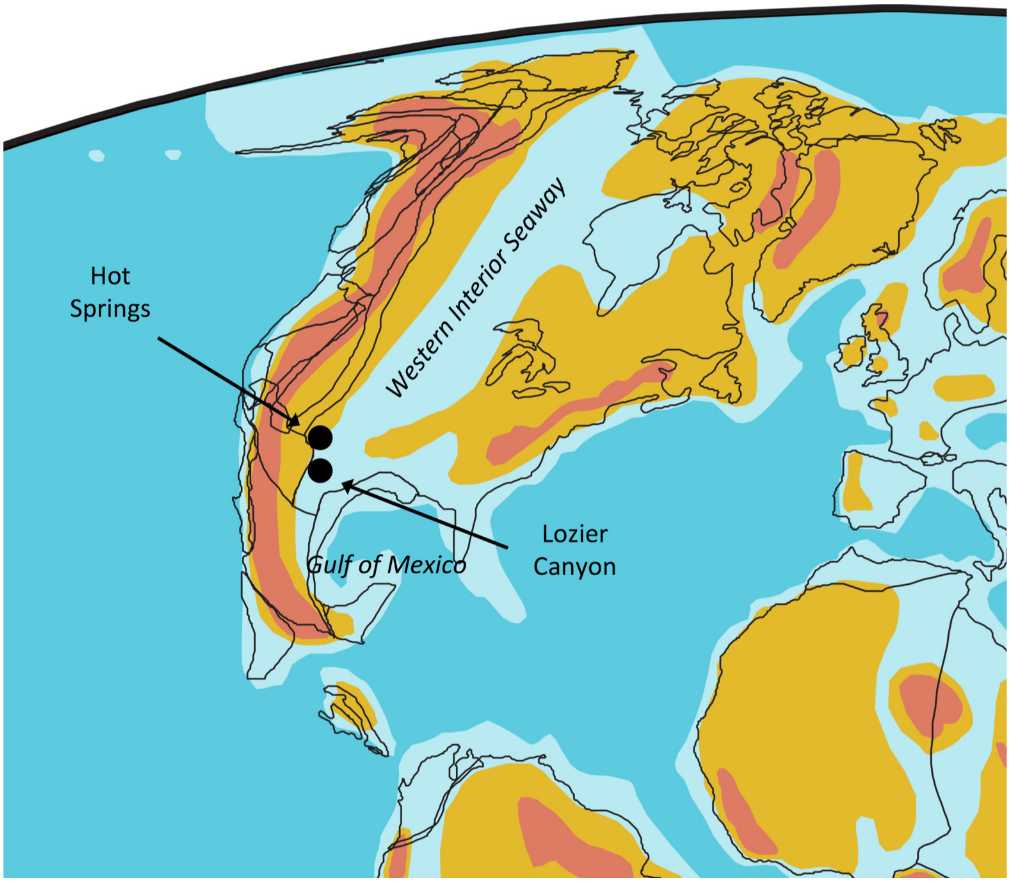


Figure 2. A paleogeographic reconstruction of North America circa 90 Ma based on Scotese (1999) where the horizontal is the paleoequator. The red represent highlands while the orange is for lowlands. For the oceans, the light blue is shallow and the darker blue is deep water.

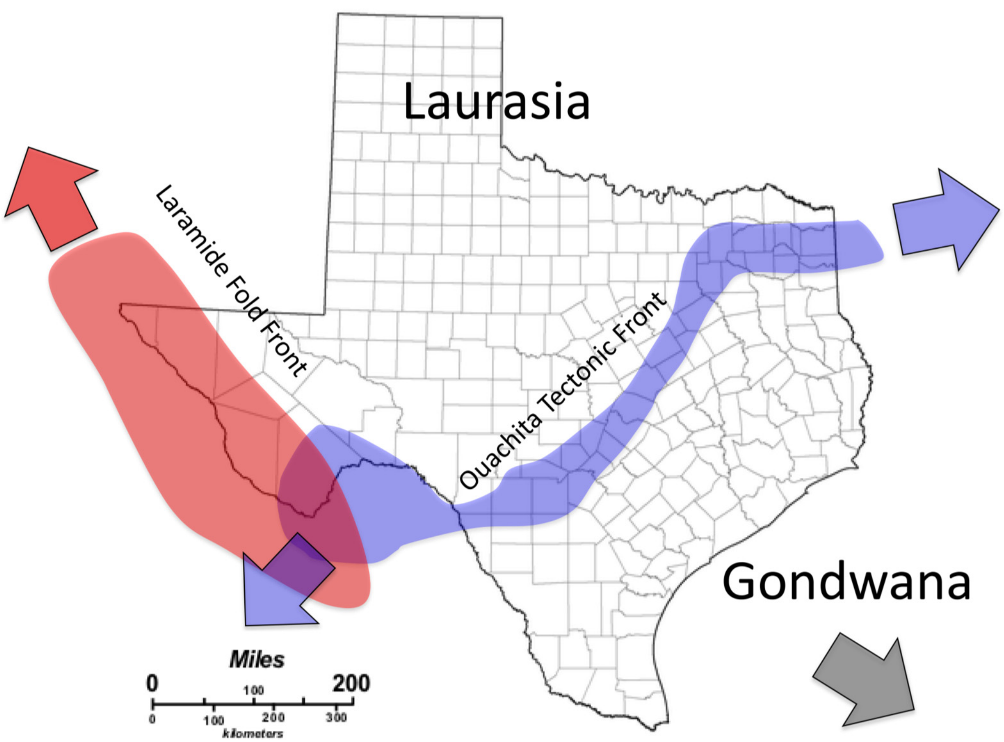


Figure 3. A map showing the positioning of the Ouachita Tectonic Front formed during the Pennsylvanian and Permian when Pangaea formed. This had an influence on the Mesozoic paleotography. Another major tectonically active area was in the Trans-Pecos region at the end of the Cretaceous and early Paleogene when the Laramide Orogeny occurred and the edge of the tectonic province is within the Trans-Pecos area. This orogeny did deform the Eagle Ford Group sediments in this region (Ferrill et al., 2016).

content, and decrease in carbonate content. The base of the overlying Austin is typically marked by a change from a funnel to blocky GR profile driven by a drop in U, K, and Th content, along with a drop in clay and slight increase in carbonate and quartz content (Fig. 5). Biostratigraphically, the classic base of the Coniacian also marks the base of the Austin.

The Eagle Ford Group in turn is commonly divided into a lower (organic-rich) Lower Eagle Ford Formation, and an upper (carbonate-rich) Upper Eagle Ford Formation (Fig. 5). The base of the Upper Eagle Ford is marked by a distinct GR drop, driven by a major decrease in U content, and the onset of a blocky GR profile. In the subsurface of South Texas, the geochemical proxy

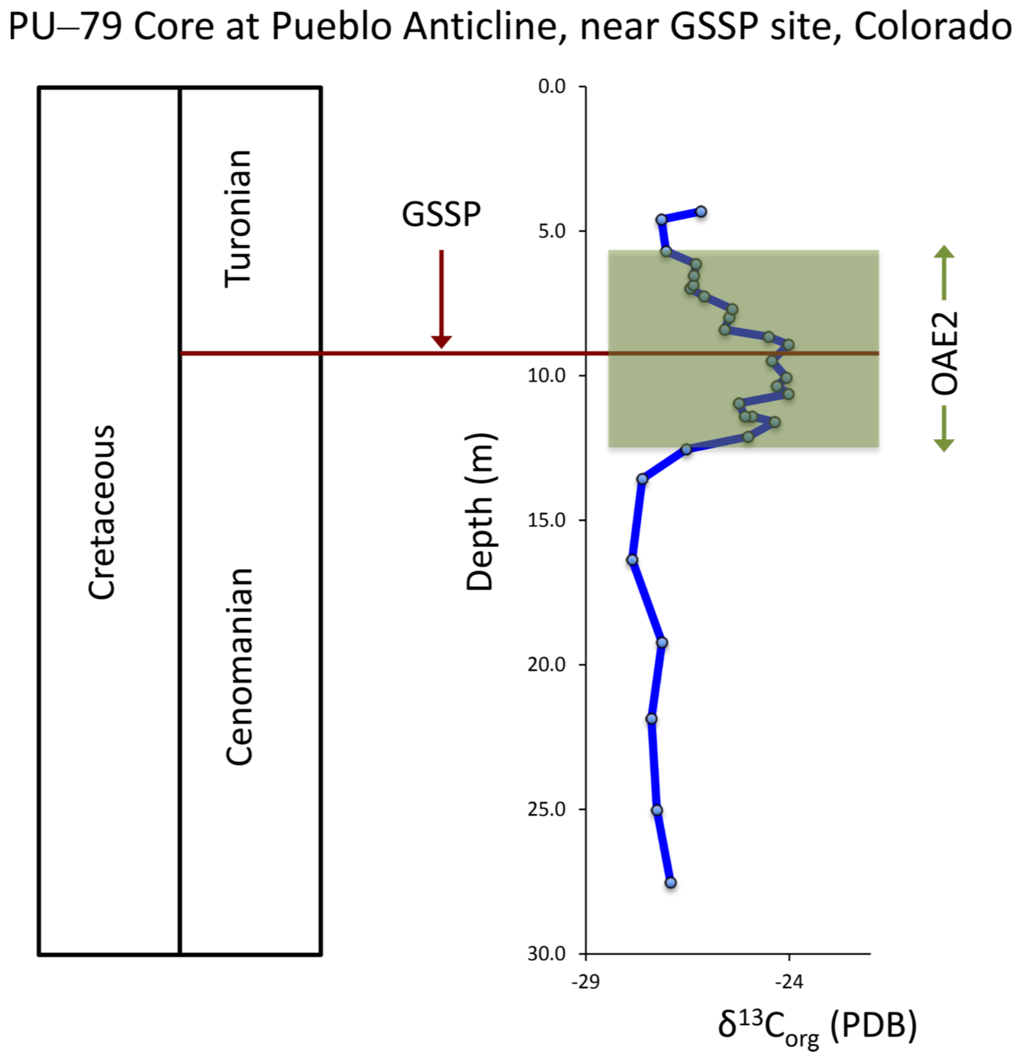


Figure 4. An example of the carbon isotope ($\delta^{13}C$) profile of the Ocean Anoxic Event 2 (OAE2) as shown by the isotope profile from the Bridge Creek Member of Greenhorn Formation at the Global Boundary Stratotype Section and Point (GSSP) near Pueblo, Colorado (the GSSP outcrop is described in detail by Kennedy et al. [2005]). The organic $\delta^{13}C$ data are from Pratt and Threlkeld (1984) and various versions from this data exist (e.g., Ogg et al., 2012).

for the OAE2 (the positive $\delta^{13}C$ isotope excursion) occurs at the base of the Upper Eagle Ford Formation.

Donovan et al. (2012) and Donovan (2016) correlated the subsurface stratigraphy of South Texas to the Lozier Canyon outcrops of West Texas (Fig. 5). Like the subsurface of South Texas, the Eagle Ford Group in outcrop is bounded by the Buda Formation below and by the Austin Group above (Fig. 6). In outcrop, like the subsurface, the base of the Eagle Ford is marked by a distinct GR increase driven by an increase in U, as well as Th and K content. Above the boundary an increase in TOC, clay, and quartz content occurs, as well as a decrease in carbonate content. Lithologically, the Buda/Eagle Ford boundary is marked by a sharp change from wackestones below, to interbedded grainstones and carbonate mudstones above. Similar to the subsurface, the base of the Austin Group is marked by a change from a funnel to blocky GR profile driven by a drop in U, K, and Th content. Lithologically, the boundary is marked by a sharp change from interbedded grainstones and carbonate mudstones below to carbonate mudstones (chalks) above. Rip-up clasts of underlying Eagle Ford are also locally observed in the basal Austin (Donovan et al., 2015a). Biostratigraphically, the classic base of the Coniacian also marks the base of the Austin.

Within the Eagle Ford Group (Fig. 6) an organic-rich, higher–GR Lower Eagle Ford Formation and carbonate-rich, lower–GR Upper Eagle Ford Formation can also be defined. A distinct GR drop driven by a major drop-off in U content marks the base of the Upper Eagle Ford. In the Lozier Canyon outcrops, as in the subsurface of South Texas, the geochemical proxy for the OAE2 also occurs in the basal portions of the Upper Eagle Ford Formation (Figs. 5 and 6).

METHODS

Introduction

This paper follows a modified version of Gradstein et al. (2012) time scale (Fig. 7). We use the classic (pre–2012) boundary for the base of the Coniacian, which corresponds to the base of the Austin Group throughout Texas. The ammonite groups that were traditionally included in the basal Coniacian, now uppermost Turonian, are highlighted in yellow (Fig. 7). It should be noted that the *Allocrioceras hazzardi* beds essentially correspond to the new proposed base of Coniacian, the *Cremnoceramus deformis erectus*/*Scaphites preventricosus* (inoceramid/ammonite biozone pair) biozone. The association of *Allocrioceras hazzardi* with the *Cremnoceramus deformis erectus* biozone was confirmed by Hancock et al. (2004). For comparing ammonite/inoceramid biozonation of Western Interior Seaway and the local ammonite/inoceramid biozonation, we used Cobban et al. (2006) and Cobban et al. (2008), respectively.

For naming sequences and comparison with previously published works on Eagle Ford Group in West Texas, the naming system for sequences uses an alpha-numeric scheme where the first letter is for geologic period (in this case, K is for Cretaceous), then the two numeric digits are assigned in ascending order from base of Cretaceous Series, and the final two letters are

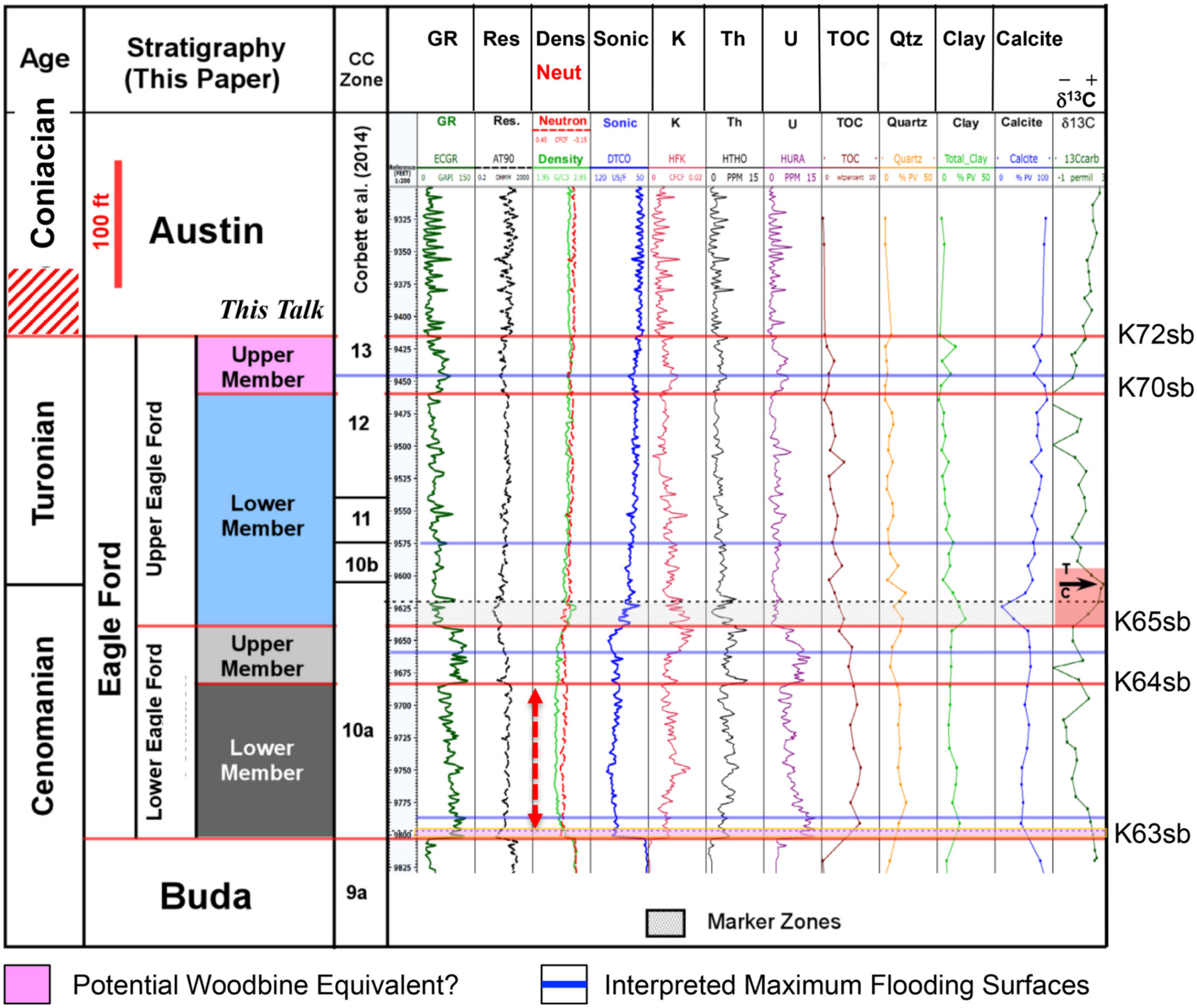


Figure 5. A South Texas well (Webb County) is shown with its well logs and petrophysical lab data. The area shaded in a red-pink color, just above the K64sb represents the Ocean Anoxic Event 2 (OAE2), identified based on a positive $\delta^{13}C$ curve and matching micro- and nannofossil biostratigraphy (Corbett et al., 2013, 2014; Lowery et al., 2014). The red-hatched area in geologic age column between Turonian and Coniacian is the time interval that used to be Coniacian (pre–2004 definition) but is considered Turonian under the current iteration of the geologic time scale (e.g., Gradstein et al., 2012). This figure is based on versions presented in Donovan et al. (2015a, 2015b), and Donovan (2016).

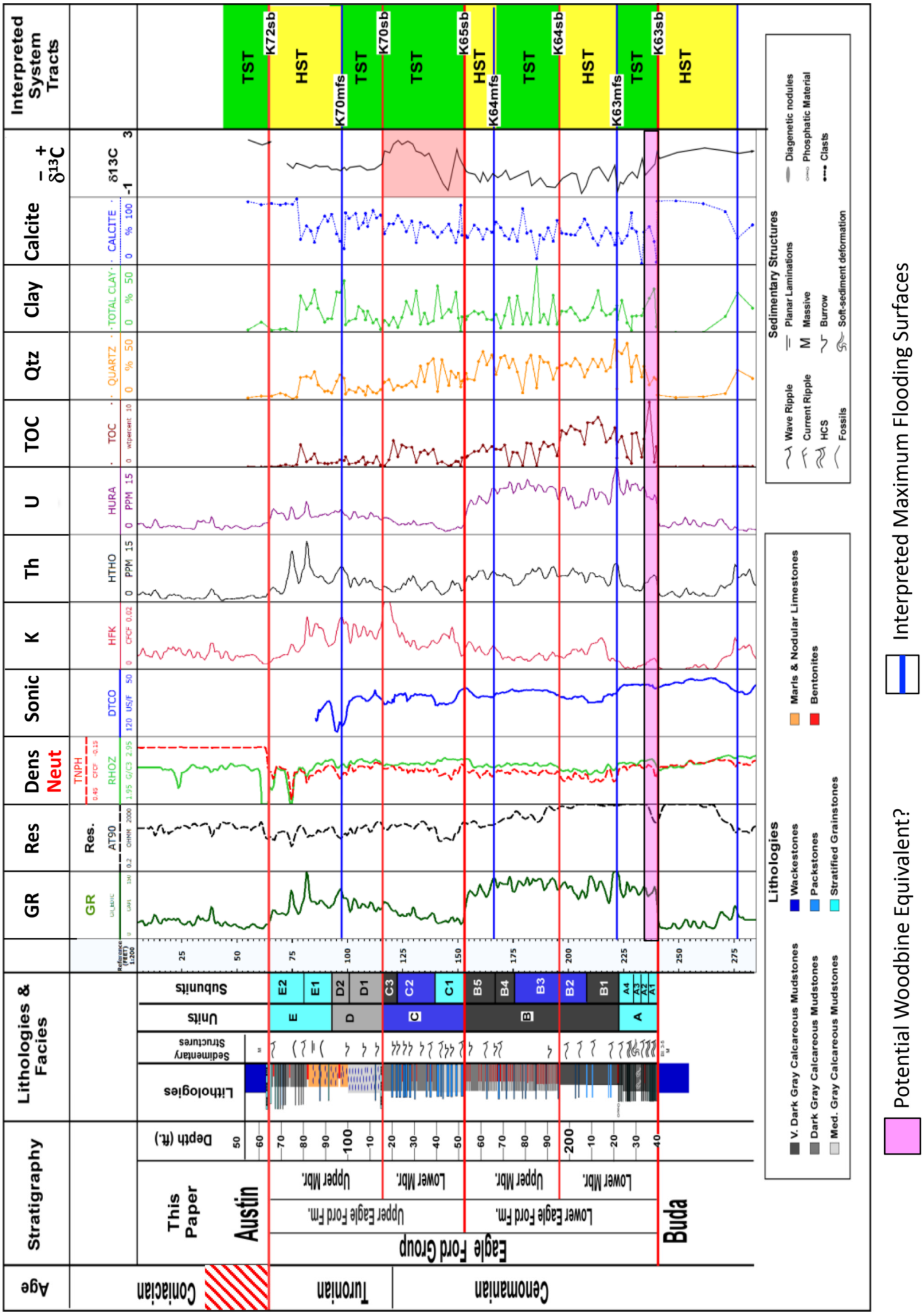
modifiers that indicate the type of sequence stratigraphic surface. For instance, sb is for sequence boundary and ts is for transgressive surface. This naming scheme has been used in many previous publications (Donovan and Staerker, 2010; Donovan et al., 2012; Gardner et al., 2013).

Measured Section

For this study, the Hot Springs section was measured at the location near section reported by Miller (1990) at coordinates, 29.182447°N and 102.993501°W, just 100 ft (35 m) from Hot Spring Trail (Fig. 9). This location is 0.22 mi (0.36 km) from the section proposed as the type section for Ernst Member of Boquillas (Cooper et al., 2007). The outcrop was measured from 6 ft (2 m) below the Buda-Boquillas contact up to 41 ft (12.5 m) above the *Allocrioceras hazzardi* bed that has been noted by all previous workers, including Udden (1907). A bed-by-bed description was made and the beds were classified using Dunham's (1962) classification. A total of 172 hand-sized samples were taken from the outcrop with a mean sample interval of 2 ft (60 cm). While in the field, a handheld GR scintillometer was used to acquire spectral GR data (U, Th, and K content) at 1 ft (30 cm) intervals. The scintillometer is a Terraplus RS–230 Gamma Ray Spectrometer. The total GR (TGR) in American Petroleum Institute (API) units is estimated using the formula of Herron and Herron (1996). For 48 of the 172 hand-size samples, a total of 50 thin sections were made for confirmation of lithology and allochem type. When petrographic observations are noted, the lithology is reported using Folk's (1974) classification because that is ideal for petrography.

Geochemistry

All 172 hand-sized specimens were analyzed with energy-dispersive X–ray fluorescence (ED–XRF) for major and trace element concentrations. The ED–XRF data was acquired using a


Age
Coniacian
Turonian
Cenomanian
Stratigraphy
This Paper
Austin
Upper Eagle Ford Fm.
Lower Eagle Ford Fm.
Eagle Ford Group
Upper Mbr.
Lower Mbr.
Buda
Depth (ft.)
Lithologies & Facies
Lithologies
Sedimentary Structures
Units
Subunits
GR
Res
Dens
Neut
Sonic
K
Th
U
TOC
Qtz
Clay
Calcite
δ13C
Interpreted System Tracts
TST
HST
K72sb
K70mfs
K70sb
K65sb
K64mfs
K64sb
K63mfs
K63sb
Lithologies
V. Dark Gray Calcareous Mudstones
Dark Gray Calcareous Mudstones
Med. Gray Calcareous Mudstones
Wackestones
Packstones
Stratified Grainstones
Marls & Nodular Limestones
Bentonites
Sedimentary Structures
Wave Ripple
Current Ripple
HCS
Fossils
Planar Laminations
Massive
Burrow
Soft-sediment deformation
Diagenetic nodules
Phosphatic Material
Clasts
Potential Woodbine Equivalent?
Interpreted Maximum Flooding Surfaces

(FACING PAGE) Figure 6. For the Lozier Canyon area in Terrell County, West Texas, well log and laboratory petrophysical data are shown from the research borehole, BP/SLB Lozier Canyon #1. The area shaded in a red-pink color between K65sb and K70sb represents the OAE2 mostly based on the $\delta^{13}C$ curve. And the pink rectangle above the Buda is the interpreted Woodbine Group equivalent. Like in Figure 5, red-hatched area in the geologic time column is Coniciacian under pre–2004 definitions of the Coniacian. This figure is based on versions presented in Donovan et al. (2015a, 2015b), and Donovan (2016).

Thermo Scientific Niton XL3t 950 GOLDD+ Analyzer (up to 36 elements are detected using the Cu/Zn filter). The XRF analyzer was calibrated using the method described by Rowe et al. (2012). For stable isotope analysis ($\delta^{13}C$ and $\delta^{18}O$) 53 of the 172 samples were analyzed using a Thermo Scientific Kiel IV Automated Carbonate Device coupled to a Thermo Scientific MAT 253, which reside at the Stable Isotope Geoscience Facility at Texas A&M University. The mean interval between isotope samples was 6.3 ft (1.9 m).

Paleontology

The work of Cobban et al. (2008) has a good summary of the ammonite zones reported from the Big Bend National Park area, mostly from the Hot Springs area. The following ammonite biozones were reported. In the basal 16 in (~0.5 m) above the top of the Buda, an *Acompsoceras inconstans* fauna (early Cenomanian) is indicated by the presence of *Moremanoceras bravoense* and *Euhystrichoceras adkinsi*. About 10 ft (3.5 m) above the top of Buda, an *Acanthoceras bellense* fauna of the middle Cenomanian is suggested by *Inoceramus arvanus*, a mollusc. Cobban et al. (2008) suggested that an ammonite reported by Cooper et al. (2008) as *Calycoceras* sp. at 12 ft (4 m) above the top of Buda is actually *A. bellense*. At about 17 ft (5 m), a collection of *Ostrea beloiti*, *Tarrantoceras sellardsi*, and *Turrilites acutus* suggests an *A. amphibolum* biozone. Now the following biozones were reported by Cobban et al. (2008) along with Cooper and Cooper (2014), but their data cannot be reliably matched to the Hot Springs measured section of this study: *Metoicoceras mosbyense*, *Euomphaloceras septemseriatum*, *Pseudaspidoceras flexuosum*, *Collignoniceras woollgarii*, *Prionocyclus hyatti*, *P. novimexicanus*, *P. quadratus*, *P. germari*, *Forresteria peruana*, and *Allocrioceras hazzardi*. The last one, *Allocrioceras hazzardi*, was confirmed from 289 ft (88 m) at Hot Springs.

For this study, Jim Pospichal of BugWare, Inc. did a quantitative assessment of 41 of the 172 hand-sized samples for calcareous nannofossil biostratigraphy. Sampling range for nannofossil biostratigraphy ranges from 3 ft (1 m) below the Buda/Eagle Ford contact through 289 ft (88 m) above the Buda/Eagle Ford contact within, which is 99 ft (33 m) above the Eagle Ford/Austin boundary.

BIG BEND LITHOSTRATIGRAPHIC INTERPRETATION

The lithologic and geochemical data collected for the Hot Springs locality at Big Bend National Park are presented in Figures 5 and 6. Similar to the subsurface of South Texas and Lozier Canyon in West Texas, the top of the Buda is marked by a distinct GR increase, driven by an increase in U, Th, and K content. Lithologically is marked by sharp change from wackestones (below) to interbedded grainstones and mudstones (above). 185 ft (56 m) above the top of the Buda, a distinct geochemical and petrophysical change, similar to the change at the base of the Austin Group chalks in South Texas and Lozier Canyon in Terrell County in West Texas was noted. At this proposed boundary, the GR profile becomes distinctly blocky, due to low U, Th, and K content. At this boundary, a change from more variable to low carbonate, silica, and Al content occurs. Lithologically, a change from interbedded carbonate grainstones and mudstones below, to carbonate mudstones above occurs. Furthermore, classic late Turonian (Eagle Ford Group equivalent) through earliest Coniacian (Austin Group equivalent) inoceramids of the respective *Inoceramus perplexus* and *Mytiloides scupini* zones (Fig. 7) were reported between 183 ft and 194 ft (55.8 m and 59 m, respectively) at this locality (Cobban et al., 2008). Based on these various criteria, the Eagle Ford/Austin contact is placed 185 ft (56.5 m) above the top of the Buda at the Hot Springs locality (Figs. 10 and 11). In general, this position corresponds to the boundary between units 3 and 4 of Copper and Cooper (2014) Ernst Member of the Bouquillas Formation (Fig. 8).

Within the newly defined Eagle Ford Group at Hot Springs, a distinct GR drop due to a major decrease in U, Th, and K occurs at 99 ft (33 m) above the top of the Buda (Fig. 10). A major increase in carbonate content and decrease in silica content also occurs at this point. Based on these criteria, the contact between the Lower and Upper Eagle Ford formations is placed at this distinct geochemical boundary. For historical context Copper and Cooper (2014) placed the boundary of units 2 and 3 of their Ernst Formation at this same positon. It should be noted however, that the geochemical proxy for the OAE2, the $\delta^{13}C$ positive isotope excursion was not observed at the Hot Springs locality (Fig. 10).

Figure 12 is a lithostratigraphic correlation between Hot Springs, Lozier Canyon, and the Swift Fasken #1 well in Webb County. The thicknesses of the Eagle Ford Group and the internal formations similar at Hot Springs and Lozier Canyon: 175 ft (53 m) at Lozier Canyon and 185 ft (56.5 m) at Hot Springs. At Lozier Canyon, the Lower Eagle Ford is 96 ft (32 m) thick vs. 99 ft (33 m) at Hot Springs. The Upper Eagle Ford is 79 ft (24 m) thick at Lozier Canyon, while it is 85 ft (26 m) thick at Hot Springs. This suggests a similar depositional setting on the flooded Comanche Platform for the Eagle Ford Group at both Hot Springs and Lozier Canyon. This is contrast to the Swift Fasken #1 well in Webb County, which is substantially thicker at about 170 ft (52 m) for Lower Eagle Ford and 212 ft (65 m) for Upper Eagle Ford.

BIG BEND INSIGHTS INTO THE UPPER CRETACEOUS SEQUENCE STRATIGRAPHY OF TEXAS

Overview

Based on work on the outcrops and subsurface across Texas, Donovan et al. (2015a, 2015b) concluded that both the Woodbine and Eagle Ford were unconformity-bounded depositional sequences (Fig. 7). They outlined that the Woodbine was an early Cenomanian siliciclastic-dominated sequence whose present distribution was primarily restricted to East and Central Texas. In terms of the surfaces defined, they placed their K60sb at its base and K63sb at its top (Fig. 7). The Eagle Ford was outlined as a middle Cenomanian to upper Turonian organic-rich sequence, which changed from more siliciclastic-rich to the northeast to more carbonate-prone towards the southwest across Texas. In terms of the surfaces defined, they placed their K63sb at its base and K72sb at its top (Fig. 7).

Donovan et al. (2012, 2015a, 2015b), Gardner et al. (2013), and Donovan (2016) also divided the Eagle Ford into four high-frequency sequences, two in the Lower Eagle Ford Formation, and two in the Upper Eagle Ford Formation (Fig. 7). They referred to these sequences as the K63, K64, K65, and K70 sequences. The K63 Sequence, which was also referred to as Low-

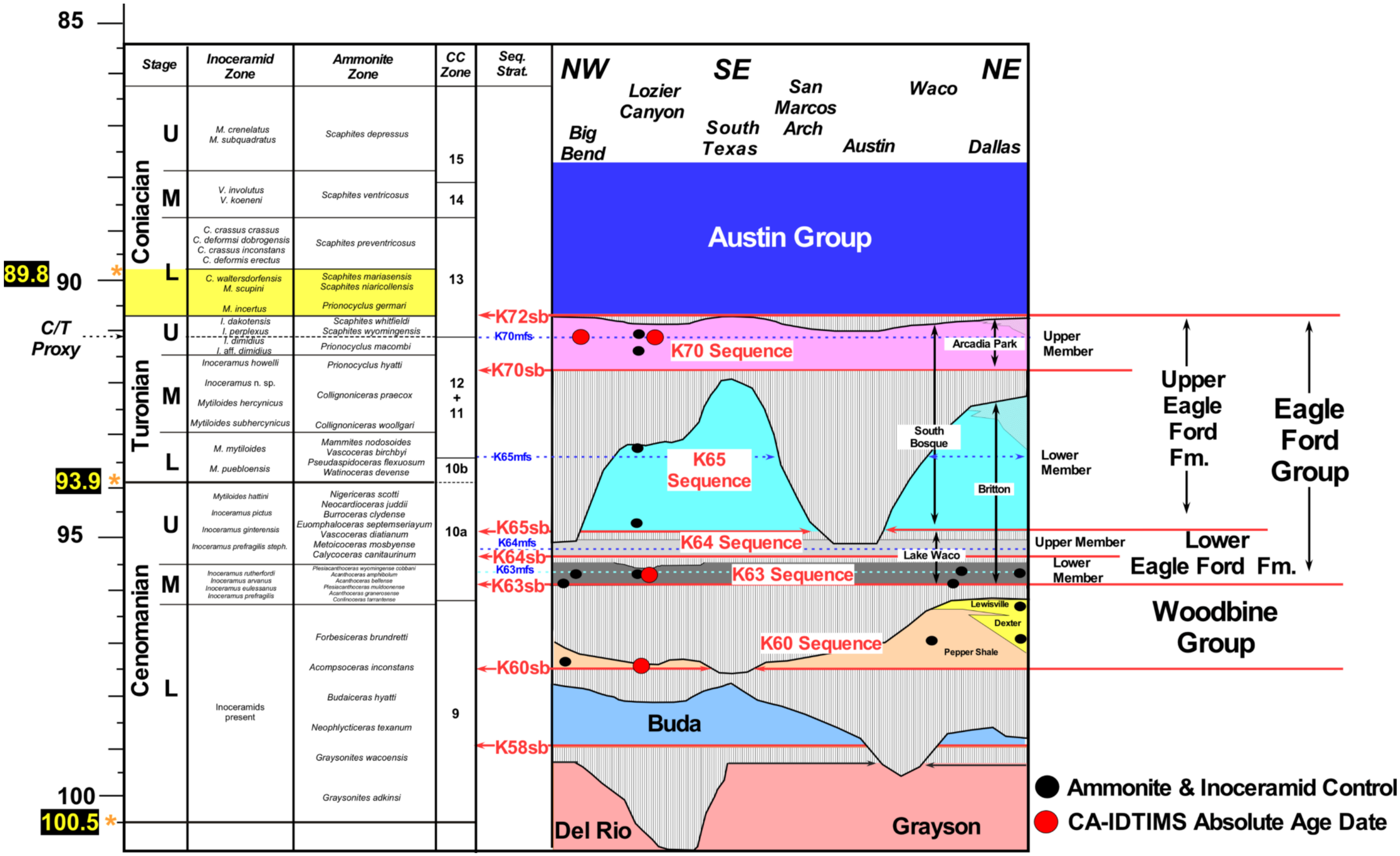


Figure 7. A chronostratigraphy for the Cenomanian through Coniacian for Texas going from Big Bend National Park to Dallas, mostly following the outcrop belt as shown in Figure 1. This plot records common regional lithostratigraphic terms and graphically records hiatuses with vertical lines as constrained by published ammonite/inoceramid biostratigraphy (Kennedy and Cobban, 1990; Cobban et al., 2008). This figure is based on Donovan et al. (2015a, 2015b).

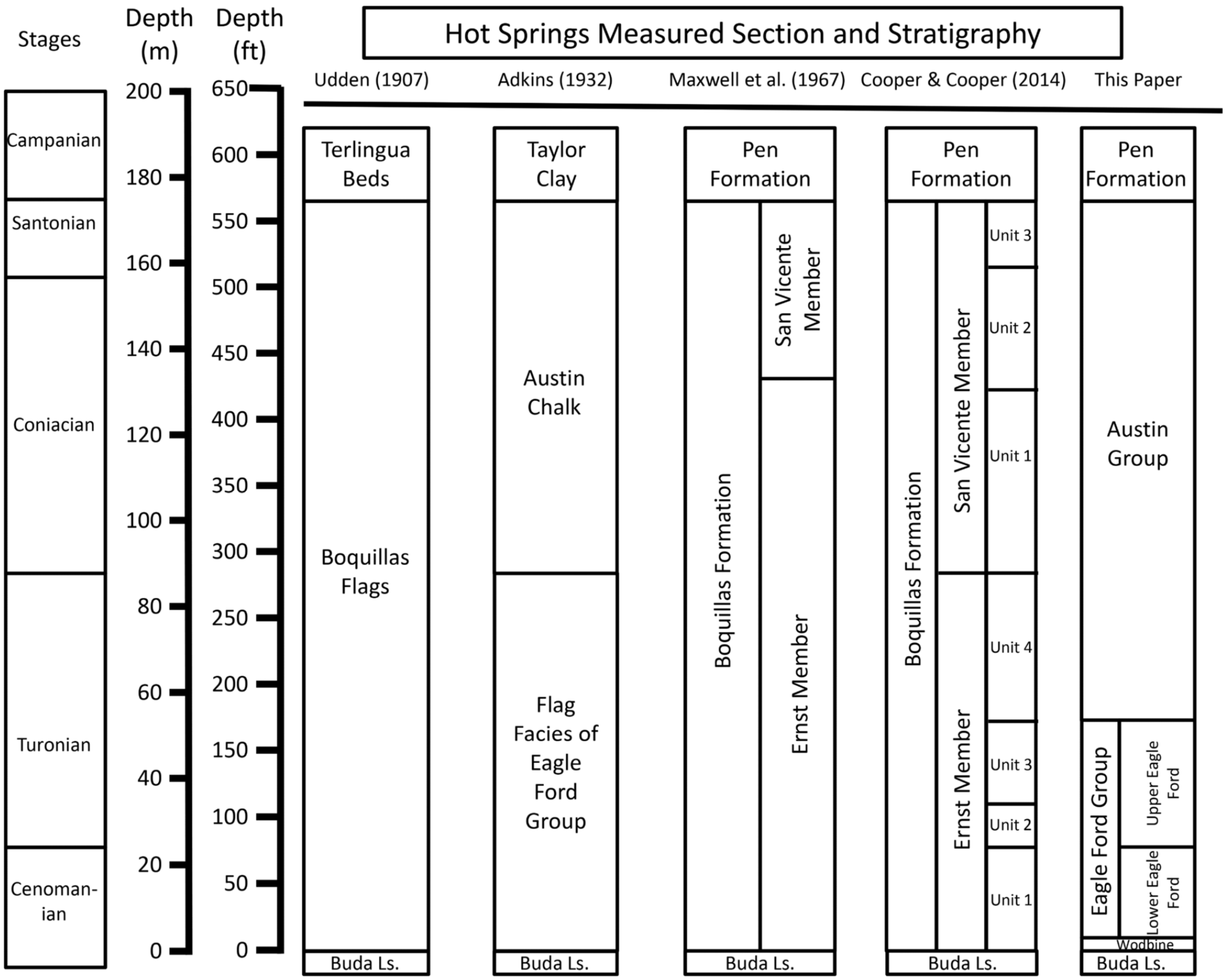


Figure 8. Comparison of the stratigraphic nomenclature for the Upper Cretaceous stratigraphic units in the Big Bend area in Brewster County, Trans-Pecos, Texas.

er (Lozier Canyon) Member of the Lower Eagle Ford Formation, was defined as a middle Cenomanian, organic-rich sequence. The K64 Sequence, which was also referred to as the Upper (Antonio Creek) Member of the Lower Eagle Ford Formation, was defined as a upper Cenomanian U– and Th–rich (bentonite-rich) and organic-poor sequence. The K65 Sequence, which was also referred to as the Lower (Scott Ranch) Member of the Upper Eagle Ford Formation, was defined as a uppermost Cenomanian to middle Turonian carbonate-rich sequence, characterized by the presence of the OAE2, and its associated positive $\delta^{13}C$ isotope excursion, at its base. The K70 Sequence, which was also referred to as the Upper (Langtry) Member of the Upper Eagle Ford Formation was defined as upper middle to upper Turonian sequence characterized by the presence of abundant burrows, hard-bodied fossils, and distinct bentonite beds. Each of the four defined sequences also had distinct mappable maximum flooding surfaces defined respectively from the base up as the K63mfs, K64mfs, K65mfs, and the K70mfs.

Woodbine Remnant?

At the Hot Springs locality, the basal 10 ft (3.3 m) of the section measured above the Buda Formation, consists of medium-bedded, hummocky-stratified packstones to grainstones, locally interbedded with very thin carbonate mudstone or bentonite beds (Fig. 13). These strata are overlain by a succession of more distinctly interbedded packstones and carbonate mudstones (Fig. 13). The sedimentary structures are suggestive of shallow storm-dominated settings as previously interpreted by Wehner et al. (2015) for basal Eagle Ford outcrops in West Texas. As illustrated on Figure 14, a slight drop in U and Th content also occurs above the contact between the two different facies at 10 ft (3.3 m) on the measured section. Interestingly, Cobban et al. (2008) reported the ammonites *Moremanoceras bravoensis* and *Euhystrichoceras adkini*, which were collected in the grainstone beds approximately 1.5 ft (0.5 m) above the top of Buda at Hot Springs. These early Cenomanian ammonites of the *Acompsoceras inconstans* ammonite biozone are also present in outcrops of the Woodbine Group along the west flank of the East Texas Basin (Cobban and Kennedy, 1989). Cobban et al. (2008) also reported *Inoceramus arvanus*, which appear to have been collected in the basal portions of the overlying interbedded packstone and carbonate mudstone succession at Hot Spring. They also stated that this inoceramid species is a good marker for the middle Cenomanian *Acanthoceras bellense* biozone, which is also present in the basal portions of the Eagle Ford Group on the western flank of the East Texas Basin (Cobban and Kennedy,

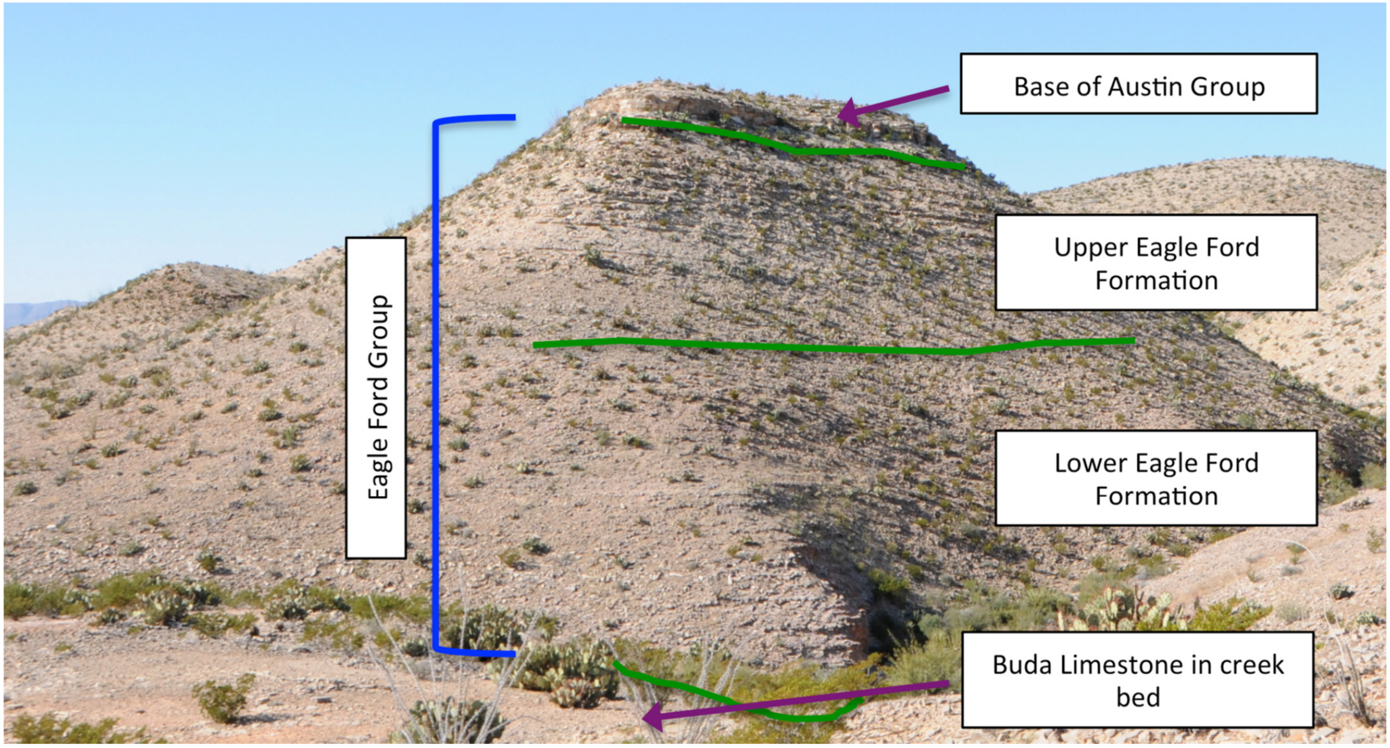


Figure 9. Photo of the Hot Springs Outcrop site measured for this study. The blue bracket marks the vertical extent of the allostratigraphic Eagle Ford Group; the green lines delineate the alloformations: Upper Eagle Ford and Lower Eagle Ford.

1989). Based on these lithostratigraphic and biostratigraphic relationships, it likely that: (1) the proper placement of the K63sb marking the base of the Eagle Ford Group is 10 ft (3.3 m) above the top of the Buda at the Hot Springs locality; (2) the K60sb, marking the base of the Woodbine Group occurs at 0 ft (0 m) on the measured section coinciding with the top of the Buda at the Hot Springs locality; and (3) the interval between 0 ft (0 m) and 10 ft (3.3 m) on the measured section at Hot Springs represents strata that are coeval to the Woodbine Group in the East Texas Basin.

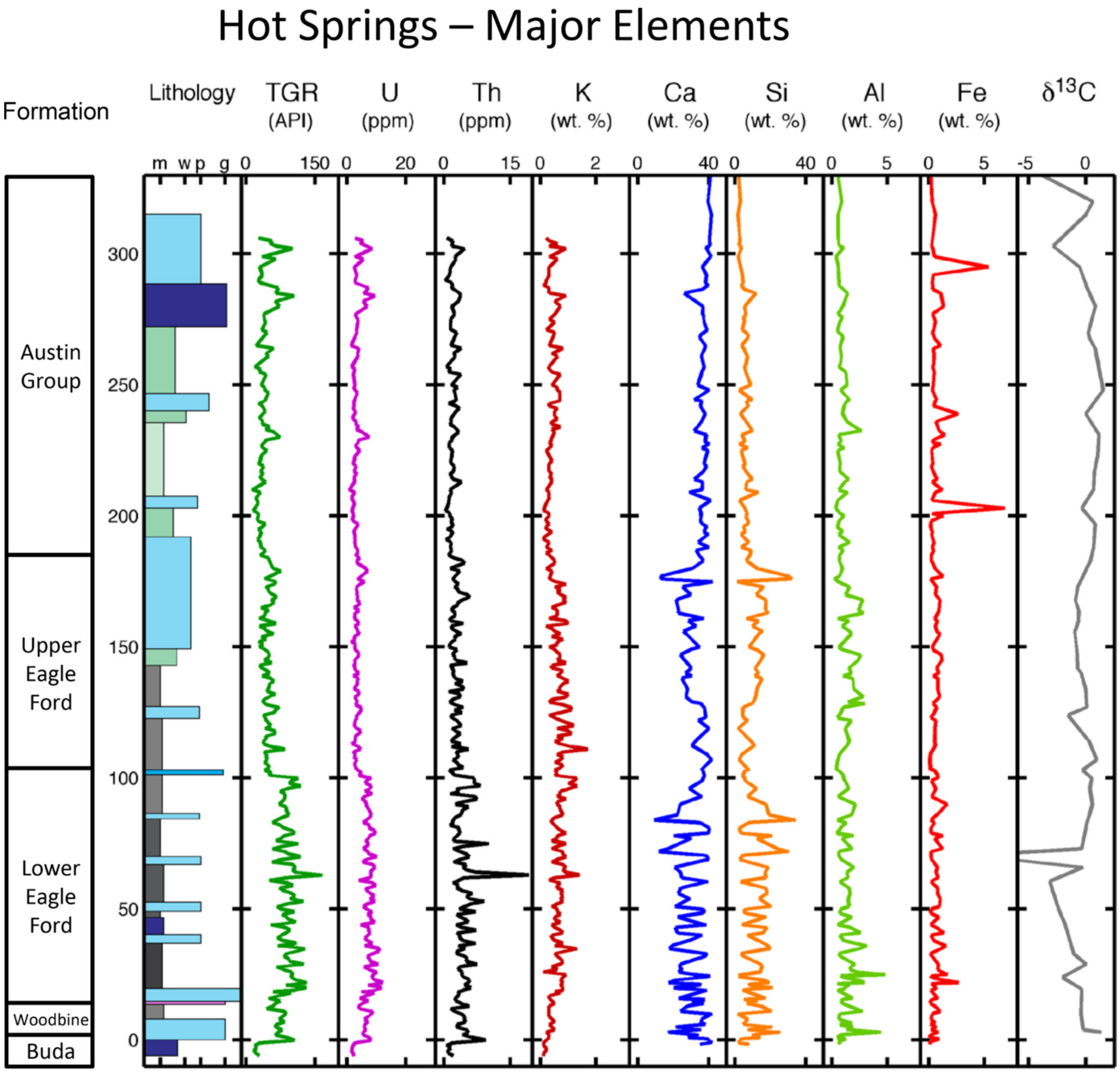
Eagle Ford Sequence Stratigraphy

Based on the various criteria outlined by Donovan et al. (2015a, 2015b) for the depositional sequences within the Eagle Ford in the outcrops from the eastern portions of West Texas (Lozier Canyon), as well as the subsurface of South Texas the following sequence stratigraphic interpretations are made for the Hot Springs locality (Figs. 10 and 11). Although TOC analysis was not conducted on the samples taken at Hot Springs section, the organic-rich K63 depositional sequence or the Lower Member of the Lower Eagle Ford Formation is interpreted from 10 ft (3.3 m) to 50 ft (15 m) on the measured section at Hot Springs. The interval between 50 ft (15 m) and 99 ft (33 m) at the Hot Springs locality is interpreted as the bentonite-, Th–, and U–rich and organic-poor K64 depositional sequence.

As mentioned previously, the interval between 99 ft (33 m) and 185 ft (56.5 m) is interpreted as the Upper Eagle Ford Formation. Like Lozier Canyon, and the subsurface of South Texas, a sharp GR drop driven by a decrease in U content occurs above this contact followed by an overall blocky GR log pattern (Fig. 10). While the log character of this boundary and overlying strata are similar at the Hot Springs locality, the specific depositional sequence present at the base of the Upper Eagle Ford Formation at the Hot Springs locality is open to debate (Fig. 12).

At Lozier Canyon and the subsurface of South Texas the K65 depositional sequence occurs at the base of the Upper Eagle Ford Formation. This carbonate-prone sequence is characterized by the presence of the OAE2 interval, whose geochemical proxy is a distinct positive $\delta^{13}C$ isotope excursion (Figure 6). This positive $\delta^{13}C$ isotope excursion was not observed at the Hot Springs section at the base of the interpreted Upper Eagle Ford Formation. As outlined on Figure 12, there are at least three possible reasons for this.

The first possible solution, as illustrated on Figure 12A is that the K65 and K70 depositional sequences are both present, but the K65 sequence is simply missing its classic $\delta^{13}C$ positive isotope excursion due to weathering and the failure to collect fresh samples. We have observed this happening at another locality in West Texas, where the excursion was absent in a roadcut along Highway 90 in Val Verde County, but reported in a borehole adjacent to the site (Eldrett et al., 2015). Denne et al. (2016) predicted this scenario and hinted at earlier by Frush and Eicher (1975). A second possible solution is that another (middle Turonian) depositional sequence (the K67?), which has not previously been identified in our work in West Texas, marks the base of the Upper Eagle Ford at Hot Springs (Fig. 12B). In this scenario, a new K67 depositional sequence is interpreted from 99 ft (33 m) to 160 ft (49 m) on the measured section overlain from 160 ft to 185 ft (49 m and 56.5 m, respectively) by the K70 Sequence, or the Upper Member of the Upper Eagle Ford. A third possible solution is that the entire Upper Eagle Ford succession at Hot Springs represents an expanded K70 Sequence or the Upper Member of the Upper Eagle Ford Formation (Fig. 12C). In this scenario, 99 ft (33 m) to 160 ft (49 m) on the measured section would be interpreted as the K70 lowstand, while 160 ft to 185 ft (49 m and 56.5 m, respectively) would represent the K70 transgressive and highstand deposits. Clearly additional biostratigraphic and/or chronostratigraphic (absolute age dating) work needs to be conducted at the Hot Springs locality to properly constrain the various interpretations.



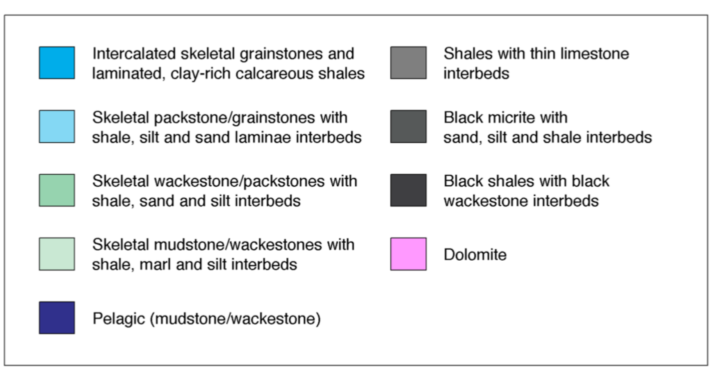
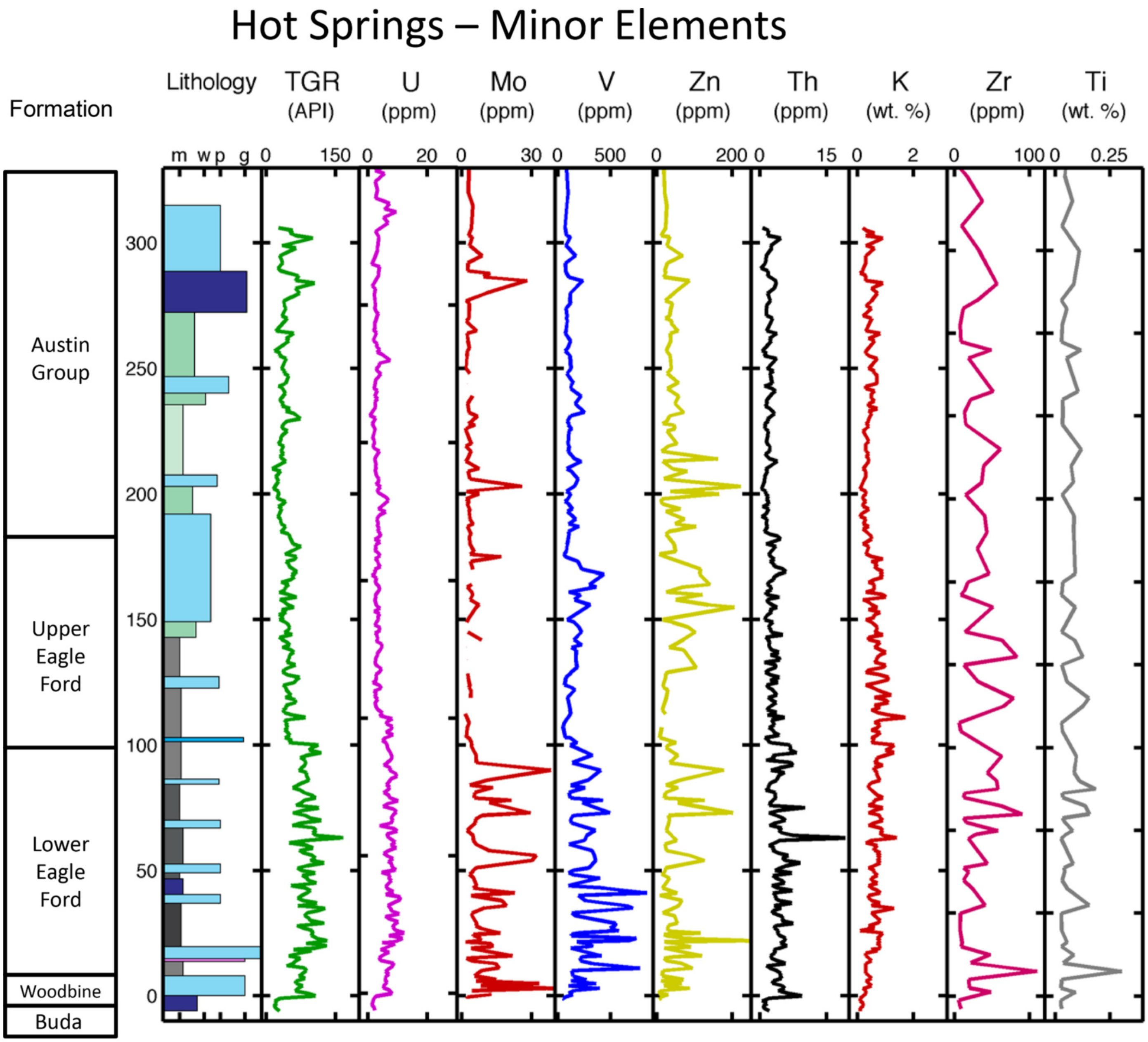


Figure 10. The lithostratigraphy combined with spectral GR logs (U, Th, and K) and selected major elements from XRF (Ca, Si, Al, and Fe) for the Hot Springs outcrop in Big Bend National Park, Brewster County, Texas. The curve labeled TGR is the total GR in API units as estimated using the formula of Herron and Herron (1996). Also a bulk carbonate δ^{13}C curve is included. The combination of these curves shows bulk geochemistry (proxying for bulk mineralogy) associated with the spectral GR curves and as well as comparison with the bulk lithology as determined from field observation. The bulk carbonate δ^{13}C curve does not preserve an obvious isotopic excursion (had been predicted to at ~100 ft [~33 m]) as initially expected at the beginning of the study.



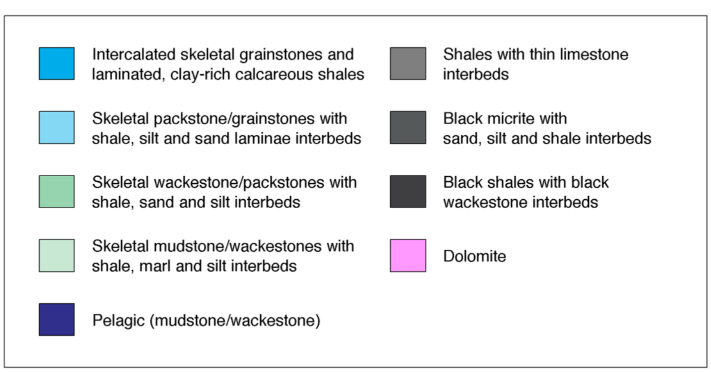


Figure 11. For the Hot Springs outcrop in Big Bend National Park, the lithostratigraphy and total GR (TGR) are displayed with the following trace elements obtained from XRF: Mo, V, Zn, Zr, and Ti. The elements, U, Th, and K are the from the handheld spectral GR log. The elements are arranged by proxy type. The redox elements are grouped together: U, Mo, V, and Zn. The terrestrial and/or detrital elemental proxies are Th, K, Zr, and Ti.

(FACING PAGE) **Figure 12.** A correlation diagram showing three interpretations of the sequence stratigraphy for Hot Springs in Big Bend National Park, Lozier Canyon in Terrell County, and the Swift Fasken #1 well in Webb County. The first scenario (correlation A) is that the isotope signal is obscured by weathering and poor outcrop preservation. The second scenario (correlation B) that there is a previously unknown sequence preserved at Hot Springs that is between K65 and K70 sequences. The third scenario (correlation C) has the Hot Springs section containing an expanded K70 sequence that has the lowstand section not normally preseved in previously studied outcrops.

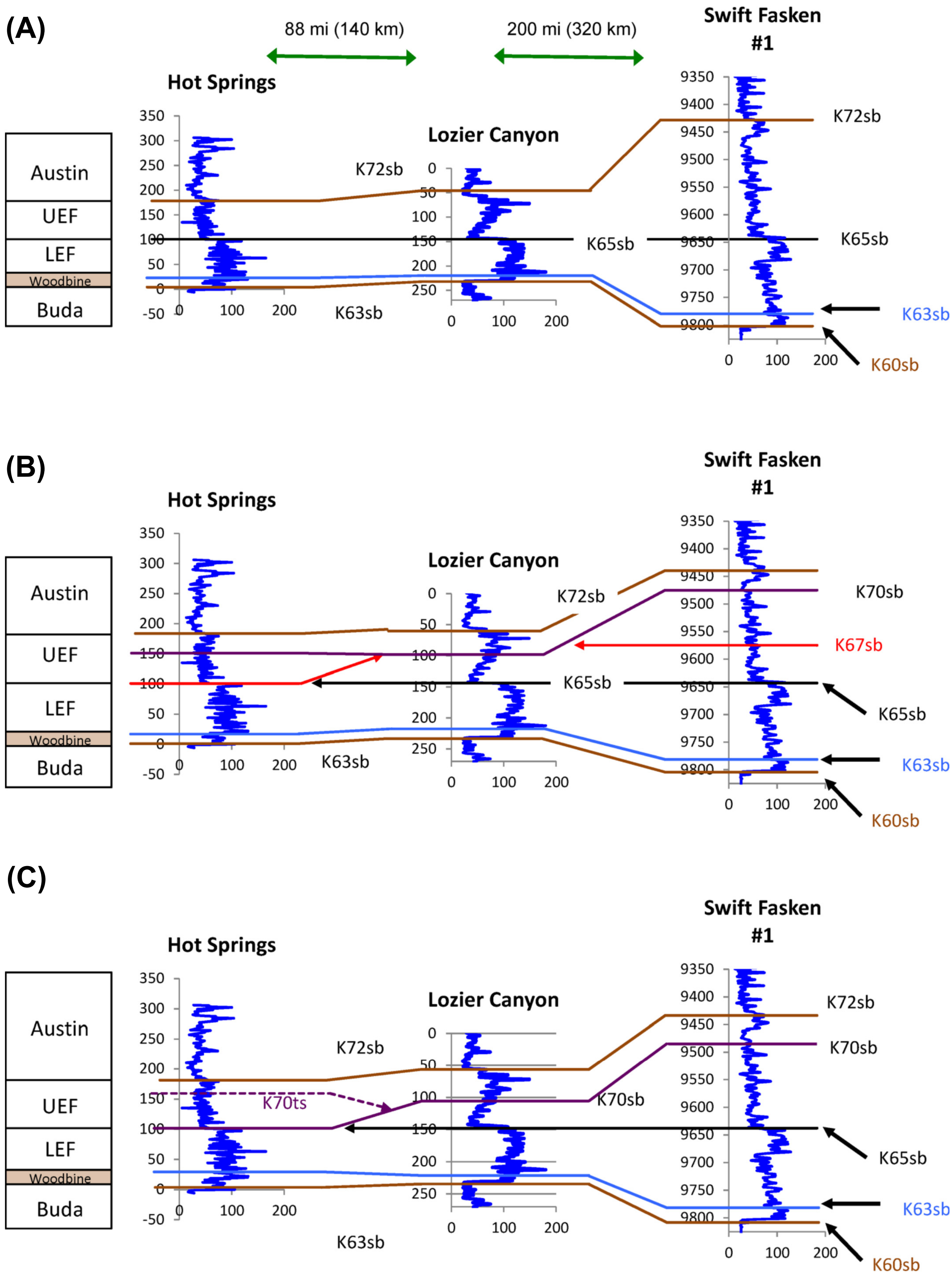

(A)
88 mi (140 km)
200 mi (320 km)
Swift Fasken #1
Hot Springs
Lozier Canyon
Austin
UEF
LEF
Woodbine
Buda
K72sb
K65sb
K63sb
K60sb
(B)
K70sb
K67sb
(C)
K70ts

Figure 13. An outcrop image of the 10 ft (3.3 m) proposed contact between the Woodbine Group equivalent and Eagle Ford Group at the Hot Springs locality.

CONCLUSIONS

Correlations from Lozier Canyon in Terrell County (West Texas) revealed that the Boquillas Formation at Hot Springs in Brewster County (West Texas) is equivalent to both the Eagle Ford and Austin groups as presently defined in the Lozier Canyon region of West Texas. The Eagle Ford Group defined herein at Hot Springs is equivalent to strata previous referred to as units 1 to 3 of the Ernst Member of the Boquillas Formation (Cooper and Cooper, 2014). Our work also suggests that unit 1 of the Ernst Member at Hot Springs is equivalent to the Lower Eagle Ford in Lozier Canyon, while units 2 and 3 of the Ernst Member at Hot Springs is equivalent to the Upper Eagle Ford at Lozier Canyon. As defined in our work the new Eagle Ford/Austin contact proposed at Hot Springs is coeval to the Eagle Ford/Austin contact as defined in Lozier Canyon, as well as in the subsurface of West Texas. The contact occurs at the classic (pre–2012) base of the Turonian stage. The newly proposed (Gradstein et al., 2012) base Coniacian occurs well above the base of the Austin Chalk in both Terrell and Brewster counties. At Hot Springs, the basal 10 ft (3.3 m) succession, directly overlying the Buda, contains hummocky stratified grainstones, which contain early Cenomanian fauna near its base. This 10 ft (3.3 m) interval is interpreted as the K60 depositional sequence, which is coeval to the Woodbine Group in the East Texas Basin. The K63sb, marking the base of the Eagle Ford Group, is placed at 10 ft (3.3 m) in the Hot Springs section, and the K72sb marking the base of the Austin Group is placed at 185 ft (56.5m) in the Hot Springs section. A distinct GR drop, driven by a decrease in U content, which also corresponds to a distinct increase in carbonate content, at 99 ft (30 m) on the measured section, is picked as the contact between the Lower Eagle Ford Formation and the Upper Eagle Ford Formation. Within the Lower Eagle Ford Formation, the K63 and K64 depositional sequences defined in Lozier Canyon appear also to be present at Hot Springs. Within the Upper Eagle Ford Formation, the characteristic positive $\delta^{13}C$ isotope excursion that typically marks the base if the Upper Eagle Ford, as well as the K65 Sequence, the Lower (Scott Ranch) Member of the Upper Eagle Ford Formation, was not observed at Hot Springs. This may be due to: (1) weathering, (2) the presence of a new (previously unidentified) depositional sequence at the base of the Upper Eagle Ford Formation at Hot Springs, or (3) the presence of an expanded K70 Sequence, the Upper (Langtry) Member of the Upper Eagle Ford Formation.

ACKNOWLEDGMENTS

We wish to thank Don Corrick, park geologist at Big Bend National Park, for helping us obtain a collecting permit (BIBE–2013–SCI–0044) from the National Park Service. He was very helpful and sincere even though the federal government shutdown that October significantly delayed our permit approval. We also thank BP America for their financial and logistical support of some of the fieldwork and laboratory work, particularly for the data collected at Lozier Canyon. Also we thank Roy Conte, Ph.D. student in geology at Texas A&M University, for arranging for the thin sections. Matthew Wehner thanks Eric Peavey for many stimulating discussions about Eagle Ford geology in West Texas because both of our projects overlap both in geologic time and space.

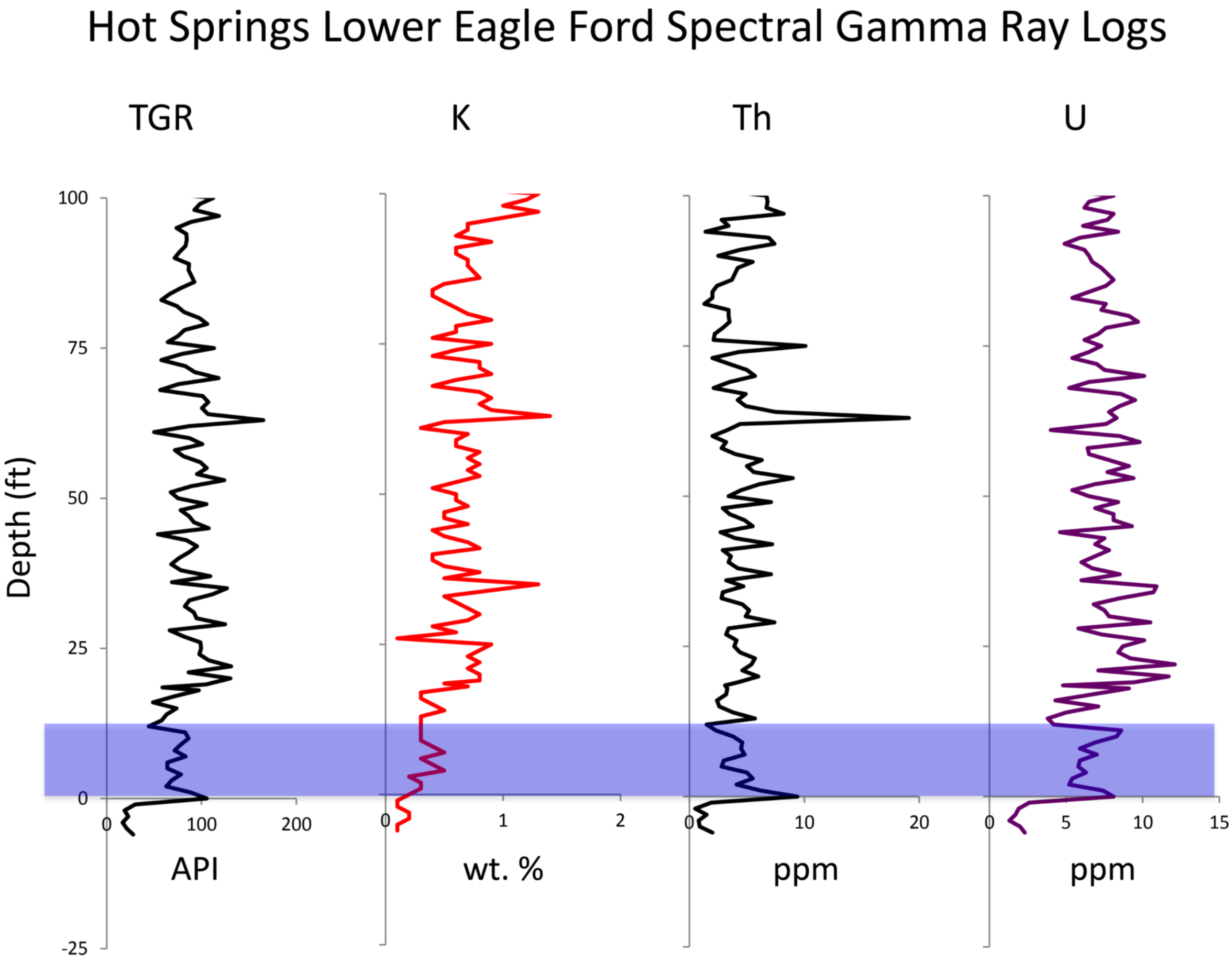


Figure 14. A close up of the lower 100 ft (33 m) of the Hot Springs handheld spectral GR logs to show the basal 10 ft (3.3 ft) section that is distinct from the other 90 ft (27 m) by a discontinuity. This break in the spectral GR logs is most apparent in the U log and total GR (TGR) log. The blue-purplish rectangle highlights the interval interpreted in this paper as Woodbine Group equivalent.

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