DETERMINING THE DEPOSITIONAL ENVIRONMENT OF THE LOWER EAGLE FORD IN LOZIER CANYON, ANTONIO CREEK, AND OSMAN CANYON, TEXAS: AN OUTCROP STUDY OF BEDDING FEATURES AT OUTCROP SCALE

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The Eagle Ford Formation is currently the most economically significant unconventional resource play in the state of Texas. There has been much debate as to the environment of deposition for the lowermost Facies A of the Eagle Ford in outcrop exposures in Lozier Canyon, Texas. Two conflicting hypotheses were proposed: 1) Sedimentary structures in Facies A are hummocky cross-stratification (HCS) and swaley cross-stratification (SCS), which indicates a shelfal depositional environment above the storm wave base (SWB). 2) Sedimentary structures in Facies A are a mixture of diagenetically separated contourites, turbidites, and pinch-and-swell beds, which indicate a distal-slope depositional environment below SWB. This research used field work, three-dimensional analysis of sedimentary structures, measurements of ripple height, and laboratory analysis to interpret the environment of deposition. The results of these observations and data suggest that the sedimentary structures in Facies A record a depositional environment above SWB.

Observation of cross-bedded structures in three-dimensions reveals (i) isotropic truncation of laminae; (ii) symmetric rounded ripples; (iii) large variations in laminae geometry, truncation, and dip inclination, attributed to fluctuations in storm intensity, frequency, and duration; and (iv) and bidirectional downlap and reactivation surfaces associated with oscillatory flow above the SWB.

This study interprets cross-bedded sedimentary structures in Facies A as swaley cross-stratification (SCS) and hummocky cross-stratification (HCS) associated with
storm events, and thus places Facies A in a depositional environment above storm wave-base (SWB).
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1. INTRODUCTION

The Late Cretaceous Eagle Ford Formation currently is the most active unconventional shale play in the world, with over $30 billion invested in 2013 and 260 rigs currently in operation (U.S. Energy Information Administration, 2014). Outcrop exposures of the Eagle Ford extend from north Texas through Waco, Austin, San Antonio and into Mexico. The best exposures of Maverick Basin deposits occur in Antonio Creek and Lozier Canyon in Del Rio, Texas (Figure 1). The depositional environment of lowermost outcrop facies in the Eagle Ford still remains controversial as to whether Facies A was deposited above or below storm wave-base (SWB). Outcrop samples were taken from Lozier Canyon, Antonio Creek, and Osman Canyon for this study. LiDAR scans were also taken throughout Lozier Canyon and Antonio Creek to determine the usefulness of LiDAR for quantitative data collection at the outcrop scale. Outcrop exposures in west Texas and subsurface studies of the Eagle Ford (Boquillas) Group have allowed geologists to determine facies, biostratigraphy, cycles, and lateral facies distribution (Adkins and Lozo 1951, Freeman 1961, 1968, Dawson 2000, Lock and Piescher 2006, Donovan and Staerker 2010, Donovan et al. 2012, Gardner et al. 2013, Wehner 2013). Lozier Canyon is an ideal location to compare and contrast bedding features in Facies A because it exposes a complete vertical section of the Eagle Ford over a large lateral extent. The lowest beds of the Eagle ford Group and the contact of Facies A in the Eagle Ford Group with the underlying Buda Formation is exposed for miles, which provides the ability to compare and contrast its 2-D and 3-D bedding
features over a large lateral extent. Studies of these outcrops indicate that the Eagle Ford Group in west Texas consists of a transgressive lower member and a regressive upper member (Donovan and Staerker 2010). The Eagle Ford Group was sub-divided into five facies (A-E) based on lithology, biostratigraphy, and characteristic log signatures (Donovan et al. 2012, Gardner et al. 2013).

Figure 1. Location of study areas in Lozier Canyon, Antonio Creek, and Osman Canyon. Triangles represent locations where samples and detailed outcrop pictures were taken.
The basal transgressive unit, Facies A, was deposited on an unconformity above the underlying Buda Formation and is not present in the subsurface to the south. Although the Eagle Ford Group was extensively studied at outcrops in west Texas (Freeman 1961, Trevino 1988, 2002, Dawson 2000, Lock and Peschier 2006, 2010, Ruppel et al. 2012, Donovan and Staerker 2010, 2012, Gardner et al. 2013, Wehner et al. 2013), the depositional environment for the lower Eagle Ford remains controversial.

Facies A, composed of fine-grained foraminiferal grainstone and packstone, commonly has small three-dimensional sedimentary structures in the outcrop belt, but these features do not occur in the subsurface to the southeast (Figure 2). Most beds in Facies A pinch out or are scoured over several meters and are laterally discontinuous. However, bedding thickness and the styles of cross-bedding are similar throughout the region based on outcrop observation throughout Lozier Canyon and at numerous roadcuts along Texas Highway 90. These amalgamated skeletal grainstone and packstone beds range from 2 cm to 25 cm thick and are separated by thin organic-rich mudstone layers (0.5 cm to 8 cm thick), with sparse bentonite beds (< 3 cm thick). Facies A is approximately 6 m (20 ft) thick in Antonio Creek, Lozier Canyon, and in exposures along Texas Highway 90 near Langtry, TX (Figure 1).

Two types of sedimentary structures in Facies A were studied to determine its depositional environment: cross-bedded samples and contorted beds. The primary focus of this study was to measure and analyze small (< 15 cm) cross-bedded sedimentary structures that are ubiquitous in Facies A. These beds were sampled, measured, and cut into blocks in order to understand the processes responsible for their deposition.
Figure 2. Sedimentary structures in Facies A. (A) Uninterpreted three-dimensional view of sedimentary structures. These structures are the focus of this study. This Facies A sample is located in Antonio Creek (AC1). Contorted beds (brackets) located along Texas Highway 90. These beds indicate movement of large amounts of sediment over a short distance. Two distinct contorted beds can be observed in Facies A at multiple locations along Texas Highway 90 and in Lozier Canyon. The conflicting interpretations for these deposits suggest that the character of this bedding is the result of seismic liquefaction or mass transport debris flows.
Large contorted beds (Figure 2b) within Facies A outcrop in Antonio Creek, Lozier Canyon, and along Highway 90, but are not the primary focus of this study because they are less diagnostic of depositional environment. Description and detailed photography at the outcrop scale was used to determine the mechanisms that created these deformation features. Observation of deformation provides insights into mechanisms that caused the deformation and the depositional environment in which they formed. The contorted beds are widespread and laterally discontinuous throughout the outcrop belt of Del Rio based on observations in Lozier Canyon, Antonio Creek, Osman Canyon, and other road outcrops along Texas Highway 90.

Difficulties in interpreting the cross-bedding in Facies A of the Eagle Ford Group have led to two disparate interpretations; either as HCS and SCS deposited in a shallow-water environment above SWB (Trevino 1988, 2002, Donovan and Staerker 2010, Donovan et al. 2012, Gardner et al. 2013, Bohacs 2014), or as pinch-and-swell beds, traction deposits, distorted turbidites, and contourite ripples that were modified by diagenetic segregation and compaction on a distal-ramp setting (Freeman 1961, 1968, Lock and Peschier 2006, Lock et al. 2010, Ruppel et al. 2012). A similar interpretation by Ruppel et al. (2012) stated that cross-bedded structures in Facies A are deep-water “HCS-like” antidune structures similar to those described by Mulder et al. (2009). These structures were interpreted to be Tb-Td Bouma turbidite intervals that were modified by standing waves at the upper-flow face of a turbidity current in a deep-water slope setting on the drowned Lower Cretaceous shelf (Ruppel et al. 2012).
The current study presents detailed observations and measurements of a suite of sedimentary structures in Facies A samples from Lozier Canyon and Antonio Creek. These samples were cut and measured, showing laminae dips that are highly variable in dip angle (10°-35°), wavelength, and bedding character. Collected data and observations suggest that the cross-bedding in Facies A is primarily small-scale SCS and HCS, and oscillatory wave-ripples associated with storm deposition, all of which are indicative of a shelfal depositional environment above SWB (Greenwood and Sherman 1986).
2. GEOLOGIC SETTING

During the Early Cretaceous the Comanche Platform (Figure 3) developed across most of Central Texas in the Western Interior Seaway (WIS). The platform-margin reef buildups on the Comanche Platform are known as the Stuart City and Santa Elena Reef trends. These reefs greatly controlled the extent of deposition and physiography of the overlying Eagle Ford Group (Donovan and Staerker, 2010).

Figure 3. Generalized paleogeographic map. This figure depicts Eagle Ford depocenters in the late Cenomanian. Regional geology map modified from Donovan and Staerker (2010). Western Interior Seaway map modified from Blakey (1989).
Deposition of Eagle Ford outcrops in west Texas coincided with periods of flooding and deposition of thick organic-rich sediment packages on the Comanche Platform and in the troughs of reef buildups in the Late Cretaceous. (Lehman et al. 2000, Donovan et al. 2012). Facies A is the lowermost facies of the Eagle Ford and was deposited in a transgressive systems tract (TST) over the Buda Formation.

Several hypotheses which have been proposed are in disagreement about the geologic setting at the time of deposition of Facies A. One group of researchers led by Donovan and Staerker (2010) propose that cross-bedded structures in Facies A are HCS and SCS and thus were deposited on a relatively flat carbonate shelf above SWB (Trevino 1988, Donovan and Staerker 2010, 2012, Gardner et al. 2013). Conversely, it was proposed by Lock and Peschier (2006, 2010) and Ruppel et al. (2012) that cross-bedded structures in Facies A are formed by deep-water density currents and thus were deposited on a deeper water slope setting below SWB (Lock and Peschier 2006, 2010, Ruppel et al. 2012)
3. BACKGROUND

The current study utilizes observations and data gathered from the field and in the laboratory to compare and contrast cross-beded sedimentary structures in Facies A with analogous depositional models and sedimentary structures (Myrow and Southard 1991, Myrow et al. 2002, Dumas and Arnott 2006). The data generated in this study were compared with combined storm-flow deposits of HCS and SCS (Harms et al. 1975; Bourgeois; 1980, Dott and Bourgeois; 1982, Leckie and Walker 1982; Aigner 1985; Midtgård 1996, Molgat and Arnott 2001) and ancient and modern deep-water contourites, turbidites, and antidunes (Bouma 1962, 1972; Middleton 1965; Heezen et al. 1966; Hollister and Heezen 1972; Barwis and Hayes 1985; Rust and Gibling 1990; Duan et al. 1993; Alexander et al. 2001; Brackenridge et al. 2011; Cartigny et al. 2014).

3.1 Tempestites and HCS/SCS

Criteria for interpreting cross-beding as HCS (Figure 4) are: i) large-scale wavelengths of 1-5 m and heights up to 0.5 m; (ii) isotropic stratification with no clear orientation; (iii) structures containing lower bounding erosional surfaces that dip at low angles of approximately 10°; (iv) laminations that thicken into crests and thin laterally into troughs; (v) dip of internal laminations normally decrease upwards (Harms et al. 1975).
Criteria for HCS in carbonate tempestites is slightly different than criteria used for sand-dominated tempestite deposits. HCS in carbonate tempestites consists of: (i) basal shell-lag and rip-up clasts; (ii) low angle stratification and irregular bedding; (iii) small hummocks with wavelengths on the dm- to- cm scale and amplitudes of 1-3 cm; (iv) occasional graded packstone rhythmites at the upper and/or lower bounds of HCS truncations (Kreisa 1981, Aigner 1985, Sageman 1996, Molina et al. 1997).

**Figure 4.** Idealized hummocky cross-stratification in 3-D. Modified from Harms et al. (1975). Idealized HCS consists of isotropically dipping laminae, mounds at the upper surface, and concave-up swaley cross-stratification in troughs.
3.2 Small-Scale HCS

Sedimentary structures resembling small-scale HCS similar to bedforms in the Eagle Ford Group Facies A can form as deep-water turbidites with antidune stratification (Prave and Duke 1991, Mulder et al. 2009, 2011). Small-scale HCS-like structures in the Hayzabia Flysch sequence (Western Pyrenees, France) were interpreted as Tc interval turbidites that were reworked by standing waves from the Kelvin-Helmholtz instability at the upper-flow interface (Mulder et al. 2009, 2011). The Kelvin-Helmholtz (K-H) instability occurs at the horizontal interface in parallel shear flows moving at different speeds or directions. Once the shear strength of the laminar interface is overcome by the frictional force between the two fluids, penetration of one fluid layer into the other takes place in the form of a wave, vortex, or billow. For a turbidity current, it is proposed that once erosion ceases and deposition begins, a standing or up-dip migrating surface wave is caused by the K-H instability (Mulder et al. 2009, 2011). It is proposed that the up-dip migration caused by the K-H instability forms antidune structures that are similar to HCS (Mulder et al. 2009, 2011). There are no other published reports of HCS or HCS-like features linked to deep-water deposition and the description of the origin of the proposed upper flow-face instabilities remains unproven (Higgs 2011, Quin 2011).

In contrast, small-scale HCS commonly is associated as tempestite storm deposits, suggesting that small-scale HCS is merely a result of the wide variety of depositional and erosional processes associated with storm events on a shelfal environment above SWB (e.g. DeRaaf et al 1977, Kreisa 1981b, Aigner 1982, 1985,

Difficulties also exist in differentiating between HCS and antidunes, because both structures have low-angle stratification and three-dimensional bedforms, often resembling one another at the outcrop scale (Prave and Duke 1990, Rust and Gibling 1990, Alexander et al. 2001, Quin 2011, Cartigny et al. 2014). However, distinctions between HCS, turbidites, and antidunes can still be made based on the evidence or lack thereof of oscillatory flow in turbidites/antidunes (Hunter and Clifton 1981, Christie-Blick et al. 1990, Einsele et al. 1991). Evidence of oscillatory flow and bedding isotropy are the most crucial elements for differentiating between storm deposits and turbidites/antidunes and can be identified by accurate interpretation of HCS, SCS, wave-ripple character, and isotropic truncation of laminae within cross-bedded sedimentary structures.

3.3 Deep-Water Turbidites

Criteria for turbidites from bottom to top includes; fining upward graded interval. Sometimes gravel and sand occur in the lowest interval (Ta); lower interval of parallel
lamination (Tb) composed mainly of coarse-grained parallel lamination, although grading sometimes occurs; interval of current ripple lamination (Tc) with ripples no larger than 5 cm in height and 20 cm in length; distinct foreset lamination often is preserved. The contact between the Tb and Tc interval often is very apparent; upper level of parallel lamination composed of very fine sand to silty shale (Td). The contact between Tc and Td also is very distinct; Shaley interval (Te) with no visible sedimentary structures. A complete Ta-Te sequence is rare and most common turbidite deposits occur as incomplete sequences (Bouma 1962).

3.4 Wave-Modified Turbidites

Shallow-water turbidites deposited above SWB were documented in several cases (Bartolini et al. 1975, Cacchione and Drake 1990, Higgs 1990, 2014, Myrow and Southard 1996, Myrow et al 2002, Lamb et al. 2008). Shallow-water turbidites also are known as ‘wave-modified turbidites’ or ‘hyperpycnites’ (Higgs 1990, 2014, Myrow and Southard 1996, Myrow et al. 2002). These marine deposits occur when storms discharge dense sediment-rich river water into the ocean. These flows are driven by excess-weight forces and create deltas above SWB that can be modified by combined flows. Wave-modified turbidites can be identified by multiple criteria; (i) well-graded Bouma-like sequences; (ii) well-developed flutes; (iii) thick divisions of climbing ripple lamination; and (iv) and asymmetric folds and abundant convolute bedding (Myrow et al. 2002, Lamb et al. 2008). Wave-modified turbidites differ from deep-water turbidites in that
turbulence required to maintain hyperpycnal flows partially comes from storm waves and is not autosuspending in a purely density-driven flow.

3.5 Study Area Description

Two canyons and several road outcrops served as study sites for this thesis (Figure 1). Lozier Canyon, located in west Texas in Val Verde and Terrell Counties, terminates at the Rio Grande River. Antonio Creek terminates into Lozier Canyon, approximately four miles north of the Texas-Mexico border. Road-side and Osman Canyon outcrops are located along Texas Highway 90, east of Lozier Canyon. Lozier Canyon contains a complete vertical succession of the entire Eagle Ford Formation on multiple well-exposed outcrop faces. Lozier Canyon also serves as a valuable study site because Facies A and the contact with the underlying Buda Formation can be accessed at multiple locations along a 6-mile stretch of the canyon. Antonio Creek has less continuous vertical exposure, but provides access to bedding exposures of Facies A (Figure). Road outcrops along Texas Highway 90 are located approximately ten miles from Lozier Canyon and provide several exposures of Facies A at multiple locations, including Osman Canyon.
3.6 LiDAR

Light Detection and Ranging (LiDAR) scanning is useful for many aspects within the field of geology, most commonly for airborne surface fault mapping over a large area (Buckley et al. 2013). LiDAR also was used to differentiate between lithology using algorithms to increase the intensity variations between separate units with different physical and chemical characteristics (Jones et al. 2009; Buckley et al. 2013). This particular study uses a Leica C10 terrestrial LiDAR to measure the variation in ripple height across the faces of outcrops of Facies A in Lozier Canyon and Antonio Creek. Once the face of an outcrop is scanned, the three-dimensional mesh of data was uploaded to Cyclone® 8.0 software where each individual ripple can be measured across the outcrop.
4. METHODOLOGY

4.1 Outcrop Sampling and Data Collection

The primary aim of this study is to use observations and measurements of sedimentary structures to help determine the depositional environment of Facies A (Figure 5). Symmetry measurements were taken from three-dimensionally exposed ripples and samples were taken of samples with visible cross-bedding in Facies A (Figure 6). A secondary side-objective of this study is to determine the usefulness of LiDAR in outcrop studies.

Figure 5. Step-by-step methodology. Used to determine whether Facies A was deposited above or below SWB.
Skeletal grainstone beds with observable cross-bedding in Facies A were sampled from multiple locations in Lozier Canyon and Antonio Creek (Figure 1). Before being removed, the samples were marked with their location, sample number, and arrow indicating which direction is up. Relatively large samples were selected so that a larger and more continuous suite of sedimentary features can be observed in each sample. Each grainstone sample was approximately 0.5 m (L) x 0.5 m (W) x 0.25 m (H). The samples were returned to the laboratory at Texas A&M University where they were cut into quarters using a large oil-based saw (Figure 7).
Because the cut from an oil-based saw is smooth, polishing the freshly cut rock face was not necessary in order to see well-defined laminations on the freshly cut surface. Most cuts were made 90° to each other to show isotropy and changes in 3-D geometry within the sample. Some extra cuts were made through the ripple crest of each sample to determine if laminations have similar geometry and truncations in all directions. Cuts revealed faces with flat laminations, whereas others have a large range of cross-bedding, truncations, and scour and drape features. The faces with the widest variety of sedimentary structures were photographed normal to the rock face.
Photographs of freshly cut faces 90° to each other were uploaded into Adobe Illustrator® where they were cropped, re-scaled, and meshed together to show a seamless image of laminae forms and truncation surfaces in three-dimensions. The meshed images were traced to accentuate bedding characteristics and make truncations more apparent. This process was used to demonstrate how beds truncate in three dimensions and allows us to observe small-scale sedimentary features that are not visible on weathered surfaces. LiDAR data was also taken for this study, but did not prove useful in making small-scale measurements of the face of the outcrop.

Ripple index (RI) measurements were taken by measuring the height of the ripple and the distance from trough to trough with a tape measure (Reineck and Singh 1975, Collinson et al. 2006). Ripple symmetry index (RSI) measurements were taken by measuring the length from the crest to the trough of the stoss side, then from the crest to the leeward side (Figure 8). Measurements for ripple symmetry were only taken on samples with 3-D exposure.
A secondary objective of this study is to evaluate the usefulness of LiDAR for the observation and description of 3D sedimentary structures. The purpose of LiDAR for this project is to create high resolution 3D images upon which quantitative measurements of sedimentary structures and bed thickness variations on a centimeter-millimeter scale can be made. For this study a green laser Leica ScanStation C10 LiDAR

4.2 LiDAR Scans

A secondary objective of this study is to evaluate the usefulness of LiDAR for the observation and description of 3D sedimentary structures. The purpose of LiDAR for this project is to create high resolution 3D images upon which quantitative measurements of sedimentary structures and bed thickness variations on a centimeter-millimeter scale can be made. For this study a green laser Leica ScanStation C10 LiDAR

Figure 8. Ripple measurements methodology. (A) Tape measure was used to measure ripple dimensions. Field assistance was provided by Matthew Wehner (in photo). (B) Methodology of taking ripple measurements. The wavelength and amplitude of each ripple was measured with a tape measure. Lengths from the trough to crest (L1, L2) were measured on both sides of ripples to acquire symmetry data.
device was primarily used for surveying and has a high-definition range of up to 300 meters. As the LiDAR device scans the outcrop face, data points are recorded in 3 dimensions (Kurz et al. 2009, 2012; Buckley et al. 2013). From the same location, the 3D data set can be stitched over a high-resolution image of the outcrop face that is simultaneously recorded by the LiDAR device, creating a 3D projection of the outcrop that can be viewed and manipulated in Cyclone®. LiDAR images were taken of portions of Facies A that showed measurable ripples and sedimentary structures. Each scan was taken over an outcrop face approximately 25 ft wide and 15 ft tall. The scanner was set up ~15 meters from the outcrop face for each scan. After scanning the outcrop, LiDAR data were uploaded into Cyclone® where the ripple heights and wavelengths were measured using the “distance point-to-point” tool.
5. RESULTS

5.1 Facies A Outcrop- Lozier Canyon

Foraminiferal grainstone and packstone beds in Facies A commonly are <15 cm thick and often are discontinuous and pinch out over a length of 9 meters, though thicker laterally continuous beds occur (Figure 9). Thickness of each grainstone bed varies laterally and can pinch out and re-appear in the same lateral section. Many grainstone/packstone beds are amalgamated containing one or more throughgoing truncation surfaces and multiple ripple structures. Grainstone/packstone beds are separated from one another by an organic-rich shale layer that normally does not exceed 10 cm in thickness or an occasional thin bentonite bed. Cross-bedded grainstone/packstone units thin up-section within Facies A. Grading is rare, but does occur in select samples. The geometry and bedding of grainstone/packstone beds in Facies A in Lozier Canyon, Antonio Creek, and Osman Canyon can be separated into two categories; (i) Symmetric pinching and swelling amalgamated grainstones with parallel laminations and cross bedding present within each layer and; (ii) relatively flat-lying thicker beds ~10-15 cm thick that are laterally continuous and do not show 3-D laminae at the outcrop scale and commonly consists of parallel laminations. Type (i) beds can be concave up, concave down, or symmetric at the outcrop.
Figure 9. Sample location LC1 and LC 2. (A) Visible change in grainstone thickness and lateral continuity occurs across the face of the outcrop. (B) Scouring into parallel laminated beds. (C) Amalgamated grainstone beds.
Type (i) beds can also have a pinched-out lens shape where the unit thickens and thins over a very short distance (~10 cm) and may pinch out and reappear as a single lens or continuous bed further across the unit. These beds have erosive and irregular bases. The dip of laminae within type (i) beds ranges from 10°-31° (Figure 9c). Steeply dipping laminae commonly cut down into underlying layers of parallel laminations. This unit (i) is most-likely to be referred to as a pinch-and-swell bed because of the way each lens is connected by a thinning unit that laterally expands into an adjacent lens within the same bed. Laminae in these units are both concordant and discordant with respect to the beds external geometry. Dips of laminae in these samples...

Figure 9 Continued.
can be as steep as 25°. Flat lying type (ii) beds sometimes have complex internal laminae that are discordant with the 3-D geometry of the sample. Cross bedding in type (ii) samples commonly occurs in multiple sequences of downlap, scour and drape features, with parallel laminations at the upper and lower bounds of the sample (Figure 10).

**Figure 10.** 90° cut sample from LC1-14. Cuts were made using an oil-based rock saw. Parallel lamination on upper and lower bounds. Erosional scoured surface below cross-bedded zone. Cross-bedding has mound shape and laminae dip isotropically in all directions.
5.2 Domal 3-D Exposures

Three-dimensional low-relief domal bedforms are exposed in a gully in Lozier Canyon close to Highway 90 (Figure 11). Erosion of the overlying strata made it possible to view a large area of the beds upper surface. The low-relief domal bedforms have an average wave height of 2.5 cm and wavelength of 14-20 cm producing an RI~8. The mounds have a slightly elliptical shape and concordant laminae that dip at a low angle when observed from the side.

5.3 Ripple Index, Symmetry, and Paleocurrent Measurements

Measurements of 2-D ripple amplitude, wavelength, and symmetry (Figure 8) were recorded at two locations in Lozier Canyon (LC1 and LC 2) (Figure 1). Ripples in Facies A are mostly symmetric with rounded crests and have an average ripple index (RI) of 6.0 and ripples symmetry index (RSI) of 1.23 (Figure 12).

Seven measurements of paleocurrent data were taken in Lozier Canyon and six were recorded in Antonio Creek (Figure 13). Measurements were taken from ripple crests and are scattered, having no regionally consistent measurement (Figure 7b). Scattered paleocurrent direction measurements around a compass are consistent with HCS paleocurrent directions (Bourgeois 1980, Brenchley 1989). Measuring paleocurrent on exposed fragments of domal upper surface, like those for HCS, would produce
Figure 11. Domal features in Lozier canyon (LC1). (A) Domes resemble HCS upper surface and are arranged in a staggered orientation (B) Cross-sectional view of domal features. Cross-bedding is concordant with domal shapes and has low-angle stratification.
scattered data like those in Figure 13. HCS-like beds described by Mulder et al. (2009) have RI values that range from 12 to 25.

Ripples in Facies A have bi-directional downlap on both sides of ripples crests (Figure 14). Bidirectional downlap is a common feature at several locations throughout Lozier Canyon and Antonio Creek. Ripples with unidirectional deposition in Facies A have RI and RSI values that are indistinguishable from RI and RSI values of ripples with bidirectional deposition ($R^2 = .042$). The tops of all measured ripples are rounded. No wave ripples with peaked crests were observed in Lozier Canyon, Antonio Creek, or Osman Canyon.

Figure 12. Ripple index and symmetry data. Blue dots are field data and the red dot is averaged data field. The data is plotted against standards for wave-dominated flow, combined flow, and unidirectional flow set by Reineck and Singh (1975), Collinson et al. (2006).
Figure 13. Rose diagram. Data represents paleocurrent measurements from Lozier Canyon (LC1 & LC2) and Antonio Creek. 13 measurements total.

Figure 14. Ripples with traced laminae. Laminae downlap on both sides of ripples crests. All of the observed ripples in Facies A have rounded crests like those in this figure above.
### 5.4 Contorted Beds

Contorted beds show a range of features in Facies A that were documented in Lozier Canyon, Antonio Creek, and Osman Canyon. The Osman Canyon outcrop is approximately 20 miles east of Lozier Canyon and Antonio Creek outcrops, which are relatively close to each other (Figure 1). Contorted beds also occur in other overlying facies within the Eagle Ford (Facies D and E) in Antonio Creek. However, Facies D and E are nodular and bioturbated, which makes distinction of features difficult.

The thickness, lateral variability, and location relative to the base of Facies A for the contorted beds in Lozier Canyon and Antonio Creek are very similar. Folded features in contorted beds at the Lozier Canyon and Antonio Creek outcrops indicate limited lateral transport. These beds are laterally discontinuous and can only be traced a few meters, with a maximum thickness of 0.6-1.5 m. The Lozier Canyon (LC1) outcrop contains two visible contorted beds that occur 1.5 and 4.5 meters from the base of Facies A and consist mostly of large clasts and deformed semi-continuous beds. More diverse features are exposed in Antonio Canyon. The contorted beds in Antonio Canyon have convolute bedding and diapiric fluid-escape structures (Figure 15).

The character of contorted beds in Osman Canyon is more laterally continuous and occurs at different heights above the Buda than those in Lozier Canyon and Antonio Creek. Osman Canyon has two distinct contorted beds that are continuous over a larger lateral area (> 60 m) and their thickness varies between 0.6 and 1.5 meters in thickness (Figure 2b). These contorted beds are located 0.9 m and 2.7 m from the base of Facies A.
Both of these contorted beds have deformed semi-continuous convolute bedding, load casts, and fluid escape structures.

![Image](image.png)

**Figure 15.** Vertical fluid escape structures in Antonio Creek. Massive grainstone formed diapiric structures during upward fluid escape and deformation of the overlying ductile shale.

### 5.5 LiDAR Scans

LiDAR was unable to aid in this study because the required small scale and three-dimensional exposure of outcrop samples could not be achieved by this device. Bedding thickness measurements proved to be inaccurate in Cyclone when compared to physical measurements with a tape measure on the face of the outcrop.
6. DISCUSSION

The multiple, parallel slices of the largest Facies A samples provide insights about 3-D geometries that are difficult to ascertain on the outcrops. Cut samples allow observation of isotropic laminae, reactivation surfaces, variable laminae dip angles, large ripple wavelengths with symmetric rounded crests, and bidirectional downlap surfaces. These features suggest deposition in a storm-wave setting above SWB. Cross-bedded structures in Facies A contain sedimentary structures that most closely resemble small-scale HCS, SCS, and other storm deposit features, which suggest deposition under combined flow conditions. Ripple height measurements (Figure 12) are indicative of a depositional environment in which wave-influence is substantial (Reineck and Singh 1975, Collinson et al. 2006).

Sedimentary structures in Facies A are not identical to the description of HCS by Harms et al. (1975) because the observed sedimentary structures have short wavelengths on the decimeter scale, and laminae dips frequently exceed 10°. Sedimentary structures in Facies A do not indicate a turbidite system (Bouma 1962), because (Tc) cross-bedded intervals are often isotropic, bidirectional, and are frequently interbedded with fine muddy sediment.
6.1 Distinguishing Between HCS and Turbidite/Antidune Stratification

Cross-bedded structures in Facies A were interpreted as antidune stratified turbidites deposited in a deep-water environment below SWB (Ruppel et al. 2012). Observation of the internal geometry of samples for Facies A shows distinctions between storm-deposited HCS and deep-water turbidites/antidunes. Samples in Facies A have internal laminations with lateral truncations, wide array of laminae dip angles, and three-dimensional isotropy (Figure 16). These features are consistent with descriptions and experimentally reproduced HCS in a combined flow (Myrow and Southard 1991, Myrow 2002, Dumas and Arnott 2006, Perillo et al. 2014).

6.1.1 Internal Laminations

Cross-bedded samples in this study have laminae dip angles that vary from 10° to 30° (Figures 17). Normally, the dip angle for turbidites and contour currents is largely governed by the angle of repose (>30°). This study suggests that the large variations in dip angle for each respective sample are controlled by several factors such as: (i) variations in aggradation rate (Dumas and Arnott 2006); (ii) prolonged events of deposition and reworking (Perillo et al. 2014); (iii) and variations in unidirectional velocity for each respective depositional event (Dumas et al. 2005). Wave-tank experiments indicate that an increase in aggradation rate results in an average increase in dip of the leeward side of cross-laminae (Dumas and Arnott 2006). Flow duration and
Figure 16. Structures produced in experiments (A) Multiple generations of scour and fill and swaley cross-stratification. A 90° cut was made through the plane marked with the dotted line to view truncation in three-dimensions. Swaley cross-stratification in this sample is compared to experimentally reproduced structures (b) and (c). (B) Wave-tank experiment. Experimentally produced swaley cross-stratification formed under oscillatory dominant combined flow, which closely resembles Facies A in Figure 16a. Modified figure from Dumas and Arnott (2006). (C) In the same series of experiments performed by Dumas and Arnott (2006), aggradation rate was increased, which caused an increase in preserved dip-angle of laminae. Produced Samples appear similar to those observed in Facies A. However, these structures lack a flat basal surface similar to structures in Facies A. Modified figure from Dumas and Arnott (2006).
velocity also are important factors that control the ability of a bedform to grow until it reaches maturity with respect to flow conditions (Perillo et al. 2014).

Figure 17. Cut samples from Lozier Canyon. This figure shows varying degrees of bedding dip angle.
Lateral truncations and truncation surfaces (Figure 18) are most likely the result of a brief change in flow direction, associated with oscillatory flow. This type of bedding character is highly unlikely in a high-velocity depositional setting that would cause antidune stratification (Rust and Gibling 1990). Antidune laminae are preserved on the stoss side of deposition, which indicates that this type of truncation (Figure 18) was not formed by antidune stratification (Simons and Richardson 1961, Middleton 1965, Rust and Gibling 1990). These truncations also are inconsistent with high-energy unidirectional flows associated with continuous trough cross-bedding deposition in turbidites because rapid density-driven flows have no method of reversing flow to cause such truncation surfaces.

Figure 18. Truncation surfaces in Facies A. These are found in numerous samples from Lozier Canyon. Arrows identify two truncation surfaces that were formed during deposition.
6.1.2 Three-Dimensional Geometry and Isotropy

The most distinct differences between combined flow wave-dominated sedimentary structures and unidirectional current-flow structures are isotropic laminae that dip evenly across 360° and the presence of symmetric wave-ripples with bi-directional downlap. Isotropic laminae (Figure 4) are characterized by similar dip angle in all directions and are a distinct characteristic of HCS and SCS (Harms et al. 1975, Bourgeois 1980, Walker and Leckie 1982, Snedden et al. 1988, Brenchley 1989). Wave oscillation associated with storm events causes sediment to be draped over an irregularly scoured surface and moves sediment into circular mounds of HCS and SCS (Southard et al. 1990, Myrow and Southard 1996). Samples from Facies A have a wide variety of internal geometries, most of which have isotropic laminae and bundled foresets that truncate symmetrically across a 90° cut (Figure 19). Concave-up drape-like geometry is most common in SCS and is deposited in scoured troughs as the synform extension of antiform HCS beds into lower areas. In fact, synforms (SCS) are most commonly preserved from HCS beds, which is why they are so frequently mistaken for trough cross-stratification (Dott and Bourgeois 1982). The ability to see isotropic truncation of SCS in three-dimensions is inconsistent with trough cross-bedding described in Tc intervals of turbidite deposits and is at too high of an angle to be confused with 3-D antidunes. Short-lived energy dispersals from the Kelvin-Helmholtz instability would not be capable of sustaining the required wave-energy to rework largely isotropic sedimentary structures like those in Facies A.
6.1.3 Domal 3-D Exposures

Three-dimensional low-relief domal bedforms in Lozier Canyon mounds have a slightly elliptical shape and concordant laminae that dip at a low angle when observed from the side, similar to HCS mounds (Harms et al. 1975). The mounds are organized in a staggered orientation, which is consistent with the domal three-dimensional upper surface of HCS bedding. Mound organization like this is inconsistent with the hypothesis that cross-bedded structures in Facies A formed by antidunes (Ruppel et al. 2012). Wave tank experiments indicate that antidune stratification produces laterally continuous trains, or crest axes, in well-ordered successions (Middleton 1965, Barwis and Hayes 1985, Rust and Gibling 1990, Alexander et al. 2001, Cartigny et al. 2014). These uniquely exposed bedforms in Lozier Canyon are interpreted as combined flow HCS mounds and further indicate deposition above SWB.
Figure 19. Samples were cut at right angles to reveal bedding features in 3D. (A) Sample LC1-9 has concave-up bowl-like shape in three-dimensions and has bundled foresets that indicate multiple generations of bundled foresets. Laminae that dip evenly across a right angle indicate isotropy. (B) Sample LC1-1 shows laminae that dip evenly across a right angle, scoured basal surfaces, and parallel laminae with low-angle stratification. (C) Sample LC1-4 has a mound-like shape in three-dimensions with laminae truncating evenly across 90°. A cross-bedded zone is bound by parallel laminations at the top and bottom of the sample. Scouring of the basal parallel laminations can be observed. Cross-bedding has a concave-up and concave-down shape in three-dimensions. (D) Sample LC2-1 has cross-bedded laminae have a domal concave-down shape and dip evenly across a right angle. Dip angle also varies laterally in this sample, indicating change in flow velocity and/or sediment supply.
Figure 19 Continued.
6.1.4 Lineation and Paleocurrent indicators

Lineations and clear paleocurrent indicators are common in turbidite and antidune stratification where strong unidirectional currents are responsible for deposition (Middleton 1965, Anketell and Lovell 1976, Stow 1979, Rust and Gibling 1990, Alexander et al. 2001). Lineations in HCS are rare and are rarely documented (Duke 1985, 1987, Brenchley 1985). Similarly, no lineations were observed in Facies A. Because the laminae dip isotropically, acquiring paleoflow vectors was not possible on 3-D exposures of cross bedded samples. The lack of consistent paleoflow indicators suggests that Facies A was deposited in an environment where unidirectional flow was
dominated by strong oscillatory flow, preventing the generation of lineations or consistent unidirectional trough cross-stratification.

6.2 Ripples

Ripples in Facies A do not occur in any particular sequence with respect to cross-bedded layers or layers of organic-rich mudstone. This being considered, the character of the ripple height, wavelength, and crest shape can still indicate whether or not the depositional environment was influenced by oscillatory motion above SWB.

6.2.1 Symmetry

Ripples in Lozier Canyon and Antonio Creek are strongly symmetric with unidirectional and bidirectional downlap. Ripples with downlap on both sides of the ripple crests indicate influence of oscillatory wave-motion (Figure 14).

Symmetric bedforms are important in recognizing wave-influence in an environment, but does not negate the possibility of asymmetric bedforms to form in wave-influenced environments as well. Asymmetric bedforms, similar to trough cross-stratification, were reproduced in wave-tank experiments still being primarily influenced by oscillatory wave-motion in combined flow (Dumas and Arnott 2006, Perillo et al. 2014). Asymmetric HCS and ripple geometry often are attributed to an increase in unidirectional current velocity in combined flow and have a preferred direction of
asymmetry towards the down-flow direction (Allen 1982, Nottvedt and Kreisa 1987, Myrow and Southard 1991). During storm surges, strong backflow currents flow seaward and can transport large quantities of sediment across a shelf, thus skewing the shape of deposited sedimentary structures and causing asymmetry as well as amalgamation (Myrow and Southard 1996, Dumas and Arnott 2006).

6.2.2 Ripple Crests

Ripples in Facies A do not exhibit the characteristic peaked-crest shape associated with wave oscillation in a shallow-water environment. Instead, the ripples in Facies A most commonly have relatively large wavelengths and rounded crests. Ripples with rounded crests were frequently observed and reproduced in combined flow settling (Harms 1969, Reineck and Singh 1980, Arnott and Southard 1990, Dumas et al. 2005). The hydrodynamic conditions required to create ripples with round crests suggests that deposition occurred during a storm event (Yokokawa 1995, Myrow and Southard 1996, Lamb et al. 2008, Myrow et al. 2008, Yamagichi and Sekigichi 2010). The presence of ripples with round crests similar to storm ripples is further evidence that Facies A was deposited above SWB. The presence of storm-related ripples and the lack of peaked crests suggests that the depositional environment was between fair-wave base (FWB) and SWB.
6.2.3 Measured Data

Mound-like geometry of HCS and SCS makes accurate paleocurrent measurements very difficult (Bourgeois 1980, Brenchley 1989). However, wave ripples often form conjunction with HCS and SCS in tempestite deposits (Aigner 1982, Dott and Bourgeois 1982). The data from wave ripples in Facies A suggests the flow regime was symmetric. Generally, lower RI values (< 4) and RSI’s (< 2.5) represent wave-dominated flow, and higher RI’s (> 15) and RSI’s (> 3) represent strong unidirectional flow (Reineck and Singh 1975 p. 35, Collinson et al. 2006 p. 76). Combined flows have RI’s between 4 and 15. Average RI (6) and RSI (1.23) for Facies A indicate that ripples are strongly symmetric and formed in a combined flow regime.

6.3 Implications for Depositional Environment

6.3.1 Comparison to structures in the Basque Flysch (Mulder et al. 2009)

The suggestion that cross-bedded features in Facies A were deposited in a similar setting as HCS-like antidune stratified turbidites in the Basque Flysch (Ruppel et al. 2012), described by Mulder et al. (2009), neglects several crucial factors that should be included when interpreting sedimentary structures and their depositional environment; (i) The Eagle Ford Group was deposited on the Comanche Platform carbonate shelf, which bears little resemblance to the bathymetry of the Saint-Jean-de-Luz intracratonic
basin (1000-1500 m) where the Basque Flysch was deposited; (ii) The Basque Flysch outcrop is 3,000 m thick, whereas the Eagle Ford is only 52 m thick in Lozier Canyon; (iii) Cross-bedded structures described as HCS-like don’t resemble strong three-dimensional resemblance to the cross-bedded structures in Facies A (Mulder et al. 2009).

In contrast to Facies A, laminae in the Basque Flysch have: (i) more lateral continuity; (ii) gently dipping laminae (< 15°) and lack ripples; (iii) frequent antidune-like stratification with a higher RI (h/l ratio); (iv) clear, unidirectional paleoflow indicators; and (v) contains no sharp breaks in grain size or scoured basal surfaces.

The hydrodynamic conditions required to deposit the structures in the Basque Flysch occur under a very narrow range of parameters that are highly unlikely to occur on a gently-dipping carbonate shelf in the WIS for Facies A, because a steeply dipping slope is required to create a K-H instability. To generate turbidites that can be reworked by upslope antidune stratification caused by the K-H instability, a high-angle paleoslope and large amount of sediment supply are required (Quin 2011). Laminae dip directions frequently reverse throughout outcrops of Facies A in Lozier Canyon and Antonio Creek (Figure 20), this type of flow reversal is unlikely on a slope that was steep enough to produce a turbidity current. One could argue up-slope wave-migration from the Kelvin-Helmholtz instability created these flow reversals. However, the energy required from such a wave would have to be sustained for a long enough time period and with enough energy to deposit high-angle cross bedding up slope, which is not hydrodynamically plausible. Instead, this study suggests that changes in dip direction are simply the result of oscillatory wave-motion in a combined flow above SWB.
6.3.2 Wave-Modified Turbidites (Hyperpycnites)

Interpretation of sedimentary structures in Facies A as HCS and SCS places the depositional environment above SWB in a shallow shelf setting in which storms frequently deposited and reworked sediment. The possibility of generating turbidity flows from excess-weight forces in a gently dipping shelfal setting is unlikely.
A relatively steep slope is required to achieve a self-sustaining turbidity current that can entrain large volumes of sediment (Swift 1986, Bangold 1962, Parker 1982). The most viable explanation for a density-driven turbidite-like deposits on a shelf would be hyperpycnites, or ‘wave-modified turbidites’ (Higgs 1990, 2014, Myrow and Southard 1996, Myrow et al. 2002, Luca and Basilici 2013). These fluvial deposits occur when storms discharge cool, dense, sediment-rich river water into the ocean, creating deltas above SWB that can be modified by combined flows. Common characteristics of hyperpycnites are; (i) well-graded Bouma-like sequences; (ii) well developed flutes; (iii) thick divisions of climbing ripple lamination; and (iv) and asymmetric folds and abundant convolute bedding (Myrow et al. 2002, Lamb et al. 2008). Cross-bedded structures in Facies A contain few of the criteria necessary for wave-modified turbidites: (i) grading in Facies A is rare, with the exception of tempestite storm event beds; (ii) facies A has no flute casts and few paleocurrent indicators; and (iii) structures in Facies A also show no indication of supercritical climbing current ripples associated with density-induced flow (Myrow and Southard 1996).
7. CONCLUSIONS

The cross-bedded structures in Facies A outcrops of the Eagle Ford Group in west Texas are interpreted as small-scale HCS and SCS end-members associated with storm deposition above SWB on a shallow-water low-angle carbonate ramp. Bedforms were deposited by combined flows with strong unidirectional currents and oscillatory wave-motion. Sedimentary features in Facies A exhibit characteristics that are indicative of storm deposits, such as: (i) laminae that drape in all directions in a mound-like geometry similar to HCS and SCS; (ii) evidence for oscillatory flow, such as symmetric round-crest ripples with bi-directional deposition on both sides of ripple crests; (iii) a wide variety of bedform geometry and laminae dip angle, which are associated with variations in storm intensity, duration, sediment supply, and relative sea level; (iv) frequently amalgamated and node-shaped shaped bedding, consistent with sediment transported across a shelf in a storm-dominated environment; (v) and a low RI and RSI of measured ripples that is consistent with formation in a wave-dominated combined flow regime above SBW.

LiDAR scans of Facies A proved not to be useful for the purposes of this study.
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