Stratigraphy and Geochemistry of the Lower Cenomanian
Maness Shale of East Texas

By

Marissa Margaret English

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# Table of Contents

List of Figures........................................................................................................iv
List of Tables........................................................................................................vi

I. Introduction .............................................................................................................1
   I.I Regional Geology ............................................................................................3
   I.II Salt Tectonics .................................................................................................6
   I.III Stratigraphy ..................................................................................................9
   I.IV Previous Work ..............................................................................................17

II. Methods and Materials .......................................................................................26
   II.I Core Description and Sample Collection ....................................................26
   II.II Sample Analysis ..........................................................................................29
   II.III Well Log Correlation ..................................................................................34

III. Results ..............................................................................................................39
   III.I Core Description ..........................................................................................39
   III.II Petrographic Analyses .................................................................................49
   III.III Biostratigraphic Analyses .........................................................................54
   III.IV XRD Mineralogical Analyses ....................................................................60
   III.V ICP-OES/MS Analyses ...............................................................................64
   III.VI Organic Geochemistry Analyses ...............................................................79
   III.VII Well Log Correlations and Maps ..............................................................82

IV. Discussion .........................................................................................................95
   IV.I Chronostratigraphy .......................................................................................95
   IV.II Paleoceanography .......................................................................................97
   IV.III Stratigraphy ................................................................................................104
   IV.IV Sediment Source .......................................................................................111

V. Summary and Conclusions ..............................................................................118

References...........................................................................................................121

APPENDIX A- Core Descriptions ..........................................................................131
APPENDIX B- Thin Section Scans .........................................................................133
APPENDIX C- Washed Residue Data .....................................................................138
APPENDIX D- XRD .................................................................................................139
APPENDIX E-ICP-OES/MS ..................................................................................140
APPENDIX F- Total organic carbon data ..............................................................142

VITA

ABSTRACT
List of Figures

Figure 1. Stratigraphic chart for East Texas................................................................. 2
Figure 2. Map of Texas structural features................................................................. 5
Figure 3. Map of East Texas salt features................................................................. 8
Figure 4. Photos of Buda-Maness contact................................................................. 11
Figure 5. S.H. Maness #1 Type Log........................................................................ 14
Figure 6. Paleogeographic reconstruction of WIS................................................... 15
Figure 7. Cross-Section through East Texas............................................................. 20
Figure 8. Wheeler diagram for Woodbine and EF Group depositional episodes........ 23
Figure 9. Log correlation of Eagle For and Woodbine depositional episodes........... 24
Figure 10. Maness Isopach Map from Denne and Breyer (2016a)............................ 25
Figure 11. Map of Study Area.................................................................................. 28
Figure 12. Type logs and tops correlated in this study.............................................. 37
Figure 13. Cross-section locations............................................................................ 38
Figure 14. Kinney 25 core description and closest log............................................. 41
Figure 15. Core photographs of Kinney 25............................................................... 42
Figure 16. Watson 55 core description and closest well log..................................... 45
Figure 17. Core photographs of Watson 55.............................................................. 46
Figure 18. Lithofacies images and descriptions...................................................... 48
Figure 19. Microfacies 1 Description...................................................................... 52
Figure 20. Microfacies 2 Description...................................................................... 52
Figure 21. Microfacies 3 Description...................................................................... 52
Figure 22. Microfacies 4 Description...................................................................... 53
Figure 23. Microfacies 5 Description...................................................................... 53
Figure 24. Macrofossils from thin section............................................................... 56
Figure 25. Microfossils from washed residue samples........................................... 57
Figure 26. Microfossils from thin section............................................................... 58
Figure 27. Calcareous nannofossils...................................................................... 59
Figure 28. XRD mineralogy for Watson and Kinney core..................................... 62
Figure 29. Ternary diagrams of XRD data............................................................. 63
Figure 30. Depth plots of major elements............................................................... 66
List of Tables

Table 1. Depth and Maness Shale thickness for both cores..........................................................26
Table 2. Thin-sections with core depth.......................................................................................29
Table 3. Lithofacies descriptions...............................................................................................49
Table 4. Microfacies description...............................................................................................50
Table 5. Chemostratigraphic zones defined..............................................................................75
I. Introduction

The Maness Shale was first identified in the East Texas Field, home to one of the most prolific hydrocarbon provinces in the U.S. The East Texas Field was discovered in 1930 by C. M. Joiner (Minor and Hanna, 1933; Lozo et al., 1951; Alexander, 1951), but the Maness Shale was not identified and formally named until 1945 (Bailey et al., 1945). Production in the East Texas Field comes from a structural-stratigraphic trap along the western flank of the Sabine Uplift. The hydrocarbons are located in Woodbine strata that are truncated and sealed by the Austin Chalk. This reservoir is sourced by the overlying, hydrocarbon-rich lower Eagle Ford that is linked to Oceanic Anoxic Event 2 (Halbouty and Halbouty, 1982; Denne et al., 2016). The Maness Shale is both a bottom seal for the combination trap in the East Texas Field as well as a fracture barrier to water-bearing strata below the Maness in unconventional Eagle Ford production near the San Marcos Arch (Patterson, 2018). As of 2010, over 31,000 wells have been drilled in the East Texas Field and it has produced 5.42 billion STBO through the mid 2000’s (Galloway et al., 1983; Ambrose et al., 2007).

The Maness Shale is not currently a conventional or unconventional target, but it has gained attention by the industry and academia with the onset of unconventional production in the Eagle Ford (Hentz et al., 2014). One reason is that it is hypothesized to be time equivalent to the lower Eagle Ford in south Texas (Hentz and Ruppel, 2010). Therefore, it could have significant hydrocarbon potential as seen in the marine, Eagle Ford shales. Secondly, the Maness Shale denotes the first sediments deposited in the Early Cenomanian after the Gulf Coast system drastically changed from a primarily carbonate system with oxygenated bottom-waters to a siliciclastic and mud-dominated system with poorly-oxygenated bottom-waters (Denne et al., 2016) (Fig. 1). Siliciclastic input was especially concentrated in the East Texas Basin, with deltaic deposits sourced from surrounding topographic highs.
Figure 1. Stratigraphic Chart for the portion of the Cenomanian section of the East Texas and Brazos basins discussed in the text (modified from Denne et al., 2016).
Without any known outcrops, the sediment source and paleoenvironment of the Maness Shale has been debated, yet unproved, in the geologic literature. Interpretations vary from deep marine, TOC-rich shale (Hudson, 2014) to deltaic muds sourced from the Sabine Uplift (Denne et al., 2016). Characterization of the source for the Maness siliciclastics is needed before further work can build an accurate sequence stratigraphic framework for the Maness/Eagle Ford/Woodbine systems on the Texas Shelf during the Early Cenomanian to Turonian (Denne and Breyer, 2016a).

This present study is an attempt to advance the geological understanding of the Maness depositional episode in east Texas, to determine the location of the source of the Maness siliciclastics, and further our understanding of its depositional environment. This study utilized geochemical, biostratigraphic and lithostratigraphic analyses to provide data on the depositional environment and to regionally correlate the Maness depositional episode, starting in the Brazos Basin and extending to the type area for the Maness in the East Texas Basin. This study tests the following hypotheses in east Texas:

1. The Maness Shale of east Texas is age-correlative to the Maness Shale of the San Marcos Arch.
2. The Maness Shale is a potential source rock.
3. The Maness Shale is composed of deltaic sediment sourced from the Sabine Uplift.

I.I Regional Geology

The Gulf Basin formed during the Late Triassic-Early Jurassic as a result of crustal extension and seafloor spreading related to the breakup of Pangaea (Galloway, 2008; Dennen and Hackley, 2012). Structural features that affected depositional patterns and paleoceanography of the Gulf Basin include the Ouachita Uplift (north), the Sabine Uplift (east), the Llano Uplift and associated San Marcos Arch (central), and the Pennsylvanian thrust belt
(Fig. 2). The Ouachita Uplift is a Paleozoic structural high that sourced the Woodbine deposits in east Texas (Stehli et al., 1972). The Sabine Uplift straddles the modern-day Texas-Louisiana border and forms the eastern boundary of the East Texas Basin. It was a structural low during the Early Cretaceous and may have become episodically active during Woodbine and Eagle Ford deposition (Laubach and Jackson, 1990). The San Marcos Arch is a southeast-trending structure associated with the Llano Uplift that forms the southern boundary of the greater East Texas Basin and was thought to form a structural high during Maness deposition (Hentz and Ruppel, 2010; Denne and Breyer, 2016a).

From the Early Cretaceous through the Early Cenomanian, present-day Texas was predominantly a carbonate platform. Along the continental shelf margin, extensive reef systems built up during the Barremian and Albian, known as the Sligo and Stuart City reefs, respectively (Galloway, 2008). These reefs may have acted as sills restricting epeiric seaways during the Cretaceous, creating anoxic-euxinic bottom-water conditions (Arthur and Sageman, 2005; Lowery et al., 2014; Phelps et al., 2014; Denne et al., 2016). These structural features, in unison with syn-depositional movement of the Louann Salt during the Late Jurassic to Early Cretaceous, created sub-basins in the Gulf Basin, some of which contain some of the most prolific hydrocarbon fields in the contiguous United States. The main depositional centers for Cretaceous sediments include the East Texas and Brazos basins in northeast Texas and the Maverick Basin in south Texas (Denne et al., 2016).
Figure 2. Map of the structural features affecting deposition on the Texas shelf during the Early Cenomanian-Turonian. Uplifts are shaded in brown, submarine platforms and arches in tan, and basins in blue. Sligo margin is in red and the Stuart City margin is in purple. Study area polygon outlined in blue. Modified from Denne and Breyer (2016a).
I.II Salt Tectonics

The East Texas Basin is a Mesozoic salt basin within the greater Gulf Coast Basin. Following rifting in the Triassic, the East Texas Basin was a restricted marine environment where over 1500 ft (460 m) of Louann Salt was deposited upon a planar unconformity across rift-fill and Paleozoic basement rocks (Seni and Jackson, 1984). Through the mid-Jurassic, the sub-basin experienced crustal cooling and subsidence, but sedimentation rates were relatively low due to the lack of terrigenous and siliciclastic deposition. By the Late Jurassic, the East Texas Basin had subsided enough to become a depocenter of progradational siliciclastic sediments of the Bossier and Cotton Valley sands (Mondelli, 2011). The influx of sediments caused differential loading, leading to movement of the Louann Salt for the first time during the Late Jurassic to Early Cretaceous (Seni and Jackson, 1984).

The movement of salt is imperative to the story of the East Texas Basin, as the development of salt domes influenced the inherent stratigraphy. The formation of salt domes occurs in three growth phases: pillows, diapirs, and postdiapirs (Seni and Jackson, 1984). The pillow stage consists of anticlinal or laccolith-shaped structures formed by uneven sediment loading and rate of deposition. Salt pillows create shallow, primary peripheral sinks where sediment accumulates while thinning over the salt pillow itself, leading to lithostratigraphic variations within the area. The East Texas Basin salt pillows are known to have influenced thicknesses and facies variations in rocks deposited from Early to Late Cretaceous (Seni and Jackson, 1984). The diapir stage occurs when the flanks of the salt pillow collapse due to the increasing upward movement of the salt. This stage is characterized by deep, secondary peripheral sinks surrounding the domes, which are commonly filled by marine and deltaic sediments in the East Texas Basin (Seni and Jackson, 1984). The postdiapir stage is characterized by steady-state salt movement, where domes remain close to the sediment surface but no longer abruptly form diapirs. In all stages, but especially postdiapir, sand and
mud distribution are influenced by the presence of localized highs in fluvial and deltaic systems (Seni and Jackson, 1984). In addition, extensional faulting within the East Texas Basin is a direct result of salt withdrawal and translation of strata above the salt (Rowan et al., 1999; Mondelli, 2011). Therefore, the evolution of salt structures and related tectonics amplified the variability in topography of the basin floor, which may have influenced the lithostratigraphy of Cretaceous strata (Fig. 3).
Figure 3. Map of salt features and associated faulting that affected deposition during the Cretaceous. The study area is outlined in blue. Modified from Seni and Jackson (1984).
I. III Stratigraphy

Washita Group: Buda Limestone

The Buda Limestone of the Washita Group laterally extends from the Maverick Basin in south Texas to the western flank of the Sabine Uplift in the East Texas Basin. In east Texas, the Buda overlies the Grayson Shale, which is age-equivalent to the Del Rio of south Texas (Hentz et al., 2014). The Buda Limestone is described as a white, non-porous to porous limestone containing a significant abundance of calcispheres (Lozo, 1945; Denne et al., 2016). The Buda Limestone contains a range of ammonites, but *Budaiceras* is the most common specimen identified in the formation (Hancock et al., 1993), restricting the Buda to the *Budaiceras hyatti* ammonite zone of the Early Cenomanian.

The Stuart City relict reef margin constrained the southern extent of Buda deposition to the Gulf Coast shelf (Hentz and Ruppel, 2010). At the terminus of Buda Limestone deposition, the Early Cenomanian records a distinctive shift in depositional patterns in the Gulf sub-basins from a dominantly carbonate system to a siliciclastic and mudstone system (Sohl et al., 1991; Denne and Breyer, 2016a). This depositional shift reflects a change in bottom-water oxygen conditions from oxic to anoxic-euxinic.

The contact between the Buda Limestone and the overlying Maness Shale is conformable, suggesting that the Maness was a transitional unit before the onset of deposition of the Eagle Ford and Woodbine Groups (Lozo, 1951; Denne et al., 2016). The presence of abundant calcispheres within the Maness supports this hypothesis, as the Buda contains calcispheres yet they are absent in the Woodbine (Denne et al., 2016). Additionally, Denne et al. (2016) determined that the Buda is unaltered if the Maness is present and is karsted in areas where the Maness is missing (Fig. 4). In east Texas, salt movement caused significant subsidence compared to other parts of the Gulf Basin, causing the East Texas Basin to remain
submerged during Maness deposition, so the contact is conformable and unaltered (Salvador, 1991).
Figure 4. Core photographs displaying the Buda-Maness contact in wells south of the San Marcos Arch. In Atascosa County, the Maness is absent and the Buda is karsted. In Karnes County, the Maness is a thin interval, but it is present so the Buda is unaltered. Core images adapted from Denne et al. (2016).
The Maness Shale was first described in a conventional core from the Shell Oil Company’s Maness Well No. 1 in Cherokee County, TX in 1945 (Fig. 5). The Lower Cenomanian shale was described as a bronze or copper to dark-gray colored, somewhat calcareous shale and claystone. It is faintly laminated to massive in the type area (Bailey et al., 1945). The Maness Shale does not crop out, so the type locality is solely based on subsurface analysis of cores and petrophysical logs. The formation was named in Bailey et al. (1945) and further examined by Lozo (1951). Lozo (1951) explained that the Maness identified in Cherokee County was often misidentified and falsely correlated with the Grayson Marl in north Texas, the Del Rio Clay in south Texas, and the basal Woodbine clay. Additionally, early works identified a *Budaiceras* ammonite and *Epistomina scaphiocolula* benthic foraminifera within the Maness Shale, placing the Maness within the Washita Group and identifying it as Early Cenomanian (Bailey et al., 1945; Lozo, 1951).

The argillaceous Maness Shale was deposited as a transitional mudrock following the termination of carbonate deposition in the Early Cenomanian. The Maness is therefore the first formation deposited in the siliciclastic and mud-dominated system with its main depocenter in east Texas (Fig. 6a). It was deposited under low-oxygen bottom-water conditions in the East Texas Basin, possibly due to the vertical barrier provided by the relict reef systems (Denne et al., 2016). To the south, near the San Marcos Arch, the basin was sediment starved and the only interval of Maness deposited there is represented by a condensed phosphatic-lag representing the maximum flooding surface and subsequent sequence boundary (Denne et al., 2016). Because this phosphatic-lag can be correlated from south Texas into the Brazos Basin, it is interpreted to be a sediment-starved hardground representing a hiatus in deposition of approximately 0.5 Ma (Denne and Breyer, 2016a). Following Maness deposition, there was a significant sea level drop followed by deposition of the fluvial-deltaic Woodbine Group.
The Woodbine delta unconformably overlies the Maness Shale in east Texas (Vallabhanemi et al., 2016). In proximal locations, the sequence boundary is a sharp contact showing an abrupt shallowing in facies, where the non-marine Dexter sands overly the Maness. In more distal areas, the prodelta muds of the Pepper Shale facies of the Woodbine depict a subtler transition with the Maness, due to the similar high-clay content in both units (Hentz and Ruppel, 2010; Denne et al., 2016).
Figure 5. Spontaneous potential and resistivity logs from the S.H. Maness No. 1, where the Maness Shale was first identified in 1945 in Cherokee County (red star). Modified from Bailey et al. (1945) and Patterson (2018).
Figure 6. Paleogeography of the Gulf Basin and Texas Shelf during the Late Albian/Early Cenomanian and Middle Cenomanian. East Texas basin is shown by the red polygon. A) Buda deposition and onset of Maness deposition. B) Woodbine deposition. Modified from Blakey (2014).
**Woodbine Group**

The fluvial-deltaic Woodbine Group was sourced from erosion of the Ouachita Uplift and the Arbuckle Mountains in Arkansas and Oklahoma (Vallabhanemi et al., 2016; Denne and Breyer, 2016a). The Woodbine has been extensively studied as it is the primary reservoir rock for the east Texas play. In the East Texas Basin, the Woodbine is sub-divided into two sand units: the lower Dexter Formation and the upper Lewisville Formation, which are separated by a minor transgression (Denne and Breyer, 2016). Distally, the Woodbine prodelta facies is the Pepper Shale, which is seen in the Brazos Basin (Adams et al., 2014). In the Brazos Basin, the Pepper Shale contains the lower Woodbine organic-rich shale, which was misinterpreted by Hudson (2014) as Maness. In south Texas, the Woodbine is not present so the Maness and phosphatic-lag are overlain by the Eagle Ford Group.

**Eagle Ford Group**

Another distinctive depositional change occurred during the Middle Cenomanian in east Texas with the onset of organic-rich shale deposition of the Eagle Ford (Denne and Breyer, 2016a). The Eagle Ford Group overlies the deltaic Woodbine sands in the East Texas Basin and in turn is overlain by the Austin Chalk. During the Late Cenomanian, movement of the Sabine Uplift initiated erosion of Woodbine sediments, which were re-deposited as the mud-rich deltaic deposits of the Harris Delta into east Texas, making the Eagle Ford in east Texas more siliciclastic-rich than in south Texas. The Lower Eagle Ford in the East Texas Basin was deposited under the anoxic-euxinic bottom-water conditions that existed before the oxygenation event associated with Oceanic Anoxic Event 2. The Sligo and Stuart City reef systems restricted the onshore basins, producing stratification of the water column that allowed euxinic conditions at depth in the East Texas Basin (Denne et al., 2014; Lowery et al., 2014).
Throughout the Middle to Late Cenomanian, eustatic sea level rise connected the Texas Shelf (Tethys Sea) with the Western Interior Seaway (WIS) (Arthur and Sageman, 2004; Denne and Breyer, 2016b), flooding the mid-continent of the present-day U.S. (Fig. 6b). This sea level maximum coincided with Oceanic Anoxic Event 2 (OAE2) at the Cenomanian-Turonian boundary, which is responsible for the formation of organic-rich source rocks worldwide (i.e., Eagle Ford, La Luna, etc.). This transgression allowed cold water from the north to invade the WIS and Texas Shelf, oxygenating the bottom waters (Denne et al., 2014). Therefore, OAE2 in the Gulf Basin is the division between the TOC-rich Lower Eagle Ford shales and the TOC-poor Upper Eagle Ford (Denne et al., 2016).

I.IV Previous Work

*East Texas*

Historically, interpretations of the Maness differ from one publication to another (e.g. Ambrose et al., 2009; Ambrose and Hentz, 2010; Hentz and Bonnaffe, 2010; Hentz et al., 2014; Hudson, 2014; Denne et al., 2016). In his work for the Louisiana Geological Survey, Anderson (1979) defined the Maness as the Upper Washita, low resistivity shale unit below the South Tyler sands. He also described a facies change in Leon County where the nomenclature changed to the Malvern shale below the Pepper shale (Fig. 7).

Ambrose and Hentz (Ambrose et al., 2009; Ambrose and Hentz, 2010; Hentz et al., 2014) integrated core data with conventional well-logs to produce a sequence stratigraphic framework for the Woodbine Group in the East Texas Field, and indicated that the Maness consists of a lower transgressive unit and an upper highstand unit with a maximum flooding surface (MFS) dated at 93.5 Ma (Ambrose et al., 2009). They showed the total thickness of the Maness Shale along the axis of the basin to be approximately 75 m (246 ft) (Ambrose et al., 2009; Ambrose and Hentz, 2010; Hentz et al., 2014).
Alternatively, a study done by Hudson (2014) included the Lower Woodbine Organic Shale (LWOS) as part of the Maness in the Brazos Basin. The thickness of the Maness in her study is about 140 ft (42.7 m) across seven chemostratigraphic zones defined by XRF elemental analyses, dividing the Maness into an upper and lower unit, mimicking Ambrose and Hentz (2010). She found TOC contents greater than 2.78% and clay content of over 53%.

The regional studies provided by Ambrose and Hentz (2010), among others, did not attempt to correlate the Eagle Ford and Woodbine groups across the San Marcos Arch (e.g., Adams and Carr, 2010; Hentz and Ruppel, 2010; Breyer et al., 2013; Hentz et al., 2014). Without regional correlations, there are significant nomenclature issues associated with the Eagle Ford and Woodbine Groups as well as erroneous age interpretations (Denne et al., 2014; Denne et al., 2016).

San Marcos Arch, South Texas

The introduction of a biostratigraphic dataset in the Eagle Ford of south Texas led to increased interest in correlating the Eagle Ford and Woodbine groups across the state (e.g. Denne et al., 2014; Lowery et al., 2014; Denne et al., 2016; Denne and Breyer, 2016a; b). One of the key elements of correlating the Eagle Ford and Woodbine Groups from south to east Texas is the ability to correlate logs across the San Marcos Arch. Previous studies (e.g., Hentz and Ruppel, 2010; Hudson, 2014) struggled to correlate the Maness and overlying strata across the arch. This has been difficult due to the considerable facies changes occurring near the arch as well as deficient integration of biostratigraphic and geochemical data (Denne and Breyer, 2016b). Recently, biostratigraphic, organic geochemical, X-ray diffraction (XRD) mineralogical, X-ray fluorescence (XRF) elemental, and petrographic analyses have been used in conjunction with well logs to describe and map the Maness Shale near the San Marcos Arch (Jennings and Antia, 2013; Denne and Breyer, 2016a; Denne et al., 2016; Patterson, 2018).
Mineralogical and geomechanical analyses of the Maness Shale near the arch showed that it has a clay content (>50%) much higher than the underlying Buda and overlying Eagle Ford (Jennings and Antia, 2013; Denne et al., 2016a; Patterson, 2018). The Maness Shale near the San Marcos Arch is identified by its high gamma ray and low resistivity signature on well logs (Jennings and Antia, 2013; Denne et al., 2016; Patterson, 2018). There is a distinctive gamma ray spike at the top of the unit, which is interpreted as a phosphate lag (Denne et al., 2016). Ammonites, foraminifera, and calcareous nannofossils have been identified in cores and thin sections at locations near the arch (Denne et al., 2016). In addition, geochemical paleoredox proxies suggest low-oxygen bottom water conditions for the Maness Shale in south Texas. This is further supported by the rarity of benthic foraminifera (Denne et al., 2016).
Figure 7. Cross-section from the Louisiana Geological Survey from north Texas to the Brazos Basin. Correlations are shown for the Buda Limestone, Maness Shale (also referred to as Malvern Shale in this study), Woodbine Group, Eagle Ford Group, and Austin Chalk. Cross-section location is shown on the map from A to A’. Modified from Anderson (1979).
Regional Correlations

This study builds off the depositional nomenclature defined by Denne and Breyer (2016a). They recognize seven depositional episodes for the Eagle Ford and Woodbine Groups in south Texas that are related to eustatic sea level changes, regional paleoceanography, and localized geologic events. These depositional episodes were correlated across the arch and into east Texas using biostratigraphic, geochemical, and petrophysical data from wells along with cores and outcrops (Denne et al., 2016; Denne and Breyer, 2016a). The depositional episodes that are the focus of this study are the Maness and EGFD100 (Fig. 8).

The Maness Shale was deposited during the first depositional episode in this model, signifying the depositional shift from carbonate deposition to siliciclastic deposition of the Gulf Coast (Denne et al., 2016). EGFD100 consists of the fluvial-deltaic Woodbine deposits with a northeast-southwest depositional trend in east Texas, and represents the onset of calcareous Eagle Ford deposition in south Texas. EGFD200 marks the onset of Eagle Ford deposition in east Texas during the eustatic sea level rise and transgression that connected the Texas Shelf with the Western Interior Seaway. During this transgressive period, EGFD300-400 consists of two deltaic systems—the Templeton Delta and the Harris Delta—deposited from eroding adjacent structural highs. The Harris Delta is of importance to this study because it is sourced from the Sabine Uplift, which is supported by an isopach map that shows an E-W depositional trend (Denne and Breyer, 2016a, their figure 26). This is similar to the patterns seen with the Maness Shale near the San Marcos Arch. Additionally, EGFD500 consists of Eagle Ford deposition through the sea level maximum at OAE2 and drowning of the delta complexes. Lastly, EGFD600 was deposited during the subsequent sea level fall that reintroduced deltaic activity (Denne et al., 2016; Denne and Breyer, 2016a).

This chronostratigraphic framework, combined with a regional log-based study, enables correlation of these depositional episodes across the arch and into the Brazos Basin. Log
correlations for wells near the arch to the north in the Brazos Basin are based on the high gamma ray spike associated with the phosphatic-lag. With the base of the Maness as the datum, the variation in thickness is evident (Fig. 9). The isopach map shows the lateral extent of the Maness Shale, from its pinch-out point near Atascosa and Karnes counties to thickness intervals of over 60 m (196 ft) to the northeast in Leon county (Denne and Breyer, 2016a; Patterson, 2018) (Fig. 10). This is a significantly thinner Maness interval than was determined by Ambrose et al. (2009). Interpretations from the log correlations and isopach map suggest that erosion was minimal following deposition of the Maness since the phosphate lag is regionally present (Denne and Breyer, 2016a). Therefore, the isopach map shows the depositional limit of the formation along an E-W trend. This suggests a possible clay-rich deltaic source from the northeast during Maness deposition, similar to the one sourcing the Harris Delta (Denne and Breyer, 2016a). This current study builds off this interpretation to further correlate the Maness Shale from the East Texas Basin to the San Marcos Arch and identify the sediment source of the Maness Shale.
Figure 8. Wheeler diagram for the depositional episodes of the Woodbine and Eagle Ford Groups from south Texas to east Texas. The age model used was developed by Denne et al. (2016). Adapted from Denne and Breyer (2016a).
Figure 9. Log correlation using the seven depositional episodes from Denne et al. (2016). Wells are located on the isopach map shown in Figure 11. The datum is the Buda-Maness contact. The phosphatic-lag atop the Maness is identified as the high gamma ray spike shown by the yellow arrows and it can be correlated across the arch and into East Texas. The log correlations support the isopach map showing that the Maness thickens as to the northeast. Modified from Denne and Breyer (2016b).
Figure 10. Isopach map of the Maness Shale from Denne and Breyer (2016a) near the San Marcos Arch. The approximate location of the arch is shown by the purple arrow. Wells used for log correlation in Figure 9 are shown on the map. The blue arrow shows the suggested sediment transport direction.
II. Methods and Materials

The purpose of this study is to increase our knowledge of the Maness in its type area, including its mineralogical and elemental composition, to tie the Maness in its type area to the Maness identified near the San Marcos Arch as well as determine the paleoenvironment and general sediment source of the Maness Shale. The study area comprises the eastern part of the Brazos Basin and the East Texas Basin and includes portions of Brazos, Robertson, Grimes, Madison, Leon, Houston, Freestone, Anderson, Cherokee, Smith, Gregg, and Rusk counties (Fig. 11).

II.I Core Description and Sample Collection

Two conventional cores, stored at the Bureau of Economic Geology at the University of Texas in Austin, TX, were analyzed in this study (Fig. 11; Table 1). Both cores are from the East Texas Field: Watson 55 in Gregg County and Kinney 25 in Rusk County. The Watson 55 well was drilled by Shell Oil Company in 1984 and the Kinney 25 well was drilled by Arco Oil and Gas Company in 1978. Geophysical logs for both of these wells are not public; therefore, the closest wells with geophysical logs were used in the analysis. The closest well with geophysical logs to the Watson 55 is Knowles Estate 1, three miles (5 km) away. The closest well to the Kinney 25 is Galan White 1, less than two miles (3 km) away.

Table 1: Depth and Maness Shale thickness for the two cores used in this study.

<table>
<thead>
<tr>
<th>Core Name</th>
<th>Location</th>
<th>Cored section ft/m</th>
<th>Core described ft/m</th>
<th>Total ft/m described</th>
<th>Total ft/m Maness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell 55 Watson</td>
<td>Gregg County, TX</td>
<td>3567’ – 3742’ / 1087 – 1140</td>
<td>3701’ – 3729’ / 1128 – 1137</td>
<td>28’ / 8.5</td>
<td>27’ / 8.2</td>
</tr>
<tr>
<td>Arco 25 Kinney</td>
<td>Rusk County, TX</td>
<td>3574’ – 3712’ / 1089 – 1131</td>
<td>3665’ – 3694’ / 1117 – 1126</td>
<td>30’ / 9</td>
<td>28’ / 8.8</td>
</tr>
</tbody>
</table>
These cores were previously described (Ambrose et al., 2009; Ambrose and Hentz, 2010) for Woodbine and Eagle Ford interpretations, but the Maness was not described in detail. Therefore, each core, extending from the uppermost five feet (1.5 m) of the Buda Limestone to the basal sandstone of the Woodbine, if present, were photographed and described in detail, paying close attention to contacts. Core descriptions include color, grain size, texture, sedimentary structures, erosional/gradational/conformable contacts, bioturbation, body and trace fossils, bentonites, nodules and concretions, and other sedimentary features. Additionally, facies changes were identified from core descriptions based on lithology, bioturbation, fossil assemblages, and bedding styles. Lithofacies were defined from the culmination of facies descriptions and XRD mineralogy. Nomenclature for lithofacies were defined using guidelines from Lazar et al. (2015).

In addition to core descriptions, samples were collected roughly every 2 ft (0.6 m) in the Kinney 25 well and every 4 ft (1.2 m) in the Watson 55 well for use in washed residue samples, smear slides for calcareous nannofossil analyses, organic geochemical analyses, thin-sections for petrographic and biostratigraphic analyses, X-ray diffraction (XRD) mineralogic analyses, and inductively coupled plasma optical emission (ICP-OES) and mass spectrometry (ICP-MS) elemental analyses.
Figure 11. Map of the study area within East Texas. The study area is outlined by the blue polygon and shows the locations of the 350 wells used in the study. Core locations are shown by the dark green star for the Watson core and the light green star for the Kinney core. Type logs are shown by the red (Lily Hoppess 1), yellow (Knowles Estate 1), and green dots (Galan White 11).
II. II Sample Analysis

*Petrographic Analysis*

The petrographic analysis utilized nine thin-sections sampled from the two cores: five from the Kinney core and four from the Watson core (Table 2). Thin sections were prepared by TPS Enterprises, LLC, in Houston, Texas at a size of 1 in x 1.75 in (2.5 cm x 4.4 cm), and a standard thickness of 20 $\mu$m. All thin-sections were analyzed by Dr. Denne and myself using a petrographic microscope and scanned at TCU using an Epson Perfection V600 Photo flatbed scanner. Transmitted and reflected light was used for both analysis and the thin sections scans. Reflected light was specifically useful in identifying the presence of pyrite within the samples.

**Table 2: Thin-section core depth.**

<table>
<thead>
<tr>
<th>Thin Section No.</th>
<th>Core</th>
<th>Depth (ft/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kinney 25</td>
<td>3665.5' / 1117.2</td>
</tr>
<tr>
<td>2</td>
<td>Kinney 25</td>
<td>3672.5' / 1119.4</td>
</tr>
<tr>
<td>3</td>
<td>Kinney 25</td>
<td>3682.5' / 1122.4</td>
</tr>
<tr>
<td>4</td>
<td>Kinney 25</td>
<td>3683.25' / 1122.7</td>
</tr>
<tr>
<td>5</td>
<td>Kinney 25</td>
<td>3687' / 1123.8</td>
</tr>
<tr>
<td>6</td>
<td>Watson 55</td>
<td>3711.25' / 1131.2</td>
</tr>
<tr>
<td>7</td>
<td>Watson 55</td>
<td>3716.3' / 1132.7</td>
</tr>
<tr>
<td>8</td>
<td>Watson 55</td>
<td>3717.5' / 1133</td>
</tr>
<tr>
<td>9</td>
<td>Watson 55</td>
<td>3725' / 1135.4</td>
</tr>
</tbody>
</table>

Sedimentologic analyses used thin-sections to determine microfacies and depositional processes based on the methods of Lazar et al. (2015). The microfacies interpretations were based on thin-section analysis of grain sizes and types, compositions, lamina continuity and geometry, and bioturbation. This petrographic analysis provided evidence to the paleoenvironment of deposition for the Maness, such as whether it was deposited below storm-
wave base in anoxic bottom-waters like the Maness near the San Marcos Arch or above storm-wave base in a more proximal, oxygenated environment (Patterson, 2018).

**Biostratigraphic Analysis**

Dr. Richard Denne conducted the biostratigraphic analysis for this study, building off the framework and zonations used in Denne et al. (2014; 2016a) and Denne (2019). The objective was to use the age-diagnostic ammonites, foraminifera, and calcareous nannofossils found near the San Marcos Arch and correlate them to the study area, if present (Denne et al., 2016; Patterson, 2018). This was used to determine if the Maness of east Texas is age-correlative to the mudstones identified as Maness near the San Marcos Arch.

Some macrofossils are ideal biostratigraphic markers, but they are usually rare or absent in core. Ammonites, particularly, provide great age constraints since some of them only lived during relatively short time periods but had widespread distribution (Denne et al., 2016). The *Budaiceras* ammonite, within the *Budaiceras hyatti* Zone, of the Early Cenomanian was identified in the Maness by Lozo (1951). No ammonites were found in this study, but other macrofossil fragments, such as inoceramids, echinoid spines, and filaments, were identified.

Foraminifera microfossils were analyzed in this study using washed residues and thin-sections to determine foraminiferal assemblages and age-diagnostic markers. Four samples from the Kinney 25 core (3691, 3680, 3677, and 3674 ft) were washed over a 63 µm sieve, and all microfossils, including foraminifera, ostracods, and other microscopic fossils were picked from the samples and identified by Dr. Denne. Benthic foraminifera are bottom dwellers that are primarily used to determine paleoenvironmental conditions, mainly bottom-water oxygenation, and paleobathymetry (Denne et al., 2016). The benthic foraminifera diagnostic for the Maness are *Epistomina lacunosa* (Lozo, 1951) and *Textularia washitensis* (Denne et al., 2016), indicating that bottom-waters were not completely anoxic during Maness deposition. Planktonic
foraminifera are used to interpret surface-water conditions, such as fertility, oxygenation, and salinity (Denne et al., 2016). The age-diagnostic planktonic foraminifera for the Maness include *Favusella washitensis* and *Rotalipora appenninica* (Denne et al., 2016). The light photomicrographs of the picked specimens were taken with a Leica DMC2900™ camera attached to a Leica M205 C™ stereo microscope.

Calcareous nannofossils were analyzed in this study using smear slides, since they are usually too small (2-30 µm) to be identified in thin-sections (Denne et al., 2016). These planktonic organisms can also be used to determine surface-water conditions in the paleoenvironment. *Braarudosphaera africana* is the calcareous nannofossil marker that has been identified in the Maness (Denne et al., 2016; Denne and Breyer, 2016a). Calcareous nannofossil zonation schemes were used to age-date the Maness in this study (Sissingh, 1977; Perch-Nielsen, 1985; Denne et al., 2016).

**Mineralogical Analysis**

X-Ray Diffraction (XRD) is a common technique used for mineralogical analysis to identify minerals and other crystalline abundances in core samples. This technique uses x-ray beams to bombard the sample with electrons and record the diffraction of the electrons off each crystal lattice. If there is no crystalline structure or the atoms are randomly distributed, there will be destructive interaction which will not produce a peak. If there is a rigid structure, then the x-ray will diffract and signal a peak. The following equation is used to calculate the d-spacings of the minerals, which can be compared to a standard reference pattern to identify the minerals:

\[
\text{Bragg's Law: } n\lambda = 2d\sin\theta,
\]

where

- \( n \) = integer,
- \( \lambda = 1.54 \) angstroms,
- \( d \) = d-spacing,
- \( \theta \) = diffraction angle
The d-spacing identifies the specific mineral that is present and the intensity of the peak on the XRD pattern determines how much of that mineral is present (Chatterjee, 2001).

The XRD analysis was performed on 10 samples by the Shimadzu Institute for Research Technologies at UT-Arlington and 2 samples by Caitlin Payblas at TCU. The samples were prepared and powdered in-house, 1 to 1.7 ounces (30-50 mL) for each sample, before being analyzed. The powders were analyzed using the Shimadzu XRD-7000. The samples were rotated at 6 rpm and ran from a 2θ of 2 to 70 degrees. The scan speed was 2 degrees/minute, therefore each sample took about 34 minutes. The x-ray voltage was 40 kV and the current was 30 mA. The scans were processed using the MDI Jade9 software package, where the sample spectras were compared to the ICDD PDF-4+2018 XRD reference spectra database. Modal mineralogy was determined using the relative intensity ratio (RIR) method within the software. This method uses corundum as a standard reference as its d-spacing and intensity can be compared to other minerals that were identified in the sample.

This analysis aided in determining the mineralogical composition and clay mineralogy of the east Texas Maness. These results were compared to the XRD data of 27 samples from two cores near the San Marcos Arch (Patterson, 2018) and additional XRD data from a study in south Texas (Ramiro-Ramirez, 2016), two studies in the Brazos Basin (Hudson, 2014; Meyer, 2016), and unpublished data from DeWitt and Robertson counties (Denne et al., 2016).

**Elemental Analysis**

There are multiple geochemical techniques available for elemental analysis, including x-ray fluorescence (XRF) and inductively coupled plasma (ICP) spectroscopy. The handheld XRF technique is more cost effective and time efficient, but ICP spectroscopy is the best technique for producing high quality geochemical data due to the abundance of elements it can analyze and its data precision (Rowe et al., 2012; Denne et al., 2016). The ICP technique requires roughly 0.25 g of a sample which is transformed into a solution by dissolution from a dilute acid
and then sprayed into the ICP as an aerosol. There are two types of ICP instruments, ICP-optical emission spectrometry (ICP-OES) and ICP-mass spectrometry (ICP-MS), that are used in combination to analyze geological samples. ICP-OES analyzes the optical spectra produced by the samples for 10 major elements and 17 high abundance trace elements with a precision of \( \sim 1\% \) for major elements and slightly less precise for the trace elements. The major elements detected include Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P. The high abundance trace elements include, but are not limited to, Be, Ce, Cr, Cu, Ni, Sr, V, and Zn. ICP-MS analyzes elemental data at a lower order of magnitude than ICP-OES, therefore it is more effective in acquiring data for low-abundance trace elements and rare earth elements. It determines elemental data for 24 low abundance trace elements including, but not limited to Mo, Ba, Be, Co, Cr, Nb, Ni, Sr, Th, U, V, and Zn. The 14 rare earth elements identified include La, Ce, Pr, Sm, Nd, Gd, Tb, Ho, Dy, Er, Tm, Yb, and Lu (Chemostrat, 2020).

Chemostrat, Inc performed ICP-OES and ICP-MS on 10 samples from each core. Data results included elemental content of the major elements in weight percent (wt %) and elemental concentrations of the trace elements and rare earth elements in parts per million (ppm). All major elements and the majority of the trace elements were plotted versus depth to determine patterns and the chemical stratigraphy between the two cores.

A primary purpose for performing elemental analysis is to interpret bottom-water chemistry and oxygen conditions during deposition. This requires the use of paleoredox proxies, including elemental abundances of vanadium, molybdenum, chromium, uranium, and phosphorous, among others. Because of the variability in carbonate content within these samples, trace elements were normalized to the aluminum content within the sample and in average shale samples by calculating their enrichment factor (EF) (i.e. Tribovillard, 2006; Algeo and Rowe, 2012; Denne et al., 2014). The following equation was used for EF calculations,

\[
EF_{\text{element}} = \frac{(\text{Element} / \text{Al})_{\text{sample}}}{(\text{Element} / \text{Al})_{\text{average shale}}}
\]
where the element and aluminum concentrations from this study are divided by the element and aluminum concentrations of the average shale sample (Tribovillard et al., 2006).

Cross-plots of EF-Mo against EF-U illustrate trends associated with the water column stratification and level of basin restriction at the time of deposition (Algeo and Rowe, 2012; Tribovillard et al., 2012). Cross-plots of Mo with TOC represent a directly proportional trend, where high TOC rocks are deposited in paleoenvironments enriched in molybdenum. Additionally, elemental abundances, such as that of phosphorous, nickel, and copper could all indicate high fertility and nutrient levels (e.g., Follmi, 1996; Tribovillard et al., 2006).

**Organic Geochemical Analysis**

With assistance from Dr. Omar Harvey, the organic geochemistry of 20 (2 mg) samples was investigated for total organic carbon content and additional elemental concentrations. Each sample was run twice: first with air and second with nitrogen. The DSC-TGA analyzer was used to heat up each sample from 25°C to 750°C at 10°C /minute, monitoring the weight percent drop in the sample. From 200°C to 600°C, the weight percent drop is due to the amount of organic matter that has burned off. This percentage is called the Total Organic Matter. Total Organic Carbon is then calculated using the following equation:

\[
\% \, TOC = 0.58 \times \% \, TOM
\]

The organic geochemical analyses aided in answering objective questions pertaining to the source potential of the Maness Shale. The TOC values produced in this analysis were used in cross-plots with elemental abundances generated from the ICP-OES/MS.

II.III Well Log Correlation

Using Enverus’ Drilling Info, a database of 350 wells was created for use in mapping the Maness from the Brazos Basin to the East Texas Field (Fig. 11). Three type logs were used in
the study area: Lily Hoppess 1 in Robertson County, Galan White 11 near the Kinney 25 core in Rusk County, and Knowles Estate 1 near the Watson 55 core in Gregg County (Fig. 12). Four horizons, top Maness Shale, Intra-Maness, False Buda, and Top Buda Limestone, were identified on the type logs, when present, and correlated across the study area. Few wells in the area have modern log suites (gamma ray, resistivity, neutron porosity, and density porosity), so this study relied heavily on gamma ray, spontaneous potential, and resistivity logs.

The top of the Buda Limestone has a consistent log response across the study area, where it is a low gamma ray (20-30 API), high resistivity carbonate. The False Buda is an argillaceous limestone stratigraphically above the Buda, but it has a higher gamma ray signature than the underlying limestone. The False Buda is commonly incorporated as part of the Buda, and therefore is usually picked as the Top Buda (i.e. Anderson, 1979; Hentz et al., 2014; etc.), but this study identifies the False Buda as the initial Maness facies. In the southern part of the study area, the False Buda is easily identified as a low gamma ray (50-70 API), high resistivity coarsening upward unit. It cannot be identified in the northern portion of the study area, as further core analysis and a more robust log suite are needed to confirm the lithology. The intra-Maness marker defines the top of the second unit within the Maness. It is a higher gamma ray (75-90 API), lower resistivity shale that is readily identified by a sharp resistivity change at the top. The top of the Maness is defined by the drop in resistivity from the overlying Woodbine to the Maness Shale. Across the axis of the East Texas Basin, this resistivity change is not as apparent, and slight decreases in the spontaneous potential log at the top Maness is also used for correlation.

A total of six cross-sections were constructed: three N-S trending cross-sections and three E-W trending cross-sections (Fig. 13). Cross-section “A” runs N-S in the southern portion of the study area across the Brazos Basin, through the Lily Hoppess type log. Cross-section “B” runs N-S along the axis of the East Texas Basin. Cross-section “C” trends along the western
flank of the Sabine Uplift through the East Texas Field, connecting the Knowles Estate and Galan White type logs near the two cores examined here. Cross-section “D” runs E-W and extends from northern Robertson County to Gregg County, near the Watson 55 core location. Cross-section “E” is E-W and runs from the type log in southern Robertson County to the type area of the Maness in Cherokee County. Cross-section “F” is also E-W oriented and connects previously correlated wells in Burleson County to the study area to Nacogdoches County. Previous studies have constructed relevant cross-sections (Anderson, 1979; Ambrose et al., 2009; Ambrose and Hentz, 2010; Hentz et al., 2014; Denne and Breyer, 2016; Patterson, 2018) and were used as references.
Figure 12. Type logs and tops used in well log correlations in this study. Type log locations are noted on Figure 11. “Man” is the top of Maness, “INT MAN” is the intra-Maness marker, “FB” is the False Buda, and “BUDA” is the top of Buda. Logs courtesy of Enverus.
Figure 13. Map of study area in the East Texas Basin showing locations of cross-sections A-F. Study area is outlined in blue and well control shown by the black dots. Cross-sections constructed are also shown.
III. Results

III.1 Core Description

Core descriptions of both east Texas cores record that the dominant lithology of the Maness in the area is an argillaceous-calcareous mudstone. Millimeter scale observations determined that there is significant vertical variability in grain size, color, concretions, bioturbation, and bedding. Additionally, the contact between the Maness and Buda is vastly different in each core. The following section describes observations that were made for both the Kinney 25 core and the Watson 55 core using the terminology of Lazar et al. (2015).

Kinney 25

The Maness in the Kinney 25 core is at least 28 ft (8.5 m) thick, with core descriptions and core photographs from 3665-3693 ft (Fig. 14) (Appendix A). The majority of the core can be described as a fine to medium mixed mudstone, with varying argillaceous, siliceous, and calcareous proportions. The Maness-Buda contact is at 3693 ft and is transitional from the underlying massive limestone of the Buda to the lower, marly facies of the Maness. The lower 8 ft (2.4 m) of the Maness (3685-3693 ft) consists of this transitional, carbonate-rich unit with alternating packages of light grey, bioturbated marls and copper-colored medium mudstones. The next 12 ft (3.7 m) (3673-3685 ft) are composed of fine to medium mudstones with thinly bedded sandstones, siderite concretions, and phosphate. The upper 8 ft (2.4 m) (3665-3673 ft) consists of lighter colored, bioturbated mudstones with a carbonate-rich marl bed. The Maness-Woodbine contact is not present in the section of the core examined in this study.

The lower Maness transitions from a bioturbated marl in the lowermost 2 ft (0.6 m) of the formation to alternating 0.5 to 1 ft (0.15 to 0.3 m) packages of laminated copper-colored mudstones and marls. One of the distinctive features of the lower Maness is color. The marls are light-grey to dark grey, the darker color indicating bioturbation where organisms brought
down overlying sediment from the mudstones (Fig. 15b). The copper-colored mudrock is typical of the Maness, as described in the type location in Cherokee County (Lozo, 1951), and is first observed at 3691 ft. The mudstones are fine to medium, laminated, and contain phosphate nodules. Additionally, an inoceramid was identified at the base of the Maness at 3693 ft within the marl (Fig. 15a).

There is a significant lithological change at 3685 ft from the calcareous mudstones and marls to iron-rich mudstones. In this interval of the core the mudstones are planar laminated and vary in color from an iron-rich red brown to dark brown or black. They are characterized by an influx of detrital sediment forming sandstone lags and diagenetic components, namely siderite and phosphate. Thin bedded (1 cm), quartz-rich, sandstone lags occur within an 11 ft (3.4 m) vertical section from 3672 to 3683 ft. The fine-sandstone beds are light colored and commonly disturbed in the cored interval (Fig. 15d). Diagenetic siderite concretions are common in the dark brown to black mudstones from 3679 to 3681 ft, often within the mudstones between the sandstone lags. The siderite is a red to red brown color and ranges in shape from rounded nodular concretions to horizontal bed-like concretions (Fig. 15c). Within the same core section, yellow sulfur was also identified. As in the lower Maness, interspersed phosphate was also recorded in the mudrocks (Fig. 15e). Body fossils were not identified within this interval, but plant fragments and fish scales were seen within bedding surfaces.

From 3665 to 3673 ft, the Maness consists of mostly lighter colored, bioturbated, medium mudrocks with a 1 ft (0.3 m) marl at 3670 ft (Fig. 15f). There are only two, very thin (< 1 cm) sandstone beds but they are disrupted and difficult to identify. There are no siderite concretions within this upper section. The mudrocks and marl are moderately bioturbated, much like the lower Maness, and burrows are evident. Additionally, an inoceramid was recorded near the top of the described section at 3665 ft.
Figure 14. Closest well log to Kinney 25 core, Galan White 11 shown to the left. Red box shows the equivalent section that was described in the Kinney 25 core (GR= Gamma Ray; RES= resistivity). Core description based on observations and core photographs is shown to the right. Letters a-f denote locations of core images in Figure 15.
Figure 15. Core photographs of the Kinney 25 core portraying lithological observations. Images correspond to labels on Fig. 14. (a) Inoceramid located at 3693 ft within the basal Maness marl. (b) Bed confined set of conjugate shear fractures within the darker colored mudstone underlying the bioturbated, light grey marl at 3691.5 ft (c) Rounded siderite concretion within the fissile, laminated mudstone at 3680 ft. Yellow is sulfur. (d) Detrital lags (white) deposited within the laminated, argillaceous mudstones at 3679 ft. Gold is pyrite. (e) Phosphate concretion within the copper-colored Maness mudstone at 3677.5 ft. (f) Carbonate bed within the Upper Maness at 3669.75 ft. (In=inoceramid, Sd=siderite, S=sulfur, Py=pyrite, Ph=phosphate).
The Maness in the Watson 55 core is at least 27 ft (8.2 m) thick, with core descriptions and core photographs from 3701-3729 ft (Fig. 16) (Appendix A). There are three sections of core missing within the described interval: 3705.5 to 3707 ft, 3718 to 3719 ft, and 3723 to 3725 ft. The core from 3719 to 3722 ft is present, but is not sufficiently intact to determine sedimentary structures. The majority of the described section is a fine to medium argillaceous-siliceous mudstone. When tested, the core did effervesce, but it was not as reactive to the diluted hydrochloric acid as the Kinney core, therefore, the assumption is that carbonate content is lower in the Watson core. The Maness-Buda contact is at 3728 ft and it is a sharp, planar contact between the underlying massive Buda limestone and the overlying mudrock, denoting a distinct change in clay content. Unlike the Kinney core, no marls were identified in the lower Maness. Instead, the lower 6 ft (1.8 m) (3722-3728 ft) of the Maness is slightly calcareous to argillaceous with silica-rich and iron-rich mudstones. The next 9 ft (2.7 m) (3713-3722 ft) consists of an argillaceous, laminated, fine mudstone. The upper 12 ft (3.7 m) (3701-3713 ft) consists of a grey to brown argillaceous mudstone with significant siderite concretions.

Above the sharp Buda-Maness contact, the lower Maness in this core is a copper to light brown to red-brown, fine to medium mudstone. It is faintly laminated and moderately bioturbated, with horizontal burrows present. Additionally, natural and induced fractures are observed; the natural fractures suggest that there is sufficient carbonate content to enhance the brittleness of the rock within the lower portion of this core (Fig. 17a). No body fossils were identified within this depth range.

From 3713-3722 ft, the Watson core consists of an argillaceous, laminated, fine to medium mudstone. In appearance, the mudrock is similar to the middle section of the Kinney core, although it lacks the presence of the detrital sandstone lags. Phosphate and pyrite concretions are commonly seen in this portion of the core, with the presence of phosphate
increasing up section (Fig. 17c). Although the mudrock is moderately bioturbated and faintly laminated, soft-sediment deformation is apparent at 3714.25 ft (Fig. 17d).

There is a distinct color and grain size shift at 3713 ft from the fine to medium copper-colored mudrocks discussed previously to a light grey, silica-rich medium to coarse mudrock with black plant fragments. The following 6 ft (1.8 m) of the core is an iron-rich, medium mudstone with abundant diagenetic siderite concretions. The siderite is orange-brown to red and differs in structure. Some siderite concretions are planar, with sharp upper and lower contacts (Fig. 17f). Other siderite concretions display more gradual contacts within the mudstone, where it is more dispersed. Phosphate and pyrite nodules as well as clay-lined burrows are commonly present within this section (Fig. 17e). The upper 3 ft (0.9 m) of the core remains an argillaceous mudstone, but siderite, phosphate, and pyrite minerals are not present.
Figure 16. Closest well log to Watson 55 core, Knowles Estate 1, shown to the left (GR = Gamma Ray; RES = resistivity). Red box shows the equivalent section that was described in the Watson 55 core. Core description based on observations and core photographs shown at right. Letters a-f denote locations of core images in Figure 15.
Figure 17. Core photographs of the Watson 55 core portraying lithological and sedimentological observations. Images correspond to labels on Fig. 16. (a) Natural shear fracture at 3726 ft within the argillaceous mudstone (b) Induced centerline and petal fracture at 3725 ft (c) Phosphate concretions within the copper-colored Maness mudstone at 3716.5 ft (d) Soft-sediment deformation at 3714.25 ft. Phosphate is also seen in this core image. (e) Red-colored siderite concretion at 3705 ft. Phosphate and burrows are preserved in the section. (f) Orange-brown siderite concretion with sharp upper and lower contacts at 3704.5 ft. Concretion inclined from right to left. (Ph=phosphate, SSD=soft sediment deformation, B=clay-lined burrows, Sd=siderite).
Lithofacies

The core descriptions identified five recurring lithofacies based on grain type, bedding, bioturbation, concretions, and lithology (Table 3). Lithofacies A-D are within the Maness and lithofacies E is restricted to the Buda (Fig. 18). Lithofacies terminology for A-D is based on XRD mineralogy using the Lazar et al. (2015) nomenclature scheme.

Lithofacies A-C are all mudrocks, but are differentiated based on dominant mineralogy and bedding styles. Lithofacies A is similar to the type description of the Maness from the Maness #1 well in Cherokee County, where it was described as a copper to dark brown argillaceous mudstone. Lithofacies B is an iron-rich, mixed mudstone. Lithofacies C is a clay-rich siliceous mudstone with calcite-cemented detrital lags. Lithofacies D and E are carbonate rich, where lithofacies D is a bioturbated marl and lithofacies E is a massive, fractured limestone representative of the Buda. Lithofacies A-D are supported by XRD mineralogical data.
Figure 18. Lithofacies established from core descriptions of both cores. Lithofacies A is a silica-rich argillaceous mudstone. Lithofacies B is the iron-rich mixed mudstone. Lithofacies C is a clay-rich siliceous mudstone with calcite-cemented sandstones. Lithofacies D is a bioturbated marl. Lithofacies E is a massive limestone, restricted to the Buda.
Table 3: Lithofacies descriptions defined from core descriptions and sample analyses.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Silica-rich argillaceous mudstone</td>
<td>Copper to dark brown color, fine to medium mud, faintly laminated, bioturbated, presence of phosphate and pyrite</td>
</tr>
<tr>
<td>B</td>
<td>Iron-rich mixed mudstone</td>
<td>Red-brown to brown color, fine to medium mud, clay-lined burrows, laminated, calcareous siderite concretions, increase in pyrite and sulfate content</td>
</tr>
<tr>
<td>C</td>
<td>Clay-rich siliceous mudstone with calcite-cemented sandstones</td>
<td>Brown to black color, fine mud, laminated, weakly bioturbated, fine-grained sand with calcite cement within lag</td>
</tr>
<tr>
<td>D</td>
<td>Bioturbated marl</td>
<td>Light grey to light brown color, highly bioturbated, greater than 25% carbonate content, shell fragments</td>
</tr>
<tr>
<td>E</td>
<td>Massive limestone</td>
<td>White to light gray, fractured, bioturbated, only in Buda</td>
</tr>
</tbody>
</table>

III.II  Petrographic Analyses

Examination of the nine thin sections from the Kinney 25 and Watson 55 cores identified five microfacies within the Maness mudstone (Table 4) (Appendix B). Core scans and petrographic analyses using a microscope were both used to distinguish the distinct microfacies assemblages, which are based on grain size and type, bedding styles, and index of bioturbation. When possible, fossil assemblages are included in the microfacies description.
Table 4: Microfacies descriptions defined from thin section and petrographic analyses.

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fossiliferous medium mudstone</td>
<td>Bioturbated; discontinuous, planar to wavy, parallel laminations; diverse faunal assemblage of fish scales, crinoids, forams, and calcispheres; presence of pyrite</td>
</tr>
<tr>
<td>2</td>
<td>Calcite-cemented quartz lag</td>
<td>Highly bioturbated; structureless or no bedding; very fine to fine sand quartz grains cemented within disturbed lag deposit; quartz overgrowths within lag</td>
</tr>
<tr>
<td>3</td>
<td>Interbedded sandstone and argillaceous fine mudstone</td>
<td>Continuous, planar, parallel thin beds of alternating calcite-cemented fine sand sized grains and fine mud; presence of pyritized forams</td>
</tr>
<tr>
<td>4</td>
<td>Indistinctly laminated coarse mudstone</td>
<td>Fine to coarse mud; clay alignment; bioturbated; discontinuous, wavy, parallel laminations</td>
</tr>
<tr>
<td>5</td>
<td>Massive argillaceous mudstone</td>
<td>Churned; internally structureless; medium mud with &lt;10% sand-sized grains; forams filled with pyrite</td>
</tr>
</tbody>
</table>

Microfacies 1 (M1) is a fossiliferous, medium mudstone observed in both cores within Lithofacies A (Fig. 19). It is important to note that M1 is only found in thin sections that are in the lower 10 ft (3 m) of the Maness, close to the Maness-Buda contact. Microfacies 2 (M2) is a calcite-cemented quartz lag, typically restricted to Lithofacies A and C (Fig. 20). The term lag has been used due to the lack of laminations or sedimentary structures associated with the quartz grains. Calcite-cement was identified, as well as quartz overgrowths, within the lags between the very fine sand grains. Microfacies 3 (M3) is an interbedded sandstone and argillaceous medium mudstone (Fig. 21). M3 is differentiated from M2 based on the planar laminations that are present within this microfacies, although both show calcite cementation. M3 is restricted Lithofacies C in the Kinney core. Microfacies 4 (M4) is an indistinctly laminated coarse mudstone (Fig. 22). Wavy, discontinuous laminations are present, observed specifically
from the parallel clay alignment in the thin section from the Kinney core at 3683.25 ft. It is restricted to the Kinney core and only observed within Lithofacies A. Microfacies 5 (M5) is a massive argillaceous mudstone within Lithofacies B (Fig. 23). In core and thin section, the red-brown color is significant, potentially indicating the presence of iron within the sediment. M5 is structureless due to the complete churning of this mudrock as a result of intense bioturbation.
**MICROFACIES 1 (M1)**

![Figure 19](image19)

*Figure 19. Microfacies 1 – Scanned image of thin section with reflected light (RL) and photomicrograph with transmitted light (TL) from Watson 3725 ft, both displaying a fossiliferous medium mudstone. Yellow box displays location of microscope image. (0.25" = 0.64 cm and 200 µm = 0.2 mm)*

**MICROFACIES 2 (M2)**

![Figure 20](image20)

*Figure 20. Microfacies 2 – Scanned image of thin section with transmitted light (TL) and photomicrograph with transmitted light (TL) from Watson 3717.5 ft, both displaying a calcite-cemented quartz lag. Yellow box displays location of microscope image. (0.25" = 0.64 cm; 200 µm = 0.2 mm)*

**MICROFACIES 3 (M3)**

![Figure 21](image21)

*Figure 21. Microfacies 3 – Scanned image of thin section with reflected light (RL) and photomicrograph with transmitted light (TL) from Kinney 3687 ft, both displaying interbedded sandstones and argillaceous fine mudstone. Yellow box displays location of microscope image. (0.25" = 0.64 cm and 200 µm = 0.2 mm)*
**MICROFACIES 4 (M4)**

![Image of thin section with transmitted light (TL) and photomicrograph with transmitted light (TL) from Kinney 3683.25 ft, both displaying an indistinctly laminated coarse mudstone. Yellow box displays location of microscope image.](image1.png)

**Figure 22.** Microfacies 4 – Scanned image of thin section with transmitted light (TL) and photomicrograph with transmitted light (TL) from Kinney 3683.25 ft, both displaying an indistinctly laminated coarse mudstone. Yellow box displays location of microscope image. (0.25" = 0.64 cm and 200 μm = 0.2 mm)

**MICROFACIES 5 (M5)**

![Image of thin section with transmitted light (TL) and photomicrograph with transmitted light (TL) from Watson 3716.3 ft, both displaying a massive argillaceous mudstone. Yellow box displays location of microscope image.](image2.png)

**Figure 23.** Microfacies 5 – Scanned image of thin section with transmitted light (TL) and photomicrograph with transmitted light (TL) from Watson 3716.3 ft, both displaying a massive argillaceous mudstone. Yellow box displays location of microscope image. (0.25" = 0.64 cm and 200 μm = 0.2 mm)
III. III Biostratigraphic Analyses

Macrofossils were identified in core and in thin section analysis (Fig. 24). Inoceramids were identified in the Kinney 25 core at 3665 ft, near the top of the described section, and at 3693 ft, near the Maness-Buda contact. They were also observed in thin section. A fish scale and *sacoccomid* swimming crinoid were identified in the thin section at 3725 ft in the Watson core. The fish scale is round with a diameter of about 0.5 mm. The swimming crinoid has a circular center stem with four limbs. In addition, mollusk fragments were observed in the Kinney core at 3683.25 ft and 3687 ft, while filaments were present at 3711 ft in the Watson core and 3682.5 ft in the Kinney core. The filaments are thin and curved, providing shelter porosity underneath.

Planktonic foraminifera were identified in the Kinney core from washed residue samples and in both cores from thin section analysis (Appendix C). The planktonic marker species for the Maness that were identified in the washed residue samples include *Favusella washitensis* and *Thalmaninnella globotruncanoides* (Fig. 25). Both species went extinct during the Early Cenomanian within the planktonic foraminifera *Thalmaninnella globotruncanoides* Zone (Ogg and Hinnov, 2012; Denne et al., 2016a). The *F. washitensis* specimens were found in the Kinney core at 3691 and 3674 ft, whereas *T. globotruncanoides* was identified at 3691 and 3680 ft (Fig. 25). *Muricohedbergella planispira*, *Planoheterohelix moremani*, and *Whiteinella* species were also found in the washed residue samples. Thin section analysis identified keeled forms of *rotaliporid* species (likely Thalmaninnela) and specimens of non-keeled forms *Hedbergella* and *Heterohelix* (Fig. 26). Overall, planktonic foraminifera are more abundant in the lower part of the Maness and less frequent in the upper part of the Maness based on results from both washed residue and thin section samples.

Benthic foraminifera include both calcareous and agglutinated types. Ten calcareous benthic foraminifera genera were identified in the washed residue samples, including *Gyroidina*
and *Lenticulina*, which were found in all examined samples (Fig. 25). An agglutinated benthic marker for the Maness, *Textularia washitensis*, was identified in a thin-section from 3665.5 ft in the Kinney core (Fig. 26). *Textularia* specimens were also identified in washed residue samples at 3674, 3677, and 3691 ft. Additional agglutinated benthic genera include *Ammobaculites* and *Hyperammina/Flabellammina*. The agglutinated forms are commonly clay or silt-lined and many specimens are pyritized. Benthic foraminifera are present throughout the Maness.

Other microfossils identified in this study include ostracods, calcispheres, echinoid fragments, and bivalves (Fig. 25). Ostracods were identified in the Kinney core in most washed residue samples and thin sections. Calcispheres are common in the Maness, and were identified in the washed residue sample at 3691 ft in the Kinney core, where they are present in abundance. This sample is from the lower marl near the Buda-Maness contact. Furthermore, echinoid fragments and bivalves are also present in most of the washed residue samples.

Calcareous nannofossils were identified in the Kinney 25 core from 3665.5 to 3691 ft and in the Watson 55 core from 3707 to 3725 ft. The most diverse assemblage of calcareous nannofossils was discovered in the Watson core at 3725 ft near the Maness-Buda contact (Fig. 27). *Nannoconus fragilis* was identified in both cores, at 3672 and 3691 ft in the Kinney well and 3725 ft in the Watson well. Nannoconids are abundant within the False Buda of the Maness, but are absent from the underlying Buda and within the clay-rich intervals of the Maness and Eagle Ford (Denne et al., 2016). *Nannoconus fragilis*, along with *Braarudosphaera africana* and *Cylindralithus sculptus*, are age-diagnostic calcareous nannofossils for the Early Cenomanian, based on their top and base occurrences. Additionally, Cenomanian markers *Axopodorhabdus albianus* and *Rhagodiscus asper* were also identified.
Figure 24. Macrofossils identified in thin section. A. Inoceramids in both images, Kinney 3665.5 ft (bar= 200 μm); B. Mollusk, Kinney 3683 ft (bar= 100 μm); C. Shell fragment, Watson 3725 ft (bar= 100 μm); D. Fish Scale, Watson 3725 ft (bar= 200 μm); E. Saccocomid, Watson 3725 ft (bar= 200 μm).
Figure 25. Photomicrographs of microfossils identified in the washed residue samples from the Kinney 25 core. A. *Gavelinella petita* calcareous benthic foraminifera, 3674 ft (scale bar= 100 µm); B. *Lenticulina* spp. calcareous benthic foraminifera, 3674 ft (scale bar= 250 µm); C. *Textularia rioensis* agglutinated benthic foraminifera, 3674 ft (scale bar= 100 µm); D. Bivalve, 3674 ft (scale bar= 250 µm); E. Echinoid spine, 3674 ft (scale bar= 100 µm); F. *Thalmaninnella globotruncanoides* planktonic foraminifera, 3680 ft (scale bar= 100 µm); G. Ostracod, 3680 ft (scale bar= 100 µm); H. *Favusella washitensis* planktonic foraminifera, 3691 ft (scale bar= 100 µm); I. Calcispheres, 3691 ft (scale bar= 250 µm).
Figure 26. Microfossils identified in thin section. A. *Hedbergella* non-keeled planktonic foraminifera, Kinney 3665 ft, TL, (bar= 50 µm); B. *Textularia washintensis* agglutinated benthic foraminifera, Kinney 3665 ft, TL, (bar= 50 µm); C. Ostracod microfossil, Kinney 3665 ft, TL, (bar= 50 µm); D. *Rotalid* keeled planktonic foraminifera, Kinney 3672 ft, TL, (bar= 50 µm); E. Pyritized calcareous benthic foraminifera, Watson 3716.3 ft, XPL, (bar= 100 µm); F. Agglutinated coiled benthic foraminifera, Watson 3725 ft, TL, (bar= 200 µm).
Figure 27. Calcareous Nannofossil assemblage in Watson core 3725 ft (Scale bar= 10 µm). A. *Braarudosphaera africana* B. *Cylindralithus sculptus* C. *Axopodorhabdus albianus* D. *Nannoconus fragilis* E. *Rhagodiscus asper*. 
III.IV XRD Mineralogical Analyses

XRD analysis was performed on six samples from each of the cores (Appendix D). The selected samples targeted different lithologies that were observed during core descriptions. Organic geochemistry, biostratigraphy, and elemental analysis were run on most of the same samples to confirm the findings. The minerals identified include quartz, feldspar, microcline and albite, high-magnesium calcite, sulfates, mica, illite, and kaolinite (Fig. 28).

The average composition of the Maness in east Texas is 36% clay, 35% quartz, and 18% calcite. The remaining 11% consists of the feldspars microcline and albite, ranging from 0-15%, as well as sulfates, ranging from 0-20.2%. The clays consist of illite+mica and kaolinite, accounting for 63% and 37% of the average total clay content respectively. Mineralogy differs between the two cores. The average composition of the Kinney 25 Maness is 37% quartz, 28% clay, and 24% calcite, with 11% minor minerals. Microcline accounts for 6%, whereas sulfates account for 5% of the minor mineral fraction. Illite+mica is 17% compared to 11% kaolinite. The average composition of the Watson 55 Maness is 44% clay, 35% quartz, and 12% carbonate, with 9% consisting of minor minerals. The feldspar content here is roughly 1% and the sulfate content average is 7%, but reaches as high as 20% in some samples. The illite+mica fraction is 29% and the kaolinite fraction is 15%. When mineralogical data from both cores is plotted on a Qtz-carb-clay ternary diagram, it is evident that the Watson core is overall significantly more clay-rich, whereas the Kinney core has greater silica and carbonate proportions (Fig. 29a).

Mineralogical compositions were necessary for defining lithofacies assemblages in this study due to the lack of variability within the mudrocks observed in core. Lithofacies A-D are supported by XRD mineralogical data and were classified based on the nomenclature scheme of Lazar et al. (2015). The XRD data points were plotted on a Qtz+Feld-Carb-Clay ternary diagram to identify patterns amongst the samples and compare mineralogical results to facies descriptions (Fig. 29b). This methodology discerned three clusters of data points, corresponding
to Lithofacies A, C, and D. One data point, representative of Lithofacies B, plotted near Lithofacies D, due to the high carbonate content associated with the presence of diagenetic siderite in this sample. Lithofacies A has an average composition of 34\% \text{ qtz+feld}, 8.7\% carbonate, and 53.4\% clay and is an argillaceous mudstone. Lithofacies B consists of 30.9\% qtz+feld, 25.8\% carbonate, 23.1\% clay, and is classified as a mixed mudstone. Lithofacies B also contains 20.2\% other minerals, namely sulfate, which skews its location on the ternary diagram. Lithofacies C has an average composition of 53.2\% qtz+feld, 11.6\% carbonate, and 29.4\% clay, classifying it as a siliceous mudstone. Lastly, Lithofacies D is 36.5\% qtz+feld, 31\% carbonate, and 27\% clay. Nomenclature for this mineralogical composition is variable, but in accordance with core observations, this study opted to refer to Lithofacies D as a marl.

Mineralogy varies vertically throughout the sampled section in both cores, establishing patterns for silica, carbonate, and clay content (Fig. 28). Silica content generally increases from the Buda-Maness contact to the mid-Maness in both cores. The greatest silica content is at 3673.5 ft in the Kinney core and at 3717.5 ft in the Watson core. Above these depths, silica content slightly decreases. Conversely, the carbonate trend decreases upward, with the exception of the marl at 3671 ft in the Kinney core. Lastly, clay content is relatively consistent throughout the Maness. There is a slight decrease in clay content at 3717.5 ft in the Watson core, coinciding with the increase in silica.
Figure 28. Mineral abundances from XRD provided by the Shimadzu Institute at UT-Arlington for the Kinney 25 (top) and Watson 55 (bottom) cores. Weight percent is plotted vs depth to illustrate lithological changes.
Figure 29. Ternary diagrams of the XRD mineral composition. A) XRD results for Kinney and Watson cores. Dark Green is Watson and light green is Kinney. B) Ternary diagram plotting the four lithofacies that were supported by XRD data. Grey markers represent Lithofacies A. Yellow marker represents Lithofacies B. Green markers represent Lithofacies C. Blue markers represent Lithofacies D. Ternary diagram modified from Lazar et al. (2015).
III.V ICP-OES/MS Elemental Analyses

Major Elements

The major elements derived from the ICP-OES analyses used in the geochemical plots include aluminum (Al), calcium (Ca), silicon (Si), iron (Fe), sulfur (S), phosphorous (P), and potassium (K) (Appendix E). For both cores, elemental weight percentages were plotted against depth to determine elemental shifts throughout the Maness (Fig. 30). Most of the major elements followed similar trends in both cores, particularly Al, Si, and K. Conversely, Ca, Fe, S, and P differ immensely in both cores. Ca is greater than 20% in both cores in the lower samples, but then decreases upward. In the Watson core, Ca remains low in the upper 8 ft (2.4 m) of the core, whereas it increases to ~15% in the Kinney core. Fe and S mostly mirror each other, but there is a significant increase in both of these elements in the Watson 55 core at 3709 ft. Weight percent for P varies from 0.02-0.05 wt% for the majority of the Maness in both cores, except at 3680 ft in the Kinney core where P spikes to over 2 wt%. There is also a slight P increase in the Watson core within the same portion of the Maness.

Cross-plots of major elements from both cores were constructed to determine patterns and associations, as well as to constrain mineralogy from the XRD analysis to associated elements. Aluminum is commonly plotted against major elements, as it is a standard for normalization as well as a proxy for clay. Al has positive linear relationships with K, Si, and Ti, but shows a negative correlation with Ca (Fig. 31). Al has higher R² values with respect to both K and Ti, most likely due to the mica and feldspars containing K and the detrital origin of both Al and Ti. Ca and Al have a negative linear relationship as does Ca and Si. Furthermore, there is no linear relationship between Al and Fe or P.

XRD and ICP data can be used in unison to further confine the minerals associated with each element. For this study, Al was plotted against the total clay content, K was plotted against
the illite+muscovite clays, Si was plotted against quartz, and Ca was plotted against calcite (Fig. 32). All cross-plots show positive linear relationships, with the carbonate having the best correlation with a $R^2$ of 0.97. ICP data is also compared to XRD data by plotting the bulk geochemical results on a ternary diagram with CaO - Al$_2$O$_3$ - SiO$_2$ end members (Fig. 33). This compares the samples in this study to the average shale sample, showing that the Maness is more silica and carbonate rich than the average shale defined by Wedepohl (1991). Additionally, the bulk geochemical ternary diagram shows overall trends that are similar to those found in the ternary diagram for the XRD data (Fig. 29; 33).
Figure 30. Depth plots of major elements from ICP-OES. Major elements shown here include Aluminum (Al), Silicon (Si), Calcium (Ca), Iron (Fe), Sulfur (S), Phosphorous (P), and Potassium (K). All major elements are shown in weight percent (wt%). A. Major elements from samples in the Kinney core. B) Major elements from the Watson core.
Figure 31. Aluminum and silica plotted against other major elements from ICP-OES data. Blue data points are for the Kinney core and orange dots are for the Watson core. Linear regression lines and r squared values are denoted for all charts except Al vs Phosphorous. A. Aluminum vs Calcium. B. Aluminum vs Potassium. C. Aluminum vs Silica. D. Aluminum vs Titanium. E. Aluminum vs Iron. F. Aluminum vs Phosphorous. G. Silica vs Calcium. H. Silica vs Potassium.
Figure 32. XRD mineralogy plotted on the x-axis versus the ICP-OES elemental data plotted on the y-axis to compare both techniques. A. Total clay content from XRD plotted with aluminum content from ICP analysis. Aluminum is considered a proxy for clay. B. Illite fraction of the clay content plotted against potassium. C. Calcite percentage, from XRD data, plotted against calcium. D. Quartz content from XRD plotted with silica content from elemental data.
Figure 33. Ternary diagram of calcium (CaO x 2), aluminum (Al$_2$O$_3$ x 5), and silicon (SiO$_2$) from ICP-OES data. Dark green data points are from the Watson core and light green are from the Kinney core. The average shale from Wedepohl (1971) that was used for calculation of enrichment factors is plotted in grey.
Trace Elements

The trace elements used in geochemical and paleoredox plots include uranium (U), vanadium (V), thorium (Th), molybdenum (Mo), nickel (Ni), chromium (Cr), zinc (Zn), copper (Cu), and manganese (Mn) (Appendix E). Trace elements were also plotted against depth to determine elemental variability in the Maness (Fig. 34). The trace elements closely mirror their trends in both cores, with the most variability in the upper section. From 3707-3712 ft in the Watson core and from 3665-3673 ft in the Kinney core, U, Mo, Zn, and Co have higher concentrations in the Watson core, whereas Mn, Cr, and Ni have greater concentrations in the Kinney core.

Due to the fluctuating carbonate content throughout the core, trace elements were normalized to the aluminum content, producing the enrichment factor (EF) for each element compared to the average shale (Wedepohl, 1991). If the enrichment factor is >1, then the element is enriched relative to the average shale. If the EF is <1, then the element is depleted in relation to the average shale (Tribovillard et al., 2006). For trace element analysis, enrichment factors are used, therefore they were also plotted against depth (Fig. 35). Most of the trace elements are depleted in the Kinney core, with only a slight enrichment in U at 3690.5 ft. At that same depth, Mo, Ni, Mn, Zn, and Co are all elevated relative to their average concentrations, but they are not enriched. The Watson core is enriched in U, Mo, Zn, and Co at 3709 ft, accompanied by a slight enrichment in V. At this depth, the U-EF is 56 compared to the 0.25-0.75 U-EF enrichment in the rest of the core.

Trace elements from detrital sources cannot be used for paleoenvironmental analysis, therefore it is important to determine which trace metals are of detrital provenance. Aluminum is a proxy for clay content, but it can also be used as a proxy for detrital input since it is often from a detrital source and is also immobile during diagenesis (e.g., Calvert and Pedersen, 1993; Tribovillard et al., 1994; Hild and Brumsack, 1998; Boning et al., 2004; Tribovillard et al., 2006).
Trace metals with good correlation to aluminum and close concentrations to the average shale are most likely of detrital input, usually elements such as Cr, U, Ba, and rarely V and Mo. For this study, an $R^2$ value of 0.75 or greater is considered detrital and was not used in further analysis for paleoredox conditions. Cross-plots determined that Cr, Th, and V are part of the detrital flux (Fig. 36). Ni was correlated slightly, but may be more of a mixed origin. Mo, Mn, Ba, and U had no correlation.
Figure 34. Depth plots of trace elements from ICP-MS. Trace metals shown here are Uranium (U), Vanadium (V), Molybdenum (Mo), Nickel (Ni), Chromium (Cr), Manganese (Mn), Zinc (Zn), and Cobalt (Co). All trace metal concentrations are in parts per million (ppm). A. Trace metals for samples in the Kinney core. B) Trace metals for samples from the Watson core.
Figure 35. Depth plots of enrichment factors (EF) of trace elements from ICP-MS. Trace metals shown here are Uranium (U), Vanadium (V), Molybdenum (Mo), Nickel (Ni), Chromium (Cr), Manganese (Mn), Zinc (Zn), and Cobalt (Co). A. EF of trace metals for samples in the Kinney core. B) EF of trace metals for samples from the Watson core.
Figure 36. Detrital plots of aluminum concentration against trace metals and select major elements that are commonly associated with detrital flux. Blue data points are for the Kinney core and orange dots are for the Watson core. Linear regression lines and r squared values are denoted. Aluminum content is in wt%. Other elements are in parts per million (ppm) unless otherwise noted. A. Aluminum vs Chromium. B. Aluminum vs Thorium. C. Aluminum vs Vanadium. D. Aluminum vs Nickel. E. Aluminum vs Molybdenum. F. Aluminum vs Uranium. G. Aluminum vs Barium (wt%). H. Aluminum vs Manganese (wt%).
Chemostratigraphy was used to correlate the Kinney and Watson cores based on major and trace elemental characteristics (Figs. 37-38). Three chemostratigraphic zones were defined based on similar patterns that were detected from the elemental depth plots for each core (Table 5). The three zones separate the Maness into three intervals: Lower Maness (Zone 1), Middle Maness (Zone 2), and Upper Maness (Zone 3).

Table 5. Major and trace elemental characteristics defined in the chemostratigraphic zones

<table>
<thead>
<tr>
<th>Zone</th>
<th>Major Elements</th>
<th>Trace Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (Upper Maness)</td>
<td>Low Al, Si, K, P; variable Ca, Fe, S</td>
<td>Enrichment in U, Mo, Zn, and Co in Watson core; slight increase in EF’s in Kinney core</td>
</tr>
<tr>
<td>2 (Middle Maness)</td>
<td>Low Ca; High Al, Si, Fe, S, and K; spike in P</td>
<td>No enrichment</td>
</tr>
<tr>
<td>1 (Lower Maness)</td>
<td>High Ca; Low Si, Al, Fe, S, P, K</td>
<td>No enrichment, except slight U-EF; Higher EF’s for U, Mo, Mn, Cr, and Co than zone 2</td>
</tr>
</tbody>
</table>

Zone 1 corresponds to the Lower Maness, where Ca has the highest concentration, and Si, Al, Fe, S, P, and K are all relatively low in concentration. Trace metals are mostly depleted in Zone 1, with the exception of a slight enrichment in uranium. The top of Zone 1 is defined by an increase in most major elements except Ca, and a decrease in most trace metal EF’s. Zone 2 is the thickest zone, and exhibits an increase in Al, Si, Fe, S, and K, and a decrease in Ca. In both cores, there is a ~5 ft (1.5 m) interval of P enrichment, which is greater in the Kinney core and more subtle in the Watson core. Conversely, Fe amounts are higher in this interval within the Watson core. Above this interval, the zone resumes its typical geochemical signatures. The top
of Zone 2 is marked by a decrease in Al, Si, K, and P and an increase in EF’s, which defines Zone 3. There are distinct differences in Ca, Fe, and S between the two cores. The Watson core has higher percentages of Fe and S, whereas the Kinney core has a higher Ca concentration. Both observations are supported by core analysis. The Kinney core has a marl within the upper 5 ft (1.5 m) of the core, leading to the increase in Ca, whereas the Watson core is siderite and pyrite rich within this interval. Zone 3 also marks the highest EF’s of the core, especially in the Watson core where U, Zn, and Co are enriched and Mo is highly enriched with an enrichment factor of 56. EF’s increase in the Kinney core in Zone 3 compared to Zone 2, but they are not above 1.
Figure 37. Chemostratigraphic zones defined by elemental data for the Kinney core. Major elements are shown in weight percent (wt%), trace elements V, Ni, and Cr are shown in ppm, and the enrichment factor of U, Mo, Mn, Z, and Co are shown. The Lower Maness is zone 1 (in blue), the Mid Maness is zone 2 (in green), and the Upper Maness is zone 3 (in orange).
Figure 38. Chemostratigraphic zones defined by elemental data for the Watson core. Major elements are shown in weight percent (wt%), trace elements V, Ni, and Cr are shown in ppm, and the enrichment factor of U, Mo, Mn, Z, and Co are shown. The Lower Maness is zone 1 (in blue), the Mid Maness is zone 2 (in green), and the Upper Maness is zone 3 (in orange).
III.VI Organic Geochemistry Analyses

Total organic carbon data was collected for 17 samples, 5 from the Watson core and 12 from the Kinney core (Appendix F). TOC values were derived from the total organic matter percentages determined by the DSC-TGA analyzer. TOC values range from 1.65% to 3.83% across both cores. The Watson core has the highest TOC values, as all five data points have TOC greater than 2%. In the Kinney core, the lowest TOC values are within the transitional Maness above the Buda-Maness contact. Data from both cores show similar trends when plotted versus depth, with lower TOC in the basal Maness, higher TOC in the middle, mudrock prone Maness, and lower TOC in the upper portions of the Maness (Fig. 39).

Enrichment of Ni, Cu, Mo, U, and V are typically cross-plotted with TOC to determine correlations and patterns between trace metals and the organic carbon in the system (Fig. 40). EF-Ni and EF-Cu plot linearly with TOC, with relatively good correlation, whereas EF-Mo, EF-V, and EF-U do not correlate as well.
Figure 39. Total organic carbon values with depth (ft) in each core. TOC values were calculated from the total organic matter determined by the DSC-TGA analyzer.
Figure 40. TOC (%) plotted against enrichment factors of uranium (A), molybdenum (B), Copper (C), nickel (D), and vanadium (E). Linear regression lines shown in some graphs with $R^2$ values. Blue dots are Kinney samples and orange dots are Watson samples.
III.VII Well Log Correlations and Maps

Three type logs were used as benchmarks to correlate the highly variable Maness mudrock across abundant facies changes from the Brazos Basin, across the axis of the East Texas Basin, to the East Texas Field (Fig. 12). Four horizons were correlated across the study area, when present, to construct cross-sections connecting key wells from the Brazos Basin to the type wells near the cores examined in this study (Figs. 41-44). The four horizons are the top of the Buda, the top of the False Buda, the intra-Maness marker, and the top of the Maness. Structure maps were created for the top of the Buda (Fig. 45) and the top of the Maness (Fig. 46), and isopach maps were constructed for the top of the Maness to top of the Buda interval (Fig. 47) and the False Buda to the top of the Buda interval (Fig. 48).
Figure 41. Cross section “A” from the Lily Hoppess type log in eastern Robertson County to Sanders 1 well in northern Burleson County. The top of the Buda is royal blue, the top of the False Buda marl facies of the Maness is light blue, the intra-Maness marker is dark green, and the top of the Maness is lime green. Only this cross-section shows the “Rabbitt Ears” marker which is in coral. This is a limestone couplet that is present in the Brazos Basin. Cross-section location from A to A’ is shown on the map.
Figure 42. Cross section “B” trending N-S from Anderson County to southern Houston County. The top of the Buda is royal blue, the top of the False Buda marl facies of the Maness is light blue, the intra-Maness marker is dark green, and the top of the Maness is lime green. The False Buda pinches out to the south and is not correlated to the Abbey Road 1R well in Houston County. Cross-section location from B to B’ is shown on the map.
Figure 43. Cross section “C” trending along the western flank of the Sabine Uplift from the Knowles Estate 1 well near the Watson core in Gregg County, through the Galan White 11 well near the Kinney core in Rusk County, to Nacogdoches County. The top of the Buda is royal blue, the intra-Maness marker is dark green, and the top of the Maness is lime green. False Buda is not correlated in this area. Cross-section location from C to C’ is shown on the map. Knowles Estate 1 Type log location is shown by yellow marker and the Galan White 11 type log location is shown by green marker.
Figure 44. Cross section “D” trends east-west extending from Robertson county, through the Lily Hoppess type log in eastern Robertson County, to Rogers 1 well in Rusk County. The top of the Buda is royal blue, the top of the False Buda marl facies of the Maness is light blue, the intra-Maness marker is dark green, and the top of the Maness is lime green. The False Buda pinches out to the west. Cross-section location from D to D’ is shown on the map. Lily Hoppess 1 type log location is shown by the red marker.
The top of the Buda ranges in depth from -2500 to -11,000 ft (-610 to -3353 m) subsea true vertical depth (SSTVD) within the study area (Fig. 45). The deepest part of the study area is in the Brazos Basin, within Madison, Brazos, and southern Houston counties. To the north of the Brazos Basin, across the Houston Arch, is the East Texas Salt Basin, where depths range from -6000 to -6500 ft (-1829 to -1981 m) near the axis of the basin to -3000 to -3500 ft (-914 to -1067 m) in the East Texas Field along the western flank of the Sabine Uplift. The top of the Maness structure map recognizes the same structural features that are seen in the Buda structure map (Fig. 46). Depths range from -2000 to -10,500 ft (-610 to -3200 m) SSTVD in the study area, with the greatest depths in the Brazos Basin and the shallowest depths in the East Texas Field.
Figure 45. Top of the Buda Limestone structure map with a 1000 ft contour interval. Main structural features of are superimposed, including the Brazos Basin (green), the East Texas Salt Basin (blue), and the Sabine Uplift (brown). The axis of the East Texas Basin is shown in red. The Edwards Reef Trend and Mexia-Talco Fault Zone bound the Greater East Texas Basin to the south and the west respectively. The Houston Arch is shown, separating the East Texas and Brazos basins. Core locations are shown.
Figure 46. Top of the Maness structure map with a 500 ft contour interval. The general trend of the Maness structure map mirrors the Buda structure map with some variability within the axis of the basin, which is shown in red. The Edwards Reef Trend and Mexia-Talco Fault Zone bound the Greater East Texas Basin to the south and the west respectively. Core locations are shown.
The top of the Buda has a consistent log signature across the study area as a low gamma ray, high resistivity carbonate. The influx of siliciclastic sediment following Buda deposition marks the onset of the Maness Shale in the East Texas and Brazos basins. The thickness of the Maness ranges from <10 ft (<3 m) along the western flank of the Sabine Uplift in Rusk County to 160 ft (48.7 m) in Leon County (Fig. 47). The thickest Maness is oriented NE-SW within Leon and Houston counties, but the thickness trend also continues to the south with at least 90 ft (27 m) of Maness in Robertson County. Specifically, the Maness at the Lily Hoppess #1 type log in Robertson County is 118 ft (36 m) thick. From the Lily Hoppess in Robertson County to the south, the Maness thins to <50 ft (15 m) in Brazos and Grimes counties (Fig. 41). The Maness also thins onto the Sabine Uplift, where it is 38 ft (11.6 m) thick at the Galan White #11 well near the Kinney core and 30 ft (9 m) thick at the Knowles Estate #1 well near the Watson core (Fig. 43).

The basal facies of the Maness in the southern part of the study area is informally known as the False Buda. The False Buda has a higher gamma ray, lower resistivity signature than the Buda, but it is also distinctly different from the high gamma ray, low resistivity signature of the overlying mudrocks of the Maness (Fig. 41). The False Buda was correlated from Burleson County to Leon County, but it was not identified to the east of the basin axis. The False Buda has a thickness ranging from 0 to 80 ft (0 to 24.4 m) in the study area, with the thickest False Buda in Leon County (Fig. 48). The isopach map shows that the thickest False Buda aligns with the thickness trend of the overall Maness, and also shows the continuation of the False Buda to the southwest. The False Buda thins to the east, south, and north, where it either pinches out or has not been identified in this or any previous study.
Figure 47. Isopach map of the Maness, from the top of the Maness to the top of the Buda. The basin axis is shown in red and core locations are shown, the light green star showing the Watson core and dark green star showing Kinney core. Contour interval is 10 ft (3 m). Current study area is shown by the blue polygon.
Figure 48. Isopach map of the False Buda facies of the Maness. The basin axis is shown in red and core locations are shown, the light green star showing the Watson core and dark green star showing Kinney core. Contour interval is 10 ft (3 m). Current study area is shown by the blue polygon.
Cross-section “D” extends from Robertson County to Rusk County, correlating the Maness along dip (Fig. 44). With the Buda as the datum, it confirms the thickness trends on the isopach and the conclusion that the Maness thickens in Leon County before thinning to the northeast. Additionally, it makes it evident that there are facies changes within the Maness and the overlying strata. This interpretation was also made by Anderson (1971) in correlations across Leon County.

The Maness isopach map constructed in this study was combined with Maness isopach maps from Patterson (2018) and Denne and Breyer (2016) to create a continuous Maness isopach from the East Texas Field to Atascosa County in south Texas (Fig. 49). In areas where there was overlap between studies, the correlations from the current study took precedence. The thickest Maness accumulated to the north of the Brazos Basin. South of the Brazos Basin, the Maness has an elongated thickness pattern, following the trend of the Gonzales-Karnes trough before reaching its depositional extent in southern Karnes County. The isopach map implies that the Maness is sourced from the north-northeast of the study area based on the thickness trend and the thinning of the Maness to the south.
Figure 49. Composite Maness isopach map from east Texas to south Texas, incorporating isopach maps from Patterson (2018), Denne and Breyer (2016), and the current study. Structural features such as the San Marcos Arch (purple), the Houston Arch (blue), and the axis of the East Texas Basin (red) are shown. The Karnes and Gonzales troughs are also shown in South Texas. Core locations from the current study are shown by the green stars, the light green is the Watson core and the dark green is the Kinney core.
IV. Discussion

IV.I Chronostratigraphy

Hypothesis 1 stated that the Maness in east Texas is age-correlative to the Maness in south Texas. Near the San Marcos Arch, impressions of the ammonite *Euhystrichoceras adkinsi* were found on bedding planes in multiple cores (Denne et al., 2016; Patterson, 2018). This ammonite species is a marker for the *Acompsoceras inconstans* ammonite zone, age-dating the Maness as Early Cenomanian, ranging from 97.25-96.8 Ma (Cobban and Kennedy, 1989).

No ammonite impressions were found in this study, so top (TO) and base (BO) occurrences of foraminifera and calcareous nannofossils were used to constrain the age of the Maness. The calcareous nannofossil zonation scheme of Denne et al. (2016) uses three calcareous nannofossil datums that were identified in this study; the top occurrences of *Nannoconus fragilis* and *Braarudosphaera africana*, both of which went extinct during the Early Cenomanian, and the base occurrence of *Cylindralithus sculptus*, which evolved during the Early Cenomanian. Therefore, the *B. africana* TO and the *C. sculptus* BO constrain the Maness to 97.3-96.45 Ma (Fig. 50).

The upper age range of the Maness was further constrained using foraminifer datums for the benthic *Textularia washitensis* and the planktonic *Favusella washitensis*. Both of these species went extinct at approximately 96.7 Ma, therefore the TO’s of these marker foraminifera were used rather than the TO of the calcareous nannofossils to constrain the Maness to 97.3-96.7 Ma, within the Early Cenomanian (Fig. 50). The nominate species for the Early Cenomanian planktonic foraminifer *Thalmaninnella globotruncanoides* Zone was also identified in several samples, providing additional evidence for an Early Cenomanian age for the Maness. Based on biostratigraphy, the Maness in east Texas is age-equivalent to the Maness in south Texas, therefore it is possible to compare data in this study to results from previous studies of the same interval.
Figure 50. Biostratigraphic zonation of Denne et al. (2016) for Eagle Ford and Woodbine Groups that was used to determine the Maness age-range based on foraminifera and calcareous nannofossils identified in this study. The blue arrow shows the TO for *Braarudosphaera africana* and the orange arrow shows the TO for *Nannoconus fragilis*, both of which were found in this study. The green arrow shows the TO for *Favusella washitensis* and the purple arrow shows the BO for *Cylindricalithus sculptus*. The age-range of the East Texas Maness is constrained to 97.3 to 96.7 Ma, shown by the green box. The age-range of the Maness of the San Marcos Arch is constrained to 97.25-96.8 Ma based on ammonite biostratigraphy (Denne et al., 2016), shown by the blue box. The timescale is from Gradstein et al. (2012), planktonic foraminifer zonation and datums are from Robaszynski and Caron (1995), calcareous nannofossil datums are from Burnett (1998), inoceramid zones are from Cobban et al. (2016), and ammonite zones are from Hancock et al. (1993) and Cobban et al. (2008).
IV.II Paleoceanography

Biostratigraphy, ichnofacies, and geochemistry were used to interpret paleoenvironmental conditions of the East Texas Basin during Maness deposition. The trace elements of uranium, vanadium, and molybdenum are commonly used as proxies for paleoredox conditions, since they are soluble under oxidizing states and less soluble under reducing states, causing them to be enriched in authigenically formed sediments in low oxygen conditions (Tribovilliard, 2006; Denne et al., 2014). Nickel, copper and the abundance of planktonic foraminifera and calcispheres are used as fertility and productivity proxies to further interpret paleoenvironmental conditions.

Bottom Water Conditions

The presence of numerous benthic foraminifera, and rare occurrences of ostracods and echinoid fragments suggest relatively oxygenated bottom waters of normal marine conditions during most of Maness deposition. This is supported by bioturbation that is evident in core examination (Figs. 15, 17, 18) and the lack of enrichment in redox proxies, especially in the lower and middle chemostratigraphic zones. Uranium is slightly enriched within portions of the Maness, but vanadium and molybdenum are depleted. Although TOC abundances within the Maness averaged 2.85%, the presence of woody material in some of the samples and the poor correlation between the redox proxies and TOC (Fig. 40) suggest a terrigenous source for the organic matter.

The bottom-waters may have been moving towards anoxic conditions near the end of Maness deposition, similar to the paleoenvironmental conditions of the Maness and Lower Eagle Ford in south Texas (Denne et al., 2014; Denne et al., 2016). TOC abundances increase from the Lower Maness to the Middle Maness (Fig. 39). Within the Upper Maness in the Watson core, there is a significant increase in iron and sulfur paired with the enrichment of molybdenum,
uranium, zinc, and cobalt (Fig. 38). Diagenetic siderite and pyrite are present at this elemental change. The molybdenum enrichment factor is 58, indicating a shift to reducing conditions where bottom waters became anoxic to potentially euxinic. The lack of enrichment in vanadium may be due to the reoxidation process, where oxygen reached an accumulation of authigenic vanadium (Tribovillard, 2006). Bottom water conditions that are anoxic to euxinic correspond with paleoredox conditions that were suggested for the Maness in south Texas by Denne et al. (2016). Conversely, the Kinney core has hematite and clay filled burrows in the Upper Maness and an assortment of benthic foraminifera and ostracods all indicating oxygen is still within the bottom waters. One plausible explanation for this immense difference in oxygen conditions between the Kinney and Watson cores is that the uppermost Maness section is not present in the Kinney core, so the shift from oxic to anoxic-euxinic conditions was not described in this study because the rocks recording that shift are not available. That interpretation also suggests that the Maness in Rusk County may have had higher sedimentation rates than the Maness 15 miles (24 km) north in Gregg County.

Siderite and pyrite are authigenic minerals that typically form under low oxygen conditions. During early diagenesis near the sediment-water interface, sulfur content was high due to the presence of organic matter. Through sulfate reduction, organic matter consuming bacteria produce sulfide, which in turn reacts with iron located in the sediment to produce pyrite (FeS$_2$) (e.g., Shimmiel and Pederson, 1990; Chester, 2000; Tribovilliard, 2006). With increased burial, eventually the influx of sulfate ions to the sediment is cut off, and at this point siderite precipitates (Fig. 51). Therefore, it is interpreted that the presence of siderite in the Middle Maness of the Kinney core indicates that it was deposited within the zone of sulfate reduction and the Watson core location was within the sulfate reduction reaction zone when the Upper Maness was deposited. The Watson core has higher abundances of organic matter and sulfate minerals within the Middle Maness, but it must not have reached the sulfate reaction at the time.
of deposition. Therefore, wherever siderite and pyrite are abundant in the cores, intermittent anoxia are interpreted for the system. The presence of siderite may also represent periods of sediment starvation, which would have shut of the sediment supply and provide ample time for siderite concretions to form.

Carbon-iron-sulfur relationships can be used to determine the amount of siderite and pyrite in the rocks, as well as how much iron is within other mineral phases (Rowe et al., 2009). Figure 52a shows this relationship by plotting sulfur and iron along with the pyrite stoichiometric line. If the data points fall along the pyrite stoichiometric line, then the majority of the iron is determined to be within the pyrite phase (Rowe et al., 2009). Here, the majority of the data points plot to the right of this line, suggesting that a majority of the iron is not within the pyrite phase. Rather, the majority of iron is held in other mineral phases, specifically within siderite and the illite clay fraction. The carbon-iron-sulfur relationship also examines the differences in redox conditions based on the sediment types that are deposited, and gives an indication to the marine conditions that prevailed at the time of deposition (Rowe et al., 2009). The majority of the Maness was deposited under normal oxic and alkaline conditions, as the majority of the data points plot along the normal marine trend (Fig. 52b-c) (Dean and Arthur, 1989; Berner and Raiswell, 1983; Rowe et al., 2009). Several data points from the upper Watson core plot within the absence of normal marine conditions zone, further suggesting a trend toward anoxic conditions.

The bottom-water oxygen conditions interpreted in this study may not apply to Maness depositional conditions within the axis of the East Texas Basin or in the Brazos Basin since the cores examined here are within the more proximal East Texas Field at depths less than 4000 ft SSTV. Elemental studies are needed to bridge the gap between the East Texas Field and the Brazos Basin.
Figure 51. Process of pyrite, siderite, and iron oxide formation below the sediment-water interface in the Maness as a factor of time and depth. 1. Sulfate in the water column and from organic matter is consumed by bacteria to produce sulfide. 2. Sulfide reacts with iron in the sediment to produce pyrite (FeS$_2$), which is commonly present in the Maness. "A" shows frambooidal pyrite at 3680 ft in the Kinney core. Scale bar= .25 mm. 3. As burial increases, iron reacts with the leftover bicarbonate from the pyrite reaction rather than sulfide to produce siderite. "B" shows siderite at 3704.5 ft in the Watson core and "C" shows siderite, along with phosphate, at 3705 ft in the Watson core. Scale bar= 2 cm. 4. Without further burial, the pyrite is oxidized to iron oxide, such as hematite. Iron oxide filled burrow at 3691 ft in the Kinney core. Scale bar= 2.50 mm. Schematic diagram modified from Wuerch (1986).
Figure 52. Carbon-iron-sulfur relationship are used to determine paleoceanographic conditions during Maness deposition through TOC, sulfur (S), and iron (Fe) content. All plots show weight percent (wt%) of elements and total organic carbon data. A. Fe vs. S shows the relation of the iron content to pyrite. Trend line denotes pyrite stoichiometry. If pyrite does not plot along the trend line, then the iron content is held in other phases. B. TOC vs. S to determine oxygenation of bottom waters and establish the relationship of sulfur to organic material. The trend line shows normal marine conditions (Berner and Raiswell, 1983; Rowe et al., 2009). C. S-Fe-TOC wt% are plotted on the ternary diagram. Most data points plot along or near the normal marine conditions trend line, with some data plotting within the absence of normal conditions zone. All data plot above the pyrite line.
Productivity and Fertility Conditions

Calcispheres and planktonic foraminifera can be used to imply periods of high fertility conditions (Denne et al., 2016). Calcispheres are abundant in the False Buda facies of the Maness and then significantly decrease upward, suggesting higher fertility in the Lower Maness with lower fertility in the Upper Maness. Similarly, planktonic foraminifer taxa are more abundant and diverse in the lower portions of the Maness but also decrease upward. Most foraminifera in this study are benthic, but a variety of planktonics within the Lower Maness give indications of fertility and salinity conditions based on their habitat preferences. Planktonics in this study resided above the photic zone, mostly inhabiting the surface waters, and some forms such as the hedbergellids were also tolerant of low salinity waters (Fig. 53) (Keller and Pardo, 2004; Denne et al., 2016). Paleoproductivity proxies, nickel and copper, support the biostratigraphic evidence that productivity during Maness deposition was low, as they are not enriched within the Maness and overall do not correlate with TOC.

TOC average in the Lower Maness is 2.6%, therefore organic matter is preserved within the interval. With relatively oxygenated waters, the preservation is most likely linked to the increase in siliciclastic sedimentation and rapid burial. The Upper Maness has more detrital influx compared to the lower parts of the Maness. This is evident in core examination and linked to carbonate production. Furthermore, this study suggests that the stratigraphy of the Buda and Maness intervals is a factor of oxygen and productivity conditions rather than sea level or sedimentation changes since the shift from a carbonate to siliciclastic system is evident across the whole Gulf Coast. As oxygen decreases in the bottom waters, carbonate production is cut off and the resulting deposits are mudrocks from terrigenous sources or hemipelagic fallout in deeper waters.
Figure 53. Habitat preferences for common Cretaceous planktonic foraminifera (Denne et al., 2016). This study identified hedbergellids, whiteinellids and heterohelicids, with few keeled, deeper dwelling foraminifera. Habitat preferences and according planktonics are indicators of fertility and productivity within surface waters.
IV.III Stratigraphy

From core descriptions alone, it was difficult to correlate between the two cores due to the overall lithologic homogeneity of the mudrocks. Combining the core descriptions with the mineralogical XRD, ICP-OES/MS elemental data, and biostratigraphic data, the Maness was separated into the Lower, Middle, and Upper Maness (Fig. 54). Furthermore, it is suggested that oxygen conditions may be the controlling factor of lithology within the Buda-Maness strata. Oxygen levels were high within the Buda, but then slightly decrease within the Maness, transitioning from a carbonate to a marl to eventually a clay-rich mudstone. The Maness stratigraphy and depositional environment is examined in this section.
Figure 54. Combination of core description, XRD mineralogical analysis, elemental analysis, and biostratigraphic analysis for each core that was used to determine the Lower, Middle, and Upper Maness. For XRD data, percentages are shown for silica (yellow), carbonate (blue), clay (grey), and other minerals (dark grey). Elemental data for silicon (Si), calcium (Ca), aluminum (Al), sulfur (S), and iron (Fe) in weight percent. Total organic carbon is in weight percent and enrichment factor of molybdenum concentration is shown. Planktic foraminifera, benthic foraminifera, and calcareous nannofossils show where each taxa were identified from thin section, washed residue, or smear slides. The upper chart is the Kinney core and the lower chart is the Watson core.
Lower Maness

The Lower Maness compositional average from both cores is 28% quartz, 27% carbonate, and 25% clay (predominantly illite), with 20% other minerals. Lithofacies D, bioturbated marl, and Lithofacies A, silica-rich argillaceous mudstone, are dominant within this interval. The culmination of XRD and ICP-OES/MS data shows that this zone is the most carbonate-rich interval within the Maness. Furthermore, the fossil assemblage of abundant calcispheres and nannoconid nannofossils suggests that the basal Lower Maness in the East Texas Basin is equivalent to the False Buda facies identified in the Brazos Basin (Denne and Breyer, 2016a; b).

Most previous studies suggest that there was a regional regression at the end of Buda deposition, exposing portions of the Texas shelf (Sohl et al., 1991). This interpretation was questioned by Denne et al. (2016) due to the Buda being unaltered where the Maness is present and karsted where the Maness is absent in south Texas, which was also demonstrated by Patterson (2018) in cores near the San Marcos Arch. In the East Texas Field, the Buda is unaltered below the Maness, and mineralogical data confirms that there is a conformable, transitional contact between the Buda and Maness, informally identified as the False Buda facies. The False Buda was only correlated within the Brazos Basin and southern East Texas Basin, but mineralogical and biostratigraphic data from the East Texas Field cores suggest that the False Buda is a continuous marl facies across the East Texas Basin. Denne and Breyer (2016a) interpret the False Buda to represent a maximum flooding surface (MFS), and this study further suggests that the slight decrease in bottom water oxygen conditions was the controlling factor increasing siliciclastic input into the system during False Buda deposition.
**Middle Maness**

The Middle Maness is primarily a silica-rich argillaceous mudrock consisting of 42% quartz, 38% clay, and 11% carbonate. Lithofacies A, B, and C are all present in both cores, but Lithofacies C, the alternating sandstones and mudstones, provides the most insight into the depositional environment of the Middle Maness. The thin, cross-stratified quartz-rich sandstone lags consist of sediment that was eroded and transported due to storm winnowing (Fig. 55). In this model within mudrock sequences, the deposits are interpreted as distal tempestites, which are commonly thin and fine-grained due to their distance of travel (Dattilo et al., 2008; Alshahrani, 2013). The idealized tempestite consists of a shallow scour surface followed by hummocky stratified sands, planar laminated sands, and wave ripple sands before returning to the mudstone layer (Einsele, 2000; Alshahrani, 2013). Distal tempestites do not typically represent the entire sequence, but are usually only composed of the planar laminated and ripple laminated deposits (Flugel, 2009). Here, the tempestites are typified by a scoured base along with planar and ripple laminated bedding, suggesting that they are distal rather than proximal.

Tempestite deposits are present in both cores, but the lags are better preserved in the Kinney core than the Watson core. The Watson core displays coarser-grained storm deposits that have been disrupted (Microfacies 2). One potential explanation is that the storm deposit was followed by a period of slow sedimentation, where both the tempestite and the surrounding mudrock were bioturbated. There is also the possibility of eddy diffusion, meaning the sediment was semifluidized when bioturbation occurred, causing eddies or wakes to stir the edges of the burrows (Lobza and Schieber, 1999). With either interpretation, bioturbation is evident meaning oxygen was present within the system.

Additionally, the quartz-grains in the Watson core are coarser grained than the quartz-grains composing the tempestite in the Kinney core, suggesting the Watson core was more proximal to the source. Therefore, the tempestites may have originated from the Sabine Uplift.
and indicate a shallow shelfal depositional environment below fair-weather wave base but above the storm wave base within east Texas. This differs from the interpretation of the Maness in south Texas, which was deposited below storm wave base in a much deeper water environment (Patterson, 2018).
Figure 55. Schematic diagram of the shelf environment between fair weather wave base and storm wave base and an idealized storm winnowed tempestite cycle in mudrocks. A) Storm deposits within mudrocks, showing repetitive tempestites as seen in this study (Dattilo et al., 2008). B) Idealized tempestite sequence (Einsele, 2000). Tempestites are composed of the following elements: 1) Scoured base, 2) Graded intraclasts, 3) Hummocky Cross Stratification, 4) Planar Laminations, 5) Wave Ripple, 6) Return to mudrock deposition. Distal tempestites may only have planar laminations and wave ripples. C) Tempestite from the Kinney core that is partially eroded, but shows planar laminations in the lower part of the tempestite with wave ripples in the upper section. D) Tempestite from the Kinney core that is highly eroded but shows hummocky cross stratification with mud drapes.
Upper Maness

The Upper Maness is mostly an argillaceous mudrock, but carbonate concretions are common. Carbonate content is in the form of diagenetic siderite in the Watson core, whereas calcite is the predominant carbonate mineral in the Kinney core. The Upper Maness is composed of 41% clay, 35% quartz, and 19.5% carbonate, with the other 4.5% being predominantly sulfates. This is the most clay-rich interval, confirming that the Maness becomes increasingly clay-rich upward (Denne and Breyer, 2016a). Silica content is less than in the Middle Maness, but thin section microfacies 4 shows the continued presence of silt-sized quartz grains within these mudrocks, as they are faintly laminated and bioturbated. Additionally, burrows within the Kinney core are clay and hematite filled, the latter supporting the increase in iron within this interval. The Watson core has a much greater increase in iron due to the siderite and pyrite frambooids present in the Upper Maness.

The Upper Maness is interpreted to consist of highstand, progradational deposits most likely sourced from a mud-prone deltaic source, as suggested by Denne and Patterson (2019) and supported by the current study. The mudstone layers in the cores in east Texas are faintly laminated and bioturbated, since they were deposited in much shallower waters in a more proximal location to the source. In south Texas, the cores examined had structureless, homogenous mudstone layers that were interpreted as fluid-mud deposits associated with a deltaic source (Ichaso and Dalrymple, 2009; Denne and Patterson, 2019). This interpretation supports the hypothesis that the Maness is deltaic and sourced from a north to northeastern sediment source and later reshaped by parallel currents (Denne and Breyer, 2016a). The diverse, mostly calcareous benthic foraminifera assemblage identified in the Upper Maness also suggest little impact of deltaic outflow on the fauna.

Whereas phosphate is interspersed throughout the cores in east Texas, a phosphatic lag is present above the Maness throughout south Texas and into the southern Brazos Basin.
(Denne et al., 2016; Patterson, 2018). This implies that south Texas was sediment starved during Maness deposition, only depositing thin phosphate concretions that were subsequently reworked into a lag deposit, whereas east Texas was dominated by siliciclastic deposition, therefore lacking this condensed section. Erosion and incision of the Maness was most likely significant in east Texas due to the Woodbine delta complex deposition following the termination of the Maness depositional episode (Denne et al., 2016; Denne and Breyer, 2016a).

IV.V Sediment Source

Data comparison

Data from this study was compared to published data from south Texas (Ramiro-Ramirez, 2016; Patterson, 2018) and the Brazos Basin (Hudson, 2014; Meyer, 2016), and unpublished data from Robertson, DeWitt, Gonzales, and Karnes counties (Denne et al., 2016) to further understand the sediment source. Mineralogical data was used to map clay, silica, and carbonate content of the Maness from east Texas to south Texas, identifying trends and shifts in lithology (Fig. 56). The overall trend indicates that the east Texas Maness is more silica-rich and less clay-rich than the Maness in both the Brazos Basin and south Texas.

Maness has its highest clay content in the Brazos Basin, with nearly 60% clay, compared to 36% clay in the East Texas Field and 38% in south Texas. Notably, clay content decreases south of the San Marcos Arch but does not follow the trend of the Karnes and Gonzales troughs as the isopach map does. Carbonate content decreases as clay content increases, therefore the Maness in south Texas is more carbonate-rich than in the Brazos Basin. The East Texas Basin is also more carbonate-rich than the Brazos Basin, which may be associated with depth or oxygen conditions. Silica content, including both quartz and feldspars, is similar to carbonate content, as it decreases from east to west into the Brazos Basin.
Additionally, silica content is roughly 25% in south Texas except at one well location in DeWitt County.

For this siliciclastic unit, the higher clay and silica content suggest that the Maness is more proximal to its sediment source in east Texas in comparison to south Texas or the Brazos Basin. Applying typical facies associations from an idealized deltaic model, it appears that the Brazos Basin Maness is within the distal prodelta facies and the east Texas Maness is within a more proximal, delta front facies of the system. This confirms previous suggestions based on lithofacies and microfacies interpretations, as the south Texas Maness has homogenous, structureless layers whereas the east Texas Maness is laminated and bioturbated. The proximal sediment supply within east Texas is dominated by terrestrial or detrital sedimentation, whereas the distal sediment supply varies between detrital influx of fine-grained material, hemipelagic clays, and biogenic calcite sedimentation (Ruppel, 2017). These interpretations suggest two possible sediment source models: 1) northeast to eastern source from the Sabine Uplift and 2) northerly source form the Ouachita highlands.
Figure 56. Interpretation and comparison of Maness mineralogical data from East Texas to South Texas. Published data is from South Texas (Ramiro, 2016; Patterson, 2018) and the Brazos Basin (Hudson, 2014; Meyer, 2016). Unpublished data is from Robertson, DeWitt, Gonzales, and Karnes counties (Denne et al., 2016). East Texas data is from the current study. All data points are shown on the Texas map with the Maness isopach map. A. Clay, silica, and carbonate wt%’s contoured across the study area. Each lithology map is from the same polygon shown in the Texas map. Well locations with mineralogical data are shown on all maps. Contour interval is 10%. B. Ternary diagram showing Qtz-Carb-Clay content of all data points to determine trends based on location on the Texas shelf. The purple trend represents the Brazos Basin, the blue trend represents south Texas, and the green trend represents the East Texas Basin.
Sabine Uplift source model

It is known that the Sabine Uplift was active during the middle Cretaceous and the Paleocene-Eocene, but little is known about the smaller-scale activations that may have caused uplifts large enough for remobilization of fine-grained material (Adams, 2009). This interpretation is applied to the Harris delta, which was active during the middle of the Late Cenomanian, at the top of the Lower Eagle Ford in east Texas. Following Woodbine and subsequent Eagle Ford deposition, upward movement of the Sabine Uplift coupled with a relative sea level drop caused erosion of the underlying Woodbine clastics and redistributed them from east to west as the Harris delta (Denne and Breyer, 2016a; b). Comparison of the Harris delta isopach map to the Maness isopach map shows similar trends and limits of deposition, suggesting that the Maness may also be sourced from the Sabine Uplift (Fig. 57) (Denne and Breyer, 2016a; b; Denne and Patterson, 2019). In this model, a relative sea level fall, upward movement of the Sabine Uplift, or subsidence of the salt basin may have acted in unison to erode and redistribute sediments, possibly from the underlying Grayson Formation, into the Maness deltaic system.
Figure 57. Isopach maps showing both the Harris delta and the Maness being sourced from the Sabine Uplift to the east. The Harris delta is shown in A (Denne and Breyer, 2016a) and the isopach of the Maness is shown in B, both within the same part of Texas. The blue arrow indicates the direction of the sediment source coming from the East. The purple arrow is the San Marcos Arch.
Ouachita Highlands source model

There is also the potential that the Maness is sourced from the north and was the first deltaic system sourced from the Ouachita Mountains prior to the onset of the Woodbine (Fig. 58). The majority of the Maness is clay-rich, but facies changes in Leon and Anderson counties suggest lithological changes in the Maness from either depositional or structural influences. Anderson (1979) identified a facies change in Leon County, renaming the Maness as the “Malvern Shale” as he continued mapping to the north and northeast. Anderson (1979) picked the top of the Maness as the contact between the incising progradational sands and the underlying shale. Therefore, he associated the sand bodies with the Woodbine Group. Conversely, Ambrose et al. (2009) suggests that the Maness has prograding sands in the northern part of the East Texas Basin. The current study identified channelized sands in northern Anderson county as well, but limited well control in the area curbed any definitive conclusions.

It is possible that the sands are Maness in age and are oriented N-S as delta front sands from a Maness-aged deltaic system sourced from the Ouachita highlands. If the Maness is sourced from the north, sediments may include a mix of redistributed Grayson marls and terrigenous input from the uplift. Therefore, this study suggests further work on the Maness to the north and south of this study area with core examination, sample analysis, and seismic incorporation to determine if there are separate Maness and Woodbine progradational systems.
Figure 58. Isopach map of the Maness overlain with the depositional model of the overlying Woodbine sourced from the Ouachita Uplift to the north. Woodbine facies map modified from Adams and Carr (2010).
V. Summary and Conclusions

The present study focused on the Maness Shale within its type area in east Texas to further understand the initial siliciclastic deposits that were laid down during the Lower Cenomanian following the terminus of carbonate deposition represented by the Buda Limestone. Geochemical properties were established through the use of XRD, ICP-OES/MS, petrology, and organic geochemical techniques to determine the mineralogy and paleoenvironment of the Maness in east Texas. Furthermore, well log correlations assembled in unison with previous work by Patterson (2018) and Denne and Breyer (2016a) mapped the Maness across east Texas from its potential source to its depositional extent in south Texas. This study addresses the following hypotheses:

1. The Maness Shale of east Texas is age-correlative to the Maness Shale of the San Marcos Arch.
2. The Maness Shale is a potential source rock.
3. The Maness Shale is composed of deltaic sediment sourced from the Sabine Uplift.

Calcareous nannofossil and planktonic foraminiferal biostratigraphy constrained the age of the Maness in east Texas to 97.3-96.7 Ma, whereas ammonite biostratigraphy placed the Maness near the San Marcos Arch within the Early Cenomanian from 97.25-96.8 Ma (Denne et al., 2016). Therefore, the Maness in east Texas is age-correlative to the Maness of the San Marcos Arch, confirming hypothesis 1. The Maness is continuous across the East Texas and Brazos basins and can be correlated from its source in east Texas to its depositional limit in south Texas.

The Maness Shale has not been a conventional or unconventional target for oil or gas exploration, but this study addressed the likelihood of its source rock potential. This study suggests that in the type area of the East Texas Field it is a potential source rock based solely
on TOC measurements, although the paleoenvironmental conditions interpreted here were not conducive to organic matter preservation. TOC values average 2.8% across both cores, which is good to very good for a mudrock (Law, 1999). Further analysis is needed to determine the type of organic material that is present within the Maness in east Texas. The Maness may slightly contribute to production out of overlying reservoirs such as the Woodbine in east Texas, but it is not a target for production on its own.

Patterson (2018) suggested that the Maness had a deltaic source coming from the north to northeast of her study area in south Texas, spurring the need for additional mapping of the Maness in east Texas. Therefore, this study's main focus was to determine the sediment source and the paleoenvironment that this mudrock was deposited in within a location more proximal to the source of the Maness. The isopach map of the Maness in east Texas supports Patterson's hypothesis that it is sourced from the north to northeast of the San Marcos Arch, most likely from a clay-rich delta, supporting hypothesis 3. The thickness trends of the isopach map suggest that the sediment source is from the Sabine Uplift, potentially from erosion of the Grayson Formation. It is also possible that the Maness is sourced from the north, specifically the Ouachita Uplift, similar to the Woodbine deltaic system.

Furthermore, it was determined that the bottom waters during Maness deposition were oxygenated. The combination of biostratigraphy, ichnofacies, and chemostratigraphy indicate that Maness bottom waters were oxic to suboxic, but may have shifted to increasingly anoxic in the upper parts of the Maness, where redox proxies become enriched. Oxygen conditions then may have been a controlling factor in the termination of carbonate deposition along the Gulf Coast during the Lower Cenomanian, represented by the lithologic transition from the Buda Limestone to the False Buda marl to the clay-rich Maness. Additionally, the Maness oxic environment and tempestite deposits suggest that it was deposited above storm weather wave
base at the location of the east Texas cores, whereas the Maness in south Texas is well below the storm weather wave base.
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Appendix A. Kinney core images and sampling locations. Letters represent facies association. Samples used for XRD (red), ICP-OES/MS (green), Organic geochemistry (blue), washed residue (purple), and petrography and further biostratigraphy (yellow) are shown.
Appendix A. Watson core images and sampling locations. Letters represent facies association. Samples used for XRD (red), ICP-OES/MS (green), Organic geochemistry (blue), washed residue (purple), and petrography and further biostratigraphy (yellow) are shown.
Appendix B- Thin Section Scans

Kinney Thin Sections

3665.5 ft – faintly laminated mudstone representative of microfacies 4; hematite filled burrow; transmitted light

3672.5 ft—laminated coarse mudstone with interspersed pyrite and organic matter, representative of microfacies 4; reflected light
3682.5 ft—tempestite deposit with pyrite rich, calcite-cemented sandstone lag; transmitted light

3683.4 ft—bioturbated mudstone representative of microfacies 5; abundance of planktonic forams; reflected light
Watson Thin Sections

3687 ft – laminated tempestite deposit representative of microfacies 3; reflected light

3711.3 ft – indistinctly laminated, bioturbated mudstone with calcite-cemented tempestite at base, representing microfacies 2; pyritized foraminifera; transmitted light
3716.4 ft – bioturbated, red-brown mudstone representing microfacies 5; pyrite filled foram visible; reflected light

3717.6 ft – red-brown mudstone with disturbed storm bed tempestite, showing microfacies 2; pyrite within storm bed; reflected light
3725 ft – fossiliferous mudstone, representing microfacies 1 with skeletal fragments, echinoid, foraminifera, and calcispheres; reflected light
### Appendix C - Washed Residue Results

<table>
<thead>
<tr>
<th>Kinney 25 Sample</th>
<th>3691’</th>
<th>3680’</th>
<th>3677’</th>
<th>3674’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planktonic foraminifera</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Favusella washitensis</em></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Muricohedbergella planispira</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Planoheterohelix moremani</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Thalmaninnella globotruncanoides</em></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Whiteinella spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcareous benthic foraminifera</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Bifarina/Bolivina spp.</em></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Gavelinella petita</em></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Gavelinella spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Gyroidina spp.</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Lenticulina spp.</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Nodosaria/Dentalina spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Oolina/Fissurina spp.</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Praebulimina spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Tristix quadrata</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Valvulineria? spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agglutinated benthic foraminifera</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Ammobaculites spp.</em></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Hyperammina/Flabellammina spp.</em></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Textularia rioensis</em></td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Textularia spp.</em></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous agglutinates</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Miscellaneous fossils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bivalves</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Calcispaces</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echinoid plates</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echinoid spines</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Inoceramid prisms</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ostracods</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

*Appendix C.* Washed residue sample results from the Kinney core. Planktonic foraminiferal, benthic foraminiferal, and miscellaneous fossils were identified and recorded by the “X”.  

139
### Appendix D - XRD data

#### Kinney Data

<table>
<thead>
<tr>
<th>Type</th>
<th>KIN 3668.5'</th>
<th>KIN 3670'</th>
<th>KIN 3673.5'</th>
<th>KIN 3677'</th>
<th>KIN 3685.7'</th>
<th>KIN 3692.9'</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
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<td>Silica</td>
<td>37.8 ± 0</td>
<td>31.8 ± 9</td>
<td>55.5 ± 8</td>
<td>42.1 ± 7.8</td>
<td>29.6 ± 17.8</td>
<td>23.3 ± 2</td>
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<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14.8 ± 3</td>
<td>8.2 ± 5.5</td>
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<tr>
<td>Carbonate</td>
<td>35.6 ± 0</td>
<td>30.5 ± 8.5</td>
<td>12.6 ± 1.2</td>
<td>8.5 ± 1.8</td>
<td>33.1 ± 19.8</td>
<td>24.7 ± 2.6</td>
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<tr>
<td>Sulfate</td>
<td>6.1 ± 0</td>
<td>4.2 ± 1.5</td>
<td>5.4 ± 1.8</td>
<td>3.4 ± 1.2</td>
<td>7.9 ± 0</td>
<td>3.9 ± 2.5</td>
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<tr>
<td>Clays - Mica Group</td>
<td>11.5 ± 0</td>
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<td>14.3 ± 12.6</td>
<td>16.6 ± 9.1</td>
<td>5.8 ± 3.6</td>
<td>26.7 ± 3.2</td>
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<td>Clays - Smectite Group</td>
<td>9 ± 0</td>
<td>10.2 ± 1.1</td>
<td>12.2 ± 3.3</td>
<td>14.6 ± 4.3</td>
<td>15.4 ± 11.9</td>
<td>6.2 ± 0.7</td>
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*All data courtesy of the Shimadzu Institute at the University of Texas at Arlington.*

#### Watson Data

<table>
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<tr>
<th>Type</th>
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<th>WAT 3714.7'</th>
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<th>WAT 3722'</th>
<th>WAT 3725'</th>
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<tr>
<td></td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
<td>Wt% ±</td>
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<td>Silica</td>
<td>36.2 ± 2</td>
<td>37.3 ± 13.4</td>
<td>47.3 ± 2.9</td>
<td>24.6 ±</td>
<td>32.4 ± 2</td>
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<td>Feldspar</td>
<td>2.3</td>
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<td></td>
</tr>
<tr>
<td>Carbonate</td>
<td>6.3 ± 4</td>
<td>7.9 ± 2.9</td>
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<td>9.8 ± 0.7</td>
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<tr>
<td>Sulfate</td>
<td></td>
<td>4 ± 1.5</td>
<td>8.5 ± 1.1</td>
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<td>10.6 ± 2.3</td>
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<tr>
<td>Clays - Mica Group</td>
<td>34.8 ± 41.7</td>
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<td>16.6 ± 1.5</td>
<td>36.5 ±</td>
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<tr>
<td>Clays - Smectite Group</td>
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<td>3.4 ± 13.9</td>
<td>1.6 ± 23.8</td>
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<td>17.8 ± 1.3</td>
</tr>
</tbody>
</table>

*Data in blue courtesy of the Shimadzu Institute at the University of Texas at Arlington.*

*Data in orange courtesy of TCU Chemistry department.*
### Appendix E - ICP-OES/MS

*Major Elements (wt\%)*

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<thead>
<tr>
<th>Major Elements</th>
<th>Al2O3</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Fe2O3</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
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<tr>
<td>Kinney_3665</td>
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<td>56.58</td>
<td>0.81</td>
<td>3.73</td>
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<td>1.13</td>
<td>10.39</td>
<td>0.58</td>
<td>1.27</td>
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<td>50.41</td>
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<td>0.04</td>
<td>1.17</td>
<td>14.37</td>
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<td>0.78</td>
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<td>59.80</td>
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<td>0.04</td>
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Vita

Marissa English was born in Houston, Texas on September 4, 1995. She grew up in Houston and attended Texas A&M University. She graduated with a bachelor of science degree in Petroleum Geology from Texas A&M in 2018. From there, she started her Master of Science degree at Texas Christian University in Fort Worth, TX working with Dr. Richard Denne within the department of geological sciences.

Marissa has interned for companies within the oil and gas industry, specifically Schlumberger and EOG Resources. Following graduation from TCU, she will begin her career with EOG Resources as a geologist in their San Antonio office, working the Eagle Ford in south Texas.
Abstract

Stratigraphy and Geochemistry of the Lower Cenomanian Maness Shale of East Texas

By Marissa English, M.S., 2020
Department of Geological Sciences
Texas Christian University
Thesis Advisor: Richard Denne, Hunter Enis Chair in Petroleum Geology

The Lower Cenomanian Maness Shale is a mudrock unit lying between the Buda Limestone and the Woodbine sandstones in east Texas and between the Buda Limestone and Eagle Ford shales in south Texas. The Maness has been studied since the 1950’s, yet much is still unknown, such as its sediment source, depositional environment, and source rock potential. This study combined mineralogical, elemental, biostratigraphic, and organic geochemical data to refine the knowledge of the east Texas Maness and compare the data to previous studies. The mineralogical composition of the Maness in east Texas is 36% clay, 35% quartz, and 18% calcite, with traces of pyrite, phosphate, and siderite concretions. Since this study confirmed that the Maness in east Texas is age-correlative to the Maness near the San Marcos Arch based on biostratigraphy, the mineralogical data was compared to studies near the San Marcos Arch and Brazos Basin to determine that the east Texas Maness is more silica-rich and less clay-rich. Furthermore, the presence of benthic foraminifera, ostracods, and echinoids suggest relatively oxygenated bottom waters, although elemental analysis indicates there may be a shift from oxic to anoxic conditions in the Upper Maness. TOC values average 2.8% suggesting that the Maness in the type area is a potential source rock, although environmental conditions were not conducive to organic matter preservation.

The thickness trend on the Maness isopach map suggests two potential deltaic sediment sources. The Maness may be sourced from the Sabine Uplift to the east, similar to the Harris delta, or it may be sourced from the northern Ouachita Uplift, similar to the Woodbine deltaic complex. In either situation, the East Texas Field is proximal to the sediment source as tempestite deposits and bottom water oxygen conditions suggest a shallow shelfal depositional environment. Conversely, the Maness in south Texas was deposited within a distal, deeper depositional environment below storm wave base. Lastly, mineralogical shifts from the Buda to the False Buda to the Upper Maness is a factor of decreasing oxygenation, which increased siliciclastic input into the system.