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**High Resolution Stratigraphy and Facies Architecture of the Upper
Cretaceous (Cenomanian-Turonian) Eagle Ford Group, Central Texas**

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Cretaceous (Cenomanian-Turonian) Eagle Ford Group, Central Texas**

by

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Abstract

High Resolution Stratigraphy and Facies Architecture of the Upper Cretaceous (Cenomanian-Turonian) Eagle Ford Group, Central Texas

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The University of Texas at Austin, 2012

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Heightened industry focus on the Upper Cretaceous (Cenomanian-Turonian) Eagle Ford has resulted from recent discoveries of producible unconventional petroleum resource in this emerging play. However, little has been published on the facies and facies variabilities within this mixed carbonate-clastic mudrock system. This rock-based study is fundamental to understanding the controls, types, and scales of inherent facies variabilities, which have implications for enhanced comprehension of the Eagle Ford and other mixed carbonate-clastic mudrock systems worldwide. This study utilizes 8 cores and 2 outcrops with a total interval equaling 480 feet and is enhanced by synthesis of thin section, XRD, XRF, isotope, rock eval/TOC, and wireline log data.

Central Texas Eagle Ford facies include 1) massive argillaceous mudrock, 2) massive argillaceous foraminiferal mudrock, 3) laminated argillaceous foraminiferal mudrock, 4) laminated foraminiferal wackestone, 5) cross-laminated foraminiferal

packstone/grainstone, 6) massive bentonitic claystone, and 7) nodular foraminiferal packstone/grainstone.

High degrees of facies variability are observed even at small scales (50 ft) within the Eagle Ford system and are characterized by pinching and swelling of units, lateral facies changes, truncations, and locally restricted units. Facies variability is attributed to erosional scouring, productivity blooms, bottom current reworking, and bioturbation.

At the 10-mile well spacing scale and greater, the data significantly overestimates intra-formational facies continuity but is successful in defining the following four-fold stratigraphy: The basal Pepper Shale is an argillaceous, moderate TOC, high CGR and GR mudrock. The Waller Member is a newly designated name used in this study for an argillaceous and foraminiferal, high TOC, massive mudrock with a generally moderate CGR and GR profile. The Bouldin Member is a high energy, carbonate-rich (foraminiferal), low TOC, low and variable CGR but high GR zone. Finally, the South Bosque Formation is an argillaceous and foraminiferal, moderate TOC, massive and laminated mudrock with a moderate CGR and GR signature. GR logs alone are inadequate for determination of facies, TOC content, depositional environment, and sequence stratigraphic implications. Using integrated lithologic, isotopic, and wireline log data, cored wells in the study area are correlated across the San Marcos Arch.

Geochemical proxies (enrichment in Mo, Mn, U, and V/Cr) indicate that maximum basin restriction occurred during deposition of the Bouldin Member. Bottom current activity influenced depositional processes and carbonate sediment input was driven by water column productivity. These primary controls on Eagle Ford stratigraphy and character are independent from eustatic fluctuation, rendering classical sequence stratigraphy unreliable.

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INTRODUCTION

The Upper Cretaceous Eagle Ford Group has long been recognized as an important source rock for productive reservoirs throughout Texas. Heightened industry focus on the Eagle Ford is a result of recent discoveries of producible unconventional petroleum resources in this emerging play. However, little has been published on the facies and facies heterogeneities within the mixed carbonate-clastic mudrock system. A rock-based study is fundamental to understanding the controls, types, and scales of inherent heterogeneities, which have implications for enhanced comprehension of the Eagle Ford Group and other mixed carbonate-clastic mudrock systems worldwide. The primary objectives of this study are to 1) define the Eagle Ford lithofacies present in the Austin, Texas area, 2) determine the lithofacies continuity on various scales, along with the processes that control intra-formational heterogeneities, 3) explore the effectiveness of elemental data in identifying variations within the Eagle Ford system, 4) calibrate geochemical data to the lithofacies which it represents, and 5) identify potential risks that could render CGR (Computed Gamma Ray Th-K) correlation unreliable. The present study utilizes a rare data set consisting of 480 total feet from 8 cores and 2 outcrops spanning a nearly 11-mile transect. Seven of the cores are contained within 2 miles, providing a uniquely high-resolution perspective for any mudrock system (figure 1). Energy Dispersive X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Rock Eval/Total Organic Carbon (TOC), stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope ratios, and thin section syntheses further enhance this study.

Mudrock depositional processes are recognized to be more complex and involved than solely hemipelagic suspension settling, as conventionally supposed. Core and outcrop studies reveal that erosional scours, sediment gravity flows, bottom current

reworking, diagenesis, and bioturbation are all processes that result in heterogeneities within the Central Texas Eagle Ford interval. Similar facies are expressed as both locally isolated as well as regionally extensive units. Crucial questions are posed regarding mudrock systems: “What is the continuity of units expressed by wireline log signals?” “What causes variable production response, and how can production be optimized across large play areas?” and “What controls rock character which in turn impacts reservoir properties?” This study utilizes a uniquely dense data set to constrain the controls on inherent facies heterogeneities and variabilities, helping to solve the above questions and to improve the comprehension of mudrock systems worldwide.

Figure 1: Location map of the study area showing cores and outcrops in the Austin, Texas area. The Eagle Ford outcrop belt spans the Texas-Mexico border, passes through the study area and continues across the Texas-Oklahoma border and into Arkansas. Adapted from the Geologic Map of Texas.

Oil and Gas Resource in the Eagle Ford

The Gulf of Mexico Basin of the United States is one of the major hydrocarbon-producing areas of the world (figure 2). Oil and gas production is known from virtually all stratigraphic units in the Gulf Coast region of the United States. Production of oil and gas comes from both carbonate and siliciclastic strata and is recognized in both conventional and unconventional accumulations (Dubiel et al., 2010). Among Upper Cretaceous Gulfian strata, the Eagle Ford has long been recognized as an important hydrocarbon source rock (Nehring, 1991; Robinson, 1997; Donovan and Staerker, 2010; Dubiel et al., 2010) that has charged clastic reservoirs such as the updip Tuscaloosa and Woodbine formations, as well as the overlying Austin Chalk (Dubiel et al., 2010). In the East Texas Basin alone, the Eagle Ford shale is responsible for 6 billion barrels (Bbl.) of oil in place (OIP) (Liro et al., 1994).

Eagle Ford shales display good to excellent hydrocarbon source rock characteristics and are rich in oil-prone materials (Liro et al., 1994; Edman and Pitman, 2010). TOC enrichment varies by author. Hentz and Ruppel (2010) recorded a range from 1-8.3% with an average of 2.8%, while values greater than 9% were recorded by Dawson (1997) and greater than 11.8% by Harbor (2011). Despite the variability in recorded TOC, the Lower Eagle Ford is consistently reported to be more organically enriched than the Upper Eagle Ford (Liro et al., 1994; Hentz and Ruppel, 2010) with averages of 5.1% TOC and 3.2% TOC respectively (Harbor, 2011). Thermal maturity indicators place the Eagle Ford between the early oil window and the late oil window (Edman and Pitman, 2010).

Figure 2: Map of the South Texas Eagle Ford play, showing the Gulf of Mexico Basin, the Hawkville Field, structural contours, oil and gas windows, and wells drilled by June 2010. Modified from U.S. Energy Information Administration, 2012.

Petrohawk Energy Corp initiated the Eagle Ford play, with the first discovery well drilled in 2008 (Durham, 2010). Well STS-241 #1H was a 3200 foot lateral well at 11,141 ft total vertical depth with 10 hydraulic fracture stages (Railroad Commission of Texas, 2012) that flowed 7.6 million cubic feet (MMcf) and 250 barrels (Bbl.) of condensate per day. This discovery became the Hawkville Field, which now spans 90 miles east-west and 15 miles north-south. Beginning with this discovery well in La Salle County, exploration focused in South Texas, extending several counties into Texas from the

Mexican border. The early Eagle Ford play attracted explorationists due to high production rates for low drilling costs (Durham, 2010) as well as high calcite content, which supported stimulated fracturing (Cherry, 2011).

Today, the Eagle Ford play consists of 20 fields, distributed across 23 counties, one field of which, the Eagleville, is distinctly an oil field. The entire play covers an area 400 miles long, 50 miles wide, and with an average thickness of 250 feet (Railroad Commission of Texas, 2012) (figure 2). The Eagle Ford represents the most recent, large discovery in Texas and is quickly becoming one of the “hottest” shale plays in North America (Pioneer Natural Resources, 2011). From the time of its inception, 26 drilling permits were issued in 2008, 94 in 2009, 1010 in 2010, and a total of 2826 permits in 2011. A staggering 30,453,253 Bbl of oil, 20,297,728 Bbl of condensate, and 243 Bcf of gas were produced in 2011 (Railroad Commission of Texas, 2012) (figure 3). There is still significant potential for new discoveries within these shale oil and shale gas plays (Dubiel et al., 2010) as the full extent of the Eagle Ford play has yet to be defined (Hentz and Ruppel, 2010).

Figure 3: The Eagle Ford Group has experienced a steady increase of oil, gas, and condensate production, as well as an increase in drilling permits since its discovery in 2008. After the Railroad Commission of Texas, (2012).

STUDY AREA

Location

Outcrops of the Texas Upper Cretaceous Gulfian Series strata form an arc extending from the Rio Grande on the Mexico-U.S. border eastward to San Antonio, then northward to the Texas-Oklahoma border, and finally eastward into Arkansas (figure 1). The strata are structurally simple, and the regional dip of the Eagle Ford is about one degree east-southeast with a strike of north-northeast (Smith, 1981; Jiang, 1989). In central Texas, the Eagle Ford outcrop belt passes through Travis County, and directly through the city of Austin, Texas (figure 1). A series of outcrops are discontinuously exposed throughout the Austin area (Young, 1977; Lundquist, 2000; Housh, 2007). Incidentally, construction began in 2011 on a 150 million dollar flood control tunnel through downtown Austin. In preparation for the project, an in-depth shallow surface evaluation was conducted by Fugro, involving the coring of 23 sites, creating a nearly 1 mile transect (figure 1). Beginning at Waterloo Park, at the intersection of E. 12th St. and Red River St., the transect follows along Waller Creek to its mouth at Lady Bird Lake, along the Colorado River (figure 1). Because of the shallow nature of the Eagle Ford Group in Central Texas, and due to the gentle dip and proximity to the outcrop belt, 10 of the collected cores penetrated the entire Eagle Ford interval, with another 3 containing only portions of it. The cores were acquired by the Bureau of Economic Geology in (2011) and are stored in the Core Research Center (CRC) repository in Austin.

South of Lady Bird Lake, a famous local outcrop located along West Bouldin Creek is bounded between the western end of Jewell St. and W. Milton St (figure 1). This outcrop is the type locality for the Bouldin Member (Adkins and Lozo, 1951; Jiang, 1989) and has been described in detail by previous authors (Feraud and Young, 1949;

Adkins and Lozo, 1951; Pessagno, 1969; Young, 1977; Liro et al., 1994; Lundquist, 2000).

In north Austin, another outcrop is also utilized in this study. It is encountered along a cutbank of Walnut Creek, upstream of Walnut Creek Metropolitan Park and south of Park Bend Rd (figure 1). It is possible that this is one of the outcrops described by Young (1977) as “in the vicinity of Water’s Park.” However, he describes the Cloice (Waller) Member, which is not exposed on this particular outcrop but is exposed further downstream. Other exposures along tributaries to Walnut Creek were studied by Lundquist (2000). In the vicinity, the current outcrop is the most well-exposed and robust. In close proximity (1600 ft) to the Walnut Creek outcrop, an additional core, the ACC provides a strong comparison to the Walnut Creek outcrop. The ACC core was drilled as an Edwards Aquifer monitoring well drilled by MHC X-Ploration Corporation for the Austin Community College. The core was drilled on the ACC Northridge Campus at north latitude 30 degrees, 24 minutes, 14.30910 seconds, and west longitude 97 degrees, 42 minutes, 20.43167 seconds (figure 1).

The primary extent of the study area is confined to Austin, Texas proper, along a nearly 11 mile, approximately north-south transect (figure 1). An extension of the primary study area into a regional perspective includes cored subsurface wells which were described by Harbor (2011). Two transects span the San Marcos Arch, one extending to the southwest from Austin across the Arch, and the other extending to the south along the dip of the arch (Figure 4). The subsurface Eagle Ford extends in a dip section from the shallow surface and outcrop belt to the Late Cretaceous shelf margin with depths of 14,000 feet (Harbor, 2011).

Figure 4: Map of the regional Eagle Ford study area with well and cross section (A-A', B-B') locations across the San Marcos Arch. The approximate westernmost extent of the Waller Member is also displayed. Regional cores were described in detail by Harbor (2011).

Data Set

The physical data set within the Austin study area is summarized in table 1. Eight shallow-depth cores were used in this study, seven of which were acquired from the Waller Creek Tunnel project, thus having no conventional log suite. Basal Eagle Ford depths range from 88-125 ft. These wells include: BT-222-PTPZ, BI-500-PT, BI-514-PTPZ, BT-204, BO-302-PT, BO-301-PTPZ, and BT-221 (figure 1). The respective names for these wells throughout the study are depicted in table 1 as 222, 500, 514, 204, 302, 301, and 221. The ACC #1 core (figure 1, table 1) was drilled for the Austin Community College as an Edwards Aquifer monitoring well and also lacks downhole logs. All of the cores were thoroughly described on a basis of sedimentary features, grain properties, and compositional attributes, which will be discussed in a later section. Cores 222, 500, 204, and 301 were selected for further data acquisition of stable carbon 13 ($\delta^{13}\text{C}$) and oxygen 18 ($\delta^{18}\text{O}$) isotopes of bulk carbonate, as well as XRF. Additional data were collected in the form of thin sections, rock eval/TOC, XRD and core photographs, with exception of core 222.

Extending from the Austin locality, regional wells that span the San Marcos Arch include:, C.J. Hendershot #1, W. Brechtel #1, H.P. Orts #2, F.T. Schauer et al #1, J.W. Blumberg #1-B, and #1 Burkland. Complete names, API numbers, counties, and operators are provided in table 1, but the names of Hendershot, Brechtel, Orts, Schauer, Blumberg, and Burkland are applied throughout this study. With the exception of Burkland, all of the cored wells have been described in detail by Harbor (2011), who collected stable isotope data and evaluated available GR logs for Hendershot, Brechtel, Orts, and Blumberg (table 1).

Austin Area Cores	Core #	Name in Study	Eagle Ford Depths (ft)	Logs	Core Description	Isotopes	Thin Sections	Rock Eval	XRD	XRF	Photos
	BT-222-PTPZ	222	51-88	No	Yes	Yes					
	Bl-500-PT	500	55-94	No	Yes	Yes	yes	Yes	Yes	Yes	Yes
	Bl-514-PTPZ	514	52-89	No	Yes						
	BT-204	204	80-116.5	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	BO-302-PT	302	52.5-90	No	Yes						
	BO-301-PTPZ	301	51-88	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	BT-221	221	52-88	No	Yes						
	ACC #1	ACC	80-125	CGR/GR	Yes					Yes	Yes
	Outcrop										
	West Bouldin Creek										
	Walnut Creek										
Regional Cored Wells	Wells	Name in Study	Eagle Ford Depths (ft)	Logs	Core Description	Isotopes	County	API	Operator		
	C.J. Hendershot #1	Hendershot	4734-4774	GR	Harbor (2011)	Yes	Caldwell	4217730218	Tesoro Petroleum		
	W. Brechtel #1	Brechtel	3280-3315	GR	Harbor (2011)	Yes	Wilson	4249330208	Prairie Producing Co.		
	H.P. Orts #2	Orts	7684-7757	GR	Harbor (2011)	Yes	Gonzales	4217730203	Transocean Oil, Inc		
	F.T.Schauer et al #1	Schauer	8093-8159		Harbor (2011)		Gonzales	4217730394	Geological Res Corp.		
	J.W. Blumberg #1-B	Blumberg	4175-4225	GR	Harbor (2011)	Yes	Wilson	4218730532	Prairie Producing Co.		
	#1 Burkland	Burkland	935-977	GR			Caldwell	4205534144	Vista Energy Corp		

Table 1: Description of data set, including cores, outcrops and laboratory analyses.

REGIONAL GEOLOGY

The southwestern-most expression of the Grenville orogeny is the 1.15-1 Ga Llano uplift in Central Texas, resulting in vast exposures of deformed core, consisting of gneisses, schists, and metavolcanic rocks (Culotta et al., 1992). An extension of the uplift, the San Marcos Arch, trends southeast-northwest and separates the Maverick Basin from the East Texas Basin (Dravis, 1980; Young, 1986) (figure 5).

The Early Triassic of North America experienced the onset of Pangean rifting, leading to the initiation of the opening of the Gulf of Mexico Basin. This can be summarized by two dominant stages. The first stage extended from the Early Jurassic through Callovian and was marked by asymmetric rifting where the North American side acted as a footwall while the Yucatan side acted as a hangingwall. The second major stage is dominated by symmetrical seafloor spreading until the Early Cretaceous (Valanginian) (Pearson et al., 2010).

Diminished subsidence over the San Marcos Arch resulted in a minor topographic high (Tyler and Ambrose, 1986) where a large carbonate platform developed in the Early Cretaceous (Donovan and Staerker, 2010). During most of the Cretaceous, the platform over the San Marcos Arch was a low-lying subaerial terrain, receiving and supplying little sediment, similar to modern day Florida (Young, 1986). The study location in Austin lies on the northeastern flank of the San Marcos Arch.

Figure 5: Paleogeographic map of Texas near the Cenomanian/Turonian boundary. The study area lies on the northeastern flank of the San Marcos Arch which separates the Maverick Basin from the East Texas Basin. The Sligo and Stuart City shelf margins form the downdip extent of the Eagle Ford. Modified from Ruppel et al., (2012).

Thick progradational carbonate packages of the Comanche Shelf developed during the Cretaceous time (figure 6). Shelfal depositional profiles with both flat-topped, raised rim, and ramp profiles originated during multiple transgressive-regressive events (Harbor, 2011). The first reef-rimmed margin, the Sligo, appeared during the Hauterivian stage and persisted through the Aptian (figure 6). Flooding during the Aptian terminated deposition of the Sligo shelf margin, and resulted in the retrogradational, organic-rich Pearsall Formation. The Aptian transgression was followed by an Albian re-

establishment of a raised rim shelf margin, called the Stuart City shelf margin (Salvador and Muñeton, 1989) (figure 6). In many parts of Texas, the Stuart City shelf margin prograded to the location of the previous Sligo shelf margin, causing a sharp physiographic break between the continental shelf and the continental slope toward the end of the Early Cretaceous. However, in Southwest Texas, progradation of the Stuart City shelf margin was stalled inboard of the Sligo margin, forming a two-step continental margin (Donovan and Staerker, 2010) (figure 5, figure 6). Until the Cenomanian time, true rudist coral communities in the Stuart City acted as constructors and formed baffles to normal wave action, which formed a nearly continuous carbonate reef rimming the Gulf of Mexico (Scott, 2010).

Figure 6: Architecture of the Comanche Shelf of the Gulf of Mexico Basin. Transgressive and regressive events led to both flat-topped, raised rim morphologies and ramped open shelf profiles. From Harbor (2011), modified from Galloway (2008), and Salvador and Muñeton (1989).

A major transgression of the Comanchian shelf in the Middle to Late Cenomanian initiated deposition of the Eagle Ford Group. By this time, differential subsidence had already created the Maverick and East Texas Basins (Hentz and Ruppel, 2010) (figure 5). To the northeast, the Woodbine delta had previously been depositing the updip Tuscaloosa and Woodbine formations in a fluvial and deltaic setting (Sohl et al., 1991; Dubiel et al., 2010) (figure 5). During the Cretaceous, much of the river borne detritus included illite (Pratt, 1984), which contributed to much of the clay component within the Eagle Ford facies. The paleogeography at the time of the Cenomanian-Turonian boundary is summarized in figure 5. Eagle Ford deposition was immediately followed by Coniacian-Santonian deposition of the Austin Chalk and subsequently the rest of the Gulfian Series (figure 6). From the Mesozoic onward, sedimentary fill in the Gulf of Mexico Basin reached thicknesses of 60,000 feet (Pearson et al., 2010).

PREVIOUS WORK

The third Geological Survey of Texas involved the tracing of the Buda-Eagle Ford contact in North and South Texas. The Woodbine Formation was also recorded south of the Brazos River where it was included in the Lower Eagle Ford, yet Cragin (1893) considered the Woodbine to be absent in south Texas. The South Bosque Formation was first named by Pranter (1902) who assigned it to the upper portion of the Eagle Ford in McLennan County and established it as a type section. Equivalent beds to the Pepper Shale were included as the base of the Eagle Ford by Adkins (1924) and Adkins and Arick (1930), who also recognized the Buda to “intermittently” underlie the Eagle Ford.

Moreman (in Sellards et al., 1932) divided the Central Texas Eagle Ford shale into the Tarrant, Britton, and Arcadia Park Formations. This division was a preliminary attempt to divide the formation based on lithologic characteristics and provided the groundwork for evaluating facies variability within the Eagle Ford (Sellards et al., 1932). The nomenclature of Tarrant, Britton, and Arcadia Park Formations was adopted in northern Texas but modified in other parts of the state. Moreman (in Sellards et al., 1932) also noticed thickness variations in the Arcadia Park Formation from 100 feet in Dallas to 10 feet in Austin and interpreted an unconformity between the Eagle Ford and overlying Austin Chalk. The following year, Adkins (in Sellards et al., 1932) proposed a “condensed zone” at the top of the Eagle Ford in southern Texas and included it in Central Texas.

Feray and Young (1949) first described the outcrop along West Bouldin Creek in Austin (figure 1). It was again studied by Adkins and Lozo (1951) who assigned the name of South Bosque Formation to the upper unit of the Eagle Ford along with its

associated condensed zone. They also applied the name “Middle Flaggy Limestone” to the unit now called Bouldin Member, and the “Cloice” to the unit now called the Waller Member. Young (1977) followed this nomenclature with the exception of the “Middle Flaggy Limestone” which he adjusted to the “Bouldin Member” (figure 7).

In West Texas, thorough outcrop-based studies have contributed to understanding the Boquillas Formation (Eagle Ford equivalent). Trevino (1988) interpreted depositional environments based on sedimentological features and interpreted the sediment to have been deposited under anoxic conditions. Miller (1990) ascribed the sharp lithologic change above the Buda to correspond to tectonic subsidence.

Sequence stratigraphic investigations were conducted by Dawson (1997) and Liro et al. (1994) who recognized that the Eagle Ford represented a 2nd order eustatic transgression of the UZA-2 supercycle. Further outcrop investigations also led Lock and Peschier (2006) and Lock et al. (2007) to incorporate the Eagle Ford of South and West Texas into a sequence stratigraphic framework. More recently, Donovan and Staerker (2010) extensively studied the Boquillas Formation and identified three transgressive-regressive cycles based on sedimentological and biostratigraphic indicators. They also proposed nomenclature changes to the Eagle Ford Formation and Langtry Formation (figure 7). Additionally, they applied a sequence stratigraphic framework to the Eagle Ford and Langtry Formations and correlated them into the subsurface of South and Central Texas.

A subsurface stratigraphic study was conducted by Hentz and Ruppel (2010) who established a regional lithostratigraphic framework for the Eagle Ford based on wireline logs. This subsurface correlation was valuable in identifying thickness and rock character trends from South Texas, across the San Marcos Arch, and into East Texas. Harbor (2011) integrated well logs and cores to identify variations of rock properties in the

subsurface. He further demonstrated that complexities in rock character result from interrelated processes of sediment production and distribution (Harbor, 2011).

Figure 7: Composite stratigraphic chart reviewing the nomenclature used in the Central Texas Eagle Ford intervals. This study adopts the names of Pepper Shale, Waller Member, Bouldin Member, and South Bosque Formation.

Biostratigraphic analysis of Cenomanian-Turonian strata in Texas has proven difficult because of the general paucity of benthonic faunal assemblages resulting from oxygen depleted water. However, planktonic taxa provide good biostratigraphic control. Previous biostratigraphic investigations have been based on ammonites (Scott, 1926; Adkins and Lozo, 1951), foraminifera (Loeblich and Tappan, 1961; Pessagno, 1969; Barrier, 1980;), and nannofossils (Thierstien, 1976; Smith, 1981; Jiang, 1989). Foraminifera-based biostratigraphy was first undertaken by Pessagno (1969) and was later followed by Barrier (1980). Barrier (1980) disagreed with Pessagno's (1969) interpretation of a basal Turonian age in the Bouldin Member in Austin, Texas. One year later, Smith (1981) confirmed Pessagno's (1969) interpretations using samples from the Langtry Formation in West Texas, the South Bosque Formation in Austin, and the Maribel Shale in Grayson County in northern Texas. Smith (1981) concluded that the Upper Eagle Ford (South Bosque in Austin) is "not older than Coniacian." At the Eagle Ford-Austin contact, Pessagno (1969) defined the Cenomanian/Turonian boundary in the Bouldin Flags member about 1.5 feet below the base of the South Bosque Formation (figure 7). This boundary was again supported by Jiang (1989) who conducted a regional outcrop biostratigraphy based on nannofossils.

Jiang (1989) demonstrated that based on nannofossils, the Bouldin Member in Central Texas (Austin) is correlative to the Bluebonnet Member in North-Central Texas (Waco) (figure 7). Therefore, even though the Cloice Member in north-central Texas (Waco) had traditionally been correlated to the lower portion of the Eagle Ford in Central Texas, the two members cannot be equivalent, and have "nothing in common." He further proposed the removal of the designation "Cloice" in Central Texas (Jiang, 1989). In the current study, the designation of "Waller Member," has been applied to this unit (figure

7), for the Waller Creek Tunnel, whose construction resulted in the acquisition of many of the cores used for this project.

In Central Texas, the following fossil assemblages have been documented within the Eagle Ford interval by Housh (2007): sponges (*Spongeliomorpha* sp.), marine bivalve molluscs (*Anomia* sp., *Inoceramus labiatus*, *Inoceramus fragilis*, *Inoceramus* sp.), oysters (*Nicaiolopha bellaplicata*, *Ostrea* sp.), Rudists (*Monopleura* sp.), sea snails (*Anhura* sp., *Tylostoma* sp.), ammonoids (*Moremanoceras* sp., *Tragodesmoceras socorroense*, *Placentoceras cumminsi*, *Neocardioceras juddii juddii*, *Acanthoceras* sp., *Euomphalus septemseriatum*, *Romaniceras mexicanum*, *Coilopoceras shispaense*, *Coilopoceras eaglefordense*, *Coilopoceras springeri*, *Coilopoceras* sp., *Collignoniceras woollgari regulare*, *Prionocyclus wyomingensis*, *Prionocyclus eaglense*, *Prionocyclus percarinatus*, *Prionocyclus hyatti*, *Prionocyclus* sp., *Sciponoceras gracile*, *Baculites grandis*, *Baculites yokoyamai*, *Baculites* sp., *Worthoceras* sp., *Scaphites* aff. *aequalis* var. *turonensis*, *Scaphites carlilensis*), marine worms (*Serpula* [Linnaeus] spp.), and echinoids (*Leiostomaster bosei*). Fish remains are also replete through the Eagle Ford succession and include: shell crushing sharks (*Ptychodus whipplei*, *Ptychodus latissimus*, *Ptychodus mortoni*, *Ptychodus* sp.), crow sharks (*Squalicorax falcatus*), smooth-toothed lamniform sharks (*Cretolamna appendiculata*, *Cretodus crassidens*, *Cretoxyrhina mantelli*, *Cretoxyrhina mantelli oxyrhinoides*), grooved, narrow-toothed lamniform sharks (*Scapanorhynchus raphiodon*), ray finned fishes (*Hadrodus* sp., *Pachyrhizodus* sp., *Enchodus petrosus*), and other unidentified fish remains as well as unidentified vertebrate animals with large casts up to 4 X 2 inches (Housh, 2007).

Previous works on the Eagle Ford are summarized in table 2. Figure 7 depicts the past and proposed nomenclature of the Eagle Ford Group.

Author	Date	Contribution
Roemer	1849 1852	Earliest descriptions of Eagle Ford as, “Black shale with fish remains.”
Shumard	1860	Provided early descriptions of Cretaceous fossils.
Hill and White	1887	Named the Eagle Ford and established a type section.
Pranther	1902	Named the South Bosque Formation
Adkins	1924	Included the Pepper Shale equivalent beds into the Eagle Ford.
Adkins and Adrick	1930	
Moreman	1932	Divided Central Texas Eagle Ford lithologically into the Tarrant, Britton, and Arcadia Park Formations. Interpreted an unconformity at the basal Austin Chalk.
Adkins	1932	Proposed a condensed zone at the top.
Feray and Young	1949	First described West Bouldin Creek outcrop.
Adkins and Lozo	1951	Applied the names South Bosque Formation, Middle Flaggy Limestone, and Cloice
Pessagno	1969	Marked the Cenomanian-Turonian Boundary in the Bouldin Member of West Bouldin Creek based on foraminifera.
Young	1977	Changed the name of “Middle Flaggy Limestone” to the “Bouldin Member.”
Trevino	1988	Interpreted depositional environments for Boquillas Formation (Eagle Ford equivalent).
Jiang	1989	Demonstrated that the Cloice Member is different in Waco than in Austin, and proposed removal of that name in Austin. Used nannofossils to confirm the Cenomanian-Turonian boundary of Pessagno (1969).
Miller	1990	Interpreted tectonism to account for Buda-Boquillas lithology change.
Liro et al.	1994	Interpreted the Eagle Ford to represent a 2 nd order eustatic transgression of the UZA-2 supercycle.
Dawson	1997	
Lock and Peschier	2006	Established a sequence stratigraphic framework for South and West Texas, based on Boquillas outcrops.
Lock et al.	2007	
Housh	2007	Described faunal assemblages present near Austin.
Donovan and Staerker	2010	Established a sequence stratigraphic framework for South and Central Texas. Recognized three transgressive-regressive cycles.
Hentz and Ruppel	2010	Established a regional lithologic framework for thickness and character changes based on well logs.
Harbor	2011	Identified rock character variations in subsurface logs.

Table 2: Summary of major contributions to the stratigraphy of the Eagle Ford system.

METHODS

Description and Classification of Facies

Classification schemes are numerous in literature, especially those for clastic or carbonate systems. An effective classification scheme for the Eagle Ford shale is one that is objective, flexible, and provides industry-recognized and accepted terms. Observation-based nomenclature is valuable in that it removes unintended genetic implications for depositional processes. In this thesis, terms used to describe carbonate rocks follow the Dunham (1962) classification, such as wackestone or packstone, while terms associated with carbonate-poor rocks are adapted from the Potter (1980) shale classification.

A flow chart describing the process of classifying and naming rocks is shown in figure 8. Rocks are first examined with respect to original carbonate content. If the carbonate content exceeds 50%, then the Dunham (1962) classification scheme is applied. If the sample contains less than 50% carbonate, then it is evaluated by grain size. In the unlikely event that a carbonate poor sample is dominated by coarse grains ($>.062\text{mm}$), then it is classified as a sandstone (Boggs, 2006). The variable content of mud-sized grains (clay minerals, detrital quartz, and calcite) further complicates rock type designation. For this reason, the term mudrock is adopted to describe fine-grained material facies of mixed composition.

Due to the variable composition of mudrocks, modifiers are used to describe important attributes, such as “argillaceous,” “foraminiferal,” or “bioturbated.” The modifier closest to the rock name is the most important, or most descriptive, whereas those further away are less characteristic. The first descriptor in a facies name makes reference to the sedimentary structures, whether it is massive, laminated, or bioturbated. For example, a facies is described as “massive argillaceous foraminiferal mudrock.” As

the title implies, this facies lacks sedimentary structures, contains less than 50% calcite, and is composed of abundant foraminifera as well as clay.

Figure 8: Mudrock facies classification flow chart.

This classification scheme based on both Dunham (1962) carbonate and Potter (1980) shale classifications, is sufficient for classifying the Eagle Ford facies. It provides terms that are both conventionally used in industry and easily modified, accounting for specific trends or variations within this highly variable system. Also, the terms are broad enough that they do not require detailed chemical analyses to assign specific names and can therefore be assigned through observation.

Physical core and outcrop descriptions were based on observable characteristics. A modified logging sheet was used to record depths, bedding contacts, sedimentary structures, rock types (with both Dunham (1962) classifications and mudrock capabilities), composition, grain type, color, cementation, and notes. Hand lens and diluted HCL were used in outcrop studies, and the additional support of a binocular microscope enhanced the core descriptions.

Thin Sections

Three Waller Creek Tunnel cores were selected for thin section sampling (table 1), to assist in facies determination. From these cores, a total of 61 thin sections were produced, including 24 thin sections from 301, 21 thin sections from 500, and 16 thin sections from 204 (figure 1, table 1). Samples for thin section preparation were removed from the intact core and cut into the approximate size with a rotary rock and tile saw. National Petrographic Services, based in Houston, TX, was an outsourced company used for final thin sample preparation, where samples were mounted onto a slide, impregnated with fluorescent epoxy, and cut to a thickness of 30 micrometers. Samples containing high proportions of water-sensitive swelling clays were cut and prepared with an oil-based tool, reducing contact with water to preserve the sample.

Analysis of the thin sections occurred at the Bureau of Economic Geology using a high resolution Nikon Eclipse LV 100 POL microscope, and photomicrographs were taken using a Nikon DS-Ril camera. The analysis of the thin sections was primarily based upon micro-sedimentary structures, as well as grain assemblages.

Rock Eval/Pyrolysis/TOC

Samples were collected for Rock Eval/Pyrolysis analysis from several Waller Creek cores, including 301, 500, and 204 (figure 1, table 1). Results were used for characterizing the organic content of the Eagle Ford interval in Central Texas, including the Total Organic Carbon (TOC), percent carbonate, calculated thermal maturity, hydrogen index, oxygen index, and oil potential. Analysis of representative samples from each Eagle Ford facies was conducted by GeoMark Research, Ltd., Houston, TX.

Approximately 10 grams of sample were prepared by crushing and treating with HCl to remove inorganic carbon. A leco TOC apparatus was utilized in measuring TOC values. Calibration involves standards that have previously determined organic carbon content. Combustion of the unknown samples was compared to the standard, determining the TOC of the sample.

Rock-Eval analyses include thermal vaporization of volatiles (the S1 peak, residual free oil), as well as pyrolysis of kerogen (the S2 peak, remaining generation potential). S2 values are used to compute Hydrogen Index (HI) by normalization involving TOC values ($HI = S2/TOC \times 100$ with units of mg (milligram) HC/g (gram) TOC). Estimates of thermal maturity are generated from the temperature at peak generation of S2 hydrocarbons, the Tmax (in °C) value. Tmax is a kinetic value and varies depending on kerogen type. The S3 peak (“organic” carbon dioxide yield during initial pyrolysis process) was used to compute the Oxygen Index (OI) by normalization with the TOC content ($OI = S3/TOC \times 100$ with units of mg CO₂/g TOC) (Harbor, 2011).

X-Ray Diffraction

Samples were collected for XRD analysis from several Waller Creek cores, including 301, 500, and 204 (figure 1, table 1). Representative samples from each Eagle Ford facies (facies 1-7) were conducted by Dr. Necip Guven at The University of Texas, San Antonio, TX (UTSA). Samples were extensively cleaned and finely powdered. X-Ray Diffraction analysis was performed with a Rigaku-Ultima IV (2007) diffractometer in the Physics Department of UTSA, with a scanning range initially limited from 2° to $44^{\circ}/2\theta$ and extended to $62^{\circ}/2\theta$ if necessary. Scanning speeds ranged from $1^{\circ}/2\theta$ to $2^{\circ}/2\theta$ per minute. The powdered samples were then scanned repetitively on different scanning modes depending on the presence of swelling clays.

In the first scanning mode, the powder sample was placed on a rough glass surface to minimize preferential orientation of the sample. For the second scanning mode, approximately 1-1.5g of the powder sample was suspended in 0.01N (normality) sodium pyrophosphate solution for approximately 24 hours. Fresh solution was periodically replaced if the acid residue and suspended clays flocculated, until a workable suspension was produced. Coarser particles, larger than 2-4 μm settle out of the suspension. The remaining liquid and suspension was then transferred to a glass slide to dry before the clay films were scanned.

A third preparation of the sample was conducted if the presence of swelling clays was still indicated. The sample was placed for 24 hours in ethylene glycol (EG). While saturated, the sample was again x-rayed to reveal the presence of swelling clay minerals such as smectites and mixed layer illites/smectites. In assistance with mineralogical identification, elemental X-Ray Fluorescence (XRF) analysis on the same samples was

conducted at the University of Kentucky, Lexington by Henry Francis (Dr. Necip Guven, personal communication, July 2011).

Stable Isotope Analysis

Several cores in the Austin locality were selected for stable isotope analysis, including 301, 500, 204 and 222 (figure 1, table 1). Powder samples were collected in 1 ft intervals throughout the Eagle Ford succession and were collected using a carpenter's drill. Sample analyses were performed by Dr. Harry Rowe at The University of Texas at Arlington, Arlington, Texas. Each powdered sample was analyzed using a UIC, Inc. coulometer to determine the concentration of total inorganic carbon (%TIC). 3-5mg of each powdered sample was reacted in 10% H_3PO_4 at 70°C during the coulometric measurement. The measured %TIC assisted in optimizing the weight for stable isotopic analysis. Approximately 200-450 μg of sample, depending upon the sample %TIC, were weighed into LABCO Exetainer vials, capped, and purged with ultra-high purity helium gas for 3 minutes each. Subsequently, the samples were acidified with three drops of 100% H_3PO_4 and equilibrated at 50°C for 13.5 hours, after which they were analyzed using a ThermoFinnigan GasBench II peripheral connected to a ThermoFinnigan Delta-V isotope ratio mass spectrometer (IRMS). Stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) were standardized using an in-house calibration (UTAH) and to Vienna-PDB (Pee Dee Belemnite). Errors for standards and samples are ± 0.1 for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (Harry Rowe, personal communication, February, 2011).

Energy Dispersive X-Ray Fluorescence

Hand-Held Energy Dispersive X-Ray Fluorescence (XRF) is quickly becoming an industry standard for acquiring inorganic geochemical data from cores and cuttings of mudrock intervals. The major benefit of XRF is that it provides an efficient means of data collection allowing for the rapid, non-destructive, quantitative measurements on drill core and clean flat rock surfaces (Rowe et al., 2012) as small as a cm scale (Smith and Malicse, 2010). Major applications of XRF include effectively assessing real-time chemostratigraphic changes, changes in bulk mineralogy, paleoredox conditions, and linking down-core geochemical changes to stratigraphic, sedimentological and paleoenvironmental observations. Current elemental calibrations account for major elements heavier than sodium including Mg, Al, Si, P, S, K, Ca, Ti, Mn, and Fe. Trace element calibrations account for the following: Ba, V, Cr, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Mo, Th, and U (Rowe et al., 2012).

XRF analysis of the Austin locality cores was conducted by Dr. Harry Rowe and students from the University of Texas, Arlington. Calibrations involved the reference materials from five internationally-accepted, commercially available standards, SDO-1, SGR-1, SCo-1, GBW-07107, and SARM-40. 86 reference material of diverse mudrock systems are also used for calibration, including 28 references from the Woodford, 20 references from the Smithwick, 16 references from the Barnett, 15 references from the Eagle Ford, and 7 references from the Ohio Shale (Kearns, 2011). Reference materials were pulverized using a 200-mesh low trace element steel pulverizer and analyzed for major and trace element composition by SGS Mineral Services, Canada. Elemental concentrations were determined by Wavelength Dispersive X-Ray Fluorescence (XRF), Inductively Coupled Mass Spectrometry (ICP-MS), and Inductively Coupled Plasma

Atomic Emission Spectroscopy (ICP-OES). Samples were then backed with boric acid and pressed into pellets at 40 tons by a 44-mm die (Rowe et al., 2012).

All analyses were undertaken using a Bruker AXS Tracer III-V ED-XRF device equipped with an Rh x-ray tube. The reference pellets were placed on top of the instrument supported by a stand and with the beam pointing upward. They were then analyzed in triplicate at low energy for major elements and high energy for trace elements. Reference samples were repositioned and re-measured to attain a sense of reproducibility. The final calibration routine resulted in a spectra from 270 analyses (90 references x 3 readings). Similarly, core samples for analysis were placed on the nose of the device with the flat slabbed surface down. Sample XRF Spectra were entered into Bruker AXS proprietary calibration software where concentrations of each element were compared to the reference concentrations using inter-element slope- and baseline-corrected peak heights from the Energy Dispersive X-Ray Fluorescence (XRF) system (Rowe et al., 2012). A more comprehensive discussion on the methods of calibration and data collection of XRF is provided by Rowe et al., (2012) and in Hughes (2011).

An equivalent Gamma Ray (GR) log can be reconstructed from elemental abundances gathered with XRF through the formula,

$$(U * 8) + (Th * 4) + (K * 16) = API$$

where U is the uranium content (ppm), Th is the thorium content (ppm), and K is the percent of potassium. Computed Gamma Ray (CGR) log, can be calculated from the Th and K content. This proved advantageous in this study because it provided a ready comparison to commonly obtained subsurface logs in addition to the removed variable signal of U. External factors influence U content, including water chemistry and organic matter preservation. The CGR curve ensures that the signal is representative of siliciclastic mineral content and reflects lithological changes, similar to a conventional

Spectral Gamma Ray (SGR) log. American Petroleum Institute (API) is a standard for measuring the natural radiation recorded by various gamma ray counting devices. The standard is a calibration test pit at the University of Houston where a radioactive cement calibrator is assigned a value of 200 API, conceived so that typical midcontinent shale would read about 100 API (Doveton and Merriam, 2004).

RESULTS

Facies

Clearly distinguishing among representative facies is a critical aspect of understanding mudrock systems. Although adorned with their distinctively dark color and generally homogenous character, mudrocks are extremely variable with high degrees of heterogeneity, which have important implications for depositional environment and sediment delivery processes. Eagle Ford facies were described in cores and outcrops on the basis of contact nature, sedimentary structures, grain size, composition, textural fabric, color, and cementation. Assessment of the mineralogical constituents within the mudrock matrix was aided by XRD and thin section analyses. Within the Eagle Ford interval, 7 characteristic facies are defined with individual implications for depositional processes. The central Texas Eagle Ford facies are:

Massive Argillaceous Mudrock

Massive Argillaceous Foraminiferal Mudrock

Laminated Argillaceous Foraminiferal Mudrock

Laminated Foraminiferal Wackestone

Cross-Laminated Foraminiferal Packstone/Grainstone

Massive Bentonitic Claystone

Nodular Foraminiferal Packstone/Grainstone

Two non-Eagle Ford facies representing the top of the underlying Buda Limestone and bottom of the overlying Austin Chalk are also defined:

Massive Skeletal Wackestone/Packstone (Buda Limestone)

Bioturbated Lime Mudstone/Wackestone (Austin Chalk)

EAGLE FORD FACIES

Massive Argillaceous Mudrock Facies

Exclusively pertaining to the Pepper Member and only observed in core, this facies weathers recessively and is not exposed in outcrop. Young (1977) attested to the recessive nature as he reported it as one of the least stable rocks in Texas. In hand sample (figure 9) it has a distinctively smooth or soapy texture and feels smooth on teeth. Although recorded as a black rock (Young, 1977), it has a dark to medium dark gray colored fresh surface in core. The mineral composition, as revealed by XRD, is primarily clay minerals (avg. 53%, range 32-68%), which in decreasing abundance include: illite, kaolinite, illite/smectite mixed layer, and smectite. Other constituents (avg. 18%, range 5-30%) include quartz, plagioclase, and potassium feldspar. Carbonate constituents (avg. 34%, range 3-60%) include primarily calcite with trace amounts of ankerite and siderite. Accessory constituents include pyrite and gypsum.

Figure 9: Massively argillaceous mudrock facies core photograph, thin section photomicrographs, and summary of characteristic features. (A) Slab photo showing the massive, dark gray fissile character. (B) Thin section photomicrograph showing the cellular structure of wood material. (C) Thin section photomicrograph depicting the fine grained nature and rare globigerinid foraminifera.

Fine-grained, clay-sized material forms the bulk of the rock matrix, but few globigerinid foraminifera are present that contribute to the carbonate fraction of this facies. In hand sample, ammonite impressions are recognizable in partings. Moderately well-cemented, this facies easily splits into thin sheets along planar as well as irregular horizons, possibly due to fissility (figure 9).

Based on the relatively low carbonate and high clay mineral content, this facies is interpreted to represent a period of high siliciclastic dilution. Massive argillaceous mudrock-filled microkarst voids within the underlying Buda suggest that this facies marked the initiation of basinal flooding. Flooding is also supported by the lack of coarser material. The depositional environment is interpreted to have been in anoxic marine conditions below storm weather wave base, as suggested by the paucity of benthonic fauna, bioturbation, and wave-generated structures.

Massive Argillaceous Foraminiferal Mudrock Facies

Massive argillaceous foraminiferal mudrock is the most common facies in the Eagle Ford succession in Central Texas. Medium to dark gray on a fresh surface and medium gray in outcrop, this mudrock is dominantly structureless yet locally displays laminae that may not be observed in hand sample (figure 10). In outcrop these rocks readily weather and crumble to the touch along horizontal cleavage planes. In hand sample this facies is distinguishable from the massive argillaceous mudrock facies in that it is more calcareous, contains a higher quantity of planktonic (forams) and benthonic (inoceramid and bivalve fragments) fauna, is lighter-gray in color, and feels gritty to the touch. Young (1977) distinguished this facies from the Pepper Shale in that this facies is “gritty and dark gray instead of black.”

Figure 10: Massive argillaceous foraminiferal mudrock facies core photograph, thin section photomicrograph, and summary of characteristic features. (A) Slab photo showing the massive, medium dark gray character. (B) Thin section photo showing fine grained nature and abundant globigerinid foraminifera and inoceramid and bivalve shells.

As revealed by XRD, this facies has a higher carbonate (avg. 51%, range 36-68%) content and a lower clay mineral fraction (avg. 39%, range 21-67%) compared to the massive argillaceous mudrock facies while retaining a similar quartz and feldspar component (avg. 16%, range 7-28%).

The gritty nature of this facies results from an increased abundance of globigerinid foraminifera, which also accounts for the increased carbonate content. The higher abundance of planktonic sediment is likely a result of nutrient enrichment in the photic zone which stimulated productivity relative to the massive argillaceous mudrock facies. Additionally, a lower degree of siliciclastic dilution could suggest a distal location where terrigenous material input is diminished. The dark gray color, lack of oxygen-dependent benthonic fauna, and the general lack of sedimentary structures suggest that the depositional environment was in anoxic marine conditions below storm weather wave base.

Laminated Argillaceous Foraminiferal Mudrock Facies

The laminated argillaceous foraminiferal mudrock is a very thinly (0.1-2 mm thick) planar to sub-planar laminated medium dark gray, calcareous rock with planktonic globigerinid foraminifera and benthonic inoceramid and pelecypod fragments (figure 11). Laminae subtly scour into underlying structures (figure 11). This facies is less abundant than the massive argillaceous foraminiferal mudrock facies, but commonly occurs in association with it.

As revealed by XRD, this facies has higher carbonate content (avg. 62%, range 57-73%) and a lower clay mineral fraction (avg. 24%, range 18-31%) from the previous yet retains a similar quartz and feldspar component (avg. 11%, range 7-13%). Pyrite framboids are observed in thin section (figure 11) and have been interpreted to have formed in the water column (Lash and Blood, 2004).

Figure 11: Laminated argillaceous foraminiferal mudrock facies core photograph, thin section photomicrographs, and summary of characteristic features. (A) Slab photo showing the laminated, medium gray character. (B) Thin section photo showing fine laminations and abundant globigerinid foraminifera. (C) Thin section showing erosional scouring.

The main feature that distinguishes this facies from the Massive Argillaceous Foraminiferal Mudstone facies is the presence of very thin planar laminations. In thin section, laminae contain high concentrations of carbonate grains, mostly globigerinid foraminifera, with lesser amounts of inoceramid and other bivalve fragments (figure 11).

Bottom current winnowing is interpreted as the mechanism for creating the planar laminated structures. The finer material is sifted out and leaves a lag or concentration of coarser material. Inoceramid fragments display abraded surfaces indicating that in situ faunal growth is unlikely and that these components were likely transported from other locations. Harbor (2011) proposed turbidity currents as a process of supplying the benthonic fauna into the basin, whereas suspension settling largely supplied the planktonic components. Although the laminations appear to be planar laminated in the limited core segment, they are likely subtly sub-planar and ripple laminated where compaction has flattened much of the apparent geometry. Correlative outcrops of the Boquillas Formation near Comstock, TX contain pervasive low angle ripple laminations, sub-planar laminations, and scour and truncation surfaces. These West Texas analogs provide additional outcrop perspectives to the cored intervals of the laminated argillaceous foraminiferal mudrock facies of Central Texas where similar depositional processes occurred.

Flume experiments by Schieber et al. (2007), and Schieber and Southard (2009) show that clay floccules can be deposited in greater current velocities than previously supposed. Mud can accumulate as grains or aggregates in currents with a competency to transport sand sized grains and erode previously deposited layers. Structures composed of low angle ripples containing low crests and localized erosion can often be misinterpreted as planar laminations (Macquaker and Bohacs, 2007; Schieber et al., 2007; Schieber and

Southard, 2009). These observations and interpretations are consistent with the current study.

Laminated Foraminiferal Wackestone Facies

The laminated foraminiferal wackestone facies is exclusively restricted to the Bouldin Member and displays a substantial increase in carbonate content compared to previously mentioned facies. The primary carbonate allochems consist of globigerinid foraminifera, along with minor inoceramid and other bivalve fragments (figure 12). A fine grained mix of carbonate and siliciclastic material constitutes the interstitial matrix (figure 12). Although generally a wackestone, localized portions and very thin lamina could justifiably be considered packstones or even grainstones. As indicated, a higher carbonate content (avg. 76%, range 75-80%) with a lower clay mineral (avg. 10%, range 8-12%) and quartz and feldspar (avg. 10%, range 8-11%) portion is distinctive of this facies, as confirmed by XRD analysis. This composition significantly differs from previous authors who describe rocks within the same interval as this facies as containing 70-95% smectite (Liro et al., 1994). Pyrite is dispersed throughout the formation, comprising about 3% by weight.

Higher depositional energy is suggested in this facies due to the higher degree of current induced structures. Very thin planar and sub planar laminations, slump folds, fine ripple laminations, and scours are pervasive throughout this facies, suggesting bottom currents as a mechanism for dispersing and reworking the sediment. The likelihood of a mild gradient on the seafloor (<1 degree) is suggested by the presence of lamina scale slump folds in observed in core as well as meter scale slump folds observed in the Walnut Creek outcrop. A gently sloping seafloor is also interpreted to be the cause of large scale (1 meter) folds in the Boquillas formation near Del Rio, TX (Ruppel et al., 2012).

Structures: Very thin planar/sub planar laminations, fine ripple laminations, scours

Composition: 76% Calcite, 10% Clay minerals, 7% Quartz

Fossils: Forams, Inoceramid and Pelecypod fragments

Color: Medium gray

Character: Moderately well cemented, peloidal

Figure 12: Laminated foraminiferal wackestone facies core photograph, thin section photomicrographs, and summary of characteristic features. (A) Slab photo showing the finely ripple laminated, medium gray character. (B) Thin section photo showing disturbed bedding and abundant globigerinid foraminifera and inoceramid fragments. (C) Thin section showing a finer grained interval.

Cross-laminated Foraminiferal Packstone/grainstone Facies

The cross-laminated foraminiferal packstone/grainstone facies (figure 13) is most commonly observed in the Bouldin Member but also encountered within the Waller Member. This facies is readily recognized in outcrop by its highly resistive and ledge-forming nature. For this reason, some authors described intervals which contain this facies as “flaggy” (Young, 1977, 1986; Jiang, 1989; Dawson, 1997) . The outcrop expression tends to be light to medium -gray to buff colored, and 1-4 inch thick beds are interstratified with shaly units, similar to observations of Young (1977). Beds of this facies are generally traceable across 50 ft in outcrop but display variable thickness. Lock and Peschier (2006) described these beds in Austin as “pinch and swell units.”

Highly calcareous (avg. 89%, range 82-97%), these rocks contain mostly globigerinid foraminifera tests, as well as highly abraded inoceramid and other bivalve fragments (figure 13). In contrast to other facies, the cross-laminated foraminiferal packstone/grainstone facies contains very low amounts of quartz and feldspar (avg. 7%, range 3-11%) and even lesser amounts of clay minerals (avg. 3%, range 0-9%). Thin to very thin sub-planar cross laminations and scours (figure 13) are evident in outcrop as well as core which give evidence to the high degree of current flow during deposition.

Cross-laminated sedimentary structures and scours suggest that this facies represents the highest energy of deposition of all Eagle Ford intervals in the study area. Additionally, these sedimentary structures are current-induced and are interpreted to result from bottom current reworking. The strong nature of the bottom currents during this time (as evidenced from sedimentary structures) is likely responsible for the removal of fine-grained material from the seafloor. The sifted result is an accumulation of coarser material, primarily consisting of globigerinid foraminifera, which is supplied from the

photic zone. Inoceramid and other bivalve fauna are heavily abraded and are interpreted to have been transported by traction flow into the study area from other locations.

Figure 53: Cross-laminated foraminiferal packstone/grainstone facies core photograph, thin section photomicrographs, and summary of characteristic features. (A) Slab photo showing cross-laminations, and light gray nature. (B and C) Thin section photos showing the abundant globigerinid foraminifera, inoceramid fragments, bioclasts, pyrite and grain-rich texture.

High rates of planktonic sediment into the basin dominated the depositional regime, and resulted from increased productivity in the photic zone. Based on the lack of bioturbation and in situ benthonic fauna, the depositional environment is interpreted to have been an anoxic marine basin. Bottom current reworking was the prominent sediment dispersal mechanism and stimulated productivity in the photic zone which resulted in increased planktonic sediment supply.

Massive Bentonitic Claystone Facies

The massive bentonitic claystone facies is observed within the Eagle Ford shale throughout Texas (Jiang, 1989). In northeastern Texas, The Britton Clay is described to have a bentonitic sub-member (Dawson 1994). In north-central Texas, the Lake Waco Formation contains thin 1-2 inch bentonite beds throughout the Bluebonnet, Cloice, and Flaggy Cloice (Jiang 1989) members. Wellbore integrity is often compromised in the Maverick Basin due to the expansive nature of the massive bentonitic claystone facies in the Lower Eagle Ford. Additionally, kaolinite-rich seams have been described in Eagle Ford equivalent Boquillas formation in West Texas (Trevino, 1988; Miller, 1990; Lock and Peschier, 2006; Donovan and Staerker, 2010; Ruppel et al., 2012;) In the famous and well-studied West Bouldin Creek outcrop (figure 1), 15 bentonites units have been observed (Jiang, 1989; Liro et al., 1994; Dawson, 1997); however, throughout the Waller Creek Tunnel cores (this study), a range between 8 and 18 bentonite beds are recorded, ranging in thickness from 0.5 to 6 inches. These beds are highly variable in thickness which will be discussed later in this paper.

In outcrop and core, bentonite beds display a characteristically sharp contact with overlying and underlying strata, weather light gray to rust-orange, and are very poorly lithified (figure 14). They crumble to the touch and readily disaggregate. XRD analysis

reveals that they are primarily composed of clay minerals (avg. 91%, range 88-93%). Of the clay minerals, smectite is the most abundant, accounting for 80%, whereas kaolinite and illite+mica mixed layer contribute 11% and 9%, respectively. This facies is characteristically non-calcareous, but thin section analysis reveals that rare globigerinid foraminifera are present.

Figure 14: Massive bentonitic claystone facies core photograph, thin section photomicrograph, and summary of characteristic features. (A) Slab photo showing the structureless, poorly lithified nature. (B) Thin section photo showing rare globigerinid foraminifera and fine grained texture.

Based on the sharp nature of the contacts with other facies, extremely high clay content, lack of calcite, and anomalously poor cementation, the bentonitic claystone facies are interpreted to represent volcanic ash deposits. The source of the ash beds is

difficult to constrain due to their diagenetically altered nature. The area around present-day Murfreesboro, Arkansas has been proposed as a contemporaneous volcanic source (Miser and Ross, 1925; Surles, 1987; Liro et al., 1994). There is currently insufficient evidence to link the bentonitic claystone facies to any particular event or episode of volcanism. In the Western Interior Basin, the Greenhorn Formation also contains bentonite intervals (Pratt, 1984), but the location of the volcanic source is undetermined.

A particularly interesting aspect of these bentonite facies is their association with the calcareous facies of the Bouldin Member. Except for a few isolated bentonitic intervals in the underlying Waller Member and the overlying South Bosque Formation, they are mostly confined to the Bouldin Member of the Lake Waco formation. Also confined primarily to the Bouldin Member are the laminated foraminiferal wackestones and the cross-laminated foraminiferal packstone/grainstone facies. As mentioned, both of these facies contain a large percentage of calcite, dominantly planktonic globigerinid foraminifera. The strong association between abundant planktonic carbonate sedimentation and occurrence of massive bentonite claystone beds suggests that these processes are related. Recent studies have connected surface water nutrient enrichment to volcanic eruptions (Duggen et al., 2007; Jones and Gislason, 2008; Duggen et al., 2010; Langmann et al., 2010). It is proposed that nutrients introduced into the ocean water system by volcanic eruptions stimulated productivity within the oxic zone and led to blooms responsible for higher carbonate sedimentation. A similar observation is made in West Texas where bentonite beds were observed in connection with more calcareous facies (Ruppel et al., 2012).

Nodular Foraminiferal Packstone/Grainstone Facies

Rocks of this facies are virtually identical to those of the cross-laminated foraminiferal packstone/grainstone facies (figure 13), being distinguished primarily in their lateral continuity. Previous workers have referred to this facies as concretions (Liro et al., 1994; Harbor, 2011), micritic limestones (Dawson, 1997), and calcarenites/calcsiltites (Frébourg et al., 2012). In this work, they are named nodular foraminiferal packstones/grainstones (figure 15). Readily observable in outcrop, these rocks lie horizontally with an oblate ellipsoidal 2-D cross section and are significantly more resistant than the surrounding mudrock. Differential compaction of the mudstone near the terminus of the nodules emphasizes the early and well-cemented nature of this facies. In outcrop these nodules range from 2 to 6 inches in thickness and display an axial range of 6 inches to several feet. In outcrop, deformation features such as slump folds are observed in some nodules, resulting in contorted geometries. There is no evidence that these rocks are likewise ellipsoidal in 3-D, but likely have linear or barcanoid geometries consistent with their mode of deposition, as discussed in the interpretation. The primary recognition criteria of this facies in core is inclined bedding (interpreted as differential compaction) near the lateral terminus of a nodular unit (figure 15). Without the observed inclined bedding at a terminus of a nodule in core, it may not be possible to differentiate between cross-laminated and nodular foraminiferal packstone/grainstone facies as both could display similar cross-laminated structures, high carbonate content, similar weathering profiles, and gradational contacts.

Figure 15: Nodular foraminiferal packstone/grainstone facies core and outcrop photographs, thin section photomicrograph, and summary of characteristic features. (A and B) Slab photos depicting characteristic expression in core, where (A) displays inclined bedding at the terminus of a nodule. (C) Outcrop expression of a typical oblate ellipsoid geometry. (E) Thin section photo showing abundant globigerinid foraminifera.

Within the study area, this facies is restricted to the Lake Waco Formation. Dawson (1997) and Harbor (2011) also noticed that these rocks are most common in the Lower Eagle Ford, (Lake Waco Formation equivalent). Nodular foraminiferal packstones/grainstones appear to show no preference for host facies and occur as isolated units associated with every Eagle Ford facies. Compositionally, they are very high in calcite, comprising 84%. Clay minerals are also abundant totaling 13%, most of which is kaolinite and smectite. Quartz and feldspars are minor constituents, accounting for only 3%. The centers of these facies contain sparry calcite and/or lignite material (Liro et al., 1994). The primary allochem within this facies is globigerinid foraminifera, with lesser amounts of inoceramid fragments and pelecypod fragments.

A conventional explanation holds that “concretions” found in mudrock successions formed by non-displacive precipitation of diagenetic calcite in void spaces in host sediment where the source of carbonate is anaerobic bacterial reduction of organic matter (Lash and Blood, 2004). In contrast, Eagle Ford nodular limestones owe their formation largely to depositional processes. As demonstrated by Rodriguez and Anderson (2004), sand or silt sized grains are reworked on the seafloor into sediment blankets and sheets when there is sufficient supply. Ripples, sand waves, and dune forms may also result from bottom current reworking in conditions of diminishing sediment supply (Shanmugam et al., 1993).

Based on the sedimentary structures, lateral and vertical distribution of the nodules, and geomorphic outcrop expression from the Eagle Ford equivalent Boquillas formation in West Texas, Frébourg et al. (2012) proposed that nodular foraminiferal packstones/grainstones were deposited as sediment waves and dunes, and represent accumulations of primarily planktonic debris that has been reworked by bottom currents. In the Austin locality, low angle foresets are observed within the nodules and thin section

analysis reveals generally well-sorted planktonic grains and highly abraded inoceramid and bivalve fragments. These suggest that bottom currents were active during time of deposition. The discontinuous nature of these nodules mimics the outcrop expression observed in West Texas, suggesting that these deposits were also formed as sediment waves and dunes, driven by bottom currents. A summary of the Eagle Ford facies and their associated attributes is found in table 3.

Facies Name	Sedimentary Structures	Mineralogy	Dominant Fauna	Color	Occurrence (Formation)	Thickness
Massive Argillaceous Mudrock	Massive	53% Clay 32% Calcite 17% Quartz	Rare Globigerinid Foraminifera	Dark Gray to Med Dark Gray	Pepper Shale	4-6 ft
Massive Argillaceous Foraminiferal Mudrock	Massive	50% Calcite 38% Clay 14% Quartz	Globigerinid Foraminifera, Inoceramid and Pelecypod Fragments	Medium Dark Gray	Waller Member, South Bosque Formation	1-5 ft
Laminated Argillaceous Foraminiferal Mudrock	Very Thin Planar Laminations, Scours	62% Calcite 24% Clay 8% Quartz	Globigerinid Foraminifera, Inoceramid and Pelecypod Fragments	Medium Gray	Waller Member, South Bosque Fm	1-5 ft
Laminated Foraminiferal Wackestone	Very Thin Planar/Sub Planar Laminations, Slump Folds, Fine Ripple Laminations, Scours	76% Calcite 10% Clay 7% Quartz	Globigerinid Foraminifera, Inoceramid and Pelecypod Fragments	Medium Gray with White/Light Gray bands	Bouldin Member	.5-1 ft
Cross-Laminated Foraminiferal Packstone/Grainstone	Very Thin Sub Planar and Cross Laminations, Scours	86% Calcite 5% Quartz 3% Clay	Globigerinid Foraminifera, Inoceramid and Pelecypod Fragments	Light to Medium Gray	Bouldin Member	.5-6 inches
Massive Bentonitic Claystone	Massive	69% Smectite 12% Kaolinite 8% Illite	Rare Globigerinid Foraminifera	Whitish Gray to Medium Rust Orange	Bouldin Member, few in Waller Member, South Bosque Fm	.5-6 inches
Nodular Foraminiferal Packstone/Grainstone	Massive, Planar and Cross-Laminated	84% Calcite 13% Clay 2% Quartz	Globigerinid Foraminifera, Inoceramid and Pelecypod Fragments	Light to Med Gray	Bouldin Member, Waller Member	1-6 inches

Table 3: Summary table of Central Texas Eagle Ford facies and associated attributes.

BUDA LIMESTONE FACIES

Massive Skeletal Wackestone/Packstone Facies

Underlying the Eagle Ford is the Buda Limestone, which contains massive skeletal wackestone/packstone (figure 16). In core, this facies is a cream to grayish white color. In outcrop within the study area, the Buda-Eagle Ford contact is not exposed (Liro et al., 1994), but in other local outcrops as well as in West Texas the Buda weathers to a light whitish gray to buff color. In the Central Texas cores, the upper 1.5 feet of the Buda marked by abundant fractures and infilled with dark gray, silt to clay-sized matrix sediment comprising the lowermost Eagle Ford massive argillaceous mudrock. The uppermost Buda facies consists almost entirely of calcite, comprising mollusk fragments, echinoid spines, foraminifera, and peloids (figure 16).

Figure 16: Massive skeletal wackestone/packstone facies core photographs, thin section photomicrograph, and summary of characteristic features. (A) Slab photograph showing the white and well cemented nature. (B) Thin section photo showing abundance of skeletal grains and peloids. (C) The Buda-Eagle Ford contact is a sharp lithological change with microkarsting in the uppermost Buda.

AUSTIN CHALK FACIES

Bioturbated Lime Mudstone/Wackestone Facies

This facies is representative of the lowermost Austin Chalk (figure 17). The key distinguishing characteristic of this facies is the abundance of burrows, which have destroyed virtually all other sedimentary structures. In outcrop, this facies is poorly-exposed due to slumping, weathering, and soil wash, as confirmed by Lundquist (2000), but has a generally cream to buff colored appearance. In cores, it is light to medium gray and very well cemented. Burrows are primarily *Planolites sp.*, with variable degrees of abundance in *Zoophycus sp.*, *Chondrites sp.*, and *Thalassinoides sp.* Thin section analysis reveals the presence of globigerinid foraminifera and phosphatic material such as fish remains, glauconite, and phosphatic coated grains (figure 17). The phosphatic coated grains are brown in hand sample, spherical to slightly elongate, and commonly pyritized in the center. It has been suggested that these grains are accretionary lapilli, or rounded tephra balls formed of concentric layers of moist ash (Blodgett, 2012, personal communication).

Figure 17: Bioturbated lime mudstone/wackestone facies core photograph, thin section photomicrograph, and summary of characteristic features. (A) Slab photograph portraying the light gray and heavily bioturbated nature. (B) Thin section photo showing the presence of glauconite, coated grains, and inoceramid fragments.

Eagle Ford Stratigraphy

TYPE SECTION

The complete, intact, and well-preserved nature of the ACC core (figure 1) qualifies it as a type section core for the Austin area (figure 18). Within this core, all facies described from the previous section are present, as well as the contacts with the underlying Buda Limestone and overlying Austin Chalk.

Buda-Eagle Ford Contact

An extremely sharp lithologic change occurs at the Buda-Eagle Ford contact, from a dense, resistant, and indurated cream colored limestone (massive skeletal wackestone/packstone) of the Buda Limestone (figure 16) to a dark gray, recessive organic-rich claystone (massive argillaceous mudrock) (figure 9) of the Eagle Ford Group. The uppermost 1 foot of the Buda Limestone in core displays a fragmented and brecciated nature, with Eagle Ford massive argillaceous mudrock facies infilling the voids. Buda pebbles and clasts are encapsulated within the Eagle Ford sediment (figure 15). Similar features are observed along highway 90 west of Del Rio in West Texas. Additionally, an undulatory contact with up to 8 inches of relief within the Buda is observed in West Texas, as well as calcite-filled voids with rhizome halos.

Figure 18: Type section of the ACC core, showing the core description, facies groupings, and Computed Gamma Ray (CGR) response generated from the Th-K from X-Ray Fluorescence (XRF) data, and the Gamma Ray (GR) response of per stratigraphic interval.

The highly brecciated and fragmented nature of the uppermost Buda in the Austin area is interpreted as karsting. Calcite-filled voids with rhizome halos in West Texas are suggestive of rootlets. These observations, along with the undulating contact in West Texas and the overall sharp lithology change are suggestive of exposure. Previous workers have described the Buda-Eagle Ford contact as an unconformity (Jiang, 1989; Liro et al., 1994; Lock and Peschier, 2006; Donovan and Staerker, 2010; Harbor, 2011) that corresponds to the mid-Cenomanian unconformity in the Gulf of Mexico (Mancini and Scott, 2006). Harbor (2011) noted that non-deposition and exposure characterize the uppermost Buda before Eagle Ford deposition. These observations contrast with those who maintain that there is insufficient evidence of exposure, (Siemers, 1978; Loucks, 2012, personal communication)

Eagle Ford Group

Central Texas Eagle Ford stratigraphy can be divided into 4 intervals which from the bottom include the Pepper Shale, the Waller and Bouldin Members of the Lake Waco Formation, and the uppermost South Bosque Formation (figure 7). Each of these intervals comprises characteristic facies sets (figure 18) which define the lithology.

Pepper Shale

The basal Eagle Ford Pepper Shale is a recessive, dark gray, argillaceous claystone, composed solely of the massive argillaceous mudrock facies. The Pepper Shale was defined in outcrop by Young (1977) in a drainage ditch downstream of the West Bouldin Creek outcrop (figure 1), but is no longer exposed. Currently, this facies is only observed in core, as no known exposure is preserved in the study area (Lundquist, 2000) due to the highly recessive nature of this interval (Young, 1977). This interval is relatively thin, comprising 4-6 feet of thickness (figure 18).

Waller Member

Overlying the Pepper Shale is the Waller Member of the Lake Waco Formation (figure 7). Descriptively, the basal contact of this unit is gradational and subtle. The contact is marked by the transition from a smooth textured massive argillaceous mudrock to a gritty textured massive argillaceous foraminiferal mudrock. An increase in carbonate content also marks the contact. Recessive, like the Pepper Shale, this unit is poorly exposed in outcrop and the full succession is only observed in core, totaling 10 feet. Dominantly composed of massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock, the Waller Member also contains minor amounts of massive argillaceous mudrock, cross-laminated foraminiferal packstone/grainstone and nodular foraminiferal packstone/grainstone (figure 18).

Bouldin Member

The Bouldin Member of the Lake Waco Formation is 10-12 feet thick in the study area and displays a significantly different character compared to the rest of the Central Texas Eagle Ford Group in that the Bouldin Member contains interbedded calcite-rich limestones and mudrocks as opposed to clay mineral-rich (figure 18). The calcite content in this member is primarily composed of planktonic globigerinid foraminifera. Accessory benthonic fauna are also present, including inoceramid fragments and other pelecypod shells. The dominant facies are laminated foraminiferal wackestone and cross-laminated foraminiferal packstone/grainstone. Nodular foraminiferal packstones/grainstones and bentonitic claystones are common (figure 18), the latter of which are restricted almost exclusively to the Bouldin Member.

The basal contact of the Bouldin Member is sharp and marked by a sharp lithologic change from massive argillaceous foraminiferal mudrock of the underlying

Waller Member to the first significant occurrence of cross-laminated foraminiferal packstone/grainstone (figure 18). Erosion at the contact is not observed.

Facies that constitute the Bouldin Member are those associated with the highest energy sedimentary features observed in the study. Cross-laminations, low angle planar to sub-planar ripples, dunes, slump folds, scour and truncation surfaces, pebble and bioclastic lags, and mud rip-ups clasts are observed within this interval. Based on the abundance of high energy sedimentary structures, the Bouldin Member is interpreted to represent deposition in the highest energy of all Eagle Ford intervals. The lack of wave generated hummocky structures suggests that bottom currents were the likely reworking mechanism. Based on the sharp nature of the contact and the dynamic facies change, and the lack of evidence for erosion, the contact is interpreted to be a paraconformity.

South Bosque Formation

The uppermost interval of the Eagle Ford Group is the South Bosque Formation (figure 7). Sixteen feet thick in the study area, the South Bosque displays similar characteristics to the Waller Member in that it is a medium-dark to medium gray, gritty mudrock. Primary facies within this formation consist of massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock (figure 18). Isolated occurrences of massive argillaceous mudrock and bentonitic claystone are also observed.

The basal contact of the South Bosque Formation with the underlying Lake Waco Formation is marked by the first occurrence and continued presence of laminated (or massive) argillaceous foraminiferal mudrock above the calcite-rich intervals of the Bouldin Member. In the type section (figure 18), the South Bosque sharply overlies a bentonitic claystone at the top of the Bouldin Member. In wells 301, 302 and 221

however (figure 1), the South Bosque overlies a cross-laminated foraminiferal packstone/grainstone bed. This packstone/grainstone bed is interpreted to be locally eroded, suggesting that the nature of the contact is disconformable.

Eagle Ford-Austin Contact

Subtle transitions mark the Eagle Ford-Austin contact. Visually, a gradational transition over 3 feet marks the contact where the Eagle Ford transitions from a medium gray, non bioturbated mudrock to a light gray heavily burrowed lime mudstone/wackestone of the Austin Chalk. Additionally, an increase in carbonate content accompanies the transition into the Austin Chalk.

The nature of the Eagle Ford-Austin contact has been disputed in literature. In the Austin area, several authors interpreted the Austin Chalk to overlie the Eagle Ford Group disconformably (Young, 1977; Jiang, 1989; Dawson and Reaser, 1990; Dawson, 1997, 2000). Hentz and Ruppel (2010) offered a contrasting interpretation, reporting a “distinctly gradational contact with the Austin Chalk.” Based on the gradational color variation and the increasing bioturbation near the contact, the Eagle Ford-Austin contact is interpreted to be gradational in this study. Increasing bioturbation is likely a result of changing oxygenation conditions at the seafloor. Anoxic bottom waters produced conditions which were less suitable for burrowing organisms, reducing the degree of bioturbation. The contact represents an increase in bottom water oxygenation with the resultant increase in bioturbation.

FACIES CONTINUITY

This study utilizes a unique data set which offers a singular perspective to the high resolution stratigraphy from shallow subsurface data. The 10 cores and outcrops studied constitute an approximately 11 mile, north-south transect, with well spacings

ranging from 50 feet to 9.4 miles (Figure 19). Facies continuity was evaluated at several scales, including the 50 ft, the 200 ft, the 500 ft, the 1 mile, and the 10 mile scale.

Figure 19: (Next Page) North-south lithostratigraphic cross section of the study area. The vertical columns are described cores and outcrops color coded by facies. Facies are color coded with lighter hues denoting the continuity of those facies. Note the degree of variability within each stratigraphic unit. Location of wells and outcrops is provided in figure 1.

Figure 19

50 Foot Well Spacing

Prior to this investigation, it was assumed that closely spaced wells, such as 514 and 500 (figure 1, figure 19) which have a 50 ft separation would display a nearly identical stratigraphy. Upon describing the cores, a high degree of facies discontinuity was observed even at extremely small scales, such as 50 feet. A nodular foraminiferal packstone/grainstone is observed in well 514 at approximately 14 ft above the Buda (figure 19). This bed, however, is absent a mere 50 ft away in core 500. This may not be surprising, since in outcrop this facies, is highly discontinuous. Although these nodular beds follow bedding horizons, encountering them in core is a matter of chance, depending on the location of the wellbore. For example, towards the top of the Waller Member in the West Bouldin Creek outcrop, Liro et al., (1994) described an interval of large, abundant, flattened calcareous concretions (nodular foraminiferal packstones/grainstones). His observation is confirmed in this study, but re-interpreted to reflect a localized feature which is not recognized elsewhere in the study area.

Another example of discontinuity is observed in cores 500 and 514 (figure 1). A 1-inch massive bentonitic claystone representing a volcanic ash fall deposit is observed approximately 14 ft above the Buda in core 500, but is not evident in core 514, only 50 ft away (figure 19). In the outcrops of the study area, a variation of ash bed thicknesses of more than 1.5 inches with the eventual disappearance of an entire ash bed is observed, a fact also noted by Liro et al., (1994). Additionally, ash bed rip-up clasts are observed in cross-laminated foraminiferal packstones/grainstones in the ACC core at 26 ft above the Buda (figure 19). These observations of thickness variations and ash bed rip-up clasts suggest that even though volcanic ash clouds likely resulted in originally continuous and extensive deposits, erosional scouring and reworking of sediment by bottom currents produced high degrees of bed discontinuity.

Another example of the effects of bottom current reworking is observed in Core 500, at approximately 13 ft above the Buda. Here, an interval of cross-laminated foraminiferal packstone/grainstone containing 3 bedding contacts transitions laterally into an interval in well 514 which contains only one bedding contact (figure 19). It should also be noted that the same interval in core 221 (figure 19) displays a relatively higher percentage of packstone to grainstone. This intra-formational heterogeneities of three beds into a single bed and the lateral facies change to a less grainstone rich facies is interpreted reflect the variable depositional energy in bottom current activity.

Both massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock demonstrate variability at the 50 ft scale. Core 500 contains an interval of laminated argillaceous foraminiferal mudrock at approximately 27 feet above the Buda which is not represented 50 ft laterally, in core 514 (figure 19). The missing interval in core 514 suggests a depositional variability between these facies, where the laminated facies represents a slightly higher energy regime, and may laterally transition into a lower energy regime within the spacing of 50 ft.

200 Foot Well Spacing

Facies continuity at the 200 ft well spacing is not substantially different from that seen at the 50 ft scale. It is observed that high degrees of facies discontinuity continue to exist within the nodular foraminiferal packstones/grainstones, massive bentonitic claystones, cross-laminated foraminiferal packstone/grainstone, and to a lesser degree, massive argillaceous foraminiferal mudrock and the laminated argillaceous foraminiferal mudrock. Unfortunately, significant portions of the cores are missing from several wells, making exact determination of continuity problematic (figure 19). It is possible that a

higher continuity of units would be observed between the cores if the sections were complete.

500 Foot Well Spacing

Cores spaced at 500 ft provide good insights into facies continuity at scales that are generally larger than outcrop, and closer to reservoir well scales. Thickness variations within facies units are readily observed. For example, Approximately 6 ft above the Buda in core 204, a 6 inch thick bed of cross-laminated, foraminiferal packstone/grainstone thins laterally to a 1 inch thick bed in core 302 (figure 19). Again, thickness variation is observed in core 204 at 30 feet above the Buda. Here, a 1 foot thick interval of laminated argillaceous foraminiferal mudrock laterally thins to 4 inches in core 302.

Lateral facies change is also observed at a 500 ft scale. At approximately 7 ft above the Buda in core 204, a localized massive argillaceous mudrock displays a smooth or soapy texture (figure 19). This same unit in core 302 displays a slightly more gritty texture and higher calcite content indicating a higher concentration of coarser material in the form of globigerinid foraminifera. The shift from a soapy textured rock to a gritty foraminiferal rock suggests a varying depositional energy.

In well 204, 68 individual units are observed. 500 Feet away in core 302, only 53 of the same units can be recognized. This indicates that even at 500 foot well spacing, Eagle Ford depositional processes produce sufficient discontinuity that only 73% of beds can be successfully correlated (figure 19).

1 Mile Well Spacing

Additional insights are gained at a 1 mile scale which could not be observed at a 50, 200, or 500 ft intervals. In cores 301 and 221 (figure 1, figure 19), an 8 inch bed of cross-laminated foraminiferal packstone/grainstone facies is present approximately 12 ft

above the Buda (figure 19). If only these two cores were available for study, a strong argument could be made that this unit is highly continuous. However, closely-spaced cores in the current study show that these “continuous” units are actually not. This type of discontinuity has implications for modeling of facies continuity in mudrock reservoir systems. A hypothetical downhole log through this interval would assuredly detect the change in lithology from an argillaceous mudrock to a competent clean limestone. A wireline log response at this interval would be similarly observed in cores 301 and 221, and commonly correlated in the subsurface. The current study clearly shows that this is not the case. Caution must be employed by stratigraphers and explorationists alike, in using subsurface wireline log response for bed recognition and correlation, in light of the stratigraphic discontinuities present within mudrock systems.

In the Bouldin Member, high degrees of thickness variability are observed, particularly with the cross-laminated foraminiferal packstone/grainstone facies. Units appear to merge, diverge, thin, thicken, pinch, truncate, and contain nodular packstone/grainstone morphologies. The mechanisms which are responsible for these changes are discussed in the 500 foot well spacing section. In general, the degree of correlatability and continuity of units decreases substantially at the 1 mile scale, where only 35% of the beds can be successfully correlated (figure 19).

10 Mile Well Spacing

Correlatability perspectives attained at a 10 mile well spacing involve cores 301 and ACC (figure 1). This is the largest offset spacing in the study area where facies beds were identified and correlated. The most continuous facies is the massive argillaceous mudrock belonging to the Pepper Shale (figure 19). This unit is exceptionally homogenous in character and thickness across the study area, with the exception of a 2 ft

thickening in the ACC core (figure 19). In contrast, the least correlatable facies is the nodular packstone/grainstone facies which is abundant throughout the Lake Waco Formation. No attempt has been made to correlate this facies across the 10 mile transect. It has already been demonstrated that even at 50 ft well spacing, these units are discontinuous. As indicated by its name, nodular foraminiferal packstones/grainstones exhibit the highest degree of lateral discontinuity, forming the poorest basis for small- and especially large-scale correlations.

Surprisingly, massive bentonitic claystones are also a poor facies for use in correlation. As discussed, this facies was initially believed to render reliable age-markers and stratigraphic ties because of the synchronous and extensive nature of volcanic ash fall deposits. Based on the considerable discontinuity of these beds caused by erosional scouring and truncation, an apparently complex interplay of processes must have been involved during and after deposition. Whereas a maximum of 18 bentonite claystone beds are observed in the study area, only 2 can be successfully correlated across 10 miles. These beds are generally useful for small scale correlations less than 500 ft well spacing, yet still are observed to pinch out along a short distance in outcrop, which is also noted by Liro et al. (1994). Within the Austin study area, only 16% of the beds can be confidently correlated across 10 miles (figure 19).

The upper portion of the Eagle Ford Group, the South Bosque Formation, is generally characterized by cyclic beds of massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock (Figure 19). In core, the cyclic pattern seems to suggest a repetitive change from low energy deposition (massive facies) to a slightly higher energy deposition (laminated facies). A shift to higher energy facies is often used as recognition criteria for cycle tops in cyclic stratigraphy. Four such “cycle tops” are present in core 301, while only three are observed in the ACC core (figure 19).

A maximum of five “cycle tops” are observed core 204, yet only one “cycle top” is continuous across the study area. Because of the discontinuity of cycle tops within the study area, facies variability is interpreted to result from depositional changes, such as variable bottom current strength, and not regionally extensive events, like eustatic fluctuation. Cycle analysis is an unreliable tool for correlation within the Eagle Ford Group of Central Texas.

Regional Facies Architecture

REGIONAL LITHOSTRATIGRAPHIC CORRELATION

The four-fold stratigraphy described in the previous section constitutes the major depositional successions of the Eagle Ford Group in Central Texas (figure 18). In the deeper subsurface these members are not defined, but rather, the Eagle Ford is divided into informal Upper and Lower units (figure 7, 18). Generally speaking, the Pepper Shale, Lake Waco Formation (Waller Member and Bouldin Member) and the basal portion of the South Bosque Formation make up the Lower Eagle Ford (Jiang, 1989) (figure 7). The remaining South Bosque Formation makes up the Upper Eagle Ford. In this regional lithostratigraphic correlation, nomenclature designations from Austin (i.e. Pepper Shale, Waller Member, Bouldin Member, and South Bosque) are carried through in the subsurface. Typical facies associated with each stratigraphic interval are summarized in figure 18.

Stratigraphically overlying the South Bosque in the subsurface, Harbor (2011) observed an interval of facies which are not recognized in Austin. He described them as: disrupted bedded foraminiferal packstone, massive inoceramid packstone, and in some locations, laminated foraminiferal and peloidal packstone (Harbor 2011) (figure 20).

San Marcos Arch North-South Transect

Cores along the San Marcos Arch have been described in detail by Harbor (2011) (table 1), who placed them into an architectural framework. Three wells, Hendershot, Orts, and Schauer were used in conjunction with the ACC well in Austin, TX to provide a north-south transect of nearly 80 miles (figure 4, figure 20).

All Eagle Ford stratigraphic units display a southward thickening along the axis of the arch (figure 20). The Pepper Shale thickens from 5 feet in Austin to approximately 12 feet in the Schauer core (figure 20), where it undergoes a facies change into laminated argillaceous foraminiferal mudrock towards the shelf margin in De Witt County (figure 5). The Waller Member experiences continued southward thickening along the arch, from 10 feet near Austin to 16 feet in the Schauer core (figure 20).

The Bouldin Member likewise thickens southward, but also begins to display a facies change. Heightened interfingering of finer grained material to the south resulted in a lower ratio of high energy calcareous facies (cross-laminated foraminiferal packstones/grainstones, nodular foraminiferal packstones/grainstones, laminated wackestones) to low energy mudrocks (laminated argillaceous foraminiferal mudrocks) (figure 20).

South Bosque Formation remains fairly consistent in thickness and character from Austin to the south, toward the shelf margin (figure 20). The Schauer core reveals that facies of the South Bosque, massive (and laminated) argillaceous foraminiferal mudrock (which are also facies of the Waller Member equivalent) become the dominant facies of the Eagle Ford Interval.

The general thickening of stratigraphic units toward the south in the Schauer core is a probable result of the relative location of cores along the San Marcos Arch. Southern locations were likely exposed to increasing subsidence away from the arch (figure 5).

Increasing accommodation associated with subsidence provided for the observed thickness variations. The facies change observed in the Bouldin Member from very high foram sediment concentration in Austin to low foram sediment concentrations toward the Schauer core (figure 20) is interpreted to result from changes in bottom current transport. Near Austin, increased bottom current activity resulted in greater concentrations of planktonic forams relative to the Schauer core. Potentially, this facies change could also be explained by variations in oxic zone productivity, where towards the south, ocean waters were apparently less suitable for foram production.

San Marcos Arch Northeast-Southwest Transect

Harbor (2011) described several cores southwest of the current study area, including Hendershot, Blumberg, and Brechtel (table 1). These cores were used in conjunction with the ACC core in Austin, TX to provide an approximately 80 mile northeast-southwest transect across the San Marcos Arch (figure 4, figure 21). The Pepper Shale, as in the north-south cross section (figure 20), can be correlated throughout the entire region. The Waller Member displays a dramatic thinning from the northeast (Austin) to the southwest (Blumberg core) and finally pinches out to the west before the Brechtel core (figure 21). In contrast, the Bouldin Member exhibits a pronounced thickening to the southwest in the Brechtel core (figure 21). As in the north-south cross section (figure 20), Harbor (2011) described an interval which is not represented in Austin but overlies the South Bosque Formation in the subsurface. This unit contains cross laminated foraminiferal packstone/grainstone, massive inoceramid packstone and adjacent laminated foraminiferal wackestone (Harbor, 2011) (figure 21).

Figure 21: Cross section B-B' based on Lithostratigraphy. This subsurface correlation is based on facies as observed in core. Hendershot, Blumberg, and Brechtel are cores that were described in detail by Harbor, (2011). This shows a general continuity of stratigraphic intervals along the San Marcos Arch with the exception of the Waller Member, which pinches out before the Brechtel well. Location of transect is provided by figure 4. Modified from Harbor, (2011).

GAMMA RAY TRENDS

Cored Eagle Ford wells in the Austin study area lack conventional downhole logs with the exception of the ACC well (figure 1, table 1). However, equivalent gamma ray logs can be constructed from elemental abundances of Th, U, and K gathered from X-Ray Fluorescence (XRF). Combined Th and K form a Computed Gamma Ray (CGR) that is representative of the clay siliciclastic content within the measured sample. The total Gamma Ray (GR) logs differs from the CGR by including U along with K and Th. The use of CGR in correspondence with GR in this study is intended to produce the same result as a Spectral Gamma Ray (SGR) log. Due to the lack of available SGR logs in the study area, downhole GR logs are treated as SGR logs and XRF data was utilized to create pseudo CGR logs. The Central Texas Eagle Ford Group displays recognizable signatures in CGR and GR that correspond to the four-fold stratigraphy defined in the type section (figure 18).

The basal Pepper Shale in the ACC core is defined by a high CGR (60-100 API) and high GR (55-65 API) response, especially in comparison to the underlying Buda Limestone (figure 18) (it should be noted that in localized intervals, such as the Pepper Shale, the CGR provides API values which are greater than the GR - a discrepancy which likely arises from the use of separate instrumentation for data acquisition). Composed solely of the massive argillaceous mudrock facies, this unit contains abundant illite, kaolinite, and smectite. These minerals are relatively rich in Th and K, accounting for the high CGR and GR profiles associated with this interval (figure 18).

The Waller Member is defined by a moderate CGR (20-60 API) and a moderate GR (35-60) pattern. Similar to the Pepper Shale, this unit is also clay mineral-rich, yet contains higher calcite content. The accordance of the CGR and the GR indicate that there is little to no U within this member (figure 18). Massive (and laminated)

argillaceous foraminiferal mudrocks are the dominant facies. Carbonate dilution in the form of planktonic globigerinid foraminifera is responsible for the decreasing clay mineral content and ensuing reduction of the CGR and GR values for this interval (figure 18).

A separation of the CGR and GR trends marks the Bouldin Member, where a low and variable or “chattery” CGR (0-40 API) contrasts with a high GR reading (80-100 API) (figure 18). The low CGR pattern is attributed to the high energy, high calcite, and clay-poor facies within the Bouldin, including laminated foraminiferal wackestone/packstone and cross-laminated foraminiferal packstone/grainstone. The “chattery” nature of the CGR profile is explained by the abundant massive bentonitic claystones which are almost entirely composed of smectite, kaolinite, and illite. The interbedding of these claystones with clean limestones produces opposing signals recognized as a “chattery” pattern. The GR curve differs from the CGR by including the U fraction in the rock. The explanation for the high GR in the Bouldin Member is that U is complexed with organic matter deposited in a restricted basin environment. As will be discussed in a later section, paleoredox proxies (enrichment in Mo, U, Mn, and V/Cr) indicate that maximum basin restriction occurred during deposition of the Bouldin Member. Another potential source of U in the Bouldin Member is the abundant massive bentonitic claystones. As mentioned, these beds are primarily restricted to the Bouldin Member and are interpreted to be volcanic ash fall deposits. U from volcanic sources was incorporated into these beds and also reworked into other units within this interval.

Finally, the South Bosque Formation is similar to the Waller Member in that it displays a moderate CGR (35-60) and moderate GR (35-70) signature (figure 18). Like the Waller Member, the dominant facies are massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock. Carbonate dilution from globigerinid

foraminifera is interpreted to result in the moderate CGR and GR of the South Bosque Formation (figure 18).

Distinguishable GR trends in the ACC core are recognized in subsurface wells extending to the southwest across the San Marcos Arch including the Burkland, Hendershot, Blumberg, and Brechtel wells (figure 22, table 1). A degree of difficulty is encountered correlating based on GR curves, and plausible correlations do not always follow lithostratigraphic relationships (figure 22). However, a general continuity of stratigraphic intervals is observed with the exception of the Waller Member, which experiences a potential pinchout in the Burkland and Brechtel wells. The same pinchout in the Brechtel well is confirmed lithostratigraphically in figure 21.

Facies determination based solely on total gamma ray GR logs (K-Th-U) is liable to provide misleading results. As observed in figure 22, a moderate GR (35-60 API) profile in the ACC core corresponding to the Waller Member followed by a high GR (80-100 API) zone corresponding to the Bouldin Member could justifiably be interpreted as a carbonate interval and a clay mineral-rich interval, respectively. Notwithstanding the apparent GR responses, the opposite facies associations are actually observed where the Bouldin Member is a clay-mineral deprived, limestone-rich interval (figure 18). Sequence stratigraphic misinterpretations could also hinge on erroneous facies designations, where the low GR “carbonate” of the Waller Member followed by the high GR “clay interval” of the Bouldin Member could indicate a cycle top, or shift from shallow to deep environment. Additionally, in the middle of the South Bosque Formation in the ACC core (figure 22), an increase in the GR curve is not matched by the CGR profile. This trend can potentially be carried regionally, but has no observed corresponding facies change. GR profiles alone are insufficient for facies determination in the Eagle Ford and comparison to the CGR curve is necessary for facies recognition.

Figure 22: Cross section C-C' based on Gamma Ray (GR) and pseudo Computed Gamma Ray (CGR) log (ACC core). GR log signatures are somewhat recognizable to the southwest across the San Marcos Arch. Color-filled intervals are based on lithostratigraphy (figure 21).

The apparently missing Waller Member in the Brechtel and Burkland wells is interpreted to represent a westward pinchout of the Waller Member. The pinchout in these wells is likely a result of their respective locations relative to the San Marcos Arch. The westernmost extent of the Waller Member stratigraphic unit is depicted in figure 4 and roughly mimics the northwest-southeast trend of the San Marcos Arch (Dravis, 1980; Young, 1986) (figure 5). Based on the orientation of the Waller Member facies extent, paleotopography was a probable control influencing stratigraphic architecture which resulted in facies changes, non-deposition, and/or erosion.

Bottom current reworking provides an alternative explanation for the missing Waller Member in the Burkland and Brechtel cores. As previously mentioned, lithofacies of the Bouldin Member contain cross-laminations, ripples, dunes, slump folds, and other structures that indicate high energy of deposition (figure 12, figure 13). Stow et al. (2002) recorded maximum velocities in bottom current to be in excess of 200 cm/s. These velocities are sufficiently competent to erode and transport clay, silt, fine sand, and even gravels (Stow et al., 2002). In some cases, bottom current energy is strong enough to prevent deposition such that erosion and transportation become dominant processes (Stow and Faugeres 1993). Erosion and scouring from bottom currents could alternatively account for the missing strata of the Waller Member.

REGIONAL ISOTOPIC CORRELATION

Stable $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes, when plotted against depth, also provide a potential basis for interwell correlation in the study area (figure 23). Cores 301, 204, 222, and 500 were selected for stable isotope analyses (figure 1, table 1). Stratigraphic boundary correlations are based on signature pattern combinations between the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ that can be recognized across wells (figure 23).

The isotope trend corresponding to the Pepper Shale is undetermined due to insufficient carbonate in the samples to produce reliable results. Isotope values for the Waller Member are light and consistent for both carbon and oxygen relative to the overall curve (figure 23). The Bouldin Member is characterized by generally heavier carbon and oxygen (more positive) compared to the Waller Member (figure 23). The South Bosque Formation exhibits somewhat lighter $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values than the underlying Bouldin Member (figure 23).

A few notable events occur within the Bouldin Member. In core 500 at an approximate depth of 73 ft, a short interval of heavy carbon depletion (-1.7 PDB) and heavier oxygen enrichment (-3.0 PDB) is observed (figure 23). A similar pattern of carbon and oxygen signatures in core 222 measures carbon at -4.3 PDB and oxygen at -3.2 PDB at 73 ft depth. These events could correspond to the oceanic anoxic event (OAE) 2 near the Cenomanian/Turonian boundary (Phelps, 2011) (figure 23). It should be noted that Pessagno (1969) and Jiang (1989) defined the Cenomanian/Turonian boundary biostratigraphically to be located 45 cm below the South Bosque Formation in Austin. These anomalous events in cores 500 and 222 are within the same stratigraphic Bouldin Member yet do not occur within time-equivalent beds. This observation provides doubt that this isotopic shift defines the global OAE that is at/near the Cenomanian/Turonian boundary.

Figure 23: (Previous Page) Cross section D-D' based on isotopic trends. (A) Isotope signatures across closely spaced wells in the Austin locality showing strong correspondence to stratigraphic intervals. Location of wells is depicted in figure 1. (B) Regional extension of isotope trends from Austin across the San Marcos Arch, including the GR trend. An interval overlies the South Bosque Formation to the south which was not observed in the study area. (C) Location of the transect as well as the approximate westernmost extent of the Waller Member.

More reasonably, these excursions are attributed to differential diagenetic depletion of nodular foraminiferal packstone/grainstone and carbonate-rich facies. Harbor (2011) observed both an enrichment and depletion in $\delta^{13}\text{C}$ from Eagle Ford concretions (nodular foraminiferal packstones/grainstones). He suggested that burial of the Eagle Ford in anoxic environments led to the differentiation of the carbon isotope character by microbial processes and methanogenesis. This study echoes the warning posed by Harbor (2011), that, with the broad use of $\delta^{13}\text{C}$ as a correlation proxy for global-sea level water conditions, care must be taken to distinguish diagenetic isotope values prior to use for regional and global correlations.

Comparison of the isotope plots from the Austin study area to wells along the San Marcos Arch is even less straightforward. In general, the isotope trends described for the Austin area cores are also observed to the west in the Hendershot, Orts, and Blumberg wells (figure 23). Based on isotope trends, correlation of stratigraphic units from the Austin Area across the San Marcos Arch generally match the lithostratigraphic correlations depicted in figure 21. However, the basal portion of Brechtel appears to be lacking the isotope trends of depleted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ that correspond to the Waller Member (figure 23).

Rock Eval/Pyrolysis Analysis

The Late Cretaceous Eagle Ford Group is a proven source rock in Texas (Robinson, 1997). Samples collected in the current study contain an average of 2.4% TOC, ranging from 0.1-8.4% TOC (50 samples). TOC values vary stratigraphically. At the base of the Eagle Ford, a dramatic increase in organic carbon is observed in comparison to the underlying Buda Limestone (figure 24). The Pepper Shale displays a general upward increase in TOC, ranging from 1.7-6.3% with an average of 3.2% TOC. The overlying Waller Member displays a large range in organic enrichment (0.1-8.4% TOC) along with the highest average overall: 3.7% TOC (figure 24). In contrast, the Bouldin Formation is characterized by the lowest TOC with an average of only 2.1% and a range of 0.4-4.1% TOC. TOC increases slightly into the overlying South Bosque Formation, which contains an average TOC of 2.5% (range 0.2-5.4% TOC) and then gradually decreases into the Austin Chalk (figure 24).

Figure 24: Comparison of TOC values in the Austin locality along with their associated facies and stratigraphic intervals. Highest average TOC is in the Waller Member, while lowest average TOC is in the Bouldin Member. Location of wells is provided in figure 1.

Normalized oil content ($S1/TOC$) averages 17.6 with a range of 10.7-27.8. Production index ($S1/[S1+S2]$) provides an average of 0.05 with a range of 0.02-0.24. Vitrinite reflectance (R_o) averages 0.49% and ranges from 0.33% to 0.67%. These maturity indicators reveal that even though substantial organic matter was preserved in Central Texas, the Eagle Ford did not reach sufficient maturity to generate hydrocarbons. Oil Potential ($S2$) values average 17.3 ranging from 0.1 and 58.8 and rank between good and excellent. Hydrogen index values average 498 and range between 72 and 699. Hydrogen index values as well as pseudo Van Krevelen plot (figure 25) suggest that type II kerogen (marine derived) is the dominant hydrocarbon form.

Figure 25: Pseudo Van Krevelen diagram of Eagle Ford Rock Eval/TOC samples showing the dominance of marine-derived type II Kerogen.

Chemostratigraphic Analysis

Energy Dispersive X-Ray Fluorescence (XRF) analysis, as discussed in the Methods section, provided element composition data that were used to evaluate the inorganic geochemistry of the Eagle Ford system. Variations in elemental composition have implications for ocean water chemistry as well as depositional setting. Certain trace metals are suitable as proxies for basin restriction because they are redox sensitive and relatively immobile in the sediment, thus preserving primary signals (Algeo and Rowe 2012). One such trace element is Mo, which has been widely used as a proxy for benthonic redox potential owing to its generally strong enrichment in organic-rich marine facies deposited under oxygen depleted conditions (Algeo and Lyons, 2006). In restricted anoxic marine systems, Mo shows significant variations from normal oceanic conditions. Normal open-oceanic conditions contain 80-100% of Mo concentration in the Saanich Inlet, 70-80% in Framvaren Fjord, and just 3-5% in the Black Sea (Algeo and Rowe, 2011).

Other redox sensitive trace elements include U, V, Mn, and Cr, which are linked to changing oxygen conditions in North America during the Cenomanian and Turonian time (Smith and Malicse, 2010; Algeo and Rowe, 2012). In this study, Mo, U, Mn, and V/Cr are geochemical proxies used for recognition of intervals when anoxic bottom conditions prevailed.

Major excursions and enrichments in these key trace elements occur in the Bouldin Member (figure 26), suggesting a period of maximum basin restriction during this time. Mo values, for example, reached 50 ppm within the Bouldin Member compared to the typical 5-10 ppm reading throughout the other members (figure 26). Another small enrichment in the Mo curve is apparent within the upper Waller Member which is not

manifest in the other geochemical proxies, perhaps suggesting a minor anoxic interval (figure 26). Although all paleoredox proxies are useful in providing a more robust constraint of maximum restriction, the Mo curve offers the clearest and most distinct profile.

Figure 26: Chemostratigraphic comparison of paleoredox proxies. Due to enrichment in Mo, U, Mn, and V/Cr, the Bouldin Member is interpreted to represent maximum basin restriction.

Although trace element abundances provide measures for paleoredox conditions, major elements such as Si and Ca are valuable for determining dominant mineralogy. Cross plots of Si versus Al ($R^2 = 0.97$) and also of Si versus Ti ($R^2 = 0.92$) (figure 27) show a strong relationship between Si, Al, and Ti, suggesting that these represent the siliciclastic component. Si percentage, when plotted against depth, mimics the CGR curve, but mirrors the calcium trend nearly perfectly (figure 28). These observations indicate that siliciclastic minerals and calcite constitute a fairly simple two end member Eagle Ford mineralogy. The correspondence between the Si curve and the CGR curve indicates that much of the siliciclastic material is in the form of clay minerals.

Figure 27: Cross plots of Si vs Al and also Si vs Ti showing a strong correspondence with R^2 values of 0.97 and 0.92, respectively.

Figure 28: Core description of the 301 core paired with the major element curves of Si, Al, and the CGR response curve. The Si and CGR curves share a similar trend but the Ca curve opposing it.

DISCUSSION

According to conventional understanding in mudrock successions, an association exists between a restricted basin environment and ideal conditions for organic matter preservation. Recognition criteria for restricted basin conditions include the presence of black, organic rich shales demonstrating a peak in TOC, a lack in benthonic fauna, and enrichment in redox sensitive trace elements. However, the correspondence of these characteristics is not observed in the Central Texas Eagle Ford succession.

Maximum TOC enrichment is observed in the Waller Member (average TOC 3.7%, maximum 8.4%) (figure 24). Facies within the Waller Member dominantly consist of massive argillaceous foraminiferal mudrock and laminated argillaceous foraminiferal mudrock (figure 18). The relatively low energy facies and high TOC could justifiably suggest that this interval represents the most distal setting and the greatest degree of basin restriction. However, geochemical proxies for anoxia and basin restriction (enrichment in Mo, U, Mn, and V/Cr) indicate that greatest basin restriction occurred during deposition of the Bouldin Member (figure 26). Surprisingly, the Bouldin Member contains the highest energy facies including: laminated foraminiferal wackestone, cross-laminated foraminiferal packstone/grainstone, and nodular foraminiferal packstone/grainstone (figure 18). These grain-rich facies are not traditionally expected to form within restricted basin conditions. The Bouldin Member is also the interval characterized by the highest GR trend (figure 22) but the lowest TOC (figure 24). Hence, two unlikely associations are observed: 1) high GR signatures with corresponding calcareous, high energy facies (figure 18), and 2) lowest TOC values (figure 24) corresponding to maximum basin restriction (figure 26). This discussion will attempt to reconcile these observed disparities and expose the dominant controls on Eagle Ford rock character.

Planktonic globigerinid foraminifera are the dominant grain type within the Bouldin Member. This sediment type was sourced from the photic zone and reflects surface water environmental conditions, not bottom water conditions. The high concentration of planktonic debris indicates accentuated productivity during this interval, providing high rates of carbonate sediment supply. As mentioned earlier, a strong association exists between the massive bentonitic claystone layers and calcareous (foraminiferal) units. In fact, the massive bentonitic claystones (interpreted to result from volcanic ash falls settling into marine waters) are almost entirely confined to the Bouldin Member. The close relationship between ash deposits and increases in planktonic sediment suggests that heightened productivity in the oxic zone is at least in part stimulated by nutrient enrichment from volcanic input. Sediment supply during the Bouldin Member deposition was related to surface water conditions, probably independent from eustatic forcing.

Notwithstanding the paleo-redox conditions suggesting maximum basin restriction and greatest organic carbon preservation (figure 26), TOC enrichment is lowest in the Bouldin Member, averaging 2.1% compared to the Waller Member's average of 3.7% TOC (figure 24). The discrepancy between high preservation potential and low TOC during deposition of the Bouldin Member is interpreted to result from carbonate dilution. Organic carbon was successfully preserved in the mud-rich facies. However, frequent influx and relatively rapid deposition of planktonic debris resulted in grain-rich carbonate facies where very low TOC was preserved. The high proportion of carbonate beds to mudrock beds within Bouldin Member resulted in low TOC values overall for this interval. Additionally, higher calcite content from the planktonic material caused the Bouldin Member to become more resistant to post-depositional compaction. Greater compaction in other Eagle Ford members allowed for differentially concentrated

TOC when compared to the Bouldin Member. Recent investigators (Ratcliffe et al., 2012) have suggested that TOC can be calculated semi-quantitatively from paleoredox proxies, particularly enrichment in Mo. However, in the current study, the disparity between paleoredox indicators and low TOC in Bouldin Member suggests that TOC calculation from inorganic chemistry data may provide misleading results.

High energy facies within the Bouldin Member are recognized by cross laminations, dune foreset laminations, low angle ripple laminations, planar to sub-planar laminations, and erosional scouring. These current-induced sedimentary structures do not reflect shallow water processes but are interpreted to result from bottom current reworking. Bottom currents, which are capable of transporting grains up to fine sand and even gravels (Stow and Faugeres, 1993; Stow et al., 2002), are independent of eustatic control. Furthermore, many of the minor components, consisting of benthonic fauna (inoceramids and other bivalves), are transported into the basin by bottom currents and consequently are not valuable as bottom condition indicators.

High degrees of facies discontinuity are observed even at particularly small scales (50 ft spacing) (figure 19). Bedding thickness variations and even pinchouts are observed in outcrop, and entire units are missing or not represented across closely spaced cores. Although facies discontinuity is observed within all intervals of the Eagle Ford, the Bouldin Member displays the most variability in facies continuity (figure 19). Greatest facies variability (erosional scouring, truncation, localized nodular facies, sediment reworking) and highest energy sedimentary structures (cross-laminations, dune foreset laminations, ripple laminations) suggest that bottom current activity and reworking was most pronounced during deposition of the Bouldin Member.

Although extremely calcareous and represented by the highest energy facies, the Bouldin Member is interpreted to have been deposited in the most anoxic marine setting.

This interpretation contrasts with classical sequence stratigraphic perspectives. High energy, carbonate-rich intervals (similar to the Bouldin Member) are commonly inferred to represent deposition proximal to an active carbonate platform. Expected characteristics of a deposit from a shallow water setting as such would display increased carbonate sediment supply, high energy facies from storm waves or turbidity currents, and decreased TOC due to sediment dilution and poor preservation in an oxygenated environment. The Bouldin Member displays these characteristics. However, the presence of current-induced structures, high degrees of facies variabilities, and paleoredox proxies demonstrate that this traditional model does not apply to the Central Texas Eagle Ford system.

Over-reliance on total GR logs (K-Th-U) is liable to provide misleading results. As observed in figure 18, the Waller Member produces moderate GR values in the ACC core which are followed by high GR values corresponding to the Bouldin Member. Based solely on the GR patterns, the following interpretation could justifiably be drawn: The Waller Member is a limestone-rich unit deposited in a higher energy, shallow water environment with low TOC and the Bouldin Member is a deep water, low energy, clay-mineral rich interval with high TOC. Furthermore, this erroneous GR interpretation could place these intervals into a sequence stratigraphic framework where the low GR “carbonate” of the Waller Member followed by the high GR “clay interval” of the Bouldin Member could indicate a cycle top, or shift from shallow to deep water environment. Notwithstanding the apparent GR profiles, the current interpretations are nearly opposite that of this erroneous illustration. It should be obvious from this discussion that GR profiles alone are insufficient in the Eagle Ford for determination of: 1) facies, 2) TOC content, 3) depositional environment, and 4) sequence stratigraphic

implications. Comparison of the GR curves to CGR curves provides Eagle Ford investigators with more accurate means for rock character determination.

Primary controls on Eagle Ford character are 1) sediment supply from planktonic foraminifera and 2) depositional re-working by bottom current activity. Globigerinid foraminifera comprise the dominant carbonate sediment type and originate in the photic zone of the surface waters. Changes in carbonate sedimentation rates are driven by surface water nutrient enrichment, stimulated in part by volcanic activity. Bottom current activity results from the interplay of both thermohaline and wind-driven currents due to with Coriolis Forces and seafloor topography (Stow et al., 2002). These primary controls, planktonic sediment supply, and bottom current reworking are processes that are independent from eustatic fluctuation, rendering classical sequence stratigraphic applications unreliable in the Eagle Ford system of Central Texas.

SUMMARY AND CONCLUSIONS

Within the Late Cretaceous (Cenomanian-Turonian) Eagle Ford interval of Central Texas, the following 7 distinctly characteristic facies are observed:

- 1) Massive Argillaceous Mudrock
- 2) Massive Argillaceous Foraminiferal Mudrock
- 3) Laminated Argillaceous Foraminiferal Mudrock
- 4) Laminated Foraminiferal Wackestone
- 5) Laminated Foraminiferal Packstone/Grainstone
- 6) Massive Bentonitic Claystone
- 7) Nodular Foraminiferal Packstone/Grainstone

Even at a particularly small spacing (50 ft), high degrees of facies variability are recorded in core data as well as outcrops. Facies variability is attributed to a number of factors including bottom current reworking and planktonic productivity. Bottom current reworking is responsible for erosional scouring, truncation, and localized distribution of facies. Planktonic productivity, possibly resulting from the nutrient enrichment of volcanic ash falls settling into marine waters, caused changes in sediment supply and depositional regime.

The lithostratigraphic continuity of facies decreases substantially with distance. For example, 73% of units are successfully correlated across a distance of 500 ft, 35% are traceable across 1 mile, and only 16% of beds are correlatable across 10 miles. At the 10 mile scale and greater, all data (inorganic geochemical data (XRD, XRF), organic geochemical data (Rock Eval/TOC), and well log data (GR)) significantly overestimate the degree of facies continuity within the Eagle Ford. However, these data are successful in defining a four-fold Eagle Ford stratigraphy. The basal Pepper Shale is an argillaceous,

fine grained (clay sized) moderate TOC, high CGR and GR zone. The Waller Member is a newly designated name used in this study for an argillaceous and calcareous (foraminiferal), high TOC, massive mudrock with moderate CGR and GR profiles. A high energy, carbonate-rich (foraminiferal), low TOC Bouldin Member displays a low and variable CGR but a high GR profile. The uppermost Eagle Ford South Bosque Formation, like the Waller Member, is an argillaceous and calcareous (foraminiferal) massive and laminated mudrock with moderate TOC, and a moderate CGR and GR response.

The Bouldin Member, although containing the most carbonate-rich and highest energy facies, represents maximum basin restriction. This is evidenced by paleoceanographic proxies, i.e., enrichment in Mo, U, Mn, and V/Cr. High energy deposition resulted from bottom current activity. Carbonate content was controlled by heightened productivity in the oxic zone, contributing a higher sediment supply of planktonic debris. Both bottom current reworking and planktonic sediment supply were controlling factors that were decoupled from eustatic sea level fluctuations, thus rendering classical sequence stratigraphy unreliable in the Eagle Ford system.

Contrary to conventional schemas, mudrock deposition is complex, involving the interplay of many controlling processes. Facies variability, often overlooked by stratigraphers and explorationists, is a significant aspect of the Eagle Ford system and has implications for source rock quality, seal capacity, reservoir characterization, and hydro-fracture potential. Caution must be employed when evaluating mudrock systems as nodular facies, ash beds, and other heterogeneities can dramatically influence correlatability. Furthermore, comparison of total gamma ray logs (GR) to CGR (gamma ray K-Th) is requisite as GR alone may provide misleading determination of facies, TOC content, depositional environment, and sequence stratigraphic implications.

Appendices

APPENDIX A: XRD DATA

Austin Locality X-Ray Diffraction Data																		
Interval					Carbonates								Clay Minerals					
Depth in ft	Feet Above Buda	Quartz	Plagioclase	K-feldspar	Calcite	Dolomite	Ankerite	Siderite	Anhydrite	Gypsum	Pyrite	TiO2	Illite + Mica	I/S mixed-layer	Smectite	Attapulgite	Kaolinite	Chlorite
WCT BI 500 PT:																		
59.5	34.5	5		3	68			1			2	+	8	5	5		3	
65.5	28.5	5		3	71		1				2	+	8	3	5		2	
73.5	20.5	8		3	83		2	1			3	+						
80.4	13.6	2		1	92		4				1	+						
91.0	1	13		1	36						3	1	23	8	5		10	
84.5	8.5	25					1	1		3	3	+	30	10	7		15	5
WCT BO 301 PTPZ:																		
59.3	28.7	10		2	55						2	+	15	3	10		3	
65.5	22.5	10		3	60	1				2	2	+	8	2	10		2	
69.2	18.8	7		2	78		2				3	+	6	2				
72.5	15.5	3		1	87		1			2	2	+					4	
83.4	4.6	28		2				1			3	1	35	10	5		15	
87.5	0.5	4		2	58						4	+	12	5	5		7	3
TiO2 is inferred from XRF data not from XRD; it can be rutile or anatase. *: organic and amorphous materials are excluded! +: present but below 1% level.																		

Austin Locality X-Ray Diffraction Data																			
Interval					Carbonates								Clay Minerals						TOTAL*
Depth in ft	Feet Above Buda	Quartz	Plagioclase	K-feldspar	Calcite	Dolomite	Ankerite	Siderite	Anhydrite	Gypsum	Pyrite	TiO2	Illite + Mica	I/S mixed-layer	Smectite	Attapulgite	Kaolinite	Chlorite	
WCT BT 204																			
87.5	29.0	7		3	56		1				2	+	10	5	12		4		100
100.0	16.5	6		5	74		1				3	+	7	4					100
102.5	14.0	5		3	80		1				2	+	4	3			2		100
112.0	4.5	14		2	43		1			3	2	1	15	8	5		6		100
115.5	1.0	22		1	1		1	1		3	2	1	23	11	12		15	7	100
ACC#1																			
103.1	22.0	5		1					2	1	3		13		60		15		100
107.9	17.2	3	2			1				1			5		80		8		100
Walnut Creek Outcrop																			
Outcrop	Outcrop	2	1		84								2	2	4		5		100
TiO2 is inferred from XRF data not from XRD; it can be rutile or anatase. *: organic and amorphous materials are excluded! +: present but below 1% level.																			

APPENDIX B: TOC, ROCK EVAL, AND THERMAL MATURITY DATA

WCT BO 301 PTPZ																
Stratigraphic Interval	Depth (ft)	Feet Above Buda	Percent Carbonate (wt%)	Leco TOC (wt% HC)	Rock-Eval S1 (mg HC/g)	Rock-Eval S2 (mg HC/g)	Rock-Eval S3 (mg CO2/g)	Tmax (°C)	Calculated %Ro (RE-TMAX)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content (S1/(S1+S2))	Production Index (S1/(S1+S2))		
Austin	48.0	40.0	83.61	0.21	0.08	0.22	0.32	0	-7.16	105	152	1	38	0.27		
South Bosque	49.0	39.0	77.22	0.26	0.06	0.26	0.23	431	0.60	100	88	1	23	0.19		
South Bosque	59.3	28.7	52.20	3.66	0.68	22.64	0.94	423	0.45	619	26	24	19	0.03		
South Bosque	63.8	24.2	63.05	3.74	0.88	24.92	0.96	418	0.36	666	26	26	24	0.03		
South Bosque	64.8	23.2	63.85	1.27	0.20	4.89	0.51	430	0.58	385	40	10	16	0.04		
Bouldin	65.5	22.5	59.83	4.00	0.77	25.99	0.94	422	0.44	650	24	28	19	0.03		
Bouldin	66.3	21.7	90.12	0.39	0.10	0.98	0.34	432	0.62	251	87	3	26	0.09		
Bouldin	66.5	21.5	79.94	1.69	0.24	8.89	0.61	423	0.45	526	36	15	14	0.03		
Bouldin	67.7	20.3	66.99	2.84	0.45	14.25	0.91	423	0.45	502	32	16	16	0.03		
Bouldin	68.0	20.0	52.89	2.39	0.43	11.33	0.87	423	0.45	474	36	13	18	0.04		
Bouldin	69.2	18.8	79.70	1.78	0.19	9.39	0.56	423	0.45	528	31	17	11	0.02		
Bouldin	70.3	17.7	85.08	2.35	0.52	11.76	0.84	419	0.38	500	36	14	22	0.04		
Bouldin	72.5	15.5	75.83	1.80	0.36	7.58	0.58	424	0.47	421	32	13	20	0.05		
Waller	73.5	14.5	84.71	0.50	0.07	1.65	0.28	432	0.62	330	56	6	14	0.04		
Waller	74.5	13.5	38.91	7.67	1.58	50.75	1.09	421	0.42	662	14	47	21	0.03		
Waller	75.0	13.0	37.72	8.43	1.91	58.79	0.99	422	0.44	697	12	59	23	0.03		
Waller	76.0	12.0	56.72	5.60	1.03	35.62	1.20	422	0.44	636	21	30	18	0.03		
Waller	77.7	10.3	37.87	7.71	2.14	53.90	0.89	421	0.42	699	12	61	28	0.04		
Waller	83.0	5.0	49.22	3.06	0.40	19.86	0.54	429	0.56	649	18	37	13	0.02		
Pepper	83.4	4.6	40.55	6.26	1.29	41.33	1.18	424	0.47	660	19	35	21	0.03		
Pepper	87.5	0.5	6.09	2.28	0.50	11.07	0.51	428	0.54	486	22	22	22	0.04		
Buda	88.5	-0.5	97.82	0.09	0.07	0.16	0.22	0	-7.16	178	244	1	78	0.30		
Buda	92.2	-4.2	98.39	0.04	0.06	0.03	0.16	0	-7.16	75	400	0	150	0.67		
Buda	98.3	-10.3	96.82	0.05	0.05	0.02	0.22	0	-7.16	40	440	0	100	0.71		

WCT BT 204

Stratigraphic Interval	Depth (ft)	Feet Above Buda	Percent Carbonate (wt%)	Leco TOC (wt% HC)	Rock-Eval S1 (mg HC/g)	Rock-Eval S2 (mg HC/g)	Rock-Eval S3 (mg CO2/g)	Tmax (°C)	Calculated %Ro (RE-TMAX)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content (S1/(S1+S2))	Production Index (S1/(S1+S2))
Austin	71.0	45.5	90.80	0.11	0.04	0.09	0.25	0	-7.16	82	227	0	36	0.31
South Bosque	78.5	38.0	78.35	0.18	0.04	0.13	0.31	0	-7.16	72	172	0	22	0.24
South Bosque	79.8	36.7	68.54	1.67	0.20	6.79	0.49	430	0.58	407	29	14	12	0.03
South Bosque	85.7	30.8	35.62	5.35	0.95	36.31	1.00	428	0.54	679	19	36	18	0.03
South Bosque	87.5	29.0	63.88	3.41	0.56	21.84	0.83	421	0.42	641	24	26	16	0.02
Bouldin	100.0	16.5	79.90	3.27	0.53	21.14	0.88	420	0.40	646	27	24	16	0.02
Bouldin	101.5	15.0	62.43	3.26	0.55	21.66	0.89	421	0.42	664	27	24	17	0.02
Waller	102.5	14.0	69.38	3.58	0.79	23.26	0.87	419	0.38	650	24	27	22	0.03
Waller	105.5	11.0	92.20	0.74	0.08	4.69	0.33	423	0.45	634	45	14	11	0.02
Waller	107.0	9.5	52.72	5.85	1.04	40.89	0.91	423	0.45	699	16	45	18	0.02
Waller	108.8	7.8	48.98	4.16	0.75	28.08	0.92	425	0.49	675	22	31	18	0.03
Waller	110.5	6.0	76.37	1.97	0.38	12.53	0.64	425	0.49	636	32	20	19	0.03
Pepper	112.0	4.5	41.12	4.67	0.81	31.34	0.97	428	0.54	671	21	32	17	0.03
Pepper	115.5	1.0	6.24	2.34	0.34	9.12	0.58	432	0.62	390	25	16	15	0.04
Pepper	116.5	0.0	81.27	0.63	0.07	1.69	0.36	431	0.60	268	57	5	11	0.04
Buda	119.0	-2.5	96.85	0.11	0.04	0.06	0.25	0	-7.16	55	227	0	36	0.40

WCT BI 500 PT

Stratigraphic Interval	Depth (ft)	Feet Above Buda	Percent Carbonate (wt%)	Leco TOC (wt% HC)	Rock-Eval S1 (mg HC/g)	Rock-Eval S2 (mg HC/g)	Rock-Eval S3 (mg CO2/g)	Tmax (°C)	Calculated %Ro (RE-TMAX)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content	Production Index (S1/(S1+S2))
Austin	50.0	44.0	74.76	0.25	0.05	0.20	0.21	0	-7.16	80	84	1	20	0.20
Austin	51.5	42.5	89.08	0.20	0.07	0.25	0.14	421	0.42	125	70	2	35	0.22
South Bosque	55.0	39.0	68.11	0.46	0.09	0.73	0.26	435	0.67	159	57	3	20	0.11
South Bosque	56.5	37.5	86.85	1.11	0.15	4.79	0.40	430	0.58	432	36	12	14	0.03
South Bosque	59.5	34.5	49.56	4.12	0.61	26.86	0.92	424	0.47	652	22	29	15	0.02
South Bosque	65.5	28.5	59.00	4.18	0.87	27.98	0.90	418	0.36	669	22	31	21	0.03
Bouldin	73.0	21.0	91.43	0.84	0.11	3.60	0.44	429	0.56	429	52	8	13	0.03
Bouldin	73.5	20.5	71.21	4.11	0.56	27.68	1.01	416	0.33	673	25	27	14	0.02
Bouldin	76.0	18.0	66.14	0.42	0.07	1.00	0.36	430	0.58	238	86	3	17	0.07
Bouldin	76.5	17.5	87.55	0.83	0.10	2.73	0.38	425	0.49	329	46	7	12	0.04
Waller	79.2	14.8	37.18	6.49	1.11	43.71	0.76	422	0.44	673	12	58	17	0.02
Waller	80.4	13.6	95.04	0.53	0.06	1.64	0.36	429	0.56	309	68	5	11	0.04
Waller	80.6	13.4	94.03	1.05	0.12	4.58	0.45	424	0.47	436	43	10	11	0.03
Waller	81.2	12.8	58.64	0.51	0.11	1.32	0.36	426	0.51	259	71	4	22	0.08
Waller	84.5	8.5	60.70	4.38	0.88	28.70	0.94	424	0.47	655	21	31	20	0.03
Waller	85.5	7.5	97.77	0.11	0.03	0.11	0.29	0	-7.16	100	264	0	27	0.21
Pepper	91.0	2.0	4.59	1.67	0.21	4.93	0.45	425	0.49	295	27	11	13	0.04
Pepper	92.5	1.0	5.92	2.09	0.36	8.91	0.42	427	0.53	426	20	21	17	0.04
Buda	93.5	-0.5	83.59	0.10	0.03	0.04	0.24	0	-7.16	40	240	0	30	0.43
Buda	97.0	-3.0	97.38	0.05	0.02	0.02	0.21	0	-7.16	40	420	0	40	0.50

APPENDIX C: CORE AND OUTCROP DESCRIPTIONS

Eagle Ford Facies

Massive Argillaceous Mudrock
Massive Argillaceous Foraminiferal Mudrock
Laminated Argillaceous Foraminiferal Mudrock
Laminated Foraminiferal Wackestone
Cross-Laminated Foraminiferal Packstone/Grainstone
Massive Bentonitic Claystone
Nodular Foraminiferal Packstone/Grainstone
Bioturbated Lime Mudstone/Wackestone (Austin)
Massive Wackestone/Packstone (Buda)

Walnut Creek Outcrop														
Strat Column	AUSTIN CHALK	EAGLE FORD GROUP					Feet	Carbonate			Siliciclastic			
								Grainstone	Packstone	Wackestone	Mudstone	Claystone	Mudstone	Siltstone

West Bouldin Creek Outcrop									
Strat Column	Feet	Carbonate				Siliciclastic			
		Grainstone	Packstone	Wackestone	Mudstone	Claystone	Mudstone	Siltstone	
AUSTIN CHALK									
EAGLE FORD GROUP									
BUDA		Pepper Shale	Lake Waco Fm		South Bosque Fm				
			Waller Mbr	Bouldin Mbr					
			0	5	10	15	20		

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Vita

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