PROCESSES INFLUENCING THE DIVERSITY OF MIDDLE PERMIAN BRACHIOPODS IN THE BELL CANYON FORMATION OF THE DELAWARE BASIN (WEST TEXAS, GUADALUPE MOUNTAINS NATIONAL PARK)

A Dissertation

by

LEIGH MARGARET FALL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2010

Major Subject: Geology

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Approved by:

Chair of Committee,	Thomas D. Olszewski
Committee Members,	Wayne Ahr
	Anne Raymond
	Debbie Thomas
	Thomas Yancey
Head of Department,	Andreas Kronenberg

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ABSTRACT

Processes Influencing the Diversity of Middle Permian Brachiopods in the Bell Canyon Formation of the Delaware Basin (West Texas, Guadalupe Mountains National Park). (August 2010)

Leigh Margaret Fall, B.S., University of New Mexico; M.S., Indiana University

Chair of Advisory Committee: Dr. Thomas D. Olszewski

A fundamental question of long standing in the study of life on Earth is, "Why are there so many species?" This question concerns the distribution of and relationships among species in the present day, but also requires an understanding of the history of diversity. Patterns of diversity result from multiple, interconnected ecological processes operating at different spatial scales. The goal of this research is to gain knowledge about processes that control diversity by using fossil data to provide a temporal perspective that is unavailable when studying modern ecological communities. The fossil record provides the only natural historical account of changes in the diversity of ecological communities in Earth's past.

This research examines the taxonomic composition and diversity of brachiopod paleocommunities in the Delaware Basin of west Texas (Guadalupe Mountains National Park). The study interval is the Bell Canyon Formation, a 5.4-Myr interval of upper Middle Permian (Capitanian) siliciclastic and carbonate rocks deposited on the toe-of-slope of the basin. Silicified brachiopods extracted from the carbonate rocks provide the basis to test two hypotheses: (1) the taxonomic composition of local fossil brachiopod paleocommunities remains uniform, and (2) the changes in diversity of local fossil brachiopod paleocommunities reflects the relative importance of regional processes. Multivariate analyses of clustering analysis and ordination, diversity partitioning, and rank abundance plots are used to evaluate brachiopod taxonomic composition and diversity within an ecological framework. Sequence stratigraphic analysis provides the means to place the results within an environmental context related to sea-level changes.

Results indicate that the reorganization of brachiopod paleocommunity structure coincides with major basinal-scale disruptions. Large disruptions allowed rare taxa and invaders from outside the basin to become dominant within paleocommunities. The dynamics within paleocommunities do not appear to prevent the replacement of the incumbent taxa with new taxa. The importance of these findings indicate that paleocommunities are not static through this interval and can be perturbed into configurations with new dominant taxa. Therefore, ecological responses of paleocommunities are resolvable at the geological time scale.

DEDICATION

I dedicate this dissertation to my family–Faye and Richard Fall, Jennifer Fall, Lisa, Mike, and Valerie Parrott, Sara and Roy Lunsford–whose support and encouragement made the completion of this work possible.

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I would like to acknowledge my committee chair–Dr. Thomas D. Olszewski–for his invaluable advice, his generous support, his unending energy, and his everlasting patience. Thank you for taking me on as your first Ph.D. student. I learned so much, and I know with Tom's guidance through my dissertation, in the classroom, and in the field, I will be able to achieve success in my career. I also thank Dr. Anne Raymond, Dr. Debbie Thomas, Dr. Wayne Ahr, and Dr. Thomas Yancey for their advice and support through this process. They served as valuable members of my committee and instructors of science.

Dr. Gorden Bell, park geologist of Guadalupe Mountains National Park, warrants special acknowledgement for sharing his stratigraphic columns for the Lamar Member localities along Williams Ranch Road, introducing me to the Reef Trail Member, and making arrangements for me to stay at the park while doing field-work. Our lengthy discussions on the debris flows of the Bell Canyon Formation were informative and thought provoking as well as the many days in the field looking at the fossils and stratigraphy in the Guadalupe Mountains.

Sara A. Marcus, my best friend and field partner, merits a very special acknowledgement. Sara spent 12 weeks in the field with me over two summers in the Guadalupe Mountains of west Texas. She braved the hot Texas sun, dangerous vegetation of lechuguilla, cholla, prickly pear, Eagle's claw, acacia, and mesquite, and treacherous footing while carrying tons of samples down steep-sided ridges and through arroyos. This dissertation would not have been possible without her unwavering help, support, and dedication in all the endeavors of my work. Also, I would like to thank Dr. Christopher G. Maples–Sara's husband–for letting me have Sara as my field partner. I have appreciated both Sara and Chris's support through the years.

My friends–Cory M. Redman and Dr. Jason R. Moore–deserve special recognition for their support and encouragement during the process of gathering and analyzing data and writing my dissertation. I want to thank Cory for allowing me to dissolve many, many large limestone samples in his back patio. Without his generous offer, I would still be dissolving my samples today. I also want to thank Jason for helping me write code in R. He is a master at programming and a great teacher of the programming language. Cory and Jason kept me sane through the writing process by going to many movies, camping, and hosting and attending costume parties with me. Their friendship means everything to me and I know our friendship will last many, many years to come. Additionally, I would like to thank the many great friends I made while at Texas A&M University–Masako Tominaga, Josiah and Mary Strauss, Stella Woodard, Rick Smith, Tara Kneeshaw, David Pierce, Kellie Wilcox-Moore and family, Clay Bowden, Regina Dickey, Chioma Okafor, Steve Lichlyter, Meaghan Julian, and Chris Klug. My apologies to anyone I have befriended during my time at Texas A&M and not included in the list above.

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NOMENCLATURE

BCF	Bell Canyon Formation
LST	Lowstand systems tract
TST	Transgressive systems tract
HST	Highstand systems tract

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CHAPTER I

INTRODUCTION

Understanding what determines species diversity is a primary goal in community ecology and paleoecology. Species diversity is broadly defined as the number of species in an area, but diversity also is concerned with species abundance and distribution and relationships among species. These patterns of diversity result from multiple, interconnected ecological processes operating at different spatial scales. Local community diversity can be defined as species with the potential to interact with each other on ecological time scales. Processes responsible for controlling local diversity include competition, predation, other density-dependent processes, as well as physical disturbance. Regional diversity can be defined as the pool of species with the potential to colonize any location. Processes responsible for controlling regional diversity include movement of individuals from one place to another (i.e., species dispersal or immigration/emigration), species invasions, and regional extinctions. Therefore, diversity of local communities reflects a balance between invasion from the regional species pool, which inflates local diversity by introducing new species, and the strength of local species interactions, which limits local diversity by reducing the likelihood of successful invasion.

Community ecological theory traditionally has viewed local species interactions as the primary control on the coexistence of species (e.g., Lotka, 1925; Volterra, 1926; Gause, 1934; Hutchinson, 1959; MacArthur and Levins, 1967), but has recognized that

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This dissertation follows the style of PALAIOS.

diversity also is influenced by larger regional processes (e.g., MacArthur and Wilson, 1967; Ricklefs, 1987; Hubbell, 2001; Holyoak et al., 2005a). This thinking has paved the way for ecological theory to incorporate processes operating at larger scales, such as dispersal from the regional biota, into models to determine the effect these processes have on the dynamics of local communities. Diversity also requires an understanding of the evolutionary and geological processes of speciation and extinction, climate change, sea level, and plate tectonics (e.g., Eldredge and Gould, 1972; Sepkoski, 1981; Valentine and Jablonski, 1991; Jackson and Overpeck, 2000) to help explain diversity patterns observed in the modern and how these larger-scale processes influenced community composition and species diversity through time.

The aim of the research presented here is to shed light on the processes that govern the diversity of fossil communities through geologic history. The fossil record provides the diversity data to address hypotheses on the dynamics of communities in a temporal perspective unavailable when studying modern ecological communities. Regional diversity is a link between local and global diversity; however, our understanding of the relationship among these difference scales of diversity and the processes underlying them are not well understood. The objective of understanding the interplay between community-level processes and regional processes is to provide more accurate interpretations and predictions of the ecological processes controlling diversity patterns in the fossil record.

The proposed research was carried out in Guadalupe Mountains National Park, where the well-understood geologic framework and a legacy of detailed taxonomic work on the fossilized brachiopods of the region present an exceptional opportunity to study changes in the diversity dynamics of ecologic communities through geologic time. The study interval for this research is the Bell Canyon Formation, a 5.4-Myr interval of upper Middle Permian (Capitanian) siliciclastic and carbonate rocks deposited on the slope of a rimmed platform. An established sequence stratigraphic framework provides temporal constraints in which to assess diversity through time within the same region. The sequence boundaries defining non-overlapping intervals of time represent environmental disruptions within the basin related to sea-level changes that could influence the ecological landscape by increasing or decreasing area and fragmentation of habitats occupied by brachiopods. The fossil data used in this research are silicified brachiopods, which are extracted from the conglomerate facies within the carbonate tongues of the formation. Brachiopods are used in theses analyses because they are the best-known fossil group in these rocks due to the work of Cooper and Grant (1972, 1974, 1975, 1976a, 1976b, 1977). Cooper and Grant collected more than 1,000,000 specimens throughout the mountain ranges of West Texas and published comprehensive taxonomic descriptions based on their material.

This dissertation is divided into three main chapters. Chapter II deals with the stratigraphy and depositional environments of the Bell Canyon Formation. Chapter III evaluates the taxonomic composition of brachiopod paleocommunities. Chapter IV partitions diversity of brachiopod paleocommunities

Chapter II correlates facies to identify significant stratigraphic surfaces to characterize the environmental heterogeneity on the slope. Sedimentological data from eight measured sections from the Bell Canyon Formation are used to define facies in the study interval. These facies are used to place the measured sections in a sequence stratigraphic framework. The identification of significant surfaces provides a means for understanding how these slope deposits are related to shallow-water deposits on the shelf in time and space.

Chapter III tests the hypothesis that the taxonomic composition of local fossil brachiopod paleocommunities remains uniform within the Bell Canyon Formation. Brachiopods are analyzed by using cluster analysis and correspondence analysis to identify and characterize paleocommunity composition. A paleocommunity is defined here as a spatial and temporal association of genera among collections. Statistical tests are applied to test for differences among the paleocommunities through time. These analyses are conducted within the sequence stratigraphic framework to assess how brachiopod paleocommunities are affected by environmental disruptions in the basin. Ecological theory is used to help understand the processes involved in the co-occurrence of brachiopod genera within each member of the Bell Canyon Formation.

Chapter IV investigates the influence of dispersal among brachiopods as a possible explanation for changes in composition and diversity of brachiopods through this ~5.4 Myr interval. Diversity of brachiopod metacommunities (a group of local communities linked by dispersal) is partitioned into within-community (alpha) and among-community (beta) components to determine the amount each component contributes to overall diversity of the metacommunities. The collections from each member are pooled together to represent a metacommunity. Beta diversity is measured to evaluate the relative change of dispersal levels (high versus low) in each member. The abundance structure of each metacommunity is evaluated to determine if the structure remains the same or changes due to environmental disruptions and metacommunity dynamics.

CHAPTER II

FACIES DISTRIBUTION ON THE SLOPE OF THE PERMIAN REEF COMPLEX IN THE DELAWARE BASIN (CAPITANIAN, BELL CANYON FORMATION, GUADALUPE MOUNTAINS NATIONAL PARK)

Introduction

The rocks exposed within the Guadalupe Mountains (Delaware Basin) of west Texas and New Mexico provide geologists opportunities to study shelf to basin exposures of a mixed siliciclastic and carbonate system from the grain-size scale up to the seismic scale. A series of carbonate ramps and platforms of Middle Permian age (~265 million years old) are exposed on the mountain escarpment. The development of the ramps and platforms through time culminated in the geologically renowned Permian Reef complex, a prominent feature of Guadalupe Mountains National Park of west Texas that records the origin, development, and demise of an ancient tropical reef (e.g., Girty 1908; King 1930; Newell et al. 1953; Brown and Loucks 1993; Wood et al. 1996; Wardlaw et al. 2000). Much work has been focused on the shelf and reef (e.g., Sarg and Lehmann, 1986; Kerans and Fitchen, 1995; Osleger, 1998; Kerans and Tinker, 1999) to identify facies and surfaces in order to develop a sequence stratigraphic framework. Work also has focused mainly on the sandstones on the slope and in the basin because of their hydrocarbon potential and their link to the shelf within a sequence stratigraphic framework (e.g., Rigby, 1958; Payne, 1976; Williamson, 1977; Beaubouef et al., 1999). Conversely, the carbonates on the slope have received less attention (e.g., Koss, 1977; Lawson, 1989; Brown and Loucks, 1993; Wilde et al., 1999; Playton, 2008).

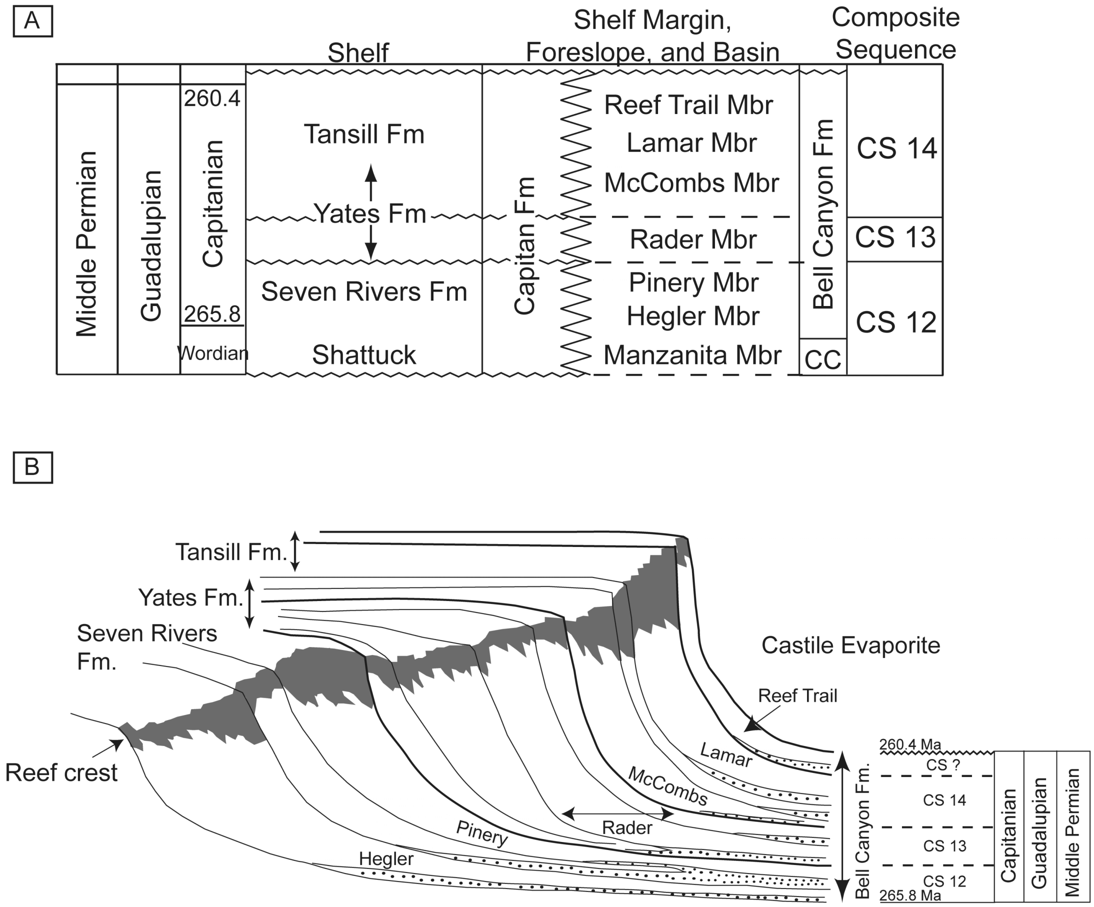
As the basin evolved from a ramp to a steep-rimmed shelf, the rocks deposited on the slope include siltstones, sandstones, and carbonates. The secular variation of siliciclastics and carbonates is attributed to changes in sea level. During times of lowstand, siliciclastics were transported to the shelf by eolian processes and delivered to the basin through gravity flow processes (Fischer and Sarnthein, 1988; Garber, 1992). During times of highstand, when the shelf was flooded and the carbonate factory was active, siliciclastics were trapped behind the shelf, and carbonate deposition dominated, with barrier and patch reefs rimming the basin. Carbonate sediment delivered to the slope and basin margin occurred through various types of gravity flow processes and included sediment from the shelf, reef, and slope.

The aim of this study is to characterize the carbonate deposits on the lower slope of the Capitanian-age Permian reef exposed in Guadalupe Mountains National Park. The Bell Canyon Formation records deposition of siliciclastics and carbonates on the slope and basin floor at a time when the shelf edge was rimmed by patch and barrier reefs. Although work has been done on the carbonate deposits of the Bell Canyon Formation, our understanding of these deposits remains unclear for environmental interpretations, and for how they fit into the sequence stratigraphic framework established on the shelf (i.e., correlation of sequence boundaries into the basin). The work presented here builds on previous sequence stratigraphic work by adding information on the slope deposits from new areas of the park and a new member in the formation that has not previously been incorporated into a sequence stratigraphic framework. Environmental interpretations of these slope deposits, specifically the debris flows, will aid the understanding for paleoecologic studies because the debris flow deposits concentrate the fossils of organisms once living on the slope environment.

Geologic Setting

This study area covers the Pinery, Rader, Lamar, and Reef Trail Members of the Bell Canyon Formation across Guadalupe Mountains National Park of west Texas (Figs. 2.1 and 2.2). Rocks found in Guadalupe Mountains National Park were deposited in the northwestern part of the Delaware Basin and exposed in the Tertiary by uplift during basin-and-range tectonism (Yang and Dorobek, 1995). The Delaware Basin was positioned north of the equator on the western margin of Pangaea and was connected to the open ocean of Panthalassa by the Hovey Channel. The fine-grained sandstones and siltstones interbedded with carbonate tongues of the Bell Canyon Formation were deposited seaward of the reef crest on a steep-rimmed platform during an approximately 5.4 Myr interval of Capitanian age (Guadalupian, Middle Permian). These slope deposits are the basinal equivalents of the Seven Rivers, Yates, and Tansill Formations on the shelf and the Capitan Formation on the shelf crest and foreslope (Fig. 2.1; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 1999; Kerans and Kempter, 2002). The sandstones and siltstones are the dominant lithology of the Bell Canyon (95%) and mainly are found on the basin margin and on the basin floor (Williamson, 1977). The carbonate members thicken towards the reef and interfinger with the Capitan Formation (Hill 1996). All the members thin towards the basin, but only the Lamar is continuous across the basin (Hill 1996). Most of the Bell Canyon

Figure 2.1–Capitanian stratigraphy and platform geometry in the Guadalupe Mountains. A) Lithostratigraphic and sequence stratigraphic framework of the Bell Canyon Formation. Modified from Kerans and Tinker (1999). Wavy horizontal lines indicate exposure surfaces (third-order unconformities) and dashed lines indicate the correlation of those surfaces into the basin. Reef Trail Member added to show lithostratigraphic position, not sequence stratigraphic position. CC = Cherry Canyon Formation. B) Cross section of the carbonate platform with shelf to basin stratigraphy. Lithostratigraphic position of the members is shown on the slope. These are tied to the composite sequences modified from Kerans and Tinker (1999). Sandstones and siltstones are shown with dots. Solid lines indicate the correlative conformities of third-order sequence boundaries from the shelf into the basin. Reef Trail Member added to show lithostratigraphic position and possible sequence stratigraphic position. Ages are from Gradstein and Ogg (2004). Modified from Tinker (1998).


A
Shelf
Shelf Margin, Foreslope, and Basin
Composite Sequence
Middle Permian
Guadalupian
Capitanian
260.4
265.8
Wordian
Tansill Fm
Yates Fm
Seven Rivers Fm
Shattuck
Capitan Fm
Reef Trail Mbr
Lamar Mbr
McCombs Mbr
Rader Mbr
Pinery Mbr
Hegler Mbr
Manzanita Mbr
Bell Canyon Fm
CC
CS 14
CS 13
CS 12
B
Tansill Fm.
Yates Fm.
Seven Rivers Fm.
Reef crest
Castile Evaporite
Reef Trail
Lamar
McCombs
Rader
Pinery
Hegler
260.4 Ma
265.8 Ma
CS ?
CS 14
CS 13
CS 12
Bell Canyon Fm.
Capitanian
Guadalupian
Middle Permian

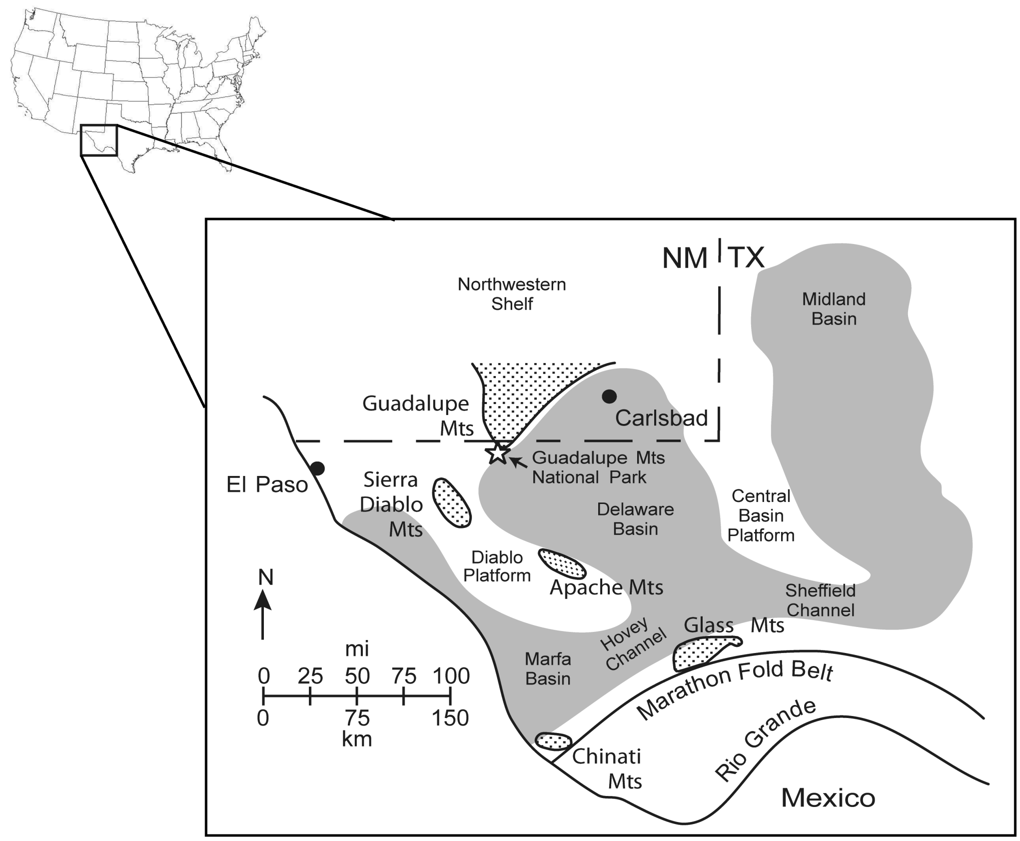


Figure 2.2–Paleogeography of the Permian Basin and location of field area in the Guadalupe Mountains National Park. Modified from Cooper and Grant (1972).

Formation reflects deposition under normal-marine conditions, but the uppermost Reef Trail Member may reflect initial stages of closure of the basin. The 200 to 300 m formation is overlain by a thick succession of evaporitic deposits of the Castile Formation, indicating isolation of the Delaware Basin and marking the close of the Guadalupian (Hill, 1996; Sarg et al., 1999).

The uppermost member of the Bell Canyon Formation is the Reef Trail Member, which was formally recognized by Wilde et al. (1999) for the beds that overlie the Lamar Member and underlie the Castile Formation. Depending on the location within the park, King (1948) originally mapped this succession of rocks as post-Lamar beds or as the Lamar Member (Rigby and Bell, 2005). The boundary between the Guadalupian and Lopingian (Late Permian) has been placed immediately below the Castile Formation in the Reef Trail Member (Lambert et al., 2002). On the shelf, the Reef Trail Member is equivalent to the upper Tansill Formation (i.e., above the Ocotillo Silt Member) based on the presence of the fusulinid *Paraboultonia* (Wilde et al., 1999). The Ocotillo Silt Member divides the Tansill Formation into two parts, with the Lamar Member correlating to the lower Tansill Formation (Tyrrell, 1969; Wilde et al., 1999); the Ocotillo Silt Member has been suggested to mark a sequence boundary (Kerans and Harris, 1993; Wilde et al., 1999). Based on measured sections, the Reef Trail Member exhibits similarities to the underlying members with debris flow deposits interbedded with turbiditic deposits, but the fossils within this member differ from the underlying biotas in containing common molluscs and sponges.

Based on previous sequence stratigraphic work, the Bell Canyon Formation consists of two and a half composite sequences (CS) bounded by third-order sequence boundaries and includes part of CS 12, 13, and 14 (Fig. 2.1; Tinker, 1998; Kerans and Tinker, 1999; Kerans and Kempter, 2002). Part of CS 12 is the Manzanita Member of the Cherry Canyon Formation. The sequence boundaries are identified on the shelf based on subaerial exposure, facies shifts, and siltstones, and are assumed to underlie siltstones and sandstones on the slope and basin (Tinker, 1998; Kerans and Tinker, 1999). The amplitude of eustatic sea-level fluctuations in the region has been calculated to be ~10 m, during a time of tectonic quiescence in the Guadalupian (Ye and Kerans, 1996). Each composite sequence consists of multiple unconformity-bounded high-frequency sequences that in turn are composed of lowstand, transgressive, and highstand systems tracts (Tinker, 1998; Kerans and Tinker, 1999). The lowstand systems tract (LST) is represented by siliciclastics deposited in the basin by gravity flow processes (Garber, 1992) or from suspension (Tinker, 1998). The shelf margin was covered under shallow water depths and carbonate deposition in the basin was at a minimum (Tinker, 1998). During deposition of the transgressive systems tract (TST), the shelf margin was aggradational (Tinker, 1998), but the shelf was not flooded until late TST (Brown and Loucks, 1993). Tinker (1998) found that on the slope, early TST deposits were a mixture of siliciclastics and carbonates derived from the shelf, but late TST deposits were dominantly carbonate. The shelf margin during the highstand systems tract (HST) was progradational (Tinker, 1998) and the shelf was flooded (Brown and Loucks, 1993). The HST is represented with fine-grained deposits in the early HST and coarser-grained deposits (i.e., conglomeratic deposits) in the late HST (Brown and Loucks, 1993).

The Rader Member records multiple failure and repeated collapse of the terminal Seven Rivers-Capitan shelf margin. Playton (2008) identified megabreccia wedges containing blocks that range in size from 5 to >10 m of reef and outer shelf material within a limestone matrix extending into the basin at multiple locations along the escarpment. Playton (2008) suggested that the collapse of the Seven Rivers-Capitan shelf margin resulted from the rapid progradation of the margin over an unstable foreslope, and coincided with the sequence boundary between the Pinery and Rader Members. These multiple failures along the margin provided places for shelf carbonates of the Yates Formation to funnel and deposit on the basin floor (Playton, 2008).

Methods

The stratigraphic cross-sections are built on eight measured sections from the northeast, central, and southwest areas of the park (Fig. 2.3). The measured sections from Williams Ranch Road area (Lm1, Lm2, Lm3, and BR), Rader on the Road (ROTR), and McKittrick Canyon (Lm4, Lm5) provide new localities for assessing the facies of the Bell Canyon Formation. None of the sections include the entire Bell Canyon Formation, but many include at least two successive members. The exceptions are at the localities PS and ROTR, where PS includes only the Pinery and ROTR includes only the Rader member. All measured sections with complete descriptions are found in Appendix.

The correlations presented here are stratigraphic hypotheses built on facies associations of siliciclastic and carbonates and coarsening-upward successions. The

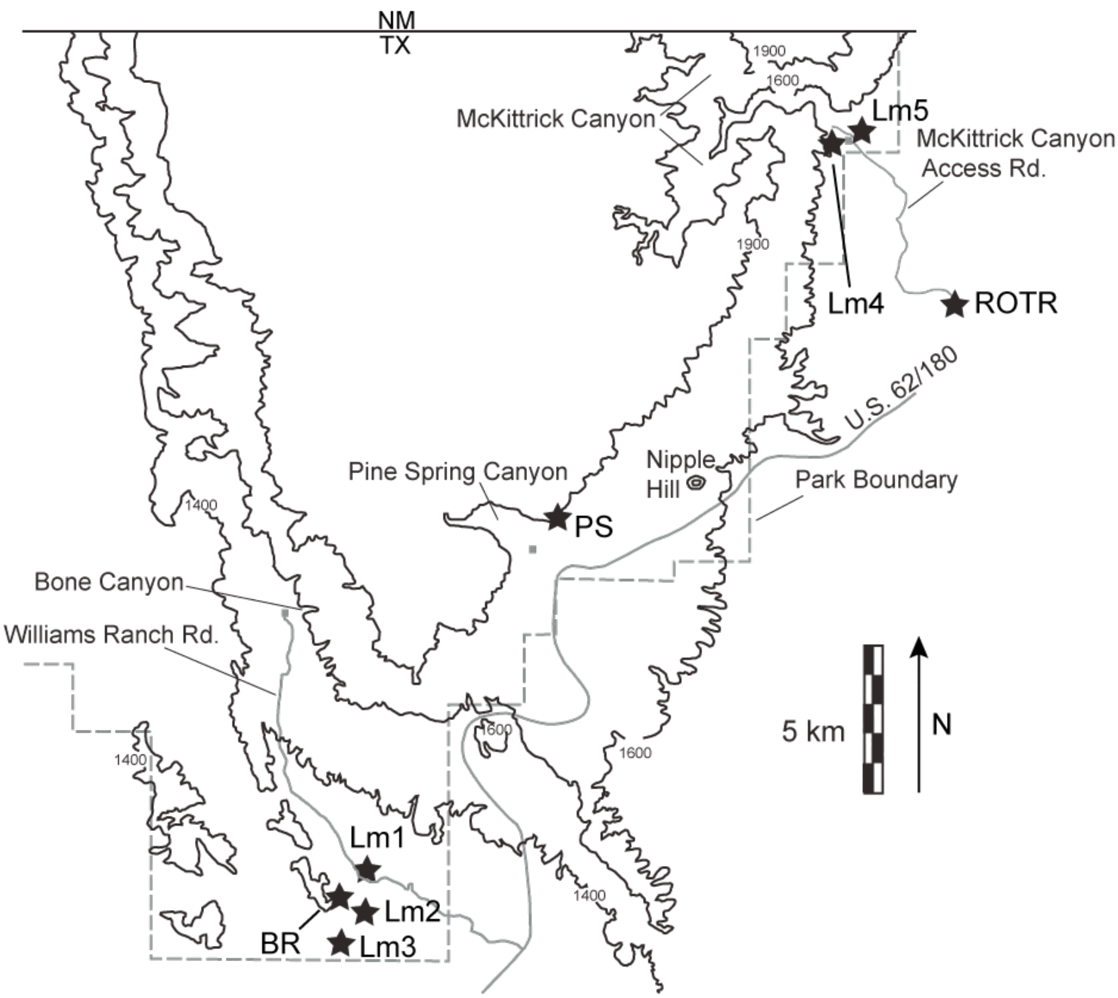


Figure 2.3–Map of Guadalupe Mountains National Park. Stars represent location of measured sections. ROTR = Rader on the Road; PS = Pine Springs; BR = Back Ridge.

facies are identified from measured sections, with additional lithologic information obtained from acetate peels and thin sections. Due to the dominant process of deposition by gravity flows, the limestone lithologies are further divided into mud-supported and grain-supported, similar to conglomerate classification of matrix-supported and clast-supported. Acetate peels were made of the conglomerate facies to capture as much of the sedimentological information as possible. Thin sections were made of massive limestone and planar limestone facies to help with identifying lithology.

Sediment-Gravity Flows

There are two dominant types of sediment-gravity flows interpreted to be responsible for the deposition of carbonate sediment on the lower slope of the Permian reef. The types of flow include debris and turbidity flows. Previous work (e.g., Rigby, 1958; Koss, 1977; Lawson, 1989; Dutton et al., 2003) on the Bell Canyon Formation also suggests that these types of flows are dominant. The following paragraphs are brief descriptions on these flow types.

Debris Flows

One end member of sediment-gravity flows is the debris flow. A debris flow is a type of cohesive flow that includes mud flows. Cohesive flows are dominated by mostly laminar flow in which sediment and particles are suspended in a cohesive matrix of clay or mud and water (Lowe, 1982; Mulder and Alexander, 2001). The difference between debris and mud flows is the size of the sediment being transported (Mulder and

Alexander, 2001). Debris flows contain greater than 5% gravel, including bolder-sized clasts of rock, with varying amounts of sand, and therefore, the resulting deposit is poorly sorted (Johnson, 1970, 1984; Cook et al., 1972; Rodine and Johnson, 1976; Leigh and Hartley, 1992; Mulder and Alexander, 2001). In contrast, mud flows contain less than 5% gravel and an almost equal proportion of mud and sand (Mulder and Alexander, 2001). Although mud flows commonly do not contain coarse sediment, these flows can transport isolated large rocks, and therefore, the resulting deposits are mudstones or mudstones with dispersed clasts (Mulder and Alexander, 2001). Debris flows have sharp, flat bases that are only slightly erosional due to the fast speed the flow travels down the slope (Mulder and Alexander, 2001). The reason for the lack of erosion and speed of the flow is the process of hydroplaning in which the head of the flow is lubricated by a wedge-shaped layer of water (Mohrig et al., 1998).

Turbidity Flows

The other end member of sediment-gravity flows is the turbidity flow. A turbidity flow transports sediments by suspension in mostly turbulent water (Lowe, 1982; Mulder and Alexander, 2001). Due to the dilute suspension of turbidity flows, there is an exchange of water and sediment through erosion, deposition, and entrainment across the flow surface of a turbidity flow (Pratson et al., 2000). This is a major difference between debris and turbidity flows. Turbidity flows have been subdivided in numerous ways. For example, Lowe (1982) subdivides flows into low-density and high-density flows based on the concentration of particles, whereas Mulder and Alexander

(2001) subdivide flows into surge flows, surge-like turbidity flows, and quasi-steady turbidity flows based on flow behavior. Low-density turbidity flows deposit the classic Bouma sequences, and for the purposes of this study, this terminology will be used here. Deposits from turbidity flows are generally recognized by their normal grading and can be divided into the classic five structural units of a Bouma (1962) sequence. It is rare for an entire Bouma sequence to be preserved within the rock record. These structural units indicate different flow regimes and include the following: (A) structureless sand that can have gravel at the base, usually erosional with tool and flute marks, (B) parallel laminated sands, (C) cross-laminated sands, (D) parallel laminated silts, and (E) capped by mud (e.g., pelagic mud), sometimes bioturbated.

Facies

Siliciclastic Facies

This facies includes both fine-grained sandstone and siltstone, which occurs infrequently compared to the carbonate facies within the sections but usually separates the carbonate tongues. When the siliciclastic facies does occur, these lithologies are commonly recessive and soft, making sedimentary structures or larger-scale features like channel-fills difficult to see (Table 2.1; Fig. 2.4). This facies is interpreted as deep-water siliciclastics that correlate to turbidite deposits further into the basin.

Table 2.1–Facies within the Bell Canyon Formation (part 1)

Facies Name	Lithology	Bedding Characteristics	Thickness and Contacts	Fossil Content
Siliciclastic	very fine to fine sandstone, quartz, some mica, usually moderately well sorted, subrounded to rounded, calcite cemented; siltstone, calcite cemented	no sedimentary structures observed, recessive, usually not well indurated	ranges in thickness, contact usually sharp and not always exposed	usually none, when occurs fossils unidentifiable
Interbedded Siliciclastic and Carbonate	siltstone, some mica, calcite cemented; wackestone to packstone, occasionally silty or sandy	thin-bedded to medium bedded, no sedimentary structures, commonly indurated but can be recessive; thin-bedded to medium bedded, no sedimentary structure observed, usually iron-stained, chert nodules or layers, can weather to platy or wavy	usually between 2 and 10 cm, but can also be up to 15 cm or a thin as 1 cm, usually siltstones are thinner, contacts usually sharp, sometimes wavy, undulatory, can increase in carbonate upsection	tops are sometimes bioturbated, some branching burrows, fossils commonly not identifiable, when identifiable fossils include brachiopods, bryozoans, crinoid columnals

Figure 2.4–Outcrop photograph of siliciclastic facies in the Reef Trail Member at section Lm2 (Williams Ranch Road) showing recessive nature of facies.

Figure 2.5–Example of interbedded siliciclastic/carbonate facies. (A) Outcrop photo of facies at section Lm1 (Williams Ranch Road). (B) Close up photo of facies to show nature of beds. Hammer at the contact between underlying siliciclastic facies and interbedded siliciclastic/carbonate facies at section Lm2 (Williams Ranch Road). (C) Outcrop photo of facies at section Lm3 (Williams Ranch Road). Hammer at the contact between interbedded siliciclastic/carbonate facies and the overlying massive limestone facies.

Interbedded Siliciclastic/Carbonate Facies

This facies is a mixture of thin-bedded siltstone and wackestone and packstone (Table 2.1; Fig. 2.5). The interbedded siliciclastic/carbonate facies occurs at most of the sections and usually overlies sandstone and underlies the carbonates. In some sections, an observed trend within the facies is for the limestone to increase and siltstone to decrease upsection. There are few fossils observed at the outcrop scale and these fossils are usually not identifiable. Sometimes fossils can be preserved in chert layers found within some of the limestones. When the tops of the limestone beds are exposed, bioturbation can sometimes be observed, including branching burrows. This facies may be genetically related to the siliciclastic facies, indicating the switch between siliciclastic deposition and carbonate deposition.

Massive Limestone Facies

The massive limestone facies occurs only within the Lamar Member sections (Table 2.2; Fig. 2.6). This facies ranges in thickness from two to eight meters in thickness and overlies the interbedded siliciclastic/carbonate facies and underlies the planar limestone facies. Where this facies occurs, it usually can be laterally traced for several meters to 10's of meters. The lithology ranges from mudstone to packstone at different localities. This facies does not display obvious sedimentary structures making environmental interpretations difficult. This facies has a sharp upper contact, and when the lower contact is exposed, it is sharp and sometimes wavy. This facies could

Table 2.2–Facies within the Bell Canyon Formation (part 2)

Facies Name	Lithology	Bedding Characteristics	Thickness and Contacts	Fossil Content
Massive Limestone mud-supported grain-supported	mudstone and wackestone, allochems include fossils and lithoclasts; packstone, allochems include fossils and lithoclasts;	massive, no observed sedimentary structures, chert in nodules and layers	ranges from 2 to 8 meters, contacts usually sharp, sometimes wavy and undulatory	fusulinids, brachiopods, bryozoans, rugose corals, crinoid columnals, bioturbation at the top of some beds
Planar Limestone mud-supported grain-supported intermediate	mudstone and wackestone, allochems include fossils and lithoclasts; packstone, allochems include fossils and lithoclasts; wackestone to packstone, allochems include fossils and lithoclasts;	medium bedded to massive, planar, parallel to wavy laminations, normally graded, or structureless, chert in nodules and layers, commonly petroliferous, weathers platy, rubbly, slabby, or massive, grainy areas of fossils not necessarily lens shape or in stringers, occasionally flame structures and soft-sediment deformation	medium to thick bedded: <1 cm, laminations: millimeter to sub-millimeter, contacts usually sharp, sometimes wavy and undulatory	fusulinids, brachiopods, bryozoans, rugose corals, crinoid columnals, echinoid spines and plates, fish bones, sponges, bioturbation at the top of beds, sometimes burrows can disrupt laminations, horizontal and vertical burrows includes *Chondrites*, *Planolites*, and *Uchirites*

A B

Figure 2.6–Example of massive limestone facies. (A) Outcrop photo at section Lm1 (Williams Ranch Road) with hammer at base and field assistant at top. (B) Outcrop photo at section Lm2 (Williams Ranch Road). Hammer at base and field assistant pointing to top. The interbedded siliciclastic/carbonate facies underlies the massive limestone facies.

represent a large-scale mud flow due to the scarcity of large clasts and dominance of fine grains.

Planar Limestone Facies

The planar limestone facies is a prominent facies found at every section. It can be divided into mud-supported (mudstone, wackestone), grain-supported (packstone), and intermediate (wackestone to packstone) depositional textures. Bedding characteristics are typically not limited to the type of depositional texture (mud-supported or grain-supported). Mud-supported planar limestone includes structureless, laminated, and normally-graded bedding. Grain-supported planar limestone includes structureless and normally-graded bedding. Structureless bedding is not usually common. Laminated bedding occurs within every section mostly as mud-supported and sometimes has distinctive light and dark laminae (Table 2.2; Figs. 2.7A, B). Laminations can be parallel or wavy, and occasionally can be disrupted by burrows. Normally-graded bedding also occurs within every section and ranges in lithology from mudstone to packstone, and occasionally as grainstone (Table 2.2; Figs. 2.7C, D). Contacts between normally-graded beds can be gradational, sharp, or wavy. The normal grading ranges in thickness from two to five centimeters. The planar limestone facies are interpreted to be deposited mainly by low-density turbidity flows, based on the location on the lower slope, the normally-graded and laminated beds, and the fine-grained particles composing these beds. The structureless limestone may be deposited

Table 2.3–Facies within the Bell Canyon Formation (part 3)

Facies Name	Lithology	Bedding Characteristics	Thickness and Contacts	Fossil Content
Conglomerate mud-supported grain-supported intermediate	 wackestone, allochems include fossils and lithoclasts packstone and grainstone, allochems include fossils and lithoclasts wackestone to packstone, allochems include fossils and lithoclasts	massive, planar, occasional lens shape, can be normally-graded but sometimes reverse-graded, amalgamated beds, occasional soft-sediment deformation, lithoclasts of various sizes, chert nodules and layers located near, at the top, or middle of bed, reef clasts from 0.2 to 4 meters	ranges in thickness typically 25-100 meters, can be as thick as 200-400 meters, contacts commonly sharp, flat, sometimes erosional and wavy	fossils are whole and fragmented, commonly silicified, include brachiopods, bryozoans, echinoid spines and plates, crinoid cup, plates, and columnals, fusulinids, rugose corals, scaphopods, bivalves, gastropods, fish bones, sponges

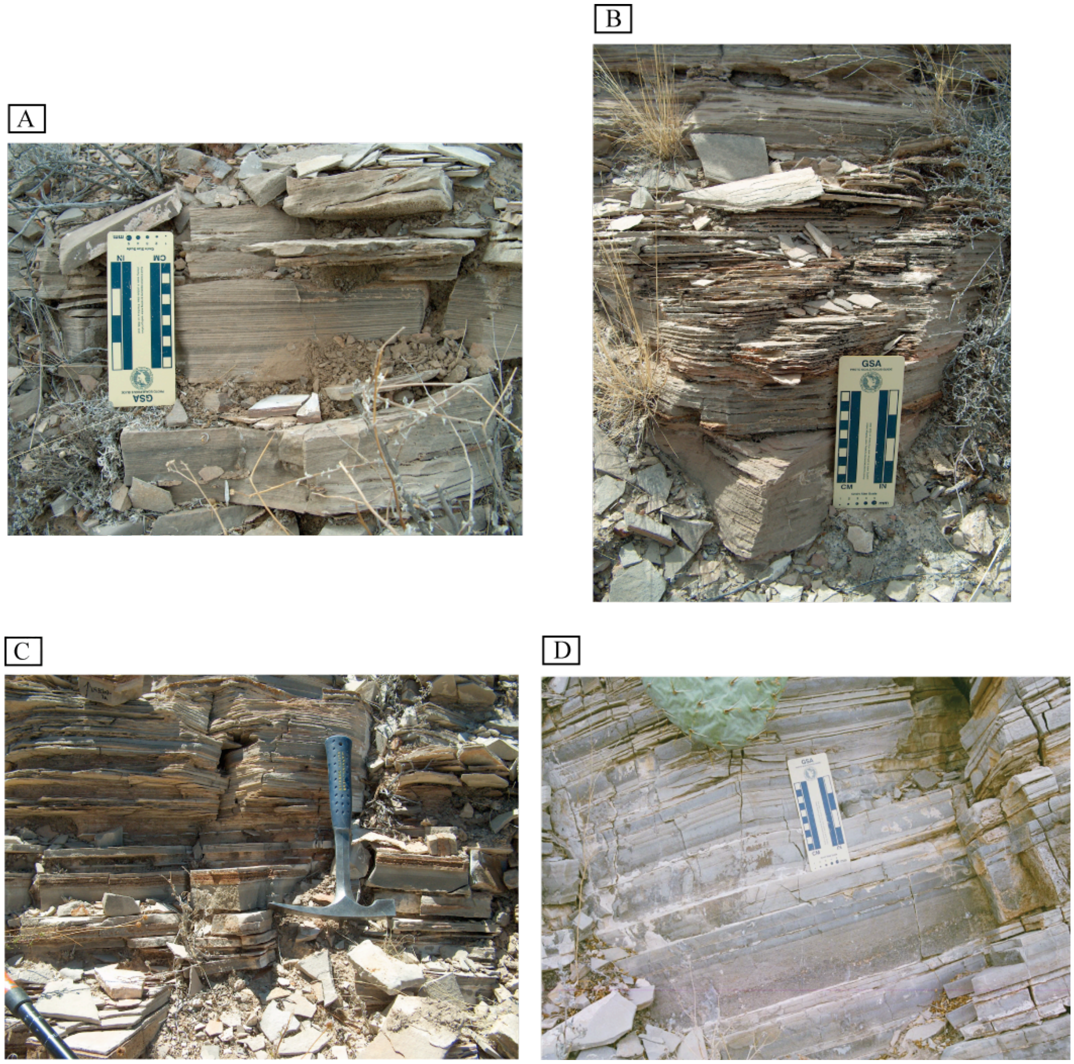


Figure 2.7–Outcrop photographs of the planar limestone facies. (A, B) Laminated beds at section Lm1 (Williams Ranch Road). (C) Normally-graded beds at section Lm2 (Williams Ranch Road). (D) Normally-graded beds at section Lm3 (Williams Ranch Road) with dark bands usually representing coarse grained and light bands representing fine grained.

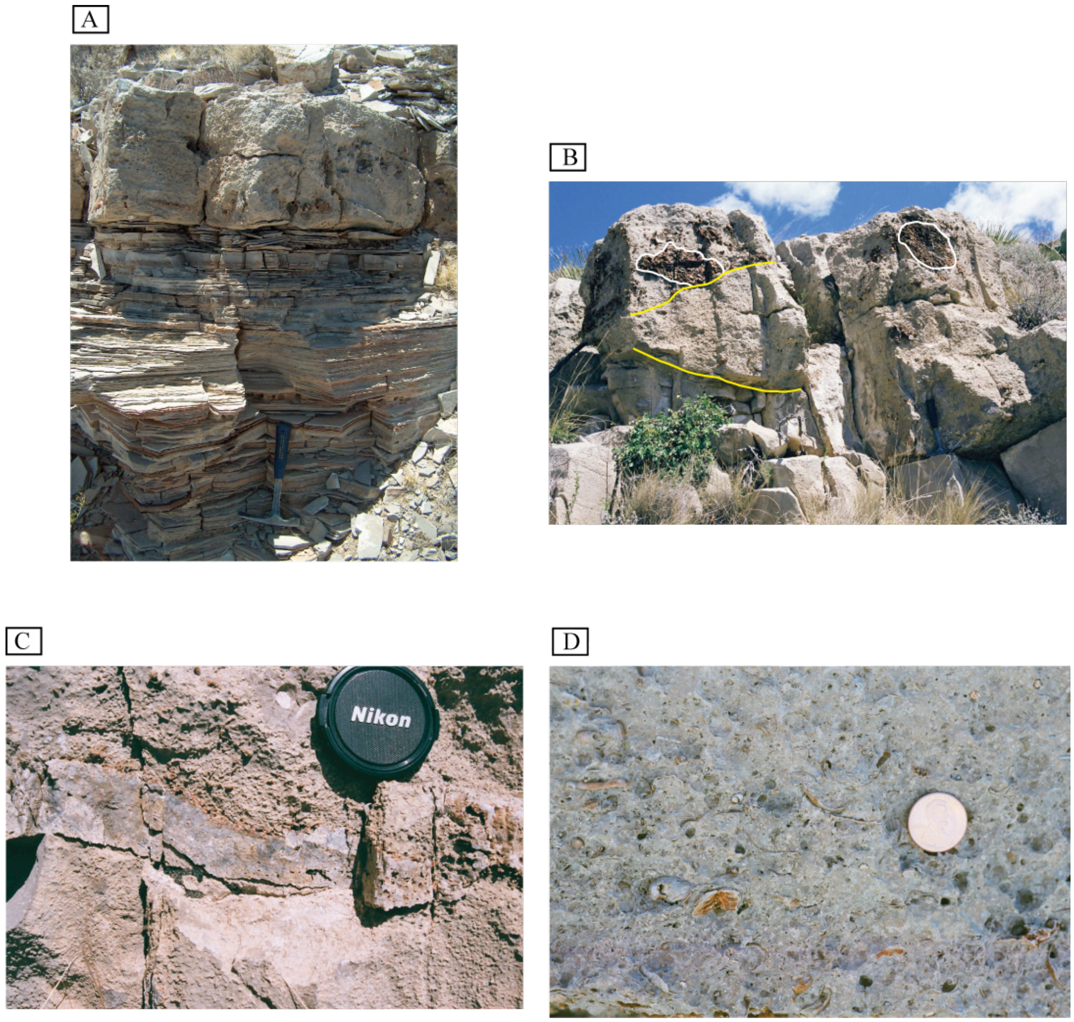


Figure 2.8–Outcrop photographs of the conglomerate facies. (A) Conglomerate facies overlying planar limestone facies with a sharp contact at section Lm3 (Williams Ranch Road). (B) Amalgamated conglomerates (yellow lines) with reef clasts (outlined in white) at section PS (Pine Springs). (C) Chert in middle of conglomerate at PS section (Pine Springs). (D) Close up of conglomerate showing the distribution of fossils at section Lm2 (Williams Ranch Road).

by a mud flow rather than a turbidity flow based on the fine-grained particles and lack of observed grading.

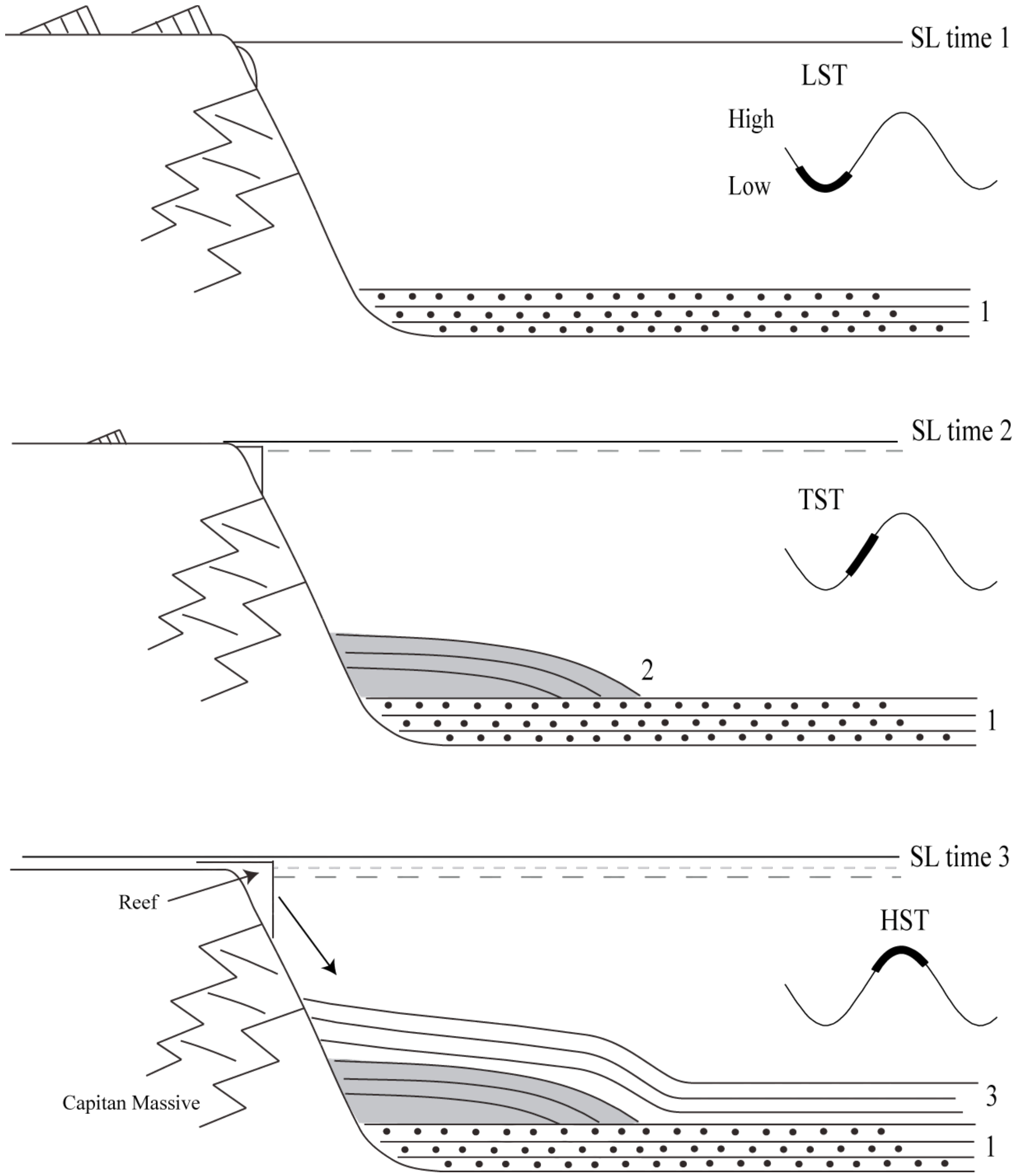
Conglomerate Facies

The conglomerate facies also can be divided into mud-supported, grain-supported, and intermediate depositional textures. This facies is found at every section and is interbedded with the planar limestone facies (Table 2.3; Fig. 2.8A). At one section, the conglomerate facies is interbedded with the siliciclastic facies. It is common for beds of this facies to be massive and planar, but occasionally they can be lens shaped. This lenticular geometry is observed at the outcrop scale and can be meters long or under a meter in length. The lower contact of this facies is commonly sharp and flat, but sometimes it can be erosional and wavy (Table 2.3; Figs. 2.8A, B). Beds within this facies change thickness along the outcrop and can be amalgamated (Table 2.3; Fig. 2.8B). Sometimes the conglomerate facies can have graded bedding with coarse bases and fine caps but it also occurs with fine bases and coarse caps. As with the planar limestone facies, chert is common, occurring near or at the top of the bed and also in the middle, usually preserving fossils within it (Fig. 2.8C). Whole and fragmented fossils and subangular to rounded lithoclasts are the common clasts found within this facies. Lithoclasts range in size from centimeters to 10's of centimeters. Their lithology also ranges from dolomite to siltstone. These clasts are usually distributed throughout the bed (Fig. 2.8D). Reef rubble clasts are found solely within this facies (Fig. 2.8B). The reef clasts are silicified and iron stained, usually bound together, containing sponges and bryozoans. The reef clasts range in size from 0.2 to four meters. Based on the massive nature of the beds, poor sorting and grading, and sharp bases, this facies was deposited mainly by debris flows.

Sequence Stratigraphic Model

The generalized sequence stratigraphic model presented here shows the distribution of facies on the slope based on the changes in sea level inferred from the correlations of the Pinery, Rader, Lamar, and Reef Trail Members of the Bell Canyon Formation (Fig. 2.9). The model is based on previous models of Brown and Loucks (1993), Tinker (1998), and Playton (2008). Time step 1 begins at a fall in sea level that exposes the shelf, but the shelf margin remains submerged under shallow water depths. Eolian dunes migrate across the shelf supplying the siliciclastic sediment to the basin (Brown and Loucks, 1993; Tinker, 1998). The siliciclastics are dominantly fine-grained sandstones and siltstones and were deposited on the basin floor by sandy high- and low-density turbidity flows within a leveed channel system (Barton and Dutton, 1999; Dutton et al., 1999; Dutton et al., 2003). The abundance of siliciclastics in the basinal sections represents the lowstand systems tract (LST) in the correlated cross-sections. Time step 2 shows a rise in sea level, representing the transgressive systems tract (TST). There is no initial flooding of the shelf during the early part of the TST and the shelf margin starts to aggrade. During this interval, silt is still being supplied to the basin, but carbonate deposition has begun (Tinker, 1998). This interval is associated with the interbedded siliciclastic/carbonate facies. By late TST, the shelf is flooded, the shelf margin remains

Figure 2.9–Generalized sequence stratigraphic model showing distribution of facies in relation to sea level. Position of sea level is shown at each time step by the sinuous curve. At time 1, siliciclastic facies are deposited during lowstand systems tract (LST) when sea level is low. At time 2, interbedded siliciclastic/carbonate facies and massive limestone facies are deposited during transgressive systems tract (TST) when sea level is rising and the shelf begins to flood. At time 3, interbedded planar limestone and conglomerate facies are deposited during highstand systems tract (HST) when sea level is high and the shelf is flooded. Modified from Brown and Loucks (1993).


SL time 1
LST
High
Low
1
SL time 2
TST
2
1
SL time 3
Reef
HST
3
Capitan Massive
1

in an aggradational mode and carbonate deposition dominates (Brown and Loucks, 1993; Tinker, 1998), resulting in the interbedded siliciclastic/carbonate and massive limestone facies. Time step 3 shows a continued rise in sea level to its highest level when the shelf is flooded, the reef margin is prograding towards the basin, and deposition of carbonates occurs on the slope by turbidity and debris flows (Tinker, 1998). This interval represents the highstand systems tract (HST), and is represented by the planar limestone facies and conglomerate facies.

Stratigraphic Correlations

Correlations are based mainly on siliciclastic and carbonate cycles divided into lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST). Each cycle represents a cycle of sea level fall and rise. During LST, sea level has not fallen below the shelf margin. When sea level begins to rise during the TST, the shelf margin begins to aggrade, and as sea level continues to rise, the shelf becomes flooded. During HST, the shelf is flooded and the shelf margin switches from an aggradational mode to progradational mode. At a smaller scale, coarsening-upward cycles were identified when possible, usually within the interbedded facies of the planar limestone and conglomerate facies. Each coarsening-upward cycle contains laminated limestones, normally-graded limestones, and some structureless limestones capped by debris flow deposits. These cycles may indicate when the shelf became unstable and shed carbonate and reef rubble into the basin, may result from storms or earthquakes, or they may indicate autogenic processes. The coarsening-upward cycles are mainly restricted to the HST.

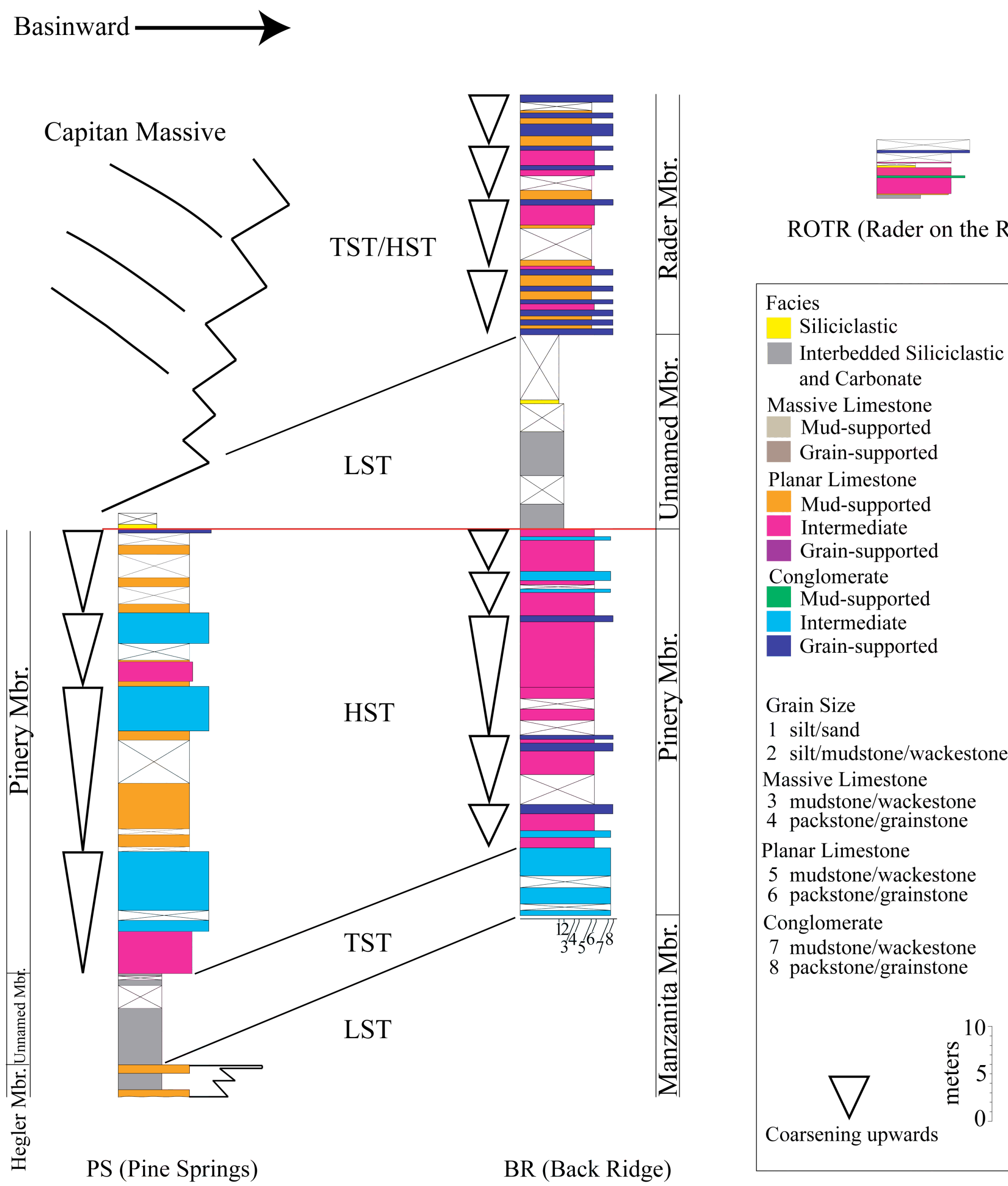
Correlations are divided into the lower Bell Canyon for the Pinery and Rader Members and the upper Bell Canyon for the Lamar and Reef Trail Members due to their lithostratigraphic and sequence stratigraphic position.

Pinery and Rader Members

The cross-section of the Pinery and Rader Members is hung at the base of siliciclastic deposits between the two carbonate packages (Fig. 2.10). The Pine Springs section is located closest to the shelf margin due to the foreslope deposits of the Capitan Massive that overlie the section. The exact position of the Back Ridge section relative to the shelf margin is unclear because the area has been down-faulted. However, it is interpreted as a distal position relative to the Pine Springs section because of the lack of the Capitan Massive associated with the section, lack of reef clasts, and scarcity of large thick debris flows. Additionally, if this section is more distal (e.g., toe-of-slope setting), then more siliciclastics should be present in the section based on previously measured sections in other areas of the park (Playton, 2008). The Rader on the Road section represents only a portion of the Rader Member and therefore it is not correlated with the other sections. The Manzanita Member of the Cherry Canyon Formation is found at the base of both sections (PS and BR).

There are some interesting differences between the two sections. The interbedded siliciclastic/carbonate facies is absent from the Back Ridge section, and the

Figure 2.10–Correlated cross-section of Pinery and Rader Members (lower Bell Canyon). Red line is indicating where sections are hung. Black lines are indicating correlation lines. Distance between PS and BR sections equals 15.6 km.


Basinward
Capitan Massive
TST/HST
LST
HST
TST
LST
Rader Mbr.
Unnamed Mbr.
Pinery Mbr.
Manzanita Mbr.
Pinery Mbr.
Unnamed Mbr.
Hegler Mbr.
PS (Pine Springs)
BR (Back Ridge)
ROTR (Rader on the Road)
Facies
Siliciclastic
Interbedded Siliciclastic and Carbonate
Massive Limestone
Mud-supported
Grain-supported
Planar Limestone
Mud-supported
Intermediate
Grain-supported
Conglomerate
Mud-supported
Intermediate
Grain-supported
Grain Size
1 silt/sand
2 silt/mudstone/wackestone
Massive Limestone
3 mudstone/wackestone
4 packstone/grainstone
Planar Limestone
5 mudstone/wackestone
6 packstone/grainstone
Conglomerate
7 mudstone/wackestone
8 packstone/grainstone
Coarsening upwards
meters
10
5
0

conglomerate facies directly overlies the Manzanita Member. At the Back Ridge section, there is an interbedded siliciclastic/carbonate facies that underlies the siliciclastic facies. At the Pine Springs section, the Hegler Member is present, but it does not occur or is not identifiable at the Back Ridge section.

The interbedded planar limestone and conglomerate facies are present and are correlated as a package between the two sections. Each package generally contains between four and five coarsening-upwards cycles. The coarsening-upward cycles at the Pine Springs section are capped by thicker conglomerate facies compared to the Back Ridge section, which results from the stacking of multiple, thicker debris flows. The multiple flows appear to have occurred more frequently within the Pine Springs section and are due to the proximal position to the shelf margin. Although some of the conglomerate facies at the Back Ridge section also have multiple debris flows within them, they are overall not as thick. This may indicate that the Pine Springs section is closer to the margin or to an unstable area on the shelf margin during progradation of the reef.

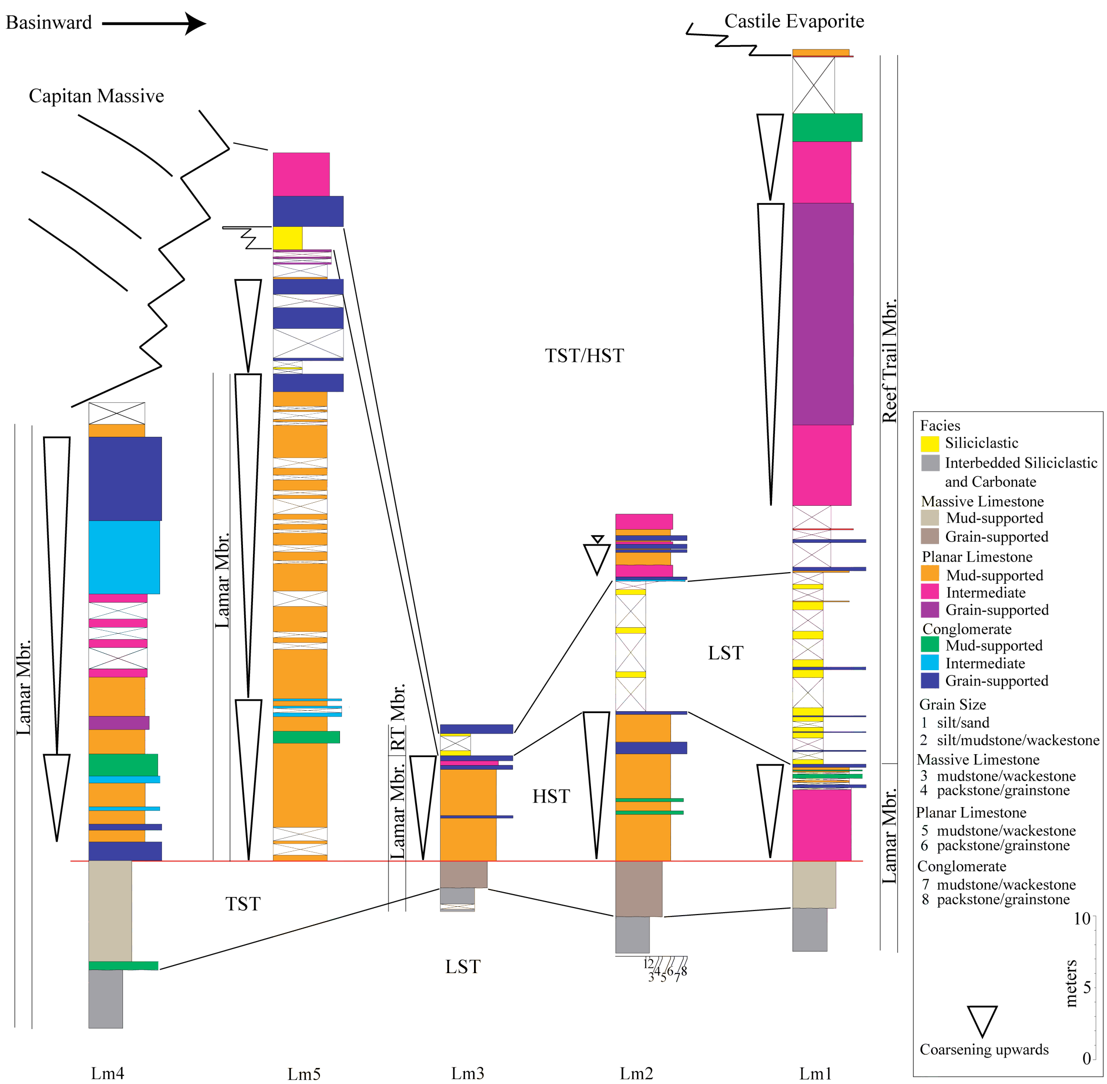
There are two cycles of the LST, TST, and HST indentified within the Pinery and Rader Members, representing two cycles of sea level fall and rise (Fig. 2.10). The first cycle includes the underlying Manzanita Member as the LST, the interbedded siliciclastic/carbonate facies and the first conglomerate facies of the Pinery Member at Back Ridge as the TST, and the interbedded planer limestone facies and conglomerate facies as the HST. The second cycle includes the next siliciclastic-dominated package as the LST and the interbedded planer limestone and conglomerate facies as the HST. The interbedded siliciclastic/carbonate facies is dominated with more siliciclastic than carbonate and therefore it is considered genetically related to the siliciclastics facies. The overlying carbonates appear to represent the HST due to the numerous coarsening-upward cycles. This indicates that the TST is missing or it is difficult to distinguish between the TST and HST at this distal position.

Lamar and Reef Trail Members

The cross-section of the Lamar and Reef Trail Members is hung at the base of the interbedded planar limestone and conglomerate facies (Fig. 2.11). The Lm4 section is proximal to the shelf margin due to the presence of the Capitan Massive at the top of this section in place of the Reef Trail Member. The Lm5 section does not have Capitan Massive overlying it, but the section is in proximity to the Lm4 section and contains abundant reef clast material, suggesting it is relatively close to the shelf margin. The three sections at Williams Ranch Road–Lm3, Lm2, and Lm1–are down-faulted and their exact position relative to the shelf margin is not known, but these sections are interpreted to be in a distal position relative to the other sections at McKittrick Canyon. Although the Williams Ranch Road sections contain reef clasts, there are more siliciclastics present. Also, the Castile Formation overlies the Reef Trail Member at Lm1 section, which suggests a distal position on the slope. All of these sections contain the recently added Reef Trail Member.

Overall, the Lamar and Reef Trail sections show similar features to each other. First, with the exception of the Lm5 section, all other sections overlie massive, fine-

Figure 2.11–Correlated cross-section of Lamar and Reef Trail Members (upper Bell Canyon). Red line is indicating where sections are hung. Black lines are indicating correlation lines. Distance between Williams Ranch Road sections (Lm1, Lm2, Lm3) and McKittrick Canyon sections (BR) equals 38.75 km.


Basinward
Castile Evaporite
Capitan Massive
TST/HST
Reef Trail Mbr.
Lamar Mbr.
Lamar Mbr.
Lamar Mbr.
RT Mbr.
Lamar Mbr.
LST
HST
TST
LST
Lamar Mbr.
Facies
Siliciclastic
Interbedded Siliciclastic and Carbonate
Massive Limestone
Mud-supported
Grain-supported
Planar Limestone
Mud-supported
Intermediate
Grain-supported
Conglomerate
Mud-supported
Intermediate
Grain-supported
Grain Size
1 silt/sand
2 silt/mudstone/wackestone
Massive Limestone
3 mudstone/wackestone
4 packstone/grainstone
Planar Limestone
5 mudstone/wackestone
6 packstone/grainstone
Conglomerate
7 mudstone/wackestone
8 packstone/grainstone
10
meters
5
0
Coarsening upwards
Lm4
Lm5
Lm3
Lm2
Lm1

grained sandstone, the interbedded siliciclastic/carbonate facies, and the massive limestone facies. Although these facies are absent from the measured section at Lm5, they are present in other locations in McKittrick Canyon so it is inferred that they are probably present but not exposed at this section. The siliciclastic facies and the interbedded siliciclastic/carbonate facies are also found at the Pine Springs and Back Ridge sections; however, the massive limestone facies only occurs at the Lamar/Reef Trail sections. Second, with the exception of the Lm4 section, all other sections have the Reef Trail Member present, but not necessarily the entire unit.

In contrast to the Pinery and Rader sections, the interbedded planar limestone and conglomerate facies contain fewer coarsening-upward cycles. Generally, there are between one to three cycles within the carbonate packages. The thickest debris flows occur at the Lm4 section, which is closest to the shelf margin. This indicates that this section is closer to an unstable area on the shelf margin during progradation of the reef. Although section Lm5 is in close proximity to the shelf margin, the debris flows do not appear to be as numerous and the coarsening-upward cycles are capped by slightly thinner debris flows, but there are areas with abundant reef clasts closer to the top of the Lamar Member. This indicates a variable depositional nature of debris flows. In the upper interbedded planar limestone and conglomerate facies, it is difficult to detect coarsening-upward cycles. Additionally, there are not as many debris flow deposits at the Williams Ranch Road sections as in the McKittrick Canyon sections.

There are two cycles of the LST, TST, and HST indentified within the Lamar and Reef Trail Members, representing two cycles of sea level fall and rise (Fig. 2.11). The first cycle includes an underlying sandstone (unnamed) and the interbedded siliciclastic/carbonate facies as the LST, the massive limestone facies as the TST, and the interbedded planar limestone and conglomerate facies as the HST. The second cycle includes the next siliciclastic-dominated package as the LST and the interbedded planar limestone and conglomerate facies as the undifferentiated TST/HST. The undifferentiated TST/HST and the lack of distinguishable coarsening-upward cycles within this part of the section suggest that a fundamental change occurred within the basin.

Discussion

Correlating sequence boundaries and other significant surfaces from the shelf to the basin is problematic because the basinal facies are not under the same influence as facies near sea level. The stratigraphic framework presented here provides evidence for sea-level change at the composite sequence scale. The Pinery, Rader, Lamar, and Reef Trail Members of the Bell Canyon Formation record cycles of siliciclastic and carbonate deposition on the slope representing the LST, TST, and HST within four composite sequences: CS 12 (Pinery Member), CS 13 (Rader Member), CS 14 (Lamar Member), and CS 15 (Reef Trail Member). There is one member not addressed in this study due to lack of accessibly, the McCombs Member. This member underlies the Lamar Member, and is part of the same composite sequence as the Lamar Member following the Tinker (1998), Kerans and Tinker (1999), and Kerans and Kempter (2002) stratigraphic framework. The McCombs Member may represent a systems tract within CS 14, similar to the Hegler Member of CS 12. Alternatively, the McCombs Member is its own composite sequence.

Each member records a cycle of sea-level change, although not all system tracts are easily recognized. Within the framework of Tinker (1998), Kerans and Tinker (1999), and Kerans and Kempter (2002), there are four high-frequency sets within the upper Seven Rivers Formation (Pinery Member equivalent) and Yates Formation (Rader Member equivalent) and two high-frequency sets within the Tansill Formation (Lamar Member equivalent). Within each high-frequency set, Tinker (1998) has identified a TST and HST, and at the composite sequence scale, Tinker (1998) also has identified a TST and HST. Both high-frequency sets and composite sequences have been correlated into the basin based on the progradation and aggradation of the shelf margin and facies tracts distributions on the shelf. It is not obvious from the correlated cross-sections of Bell Canyon Formation members how to recognize the high-frequency sets in the basin; however, correlative conformities and maximum flooding surfaces are interpreted from the cross-sections to identify systems tracts at the composite sequence scale. Therefore, it is proposed that the start of the coarsening-upward cycles within the interbedded planar limestone and conglomerate facies is the base of the HST, which places the maximum flooding surface at the contact between the base of these facies and the top of the interbedded siliciclastic/carbonate facies (or massive limestone facies). Additionally, the start of the siliciclastic facies (or interbedded siliciclastic/carbonate facies) is the base of the LST.

The correlations presented here do not show the proposed pattern at every section, which makes the interpretation of systems tracts difficult. Within the Pinery and Rader correlations, the second LST-TST-HST cycle of the lower Bell Canyon is identified, but it is not clear how to differentiate the TST and HST in the overlying interbedded planar limestone and conglomerate facies within the Rader Member. There are four coarsening-upward cycles within this facies, which is used to identify the HST of a sequence. In the lower part of the sections, interbedded siliciclastic/carbonate facies used to recognize the TST is missing. Also, the massive limestone facies (mud flow-type deposit) used to identify the TST within the lower part of the sections is missing. Alternatively, this package of interbedded planar limestone and conglomerate facies could represent the TST and not the HST. The interbedded planar limestone and conglomerate facies contain numerous debris flows compared to the equivalent facies within the Pinery Member. Within the Rader Member at other locations, there are megabreccia wedges that represent repeated large-scale failures of the shelf margin and mark the sequence boundary of CS 13 (Tinker, 1998; Playton, 2008). These areas of failure provide a way for grain-dominated packstones to accumulate on the slope and in the basin, thereby possibly representing transgression after the sequence boundary (Tinker, 1998; Kerans and Tinker, 1999; Playton, 2008). Based on the lithology of the conglomerate (packstone) and abundant fusulinids, it is proposed that this interbedded planar limestone and conglomerate facies is the TST.

A similar situation is observed within the Lamar and Reef Trail correlation. The Reef Trail's LST is identified, but it is not clear how to differentiate the TST and HST in the interbedded planar limestone and conglomerate facies because of the difficulty in picking coarsening-upward cycles, especially at the Lm1 section. The planar limestone facies is thicker at Lm1 than at other locations, but the other sections are incomplete. The Reef Trail Member contains molluscan-rich beds, including scaphopods, not found in other members. Very little has been published on the Reef Trail Member: mostly fossil occurrences of biostratigraphic importance (e.g., Lambert et al., 2002), or newly discovered fossils in the region (e.g., Rigby and Bell, 2005). The original publication from Wilde et al. (1999) that named the Reef Trail Member presented a composite stratigraphic column from around the McKittrick Canyon area, where the Lm5 section was measured, for recognizing the Guadalupian-Lopingian boundary. Wilde et al. (1999) proposed that reef growth was restricted, and in conjunction with increased siliciclastic deposition and evaporitic conditions, caused the environment to become increasingly inhospitable for life. Issues with identifying the TST and HST in the Reef Trail Member may result from changing conditions in the basin associated with the decline of the reef. The molluscan-rich beds may represent taxa that were previously restricted to living on the shelf were able to live on the slope, reflecting the changing conditions within the basin. Another explanation for the problem differentiating between the TST and HST may be a similar situation to the massive shelf failure in the Rader Member. If the shelf margin became restricted, then there may have been reentrants for shelf carbonates to funnel and deposit on the slope and basin floor. Similar to the abundant fusulinids within the Rader Member, the molluscan-dominated beds may reflect the funneling of taxa living on the shelf onto the slope during a transgression.

The Lamar Member contains a massive limestone facies that is not found within the other members of the Bell Canyon Formation. This facies is found to occur on the northeast and southwest sides of the park, indicating that it is widespread. The massive limestone facies replaced the interbedded siliciclastic/carbonate facies of the TST observed within the lower Bell Canyon. The significance of this facies is not well understood at this time, but the facies could indicate a change in the basin that would promote carbonate deposition over siliciclastic deposition. By time of deposition of the massive limestone facies, most siliciclastic deposition was turned off. One hypothesis is that transgression was rapid, flooding the shelf margin and shelf, and trapping the siliciclastics when compared to the transgressions during the Pinery and Rader Members.

Conclusions

A sequence stratigraphic analysis of the Pinery, Rader, Lamar, and Reef Trail Members of the Capitanian Bell Canyon Formation reveals four cycles of sea-level change on the lower slope of a rimmed platform. Each cycle at the composite sequence scale includes the lowstand systems tract, highstand systems tract, and transgressive systems tract. The Bell Canyon Formation was deposited on the lower slope, and therefore, identifying significant surfaces is difficult because facies shifts associated with changes in the position of the shoreline are not recorded in the same manner within deep-water deposits. This study identifies facies and coarsening-upward cycles within the carbonate members as a way to recognize significant surfaces and to provide a way to correlate onto the shelf. Based on the results presented here, a new composite sequence is proposed to include the Reef Trail Member.

CHAPTER III

ENVIRONMENTAL DISRUPTIONS INFLUENCE TAXONOMIC COMPOSITION OF BRACHIOPOD PALEOCOMMUNITIES IN THE MIDDLE PERMIAN BELL CANYON FORMATION (DELAWARE BASIN, WEST TEXAS)*

Introduction

Understanding the processes controlling species diversity is fundamental for understanding ecosystem functioning, determining how diversity is maintained, depleted, or increased, and assessing how organisms respond to global change. Community ecological theory proposes that local species interactions is the primary control on the coexistence of species (e.g., Lotka, 1925; Volterra, 1926; Gause, 1934; Hutchinson, 1959; MacArthur and Levins, 1967), but that diversity also is a result of a balance between such multiple, important, and interconnected ecological processes as local species interactions within communities and dispersal from the regional biota (e.g., MacArthur and Wilson, 1967; Ricklefs, 1987; Hubbell, 2001; Holyoak et al., 2005a). Equally important, diversity requires an understanding of the underlying historical component for the observed distribution of and relationships among species. For that reason, evolutionary processes of speciation and extinction and geological processes of

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*Reprinted with permission from "Environmental disruptions influence taxonomic composition of brachiopod paleocommunities in the Middle Permian Bell Canyon Formation (Delaware Basin, west Texas)" by Leigh M. Fall and Thomas D. Olszewski, 2010. PALAIOS, 25, 247–259, Copyright [2010] by SEPM (Society of Sedimentary Geology).

climate change, sea level, and plate tectonics play a role in influencing community composition and species diversity through time (e.g., Eldredge and Gould, 1972; Sepkoski, 1981; Valentine and Jablonski, 1991; Jackson and Overpeck, 2000).

Paleoecologists study species diversity with a temporal perspective that is unavailable when studying modern ecological communities. The fossil record provides the only historical account of changes in the diversity of ecological communities in the Earth's past. Within the fossil record, paleontologists have identified patterns of stability in the diversity and composition of communities over millions to tens of millions of years (e.g., Olson, 1952; Boucot, 1990; Brett and Baird, 1995; Olszewski and Erwin, 2009). Intervals of long-term community stasis in the fossil record have been attributed to local physical environment or species interactions within communities (Brett and Baird, 1995; DiMichele and Phillips, 1996; Jablonski and Sepkoski, 1996; Pandolfi, 1996; Brett et al., 2007). Patzkowsky and Holland (2003, 2007) hypothesized that diversity of local fossil communities also can be influenced by regional processes like invasion rather than solely by species interactions within communities. Diversity patterns of local fossil communities, therefore, are an emergent property of interactions between processes acting at different scales rather than a result of one single process. Understanding the interplay between local and regional biotic and abiotic processes will provide more accurate interpretations and predictions for diversity patterns in the fossil record.

This study tests whether the taxonomic composition of local fossil brachiopod paleocommunities remains uniform within the Pinery, Rader, Lamar, and Reef Trail

Members of the Middle Permian Bell Canyon Formation (BCF) (Delaware Basin, west Texas). Brachiopods are a diverse and abundant fossil group in the rocks of the Guadalupe Mountains, and they are well known in the Delaware Basin thanks to the work of Cooper and Grant (1972), who collected more than 1,000,000 specimens throughout the mountain ranges of west Texas, and published comprehensive taxonomic descriptions based on their material. An established sequence stratigraphic framework within the Guadalupe Mountains provides temporal constraints in which to assess diversity through time. Two third-order sequence boundaries have been recognized by subaerial exposure, facies shifts, or siltstone deposits on the shelf and are extended onto the slope within the BCF (Tinker, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 1999; Kerans and Kempter, 2002). The sequence boundaries represent episodes of environmental disruption within the basin potentially accompanied by changes in community diversity. The environmental disruptions were related to a change in sea level, which could influence ecological and physical conditions in the basin. Uniform community composition through the BCF during these disruptions would suggest that either differences in environmental conditions in the slope environment do not affect taxonomic compositions because biotic interactions play an important role in forming paleocommunities (i.e., some taxa are better competitors; see Pitman et al., 2001), or that sea-level changes did not disrupt environmental conditions due to the water depth on the slope (~300 to 500 meters) (Tinker, 1998). Brachiopod presence-absence data are analyzed using cluster analysis and correspondence analysis to identify and characterize paleocommunity composition through the BCF. Rank-occurrence plots (i.e., proportion of generic occurrences) are used to explore the changes in composition of the metacommunity and the resulting distribution of paleocommunities for each member. Results show that the taxonomic compositions of brachiopod paleocommunities within the Lamar Member are different than other members of the BCF, suggesting a fundamental change in the dynamics controlling generic diversity.

Background

Metacommunity Theory

Leibold et al. (2004) and Holyoak et al. (2005a) put forth a theoretical framework to evaluate species diversity at various spatial scales connected across space. The basis of this framework is the metacommunity: a group of local communities linked by dispersal of potentially interacting species (Wilson, 1992; Leibold et al., 2004; Holyoak et al., 2005a). Within this framework, local communities are embedded in the metacommunity and the variation in the pattern observed at the local scale is an indicator of the interplay between the dynamics of a larger regional biota and the local community (Leibold et al., 2004; Holyoak et al., 2005a). The degree of embedding of local communities varies among ecological models and, therefore, results in different types of metacommunities (Volkov et al., 2007). For example, in a neutral model metacommunity (Hubbell, 2001) immigrants are provided to the local community but the metacommunity does not receive immigrants from the local community (Volkov et al., 2007).

Four models have been proposed by Leibold et al. (2004) and Holyoak et al. (2005b) that describe metacommunity patterns with the aim of investigating such processes as colonization-extinction dynamics influencing the spatial dynamics of communities—changes in species distributions or abundances across space. The purpose of outlining the metacommunity models in this paper is to present the various mechanisms that might explain the patterns obtained in this analysis. The four models are as follows:

1. The *patch dynamic* model assumes that species coexist through a tradeoff between competition and colonization. Species that are superior colonists (i.e., poor competitors) arrive at a patch before superior competitors (i.e., poor colonists) arrive and dislodge the weaker competitors (Tilman, 1994). A patch is defined as a discrete area of habitat (Holyoak et al., 2005b). In this model, local diversity patterns are explained by the balance between extinction and colonization (Chase et al., 2005), and regional diversity patterns are explained by competition-colonization trade-off (Chase et al., 2005). Species composition at the local scale varies through time, whereas at the regional-scale composition is more constant (Chase et al., 2005). All patches are identical in this perspective—species perceive environment as being homogeneous.

2. The *species sorting* model assumes the environment is heterogeneous among patches allowing species to sort themselves along gradients and to persist in their optimal environment. Local and regional community diversity is more dependent on species interactions and the abiotic environment, and less on the rate of dispersal among patches (Holyoak et al., 2005b). Dispersal operates to permit species to reach patches in

their preferred environment (i.e., track environmental conditions), but does not perturb the abundances or composition within patches from their equilibrium—communities cannot be invaded (Holyoak et al., 2005b). Local diversity patterns are predicted to depend on local biotic and abiotic conditions, whereas regional patterns are predicted to depend on both local biotic and abiotic conditions, as well as the amount of heterogeneity among patches (Chase et al., 2005). Local and regional compositions are expected to remain constant through time, but variations can occur with changes in environmental conditions (Holyoak et al., 2005b).

3. The *mass effects* model assumes that dispersal (i.e., immigration and emigration) influences local and regional diversity and taxonomic composition by the movement of species (or individuals) to enhance the population density. Mass effect is the movement of individuals from a favorable patch to a less favorable patch where individuals cannot be self-maintained (Shmida and Wilson, 1985). The environment is assumed to be heterogeneous, but it also could be homogeneous. Patterns of local diversity are predicted to depend on local species interactions and abiotic factors but also on the rate of dispersal (Chase et al., 2005). Patterns of regional diversity depend on local diversity, the degree of heterogeneity among patches, and their connectivity via dispersal (Chase et al., 2005). Species composition, at the local and regional levels, is expected to remain constant through time, if the movement of taxa is also constant (Holyoak et al., 2005b). The *species sorting* and *mass effects* models are somewhat similar but differ by the rate of dispersal, which influences local species interactions

within communities and the local species-environment relationship (Holyoak et al., 2005b).

4. The *neutral* model assumes that all species within a local community are ecologically equivalent—equal rates of birth, death, immigration, and competitive ability (Hubbell, 2001). Ecological equivalency means that no species has an advantage under any given condition within the community (Hubbell, 2001). In this model, species composition varies through time by ecological drift, a stochastic process driven by chance where species replacement is from the local community (i.e., birth) or the metacommunity (i.e., immigration), or speciation. Local and regional diversity patterns are predicted to depend on the balance between extinction and colonization dynamics, and a balance between extinction and speciation, respectively (Chase et al., 2005).

The metacommunity models outlined here operate over ecological time scales, with the exception of the *neutral* model. Any predications made for fossil communities based on these models can change because of the difference in time scale associated with paleoecological samples. First, these models do not incorporate evolutionary time, which can place limitations on making predictions about temporal turnover at regional scales. In contrast to the metacommunity at ecological scales, the metacommunity over evolutionary time is unlikely to be static due to originations and extinctions. Nevertheless, in regions, like the Delaware Basin, where there are few originations and extinctions at the generic level, the metacommunity can be assumed to be relatively static. Second, when working with paleoecological samples, it has been found that the variation among collections is dampened in death assemblages due to time averaging

(Tomašových and Kidwell, 2009a). This does not, however, have to limit interpretations if all values are biased in the same way, as in the study here, then interpretations can still be made about the processes influencing fossil diversity. In addition, Tomašových and Kidwell (2009b) evaluated these metacommunity models with live and dead molluscan assemblages to assess the relationship between composition and environmental and spatial gradients, and found that important aspects of metacommunities were captured in the death assemblages.

Geologic Setting

This study focuses on the BCF, a 5.4-Myr-interval of upper Middle Permian rocks deposited on the northwestern margin of the Delaware Basin exposed in the Guadalupe Mountains (Fig. 3.1). The Delaware Basin was located on the western edge of Pangaea within a subtropical zone just north of the equator (Zeigler et al., 1997). Extensive evaporitic deposits and broad coastal siliciclastic sabkhas indicate an arid climate in the region (Ward et al., 1986; Andreason, 1992; Zeigler et al., 1997; Osleger, 1998). The Delaware Basin was connected to the open ocean of Panthalassa by the Hovey Channel and to the Midland Basin by the Sheffield Channel (Fig. 3.1). Within the Delaware Basin, changes in sea level influenced periods of carbonate and siliciclastic deposition. During times of highstand, carbonate ramps and platforms formed with barrier and patch reefs, mainly composed of sponges, algae, and bryozoans, rimming the basin. During times of lowstand, when sea level dropped to expose the shelf, siliciclastic

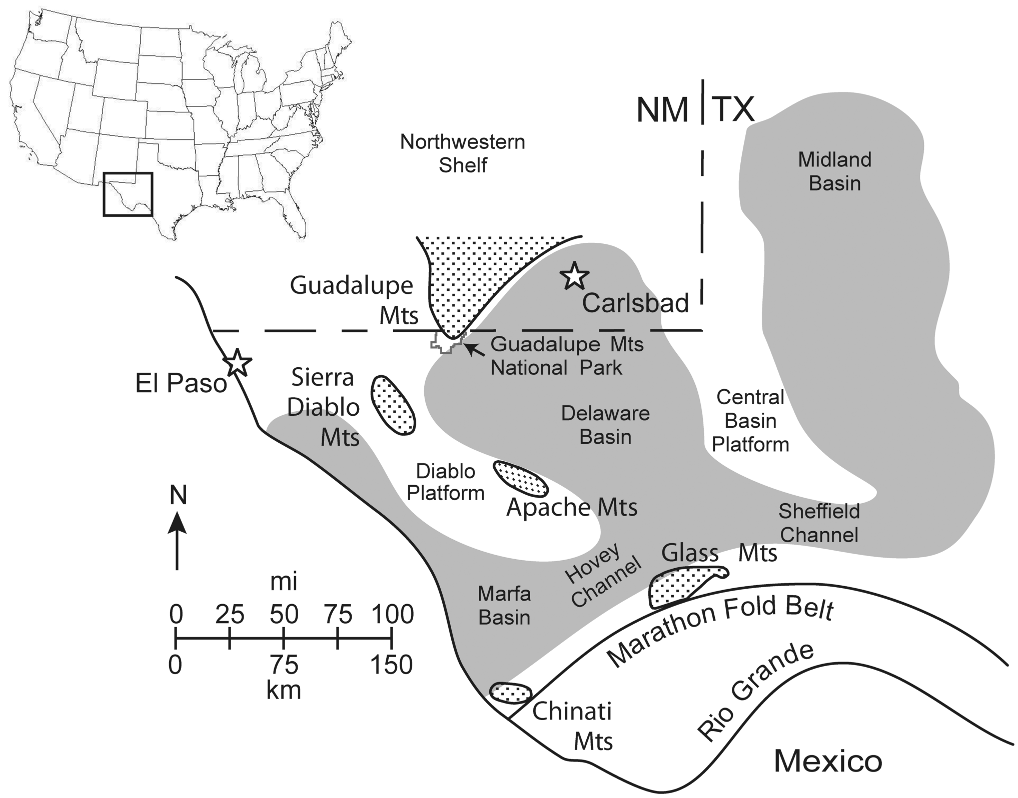


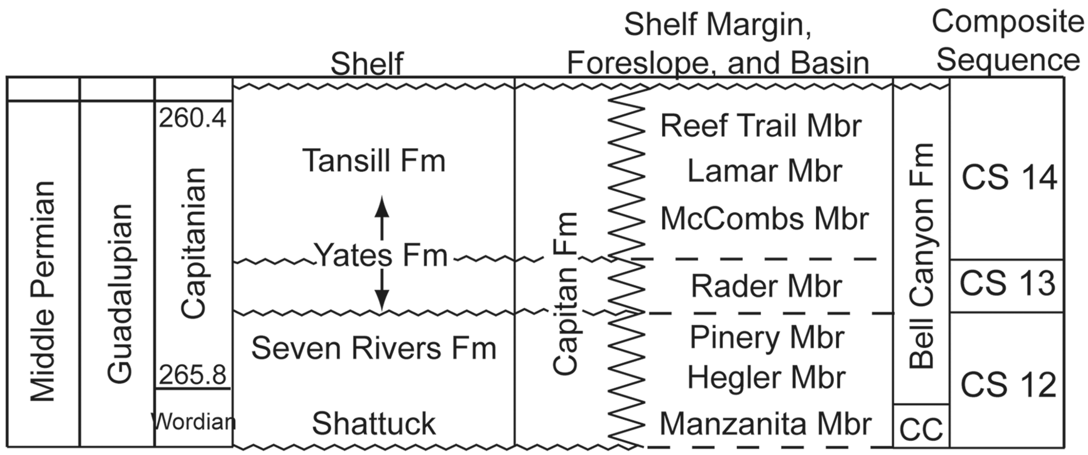
Figure 3.1–Paleogeography of the Permian Basin. Modified from Cooper and Grant (1972).

deposition dominated, with eolian sand bypassing the shelf and deposited into the basin by turbidity currents (Fischer and Sarnthein, 1988; Gardner, 1992). The amplitude of eustatic sea-level fluctuations in the region has been calculated to be ~10 m, during a time of tectonic quiescence in the Guadalupian (Fig. 3.2A; Ye and Kerans, 1996). The Guadalupe Mountains expose these carbonate ramps and platforms of Early and Middle Permian age, which, through time, culminated in the Permian Reef complex, a prominent feature of Guadalupe Mountains National Park.

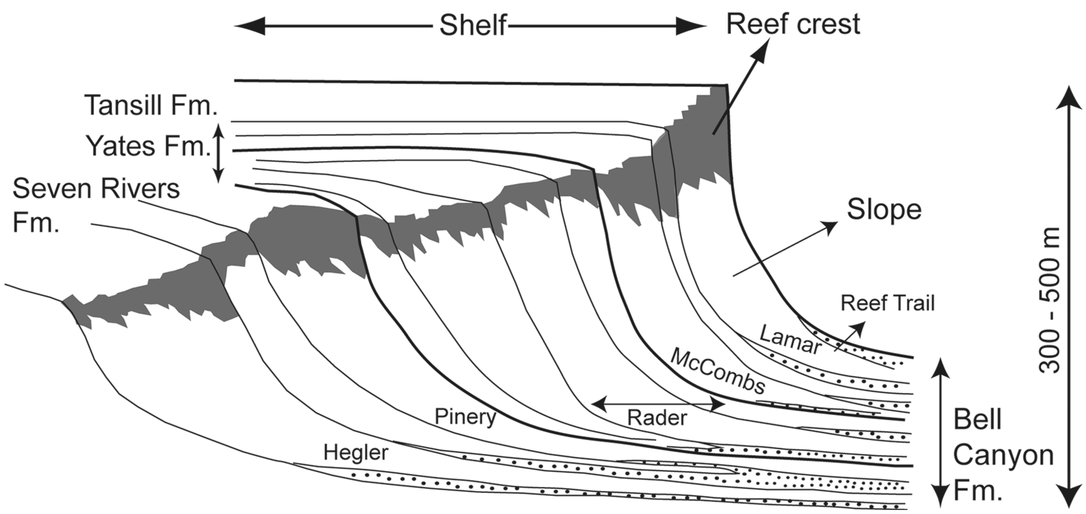
The BCF, which is Capitanian (Guadalupian, Middle Permian) based on conodonts, fusulinids, and ammonoids (Fig. 3.2A; Gradstein and Ogg, 2004), represents the final stages of normal marine deposition within the Delaware Basin. It is overlain by a thick succession of evaporitic deposits, indicating isolation of the Delaware Basin (Sarg et al., 1999). The BCF is the lithostratigraphic basinal equivalent of the Seven Rivers, Yates, and Tansill Formations on the shelf and the Capitan Formation on the shelf crest and foreslope (Fig. 3.2; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 1999; Kerans and Kempter, 2002). Generally, the BCF is characterized by fine-grained sandstones and siltstones interbedded with carbonate tongues deposited on the steep slope of the platform and the basin floor by sediment-gravity flows or possibly fluid-density currents, seaward of the Permian Reef complex (King, 1948; Newell et al., 1953; Rigby, 1958; Koss, 1977; Williamson, 1977; Lawson, 1989; Brown and Loucks, 1993; Hill, 1996). Sandstones and siltstones are the dominant lithology (95%) of the BCF and are found mainly on the basin margin and on the basin floor (Williamson, 1977). The carbonate tongues thicken towards the reef,

Figure 3.2—Bell Canyon Formation stratigraphy and platform geometry in the Guadalupe Mountains. A) Stratigraphic framework of the BCF with composite sequences modified from Kerans and Tinker (1999). Wavy horizontal lines indicate exposure surfaces (third-order unconformities) and dashed lines indicate the correlation of those surfaces into the basin. Reef Trail Member added to show lithostratigraphic position, not sequence stratigraphic position. CC = Cherry Canyon Formation. Ages are from Gradstein and Ogg (2004). B) Cross section of the carbonate platform during deposition of BCF with shelf, reef crest, and slope environments identified. BCF sandstones and siltstones shown with dots. Modified from Tinker (1998). Reef Trail Member added to show lithostratigraphic position. Estimated vertical distance is shown from shelf crest to the toe of slope from Tinker (1998).

A


Shelf
Shelf Margin, Foreslope, and Basin
Composite Sequence
Middle Permian
Guadalupian
Capitanian
260.4
265.8
Wordian
Tansill Fm
Yates Fm
Seven Rivers Fm
Shattuck
Capitan Fm
Reef Trail Mbr
Lamar Mbr
McCombs Mbr
Rader Mbr
Pinery Mbr
Hegler Mbr
Manzanita Mbr
Bell Canyon Fm
CC
CS 14
CS 13
CS 12

B


Shelf
Reef crest
Tansill Fm.
Yates Fm.
Seven Rivers Fm.
Slope
Reef Trail
Lamar
McCombs
Rader
Pinery
Hegler
Bell Canyon Fm.
300 - 500 m

interfingering with the Capitan Formation—rocks representing the reef and the forereef—and thin towards the basin (Fig. 3.2B; King, 1948; Newell et al., 1953; Babcock, 1977; Koss, 1977; Hill, 1996). Total thickness of the formation varies from 200 to 300m (Hill, 1996). The carbonate tongues are formally recognized members in the BCF, and include, in stratigraphic order: Hegler, Pinery, Rader, McCombs, Lamar, and Reef Trail (Fig. 3.2A).

Within the BCF, there are two and a half composite sequences (CS12 through CS14) generally recognized (Fig. 3.2A; Tinker, 1998; Kerans and Tinker, 1999; Kerans and Kempter, 2002). Kerans and Tinker (1999) define a composite sequence as sets of unconformity-bound, high-frequency sequences within lowstand, transgressive, and highstand sequence sets. Each composite sequence is bounded by third-order sequence boundaries identified from unconformities—subaerial exposure, facies shifts, siltstones—on the shelf and contains between two and four high-frequency sequences. The unconformities associated with the sequence boundaries represent disruptions in the basin related to falls in sea level and divide the study interval into nonoverlapping periods of time. The unconformities on the shelf are assumed to underlie siltstones and sandstones on the slope and basin (Tinker, 1998; Kerans and Tinker, 1998). The siliciclastic beds are interpreted to be the lowstand system tracts (LST) of the composite sequence, whereas the carbonate tongues represent both the transgressive (TST) and highstand (HST) system tracts (Tinker, 1998; Kerans and Tinker, 1998). The exact part of the composite sequence the Pinery, Rader, Lamar, and Reef Trail Members represents is currently unknown due to the lack of recognizable surfaces in the field. Each member used in this study corresponds to the TST and HST of a different composite sequence (Fig. 3.2A).

The Reef Trail Member, first recognized by King (1948) as post-Lamar beds, is named for the beds that overlie the Lamar Member and underlie the Castile Formation (Wilde et al., 1999). The boundary between the Guadalupian and Lopingian may be at the base of the Reef Trail Member or lie somewhere within the member (Wilde et al., 1999). The Reef Trail Member is not explicitly incorporated into previous sequence stratigraphic studies (i.e., Kerans and Tinker, 1999). The Reef Trail Member may be a part of the same composite sequence as the Lamar Member or a separate sequence. For this analysis, the Reef Trail Member is considered as a unit equivalent to the Pinery, Rader, and Lamar Members, each of which correspond to a separate composite sequence.

Within each member, the facies identified include interbedded limestones and siltstones, laminated planar limestones, graded limestones, thick planar limestones, and debris-flow conglomerates. The debris-flow conglomerates are the focus in this study because brachiopods are predominantly found within this facies. The lithology of the debris-flow conglomerate facies ranges from packstone to grainstone with whole and fragmented fossils. The conglomerates also contain chert as nodules or as layers in the middle, near the top of beds, or on top of beds, lithoclasts of various sizes, and occasionally reef debris. The massive debris-flow conglomerates change thickness along the outcrop and are characterized by sharp, flat bases. Flows are commonly amalgamated. Fossils and lithoclasts are commonly distributed throughout a flow and in rare instances fossils can be aligned without a specific orientation in horizons.

Additionally, flows can occur with coarse bases and fine caps with chert occurring near or at the top of the bed. Fossils within debris flows include crinoid columnals, crinoid cups and plates, bryozoans, rugose corals, fusulinids, sponges, echinoid plates and spines, and brachiopods. Mollusks are rarely preserved within members of the BCF, except in the upper part of the Reef Trail Member. Mollusks found in this part of the formation include bivalves, gastropods, and scaphopods.

Postmortem transportation of shells in some depositional settings can make comparing beds, even the same types of beds, difficult for paleoecological studies (Zuschin et al., 2005). The primary process for transport of brachiopods in this area is by sediment-gravity flows. Brachiopods are predominantly found in the debris-flow deposits and are uncommon to absent in the interbedded facies (e.g., laminated planar limestones). The debris-flow deposits may represent at one time stable environments that allowed brachiopods to colonize the seafloor. There is no evidence that brachiopods were subjected to wave or current agitation processes. Additionally, there do not appear to be substantial differences in the nature of the debris flow deposits among the members, meaning that all show such similar features as lack of grading, sharp lower contact, and a wide range of clast sizes. These features are more consistent with the physical characteristics of debris flows than turbidity flows (Mulder and Alexander, 2001). Transport distance down the slope is unknown and probably variable, but brachiopods collected from the debris flow deposits do not appear to be from the reef. Most of the reef material is present as clasts ranging in size from ~0.2 m up to 4 m of silicified material, usually bound together, containing sponges and bryozoans, and iron stained. In contrast, sampled brachiopods were not clumped together, but were commonly free individuals. Further, the laminated planar limestone and thick planar limestone facies interbedded with the debris flow deposits contain bioturbation from benthic organisms, which indicates oxygen levels were high enough for macro-organisms at various times on the slope. Although the bioturbation is not pervasive, burrows appear at most locations in vertical and horizontal orientations and range in types from *Chondrites* (mm in size) to *Planolites* (cm in size) to *Uchirites* (cm in size). Previous studies (Grant, 1971; Cooper and Grant, 1972; Babcock, 1977) also support the hypothesis that the majority of the brachiopods in the BCF were once living on the slope and not within the reef itself.

Materials

Compositional turnover was evaluated by focusing on one facies in the BCF. All collections sample the debris-flow conglomerate facies and the transgressive and highstand systems tracts of the composite sequence, as each carbonate tongue represents both the transgressive and highstand systems tracts. The environment is expected to remain relatively similar whether collections are from the transgressive or highstand deposits because of their position on the slope in water depths estimated to be 300 to 500 m (Brown and Loucks, 1993: Tinker, 1998). Each member represents the same region at different times, providing multiple measurements of diversity through time.

Blocks of limestone containing silicified brachiopods were collected from the Pinery (N=10), Rader (N=10), Lamar (N=8), and Reef Trail (N=17) Members on the southwest, central, and northeast sides of Guadalupe Mountains National Park (Table 3.1; Fig. 3.3). The amount of material collected for each bulk sample varied from 0.9 kg to 12 kg, depending on the difficulty of collecting from the debris flow deposits. Twenty-three of the 45 collections represent a single collection from a single bed (i.e., temporal samples), whereas 22 collections sample the same bed twice along strike (i.e., spatial samples). The spatial extent of the study area is ~40 square kilometers and includes an area of the park—WR (Williams Ranch Road) and BR (Back Ridge) (Fig. 3.3)—not collected by previous workers (Newell and Cooper and Grant), thereby adding new information on the spatial variation of brachiopod associations in the Guadalupe Mountains.

Sampling through most of the BCF sequence was attempted; however, this was not possible at two locations—PS (Pine Springs) and ROTR (Rader on the Road) (Fig. 3.3). ROTR samples only the Rader member, and PS samples only the Pinery, unlike in other sections where two members were sampled. Collections from the ROTR location sample only the upper part of the Rader Member. Collections from the PS location, however, do sample through the entire Pinery Member. All of the other sections entirely sample two successive members within the BCF. Not all members were sampled (i.e., Hegler and McCombs) because of the lack of appropriate facies or the lack of accessible outcrop within the park. Additionally, not all debris flows were sampled due to varying degrees of accessibility and extractability. For a debris-flow conglomerate to be sampled, it had to have at least one visible brachiopod on one face of the exposed bed. Samples were dissolved in a tub of 10% HCl lined with 850 micron mesh to

Table 3.1—Summary of generic richness within the members of the BCF. Total richness is by each member and each locality. Number of collections is in parentheses. PS = Pine Springs; BR = Back Ridge; ROTR = Rader on the Road; WR = Williams Ranch Road; McK = McKittrick Canyon.

Bell Canyon Member	Total Generic Richness (S)	PS (S)	BR (S)	ROTR (S)	WR (S)	McK (S)
Pinery	27 (10)	26 (5)	21 (5)	-	-	-
Rader	34 (10)	-	22 (6)	27 (4)	-	-
Lamar	40 (8)	-	-	-	37 (4)	28 (4)
Reef Trail	36 (17)	-	-	-	36 (12)	18 (5)

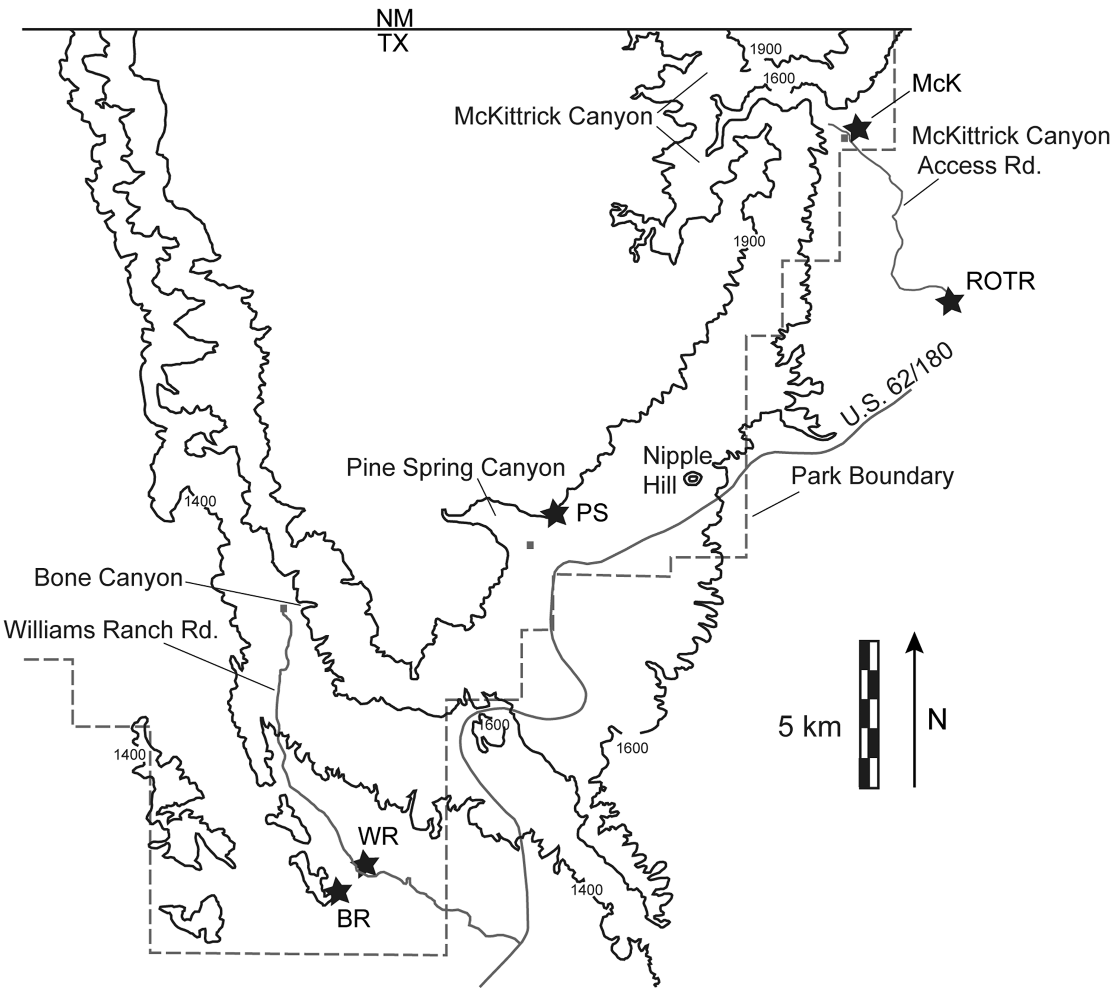


Figure 3.3—Locality map of Guadalupe Mountains National Park. Stars represent collection locations. McK = McKittrick Canyon; ROTR = Rader on the Road; PS = Pine Springs; WR = Williams Ranch Road; BR = Back Ridge. McK includes Lamar (40 m) and Reef Trail (17.23 m) Members. ROTR includes the Rader Member (6.165 m). PS includes the Pinery Member (59.705 m). WR includes Lamar (21.69 m) and Reef Trail (50.02 m) Members. BR includes Pinery (51.21 m) and Rader (25.345 m) Members. Redrawn from Guadalupe Peak 30 x 60 minute quadrangle.

remove the silicified brachiopods from the limestone matrix. Variations in mesh size influence paleontological patterns: using too small a mesh potentially includes a high number of juveniles or spatfall resulting in a weaker correspondence to the live assemblage, whereas using too large a mesh can result in not capturing juveniles and removing too many specimens (Kidwell, 2002; Kowalewski and Hoffmeister, 2003). The use of 850 micron mesh in this study follows the methodology used by Cooper and Grant (1972), allowing direct comparison with their dataset. Once the limestone was dissolved, the screen was removed from the tub and all brachiopods were picked from the screen. A qualitative estimate of the size-frequency distribution of brachiopods within a couple of the collections suggests that brachiopods generally are not size sorted. Brachiopod individuals include identifiable fragments as well as articulated and complete specimens. For a fragment to be considered identifiable, part or the entire hinge had to be present. Most individuals (>70%) are represented by a single valve. Although preservation of such internal structures as spiralia and loops is not common, pieces of spiralia and loops are found occasionally within the residue, indicating that these structures were sometimes present; it is unclear if these delicate structures are uncommon due to the processing of specimens or lack of preservation. Preservation of such external structures as productid spines tends to be uncommon but spines are present in the residue. It is possible that either the dissolution process or transportation may be breaking spines off the shell.

Brachiopods were identified to the generic level using the monographs of Cooper and Grant (1974, 1975, 1976a, 1976b), and faunal lists were compiled for each sample.

Statistical analyses were performed at the generic level for several reasons: (1) identifications at the generic level are more robust than species identifications when working with fragmented material (Patzkowsky and Holland, 2003), which is typical of the BCF; (2) almost half of the genera within the BCF are monospecific; and (3) a proportion of the brachiopods could not be identified to species due to preservation state. Furthermore, similar ordination results were obtained using both generic- and species-level identifications of brachiopods from the Cooper and Grant collections, suggesting that a strong signal emerges for this region even when analyzing at the higher taxonomic level (Olszewski and Erwin, 2009).

Methods

Cluster Analysis

Cluster analysis was used to determine how well taxa grouped together in order to help identify paleocommunities. Herein, the term paleocommunity refers to a spatial and temporal association of genera among collections. The dataset uses presence-absence data of 42 brachiopods identified to the generic level from the members of the BCF. Presence-absence data rather than abundance data are used for this analysis because binary data are commonly used when assessing the similarity among and persistence of paleocommunities (e.g., Rahel, 1990; Koleff et al., 2003), and some collections have a small number of specimens, resulting in poorly constrained relative abundances (Olszewski and Patzkowsky, 2001). Genera that occur in ≤5% of the collections were excluded to reduce the influence of rare genera. There were no collections with only a single genus. Clustering was conducted with three different measures–Jaccard (metric), Kulczynski (semimetric), and Ochiai (nonmetric) measures and four linkage methods–nearest neighbor (or single linkage), farthest neighbor (or complete linkage), group average (or UPGMA), and Ward's to represent the range of available clustering techniques (Legendre and Legendre, 1998). The purpose of using multiple methods is to assess the robustness of the clustering pattern (Redman et al., 2007). Overall, all four linkage methods produced two to three robust clusters with generally the same taxa composing these clusters. Group average (UPGMA) was the best performer with all three binary coefficients based on cophenetic correlations. Cophenetic correlation compares the calculated distance matrix to the distance matrix based on the dendrogram, and when there is perfect correspondence between the two matrices, the correlation value equals one (Legendre and Legendre, 1998). Ward's method had the lowest cophenetic correlation but produced well-defined clusters. Among the coefficients, Jaccard in combination with UPGMA had the highest correlation of 0.89, therefore, the results from UPGMA with the Jaccard coefficient are presented here. The Jaccard coefficient (defined as a distance coefficient) is the best-known metric using presence-absence data in which all terms have equal weight; it measures at the proportion of taxa shared between two sites (Legendre and Legendre, 1998):

$$D_J = 1 - a/(a + b + c) \tag{3.1}$$

where a = total number of genera shared between two sites; b = total number of genera found in the first site but not the second; and c = total number of genera found in the second site but not the first. Cluster analyses were performed using the vegan package (Oksanen et al., 2008) and labdsv package (Roberts, 2007) in R 2.6.2 (R Development Core Team, 2008).

Correspondence Analysis

To visually assess the taxonomic compositions of brachiopod paleocommunities within the BCF, the data were ordinated with correspondence analysis (CA). Ordination is a method that arranges objects (i.e., collections) according to their similarity along axes in reduced space, usually in two or three dimensions. Correspondence analysis (CA) is a type of ordination that calculates sample scores as a weighted average of species scores and species scores as a weighted average of sample scores (ter Braak, 1995). CA was chosen for this analysis because it has been shown to recover the underlying data structure with simulated data when compared to other metric ordination techniques (e.g., principal component analysis) (Kenkel and Orlóci, 1986). Plus, unlike nonmetric ordinations (e.g., nonmetric multidimensional scaling), CA superimposes *a priori* both taxa and collections in the same ordination space, allowing a direct comparison between the two.

A concern of CA is that it can produce an arch effect, which is an artifact caused by fitting nonlinear relationships (i.e., unimodal distributions of species along a gradient) in Euclidean space (ter Braak, 1995). The arch effect results when the first axis is folded in the middle, compressing the ends of the axis close together, to obtain the second axis (Hill and Gauch, 1980; ter Braak, 1995). A popular way to correct the arch effect is by detrending, which straightens the arch by diving the axis into segments and adjusting the mean score of each segment to zero (McCune and Grace, 2002). No arch, however, was evident with the data used for this analysis.

Ordination also was conducted with two other methods–nonmetric multidimensional scaling (NMDS) and detrended correspondence analysis (DCA)–commonly used in ecological and paleoecological studies. All ordinations produced similar patterns, indicating the patterns in the analyses are robust. The results from the correspondence analysis are presented here. Ordinations were performed using the vegan package (Oksanen et al., 2008) in R 2.6.2 (R Development Core Team, 2008).

Statistical Analyses

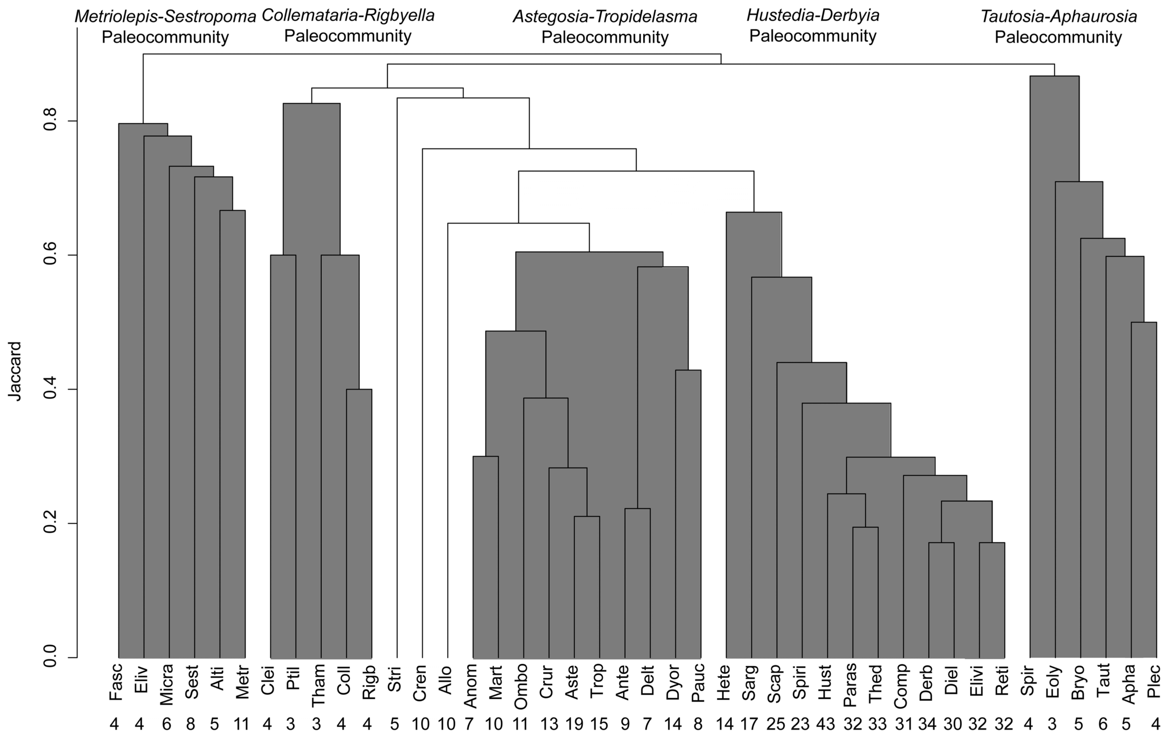
Two statistical analyses, nonparametric MANOVA and Mantel tests, were performed on the data to statistically evaluate the compositional changes within the BCF. A nonparametric multivariate analysis of variance is used to test the null hypothesis that there are no compositional differences among the four members of the BCF. The statistical method of nonparametric (or permutational) MANOVA partitions the variation (sums of squares) in the composition of brachiopod paleocommunities within the collections from the Pinery, Rader, Lamar, and Reef Trail Members using the Jaccard distance measure. The Jaccard distance measure was chosen because this measure was used in the cluster analysis. Mantel tests were performed to evaluate the taxonomic similarity between two members. Mantel tests quantify and evaluate compositional turnover in the BCF by testing the null hypothesis that stratigraphically adjacent members are more similar to each other in taxonomic composition than stratigraphically distant members. Mantel tests compute a statistic by comparing two distance (or similarity) matrices to determine how significantly the matrices are correlated to one another (Mantel, 1967; Legendre and Legendre, 1998). The correlation method used for this analysis is Spearman because it is a rank-based measure and the data do not have to conform to a normal distribution (Sokal and Rohlf, 1995). Both statistical analyses were run with 4,999 permutations for an α-level of 0.01 under the null hypothesis (Anderson, 2001; Manly, 2007). Analyses were performed using the vegan package (Oksanen et al., 2008) in R 2.6.2 (R Development Core Team, 2008).

Results

Brachiopod Paleocommunities

There are five general groups of brachiopods identified in the cluster analysis (Fig. 3.4). Each paleocommunity is named for the two genera occurring in the highest proportion among the collections. The *Metriolepis*-*Sestropoma* paleocommunity is composed of infrequent taxa that occur in all the members of the BCF. This group is defined as infrequent because these taxa occur in 9% to 24% of the collections. Of the taxa within this group, *Metriolepis* (Metr), *Sestropoma* (Sest), and *Micraphelia* (Micra) occur the most frequently (13%–24%).

Figure 3.4—R-mode cluster analysis of 42 brachiopod genera collected in the BCF members. Clusters are identified based on the stem length and breaks in data. Numbers represent the occurrences within the collections. Allo = *Allorhynchus,* Alti = *Altiplecus,* Anom = *Anomaloria,* Ante = *Anteridocus,* Apha = *Aphaurosia,* Aste = *Astegosia,* Bryo = *Bryorhynchus,* Clei = *Cleiothyridina,* Coll = *Collemataria,* Comp = *Composita,* Cren = *Crenispirifer,* Crur = *Crurithyris,* Delt = *Deltarina,* Derb = *Derbyia,* Diel = *Dielasma,* Dyor = *Dyoros,* Eliv = *Eliva,* Elivi = *Elivina,* Eoly = *Eolyttonia,* Fasc = *Fascicosta,* Hete = *Heteralosia,* Hust = *Hustedia,* Mart = *Martinia,* Metr = *Metriolepis,* Micra = *Micraphelia,* Ombo = *Ombonia,* Paras = *Paraspiriferina,* Pauc = *Paucispinifera,* Plec = *Plectelasma,* Ptil = *Ptilotorhynchus,* Reti = *Reticulariina,* Rigb = *Rigbyella,* Sarg = *Sarganostega,* Scap = *Scapharina,* Sest = *Sestropoma,* Spir = *Spiriferella,* Spiri = *Spiriferellina,* Stri = *Strigirhynchia,* Taut = *Tautosia,* Tham = *Thamnosia,* Thed = *Thedusia,* Trop = *Tropidelasma.*



Metriolepis-Sestropoma Paleocommunity
Collemataria-Rigbyella Paleocommunity
Astegosia-Tropidelasma Paleocommunity
Hustedia-Derbyia Paleocommunity
Tautosia-Aphaurosia Paleocommunity
Jaccard
0.0
0.2
0.4
0.6
0.8
Fasc Eliv Micra Sest Alti Metr Clei Ptil Tham Coll Rigb Stri Cren Allo Anom Mart Ombo Crur Aste Trop Ante Delt Dyor Pauc Hete Sarg Scap Spiri Hust Paras Thed Comp Derb Diel Elivi Reti Spir Eoly Bryo Taut Apha Plec
4 4 6 8 5 11 4 3 3 4 4 5 10 10 7 10 11 13 19 15 9 7 14 8 14 17 25 23 43 32 33 31 34 30 32 32 4 3 5 6 5 4

The *Collemataria-Rigbyella* paleocommunity also contains infrequent taxa, but almost exclusively within the Lamar and Reef Trail Member. The only exception is *Thamnosia* (Tham), which occurs in a single Rader Member sample. Taxa within this group occur in only 7% to 9% of the collections. This assemblage is dominated by productids (i.e., three out of the five genera), including two lyttoniids–*Collemataria* (Coll) and *Rigbyella* (Rigb).

The proportion of spiriferids in the *Astegosia-Tropidelasma* paleocommunity is 43%, which is the highest of any group in the analysis, and includes *Astegosia* (Aste), *Anomaloria* (Anom), *Martinia* (Mart), and *Crurithyris* (Crur). Most taxa within this group occur within the Lamar and Reef Trail Members collections. There are, however, four exceptions—*Anteridocus* (Ante), *Deltarina* (Delt), *Dyoros* (Dyor), and *Paucispinifera* (Pauc)—that occur infrequently in the collections of the Pinery and Rader Members and cluster together within this paleocommunity.

The *Hustedia-Derbyia* paleocommunity is composed of brachiopods found in most samples and all members within the Bell Canyon. Sixty-nine percent of the collections contain at least half of these ubiquitous taxa. This assemblage is dominated by spiriferinids, specifically punctate spirifers: *Paraspiriferina* (Paras), *Reticulariina* (Reti), *Spiriferellina* (Spiri), and *Sarganostega* (Sarg). The top three genera include *Hustedia* in 96% of collections (Hust), *Derbyia* in 76% of collections (Derb), and *Thedusia* in 73% of collections (Thed). The ubiquitous group is the most diverse, containing 12 genera and six of the seven orders found in all the collections. There are no rhynchonellid brachiopods within this assemblage, however.

The *Tautosia-Aphaurosia* paleocommunity is dominated by rhynchonellids. The taxa within this group are infrequent and occur across all members, but they do not group with the other infrequent taxa of the BCF, indicating the group is distinct. Taxa occur in 7% to 13% of the collections.

Analysis of Paleocommunity Composition

Correspondence analysis of 45 collections and 42 genera reveals separation among collections by taxonomic associations into two main compositional groups along CA axis 1 (Fig. 3.5). Bell Canyon 1 (BC1) contains the Pinery Member, Rader Member, and seven Reef Trail Member collections associated with the *Metriolepis-Sestropoma* (1), *Hustedia-Derbyia* (4), and *Tautosia-Aphaurosia* (5) paleocommunities. Bell Canyon 2 (BC2) contains the Lamar Member and nine Reef Trail Member collections associated with *Collemataria-Rigbyella* (2) and *Astegosia-Tropidelasma* (3) paleocommunities. The zeros represent the taxa not coherently grouped in the cluster analysis. The BC1 and 2 clouds share the *Hustedia-Derbyia* paleocommunity, which is ubiquitous across all members of the BCF. One Reef Trail Member collection (Rt5-1c) plots separately from both groups. There is one taxon—*Eliva* (Eliv)—that plots separately from other taxa and collections on the ordination. If *Eliva* is removed, the same pattern of separation among collections remains present, but the outlying Reef Trail Member collection plots within BC2. Within each compositional group, there is further separation of collections and paleocommunities along CA axis 2. CA axis 2

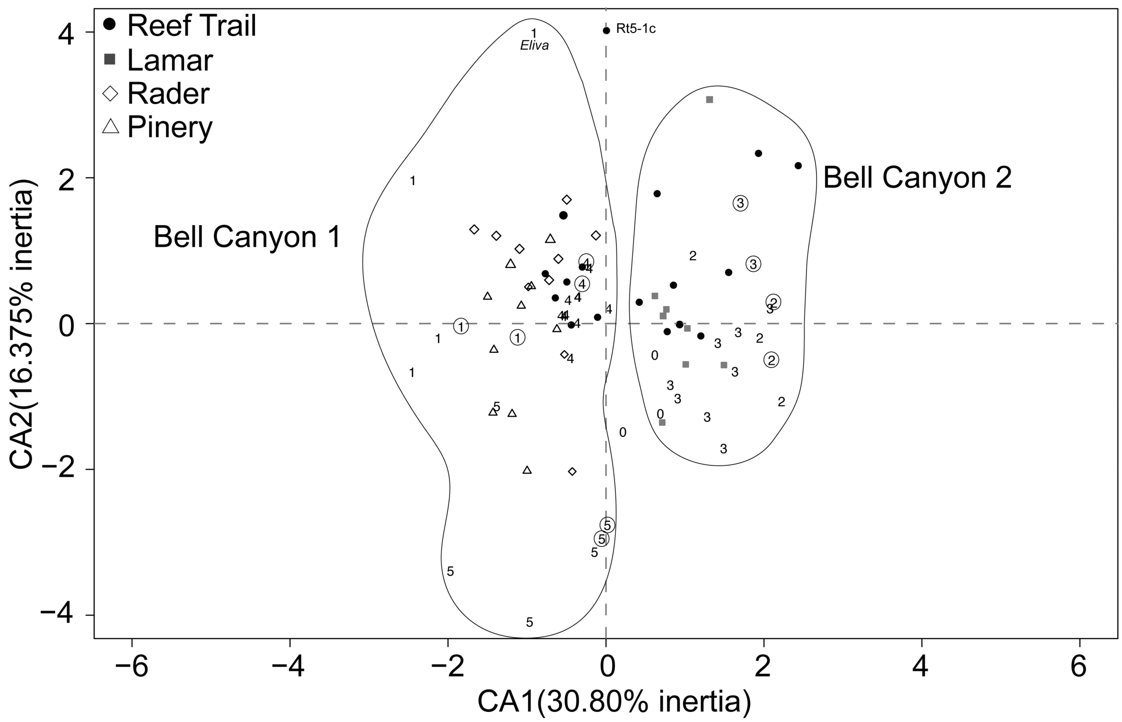


Figure 3.5—Correspondence analysis of the Bell Canyon collections and genera. Outlined regions indicate two main compositional groups, interpreted from the separation among collections. Each point represents a collection and the different symbols represent members of the BCF. Numbers represent the taxa belonging to the brachiopod paleocommunities identified in the cluster analysis (e.g., 3 = *Astegosia-Tropidelasma* paleocommunity). Circled numbers represent the two genera occurring in the highest proportion among the collections. Inertia percentage shows the amount of variation accounted for by each axis. Units are mean standard deviations. 1 = *Metriolepis-Sestropoma*; 2 = *Collemataria-Rigbyella*; 3 = *Astegosia-Tropidelasma*; 4 = *Hustedia-Derbyia*; 5 = *Tautosia-Aphaurosia*.

generally separates the Pinery Member from the Rader Member collections and the Lamar Member from the Reef Trail Member collections, although there is slightly more overlap between the collections of the Pinery and Rader Members (Fig. 3.5).

When the proportion of collections occupied by individual taxa (i.e., occupancy) for BC1and 2 are plotted against each other, the occupancy of taxa contributing to BC1 and 2 differs (Fig. 3.6). Proportions are calculated by number of occurrences divided by number of collections. BC1 has 27 collections and BC2 has 18 collections based on ordination results. Taxa plotting below the 1:1 line in Figure 3.6 have disproportionately more occurrences in BC1, whereas taxa plotting above this line have disproportionately more occurrences in BC2. Taxa from the *Hustedia-Derbyia* paleocommunity plot along the 1:1 line, indicating constancy in their high occupancy among BC1and BC2 and the ubiquitous nature of this paleocommunity. Taxa composing the other four paleocommunities occur in either BC1 or BC2. For example, the *Astegosia-Tropidelasma* (3) paleocommunity is found in high proportion within BC2 and low proportion or not found in BC1. Most taxa of the *Metriolepis-Sestropoma* (1) paleocommunity are found in low to moderate proportion in BC1and do not occur in BC2 (e.g., *Sestropoma*, *Micraphelia*, *Fascicosta*). Only one taxon—*Thamnosia*—from the *Collemataria-Rigbyella* (2) paleocommunity occurs in very low proportion in BC1, whereas the other taxa within this paleocommunity do not occur in BC1. The zeros represent the taxa not coherently grouped in the cluster analysis.

As shown by the ordination of brachiopod genera in Figure 3.7A, the previously identified paleocommunities plot in different areas. Taxa from the *Hustedia-Derbyia*

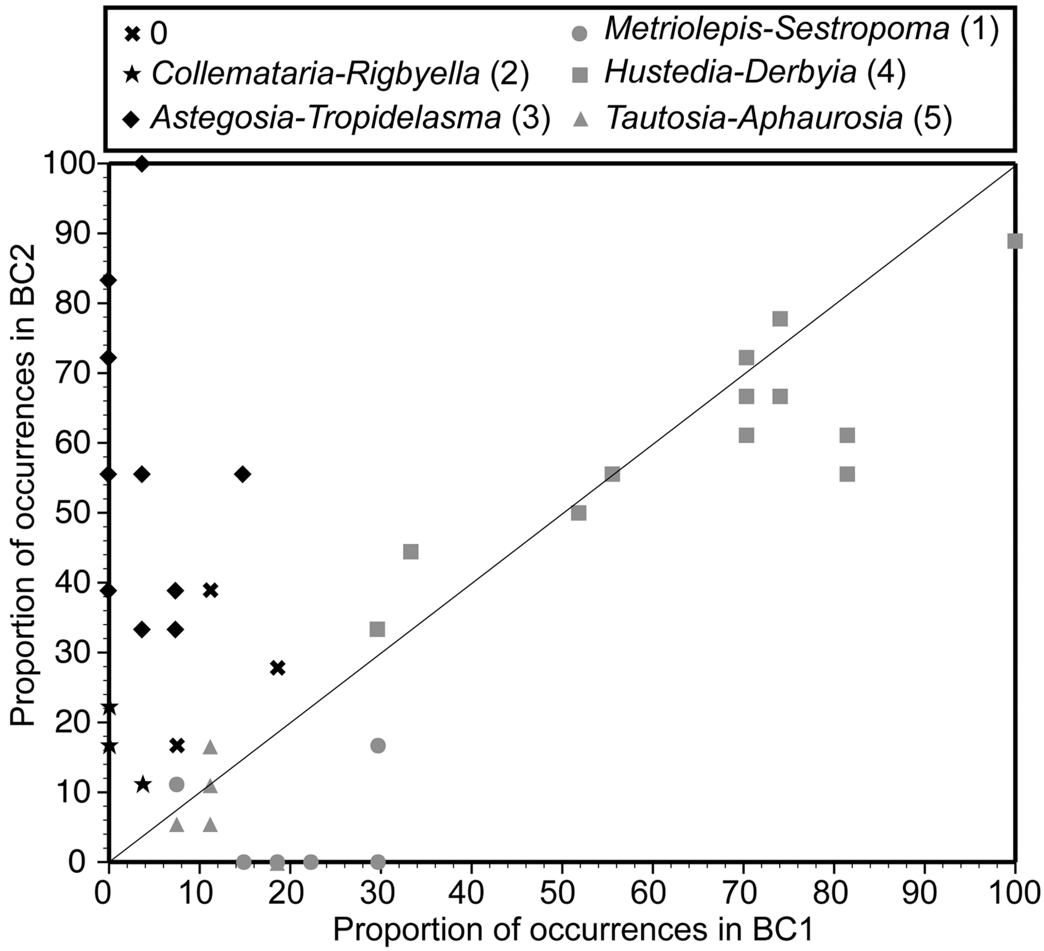
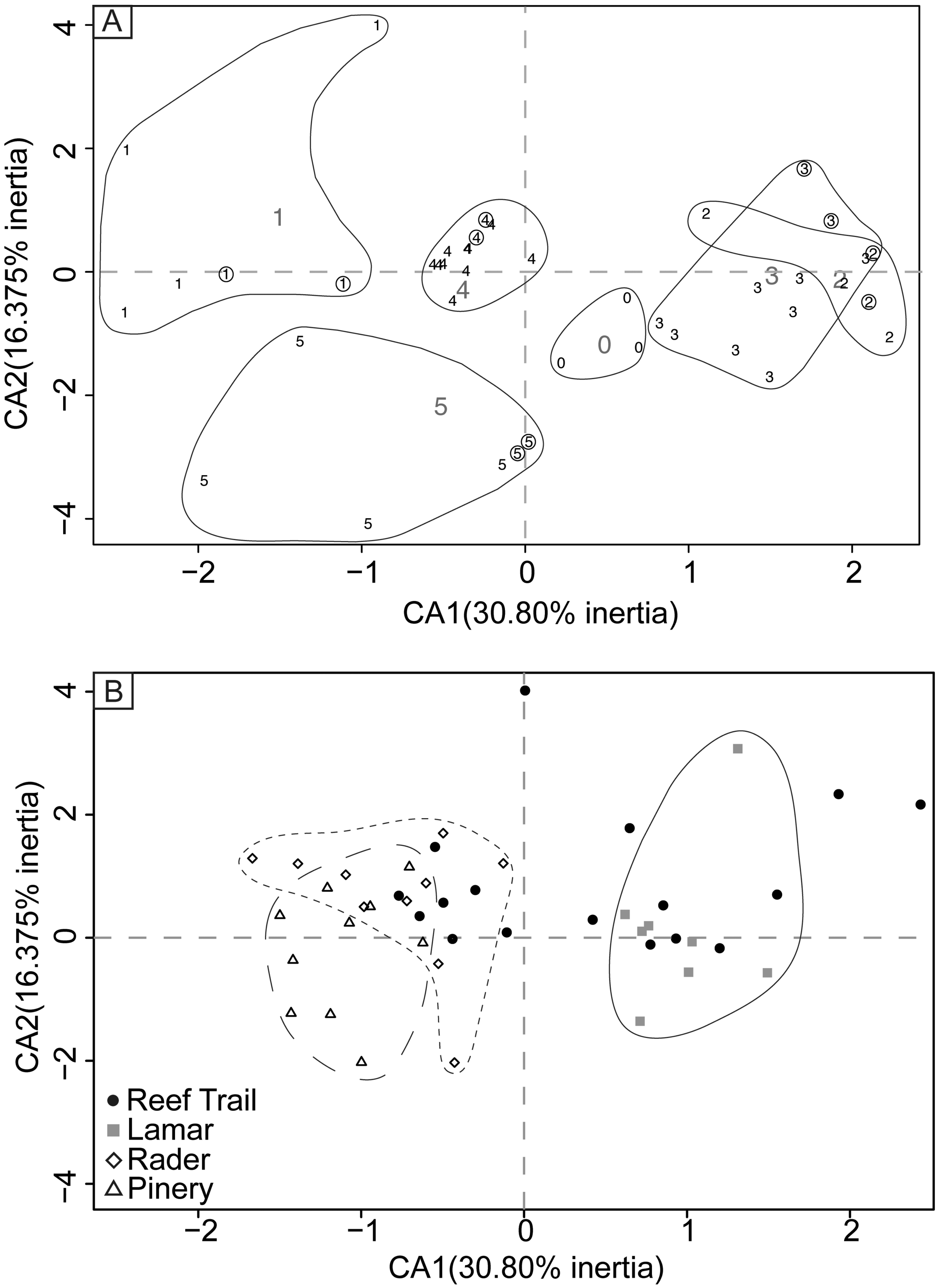


Figure 3.6—Proportion of collections occupied by individual taxa in Bell Canyon 1 (BC1) and Bell Canyon 2 (BC2). Each symbol represents a brachiopod genus. Different symbols represent paleocommunities identified in cluster analysis. Gray symbols are BC1 taxa and black symbols are BC2 taxa. Numbers in parentheses represent the paleocommunity used in the ordinations. 1:1 line represents equal proportion between the two groups. Genera plotting below this line are more likely found in BC1 and genera plotting above this line are more likely found in BC2.

Figure 3.7—Separate correspondence analyses of the Bell Canyon collections and genera. Note the change of scale along the axes compared to Figure 3.5. (A) Brachiopod genera only. Outlined regions are clusters from Figure 3.4. Small numbers represent each brachiopod genus and large number represents the community centroid. (B) Collections only. Outlined regions are the members: long dashes = Pinery Member collections; short dashes = Rader Member collections; and solid line = Lamar Member collections. Reef Trail Member not outlined due to spread of points. Each point represents a collection and the different symbols represent members of the BCF. Inertia percentage shows the amount of variation accounted for by each axis. Units are mean standard deviations.


A
CA2(16.375% inertia)
CA1(30.80% inertia)
B
CA2(16.375% inertia)
CA1(30.80% inertia)
Reef Trail
Lamar
Rader
Pinery

paleocommunity are found in all collections and, therefore, are tightly clustered in the middle of the ordination, near the origin. The *Metriolepis-Sestropoma* (1) and *Tautosia-Aphaurosia* (5) paleocommunities do not overlap; taxa within these paleocommunities do not cluster tightly, possibly indicating that they co-occur less with other genera within the collections. Two paleocommunities overlap each other—*Collemataria-Rigbyella* (2) and *Astegosia-Tropidelasma* (3)—but separate in higher ordination dimensions. These paleocommunities generally are more tightly clustered than the *Metriolepis-Sestropoma* (1) and *Tautosia-Aphaurosia* (5) paleocommunities.

Examining the correspondence analysis of collections, there is a compositional change in brachiopod paleocommunities from the Pinery and Rader Members to the Lamar Member; however, the Reef Trail Member shows a different pattern (Fig. 3.7B). Reef Trail Member collections segregate by neither geographic location nor stratigraphic position (i.e., ordered temporal position in a section). The results indicate that taxonomic composition varies greatly within the Reef Trail Member. Reef Trail Member collections plotting within BC1are dominated by the *Hustedia-Derbyia* paleocommunity, contain no or one taxon from the *Astegosia-Tropidelasma* paleocommunity, and contain no taxa from the *Collemataria-Rigbyella* paleocommunity. Conversely, Reef Trail Member collections within BC2 are dominated by *Astegosia-Tropidelasma* and *Hustedia-Derbyia* paleocommunities.

The nonparametric MANOVA demonstrates that there are significant ($p<0.0001$, Table 3.2) compositional differences within the BCF at the generic level, which supports the ordination pattern in Figures 3.5 and 3.7B. The MANOVA test evaluates differences

Table 3.2— Results for a nonparametric multivariate analysis of variance (Anderson, 2001) evaluating the compositional change among the four members of the BCF. Distance measure used was Jaccard. *** = $p < 0.001$. Test was performed using the vegan package (Oksanen et al., 2008) in R 2.6.2 (R Development Core Team, 2008).

	Degrees of Freedom	Sums of Squares	Mean Squares	F Model	R^2	Pr(>F)
Members	3	2.06676	0.68892	3.15012	0.1873	0.0002***
Residuals	41	8.96657	0.21870		0.8127	
Total	44	11.03334			1.0000	

among the members together. Evaluating compositional changes between two members with Mantel tests provides an additional means of assessing taxonomic changes at a finer level. Generally, most members significantly share genera whether they are stratigraphically adjacent or distant from each other (Table 3.3; Fig. 3.8). Although most correlations are significant, the correlation values are relatively low. Looking at the highest correlation of 0.515 between the Rader and Reef Trail Members, the correlation predicts just over 50% of the same genera to occur in both of the members. The correlation between the Pinery and Reef Trail Members shows no significant relationship with the genera they share. Additionally, these members are the most stratigraphically distant. These results of the Mantel tests indicate that members may share some genera, possibly the genera of the *Hustedia-Derbyia* paleocommunity, but a large portion of the genera cannot be predicted based on the correlation values.

Taxonomic Occurrence through Time

The use of rank-occurrence plots provides information on the member-scale metacommunity composition of brachiopods in the BCF. Rank-occurrence plots report the proportion of brachiopod occurrences based on the number of collections within each member. These plots highlight the replacement of established brachiopods with new taxa that occur at high proportions when they first appear in the collections (Fig. 3.9). Each taxon is coded by its membership within a paleocommunity to show the distribution of brachiopod paleocommunities in each member based on their proportion

Table 3.3—Results for Mantel tests evaluating the similarity of collections from stratigraphically adjacent members of the BCF. R values are Spearman's rank correlation. Parentheses indicate number of genera in common. * indicates $\alpha < 0.001$; ** indicates $\alpha < 0.0001$. Test was performed using the vegan package (Oksanen et al., 2008) in R 2.6.2 (R Development Core Team, 2008).

	Pinery	Rader	Lamar	Reef Trail
Pinery	-	0.386 (22)*	0.488 (19)*	0.239 (20)
Rader		-	0.372 (24)*	0.515 (23)**
Lamar			-	0.412 (33)*
Reef Trail				-

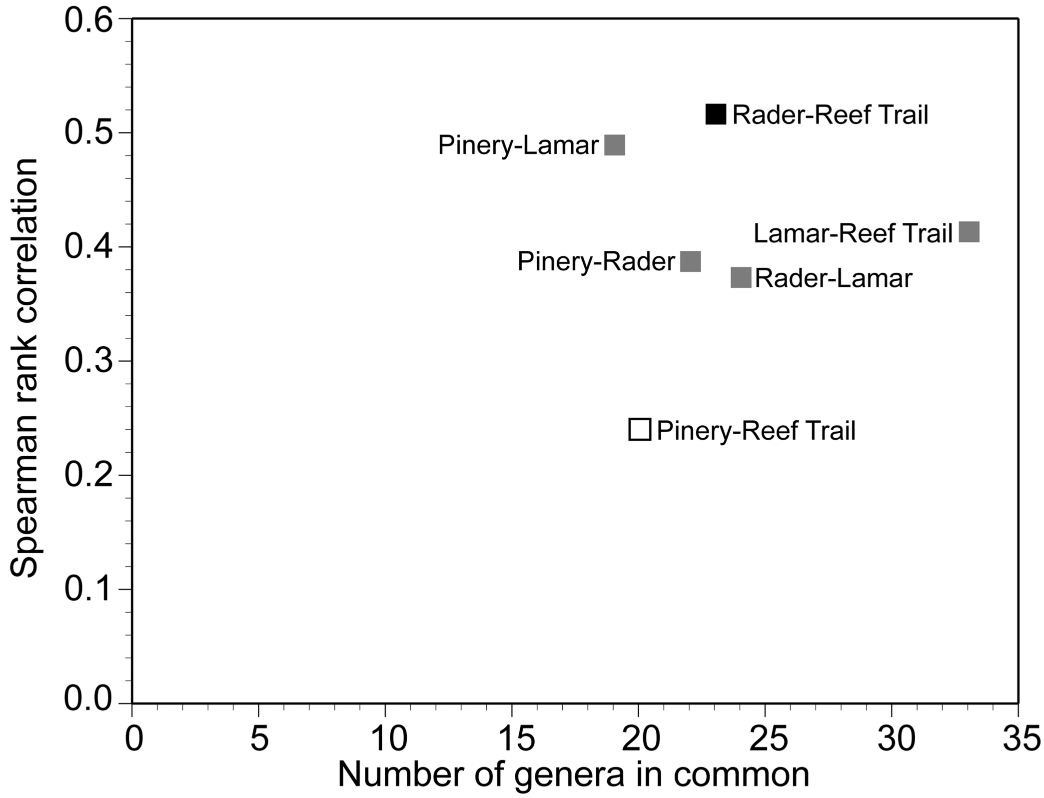
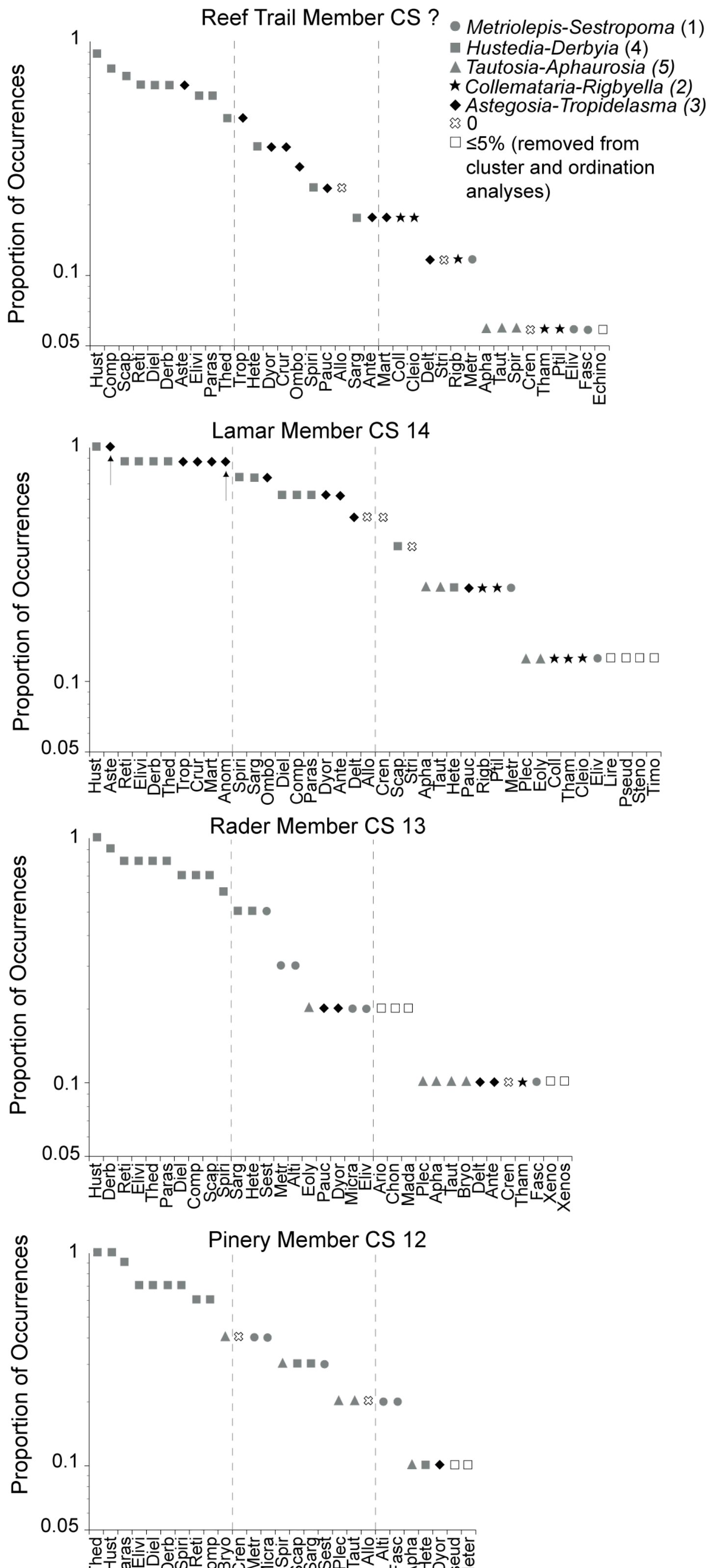


Figure 3.8—Plot of results from Mantel tests showing Spearman rank correlations as a function of the number of genera in common among the members of the BCF. Empty squares indicate no significance; gray squares indicate $\alpha < 0.001$; black squares indicate $\alpha < 0.0001$.

Figure 3.9—Rank-occurrence plots for each member of the BCF. Each taxon is labeled by its paleocommunity membership identified in the cluster analysis. See Table 3.1 for richness and collection counts for each member. The gray dashed lines divide taxa into the ten most common and second most common in order to evaluate the change in dominance of brachiopods within the metacommunity at member-level temporal scales. Arrows indicate invaders into the basin. The unfilled boxes represent the genera that were removed from the cluster analysis and ordination analyses because they occur in ≤5% of the collections. Ario = *Arionthia;* Chon = *Chonetinetes;* Echino = *Echinosteges;* Heter = *Heterelasma;* Lire = *Lirellaria;* Mada = *Madarosia;* Pseud = *Pseudoleptodus;* Steno = *Stenoscisma*; Timo = *Timorina;* Xeno = *Xenosaria;* Xenos = *Xenosteges*.


Reef Trail Member CS ?
Metriolepis-Sestropoma (1)
Hustedia-Derbyia (4)
Tautosia-Aphaurosia (5)
Collemataria-Rigbyella (2)
Astegosia-Tropidelasma (3)
0
≤5% (removed from cluster and ordination analyses)
Proportion of Occurrences
1
0.1
0.05
Hust Comp Scap Reti Diel Derb Aste Elivi Paras Thed Trop Hete Dyor Crur Ombo Spiri Pauc Allo Sarg Ante Mart Coll Cleio Delt Stri Rigb Metr Apha Taut Spir Cren Tham Ptil Eliv Fasc Echino
Lamar Member CS 14
Proportion of Occurrences
1
0.1
0.05
Hust Aste Reti Elivi Derb Thed Trop Crur Mart Anom Spiri Sarg Ombo Diel Comp Paras Dyor Ante Delt Allo Cren Scap Stri Apha Taut Hete Pauc Rigb Ptil Metr Plec Eoly Coll Tham Cleio Eliv Lire Pseud Steno Timo
Rader Member CS 13
Proportion of Occurrences
1
0.1
0.05
Hust Derb Reti Elivi Thed Paras Diel Comp Scap Spiri Sarg Hete Sest Metr Alti Eoly Pauc Dyor Micra Eliv Ario Chon Mada Plec Apha Taut Bryo Delt Ante Cren Tham Fasc Xeno Xenos
Pinery Member CS 12
Proportion of Occurrences
1
0.1
0.05
Thed Hust Paras Elivi Diel Derb Spiri Reti Comp Bryo Cren Metr Micra Spir Scap Sarg Sest Plec Taut Allo Alti Fasc Apha Hete Dyor Pseud Heter

of occurrence. The proportion of occurrences is calculated by the number of times a genus occurs within a member divided by the number of collections within a member (i.e., occupancy).

Overall, rank-occurrence plots show slightly different shapes through the BCF. The Pinery, Rader, and Reef Trail Members appear to have similar shapes to their curves, whereas the Lamar Member curve has a more convex-up shape because of the high proportion of occurrences in more taxa. A Wilcoxon Rank Sum test was used to determine if there are statistical differences with the median occupancy—the proportion of collections occupied by individual taxa—among the members (Table 3.4; Sokal and Rohlf, 1995). Results indicate that the Lamar Member is statistically different from the Rader and Reef Trail Members. The lack of significant difference between the Pinery and Lamar Members may be due to the difference in number of genera. Regardless, this statistical analysis lends support to the clustering and ordination analyses that the Lamar Member is different than other members of the formation, not just in terms of composition but also in terms of structure.

The metacommunity shows a change in dominance of brachiopods through the BCF when comparing the twenty most occurring genera (Fig. 3.9). Of the first 10 genera, the Pinery and Rader Members share the same nine genera, which are part of the *Hustedia-Derbyia* paleocommunity. This trend changes in the Lamar Member when some of these taxa (e.g., *Paraspiriferina*, *Dielasma*, *Composita*) are replaced in dominance with *Astegosia*, *Tropidelasma*, *Crurithyris*, *Martinia*, and *Anomaloria* from the *Astegosia-Tropidelasma* paleocommunity. The term replace is used because genera

Table 3.4—Results of Wilcoxon Rank Sum test evaluating median differences in occupancy among the four members of the BCF. P-values (two-sided) in parentheses. Bold text indicates significant values. Test was performed using the coin package (Hothorn et al., 2006) in R 2.6.2 (R Development Core Team, 2008).

	Pinery	Rader	Lamar	Reef Trail
Pinery	-	521 (0.3649)	462 (0.3206)	621 (0.06019)
Rader		-	**475.5 (0.02536)**	708 (0.2602)
Lamar			-	**1007 (0.002438)**
Reef Trail				-

are still present within the metacommunity but have lower occurrences within the collections. These five genera of the Lamar Member decrease in dominance in the Reef Trail Member and are replaced again by genera from the *Hustedia-Derbyia* paleocommunity. Only one taxon, *Astegosia*, remains in the ten most occurring genera. When comparing the next ten brachiopod genera, there are few genera in common among the members (Fig. 3.9). There are only four genera in common between the Pinery and Rader Members compared to six genera between the Lamar and Reef Trail Members.

The Lamar Member plot shows the most interesting results because there are new taxa found within the collections that replace the established taxa of the *Hustedia-Derbyia* paleocommunity. These taxa are not restricted to low proportion of occurrences, but are distributed throughout the plot (Fig. 3.9). The first appearances of the taxa *Tropidelasma*, *Crurithyris*, *Martinia*, and *Ombonia* plot at high occurrence values, whereas *Rigbyella*, *Ptilotorhynchus*, *Collemataria*, and *Cleiothyridina* plot at low occurrence values. These new taxa compose the *Astegosia-Tropidelasma* and *Collemataria-Rigbyella* paleocommunities, respectively. Included in the *Astegosia-Tropidelasma* paleocommunity are two immigrants from outside the basin—*Astegosia* and *Anomaloria*. Neither of these taxa appear in the Delaware Basin until the Lamar Member, but they are known from Northwest China and Thailand in Early and Middle Permian time (Waterhouse and Piyasin, 1970; Grant, 1976; Chen et al., 2003; Chen and Shi, 2006). Neither the first appearances of *Astegosia* and *Anomaloria,* nor other members of the *Astegosia-Tropidelasma* and *Collemataria-Rigbyella* paleocommunities caused the extinction of any taxa from the *Hustedia-Derbyia* paleocommunity when these brachiopods became prominent constituents of the metacommunity.

Discussion

Nature of BCF Brachiopod Paleocommunities

The results from these analyses do not support a uniform taxonomic composition of brachiopod paleocommunities though the BCF. Ordination analyses reveal two compositional groups within the formation, identified as BC1and BC2 (Fig. 3.5). These compositional groups appear to be primarily associated with stratigraphic units rather than geographic location or facies. BC1 includes all samples from the Pinery and Rader Members and some of the collections from the Reef Trail Member, whereas BC2 includes only collections from the Lamar and Reef Trail Members. The observation that collections from the Reef Trail Member fall within both the BC1 and BC2 compositional groups suggests that the taxonomic composition returned to associations resembling those in the Pinery and Rader Members after the disruption evidenced by Lamar Member collections (Fig. 3.9). The appearance of the BC2 association coincides with an unconformity between the Rader and McCombs Members separating CS13 from CS14 (Fig. 3.2A). Environmental disruption associated with a major unconformity could have influenced the ecological landscape by increasing or decreasing the habitable area (i.e., optimal environment conditions) for brachiopods to occupy or by increasing or decreasing connections to species pools in other basins (Olszewski and Erwin, 2004). Within the lower BCF, the taxonomic composition of brachiopod paleocommunities of the Pinery and Rader Members does not vary, even though an unconformity separating CS12 and CS13 has been identified by previous workers (Kerans and Tinker, 1999; Kerans and Kempter, 2002). Despite the fact that the sequence boundary of CS14 does not directly underlie the Lamar Member (Fig. 3.2A), when the major change in brachiopod metacommunity composition is identified, the contrast in the brachiopod metacommunity response between the CS12-CS13 unconformity and the CS13-CS14 unconformity indicate that not all composite sequence boundaries, and possibly the sea level changes thought to have driven them, are of the same magnitude within the Delaware Basin. The use of brachiopod compositional changes provides evidence for recognizing the magnitude of unconformities and aids in the correlations of important sequence stratigraphic surfaces from the shelf into the basin.

The lack of collections from the McCombs Member needs to be addressed to discount a possible sampling bias responsible for the brachiopod metacommunity turnover. No collections were made from the McCombs Member due to lack of available outcrop. Recent analysis of Delaware Basin brachiopod data from Cooper and Grant (1974, 1975, 1976a, 1976b), however, identify a separation between the lower BCF (Hegler, Pinery, and Rader) and upper BCF at the genus level and shows that the McCombs Member collections plots with the Lamar Member (Olszewski and Erwin, 2009). The reproducibility of this result using two different data sets implies that the stratigraphic pattern observed in this study is robust and not an artifact of sampling.

The change in metacommunity structure and composition between CS13 and CS14 appears to reflect a biological reorganization of brachiopod associations without a fundamental change in the nature of available habitats. Based on the lack of evidence for an environmentally controlled faunal gradient in the ordination results (consistent with Olszewski and Erwin's [2009] analysis of Cooper and Grant's data), it seems unlikely that the distinction between BC1 and BC2 is simply due to a shift in facies. Alternatively, the change from BC1 to BC2 could reflect a change in seafloor heterogeneity, but using brachiopod life strategy as a proxy for seafloor type, there is no evidence for a change in heterogeneity. For example, there are no changes in the proportion of forms that lived unattached on soft seafloors (e.g., productids and chonetids), attached by a pedicle (e.g., spiriferids), cemented forms (e.g., *Collemataria*), or coralliform forms (e.g., *Sestropoma*) through the BCF.

Influence of Dispersal on BCF Brachiopod Paleocommunities

The accommodation of new brachiopod genera into paleocommunities of the Delaware Basin has implications for diversity dynamics. Two entirely new brachiopod genera in the Delaware Basin, *Anomaloria* and *Astegosia*, possibly from the Paleo-Tethys (Northwest China and Thailand), successfully colonize local paleocommunities of the Lamar Member to become prominent constituents of the BC2 compositional group (Figs. 3.5, 3.9). Also, some brachiopod genera, such as *Crurithyris*, *Ombonia*, and *Martinia*, from the *Astegosia*-*Tropidelasma* paleocommunity appear for the first time as prominent constituents in the Lamar Member in this study; however, Cooper and Grant (1977) report them as rare in the lower BCF. The sudden prominence of these previously absent or rare brachiopods demonstrate that the established *Hustedia*-*Derbyia* paleocommunity was able to accommodate the arrival of taxa from the *Astegosia-Tropidelasma* paleocommunity. This implies either a change in habitat that provided opportunities for the new taxa or that the *Hustedia-Derbyia* paleocommunity was not characterized by strong competitive interactions that would have excluded colonists. Either way, the new taxa have a high occurrence and are the major brachiopods in most Lamar Member collections, indicating that resources were available and accessible to the new taxa (Tilman, 2004; Patzkowsky and Holland, 2007).

As might be expected, the pattern shown in this study is consistent with the operation of more than one ecological process. First, the high occurrence of most genera in the *Hustedia*-*Derbyia* and *Astegosia*-*Tropidelasma* paleocommunities suggests that interpatch movement was high throughout the BCF and across the study area, which is more consistent with the *mass effects* or *species sorting* models than the *patch dynamics* and *neutral* models (Holyoak et al., 2005b). Further arguing against the *patch dynamics* and *neutral* models is the fact that temporal turnover associated with the transition from BC1 to BC2 occurs throughout the study area. This argues against dispersal limitation, which is the primary process keeping local paleocommunity composition different in the *patch dynamics* and *neutral* models even on relatively homogeneous landscapes like that of the BCF (Hubbell, 2001; Holyoak et al., 2005b). Given environmental information on the BCF, it appears that the environment was relatively homogeneous, which suggests that areas on the slope differed only in the composition of brachiopods. The *mass effects* and *species sorting* models assume that patches are dissimilar in their attributes so that species live in a patch with favorable conditions, which means species are not found everywhere and are favored at certain patches (Holyoak et al., 2005b). The environment does not have to be heterogeneous for mass effects to occur (Holyoak et al., 2005b), which strengthens the argument of the *mass effects* model. Without further evaluation of the environmental conditions to identify possible subtle changes in habitat conditions within the members, however, it is not possible to discount the *species sorting* model. It is hypothesized, therefore, that aspects of the *mass effects* and *species sorting* models contributed to the diversity pattern of BCF brachiopods, indicating the influence of dispersal along with possible environmental preferences of genera.

Conclusions

(1) Compositional turnover of brachiopod paleocommunities has been identified to occur in the Lamar and Reef Trail Members of the BCF. This turnover is hypothesized to coincide with an environmental disruption possibly related to a change in sea level. Associated with the change in composition, there are two entirely new brachiopods that immigrate into the Delaware Basin and are able to colonize as prominent components into Lamar Member paleocommunities. Compositional turnover could be attributed to dispersal as a mechanism that influences local species interactions and local species-environment relationship based on the results obtained from these analyses. Dispersal is not the only process acting but it may be operating to influence processes acting at a local level.

(2) Environmental conditions are interpreted to be relatively homogeneous because of the position on the slope and brachiopods occur in one facies. Although the

habitat is regarded as homogeneous, it is possible that sea-level changes prior to the Lamar Member subtly altered environmental conditions to allow the carrying capacity of the environment to increase. The immigration of new taxa into the basin and the change in taxonomic composition may record these changes not otherwise observed.

(3) Results from these analyses indicate disruptions related to sea-level change influenced paleocommunity composition differently. The metacommunities of the Lamar Member did not return to the state prior to the disruption as observed in the Pinery and Rader Members. The compositional changes also have sequence stratigraphic implications concerning the use of brachiopods in aiding the recognition and correlation of the unconformities identified on the shelf and tracing them into the basin.

CHAPTER IV

EFFECTS OF BASINAL DISRUPTIONS ON METACOMMUNITY PROCESSES AND STRUCTURE (BRACHIOPODA, DELAWARE BASIN)

Introduction

Diversity patterns are a reflection of multiple interconnected processes operating at different scales. The concept of a metacommunity, defined as a group of local communities linked by dispersal of potentially interacting species, is intended to bridge the gap among the different scales on which ecological processes act, by embedding local communities within a larger regional framework (Wilson, 1992; Leibold et al., 2004; Holyoak et al., 2005a). The metacommunity concept illustrates how the interplay among processes operating at different scales affect the abundance structure, diversity, and composition of local communities. Dispersal is an ecological process that links local and regional diversity (McArthur and Wilson, 1967; Shmida and Wilson, 1985; Loreau, 2000; Mouquet and Loreau, 2003; Leibold et al., 2004; Holyoak et al., 2005a) by determining how individuals and species are distributed on the landscape.

A fundamental question of long standing in the study of life on Earth is what determines species diversity. This question concerns the distribution of, and relationships among species in the present day, but also requires an understanding of the history of diversity. The fossil record provides the only historical account of changes in the diversity of ecological communities in the Earth's past. Paleoecologists study species diversity with a temporal perspective that is unavailable when studying modern ecological communities. The fossil record, therefore, offers the opportunity to assess ecological processes acting at evolutionary scales under a diverse array of environmental conditions. By adding a historical component of diversity to the metacommunity concept, a better understanding of the processes influencing diversity can be achieved.

This paper investigates the influence of dispersal as a possible explanation for changes in composition and diversity of brachiopods of the Middle Permian Bell Canyon Formation. Changes in among-community diversity (known as beta diversity) values are used as an indication of the relative influence of dispersal. This analysis will assess the contribution of within-community diversity (known as alpha) and among-community diversity to the total diversity of the metacommunity (gamma diversity) by applying diversity partitioning at the member scale. The collections from each member are pooled together to represent the metacommunity. Genus-level rank abundance curves are used to evaluate how the abundance structure of each metacommunity changed relative to environmental disruptions.

The results presented here show that ecological processes can be detected in geological data and show that regional-scale environmental disruptions contributed to the changes in the abundance structure, composition, and diversity of brachiopods within the Bell Canyon Formation by influencing dispersal within the metacommunity. Metacommunities of the Bell Canyon Formation are not static with respect to the dominant taxa, and when perturbed, they do not always return to their previous compositions or structures.

Geologic Background

The Bell Canyon Formation (upper Middle Permian) within Guadalupe Mountains National Park supplies the context to evaluate diversity of brachiopods in the Middle Permian. Brachiopods are the best-known fossil group in these rocks due to the work of Cooper and Grant (1972, 1974, 1975, 1976a, 1976b, 1977), who collected more than 1,000,000 specimens throughout the mountain ranges of West Texas, and published comprehensive taxonomic descriptions based on their material. Previous sequence stratigraphic work divided the Bell Canyon Formation into two and a half composite sequences bounded by third-order sequence boundaries (Fig. 4.1; Tinker, 1998; Kerans and Tinker, 1999; Kerans and Kempter, 2002). The sequence boundaries represent environmental disruptions that could influence the ecological landscape by increasing or decreasing area and fragmentation of habitats occupied by brachiopods. The composite sequences also represent non-overlapping intervals of time.

The Bell Canyon Formation spans ~5.4 Myr and contains fine-grained sandstones and siltstones and carbonate tongues that were deposited on the steep slope of the platform by sediment-gravity flows seaward of the geologically renowned Permian Reef complex (Fig. 4.1; King, 1948; Newell et al., 1953; Rigby, 1958; Koss, 1977; Williamson, 1977; Lawson, 1989; Brown and Loucks, 1993; Hill, 1996).

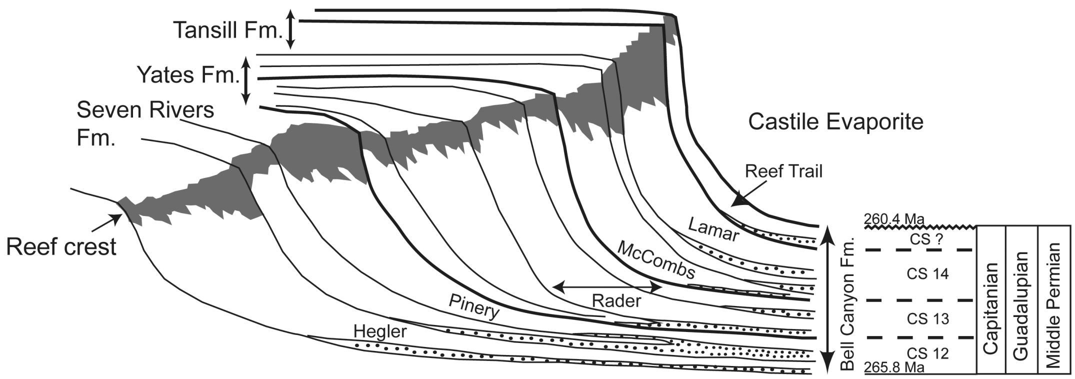


Figure 4.1–Cross section of the carbonate platform during deposition of Bell Canyon Formation with reef crest environment identified. Lithostratigraphic position of the members is shown on the slope. These are tied to the composite sequences modified from Kerans and Tinker (1999). Sandstones and siltstones shown with dots and interpreted to be lowstand system tracts of composite sequences. Solid lines indicate the correlative conformities of third-order sequence boundaries from the shelf into the basin. Reef Trail Member added to show lithostratigraphic position and possible sequence stratigraphic position. Ages are from Gradstein and Ogg (2004). Modified from Tinker (1998).

The unconformities associated with sequence boundaries observed on the shallow platform signify disruptions in the basin related to sea-level fall. In the corresponding deep-water deposits, the siliciclastic rocks are interpreted to be the lowstand systems tracts (LST), and the carbonate tongues, which coincide with formally recognized lithostratigraphic members (Fig. 4.1), represent both the transgressive (TST) and highstand (HST) systems tracts of composite sequences (Tinker 1998; Kerans and Tinker, 1999). The Reef Trail Member was not incorporated into a sequence stratigraphic framework of Kerans and Tinker (1999); however, other workers have suggested that a sequence boundary may be present below the member (Kerans and Harris, 1993; Wilde et al., 1999), so in this study, the Reef Trail Member will be treated as an additional composite sequence.

Brachiopod diversity was evaluated within the debris-flow conglomerate facies of the Bell Canyon Formation, because this facies is the predominant source of silicified brachiopods. The nature of these deposits is consistent with a debris flow interpretation due to a general lack of grading, sharp basal contacts, and wide range of clast sizes (Mulder and Alexander, 2001). Some flow deposits have coarse bases and fine caps and others have fine bases and coarse caps. Most debris flow deposits change thickness along outcrop and can become amalgamated. The conglomerate facies contains whole and fragmented fossils, lithoclasts of various sizes, chert, occasional reef debris, and range in lithology from matrix to clast supported. Fossils and lithoclasts are commonly distributed throughout a flow deposit. Fossils include crinoid columnals, cups and plates, bryozoans of various morphologies, rugose corals, fusulinids, sponges, echinoid plates and spines, and brachiopods. Molluscs are not commonly silicified; however, bivalves, gastropods, and scaphopods are silicified in the upper part of the Reef Trail Member.

Data

Collections of silicified brachiopods were made by sampling blocks of limestone from the Pinery (N=10), Rader (N=10), Lamar (N=8), and Reef Trail (N=17) Members (Fig. 4.2). The blocks of limestone were dissolved in tubs containing 10% HCl and lined with 850 micron mesh, following Cooper and Grant (1972). Faunal counts include 53 brachiopod genera and 6,038 individuals. Brachiopods were identified to the genus level due to the fragmentary nature of the brachiopods and their preservation state. All size ranges of brachiopods were picked from the mesh. For a fragment to be considered identifiable, part or the entire hinge had to be present. The collections are dominated by single values (>70%), but articulated and complete individuals are also present. Due to the nature of the deposits, it is assumed that there is a low probability that isolated brachial and pedicle valves came from a single individual, and therefore, counts of brachiopods were made using the maximum number of individuals, or the XNI approach, which maximizes the number of individuals within an assemblage by counting each valve as one individual (Gilinsky and Bennington, 1994).

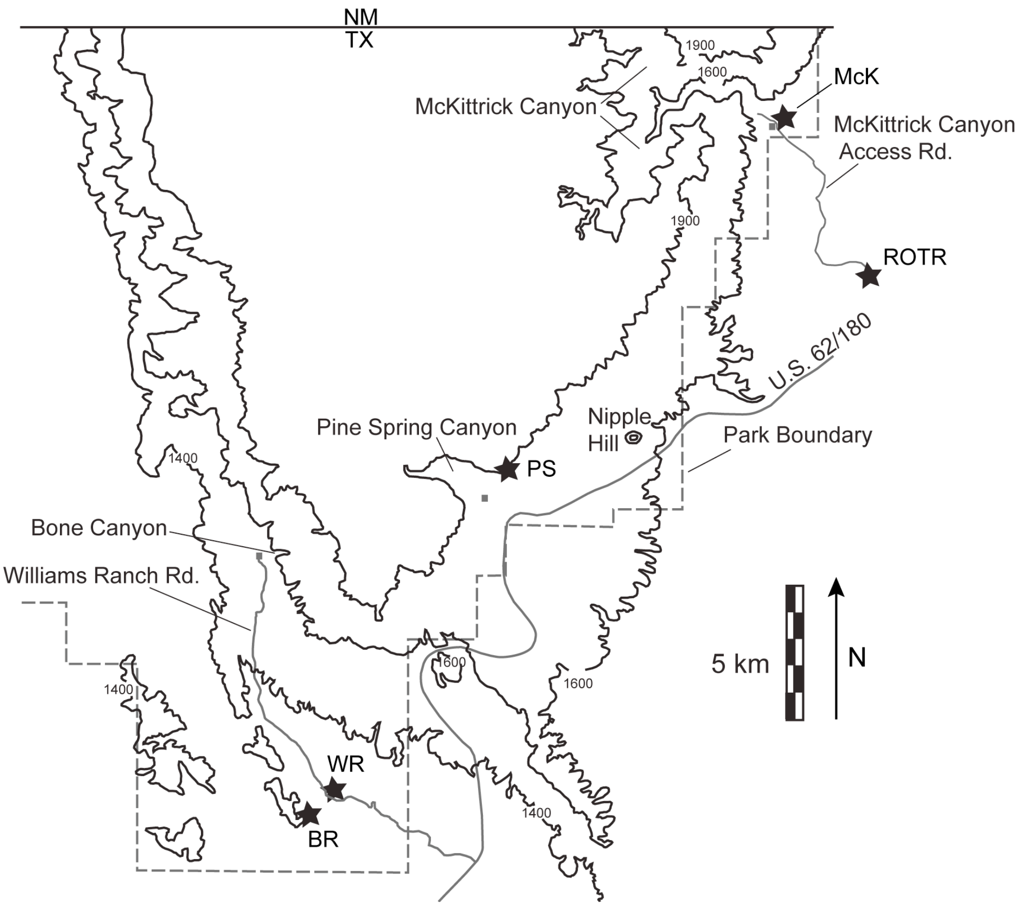


Figure 4.2—Locality map of collections within Guadalupe Mountains National Park. Stars represent collection locations. Redrawn from Guadalupe Peak 30 x 60 minute quadrangle.

Methods

Following the methodology of Jost (2006, 2007), brachiopod diversity was partitioned into alpha and beta components using the Shannon index to evaluate the amount each component contributes to overall diversity of the metacommunities (gamma component, γ) in each composite sequence of the Bell Canyon Formation. In order to account for sample size bias in the measurement of diversity, all collections within each member were randomly subsampled to 772 individuals, the fewest number of individuals observed in any member. This procedure was repeated 1,000 times to calculate an average alpha diversity. All subsampling and diversity calculations were performed in R 2.6.2 (R Development Core Team, 2008).

Although ubiquitous in the ecological and paleoecological literature, the Shannon index (H) can be difficult to interpret because it measures the entropy or uncertainty of correctly predicting the species identity of the next individual collected. Shannon index values are more easily interpreted and compared if they are converted from entropy values into effective number of species, which gives the number of equally-likely species required to produce a particular value of the index (Hill, 1973; Jost, 2006; Jost et al., 2010). To convert values from the Shannon index into effective number of species, the following equation is used (Jost, 2006):

$$^{1}\mathrm{D} = \exp\left(\sum_{i=1}^{S} p_i \ln(p_i)\right) = \exp(\mathrm{H}) \qquad (4.1)$$

where S = number of species and p_i = proportion of species i. As demonstrated by Jost et al. (2010), effective number of species essentially provides an estimate of richness that normalizes different abundance distributions.

Diversity can be partitioned into within-community (α) and among-community (β) components to evaluate the contribution of each to the total diversity (gamma, γ). The within-community component measures the taxonomic richness within a local community or sample, and the among-community component measures the taxonomic differentiation between communities or samples.

Within-community and metacommunity diversity can be directly computed using equation 4.1. Following Whittaker (1960, 1972), beta diversity can be measured by dividing total diversity by average local diversity:

$$\beta = \gamma/\overline{\alpha} \tag{4.2}$$

This form of beta is the number of compositionally distinct local communities required to account for the total observed diversity in the region: it is a dimensionless ratio between the number of species in the region compared to an average site (Legendre et al., 2005).

Results

After an increase in diversity from the Pinery Member, rarefied regional richness does not change appreciably among the Rader, Lamar, and Reef Trail Members (Table 4.1). However, when diversity is measured in terms of effective number of genera based on the Shannon index, regional diversity increases from the Pinery Member to the Rader

Member, decreases in the Lamar Member, and then shows a large increase to a maximum in the Reef Trail Member (Fig. 4.3; Table 4.1); all these changes are statistically significant. Beta diversity reflects the amount of homogenization among communities. In a metacommunity context, small beta values are interpreted to represent a higher influence of dispersal, whereas large beta values represent a lower influence of dispersal (Mouquet and Loreau, 2003).

The amount of among-community diversity (beta) contributing to regional diversity also changes through the Bell Canyon Formation, with the highest level in the Reef Trail Member and the lowest in the Lamar Member (Fig. 4.3). This result suggests a change from higher levels of dispersal in the Pinery, Rader, and Lamar Members to a lower level of dispersal in the Reef Trail Member.

Rank abundance distributions describe the underlying structure of an assemblage. The generic rank abundance curves of each member of the Bell Canyon Formation are similarly shaped, suggesting that these metacommunities have a consistent abundance structure through time (Fig. 4.4). This is supported by a Kolmogorov-Smirnov two-sample test (Table 4.2; Tokeshi, 1993; Magurran, 2008), which detected no significant differences among the members.

In spite of this, there is a difference in the identities of the dominant taxa in each metacommunity. In both the Pinery and Rader Members, the most common genus, *Hustedia*, stands above a flatter portion of the distribution including the next six or seven genera, after which the abundances drop sharply and decrease in abundance. In contrast, the most common eight genera form a steeper segment of high dominants in the

Table 4.1–Diversity of Bell Canyon Formation brachiopods. Note rise and drops in diversity calculated by taking the smaller gamma (γ) diversity value and dividing it by the larger diversity value and subtracting 1. Rarefied to 772 individuals.

Bell Canyon Member	Actual generic richness γ (S)	Rarefied generic richness γ (S)	Effective number of genera $^1D_\gamma(H)$	Effective number of genera $^1D_\alpha(H)$	Effective number of genera $^1D_\beta(H)$
Pinery	27	27	9.49	5.24	1.81
Rader	34	~33	11.25	6.33	1.78
Lamar	41	~32	10.34	6.56	1.58
Reef Trail	36	~31	14.20	4.35	3.27

Table 4.2–Results from Kolmogorov-Smirnov two-sample test. Note number in parentheses is the p-value. Tests performed in R 2.6.2 (R Development Core Team, 2008).

	Pinery	Rader	Lamar	Reef Trail
Pinery	-	0.1394 (0.9317)	0.1509 (0.8526)	0.1492 (0.8909)
Rader		-	0.1442 (0.8344)	0.1471 (0.8558)
Lamar			-	0.1765 (0.609)
Reef Trail				-

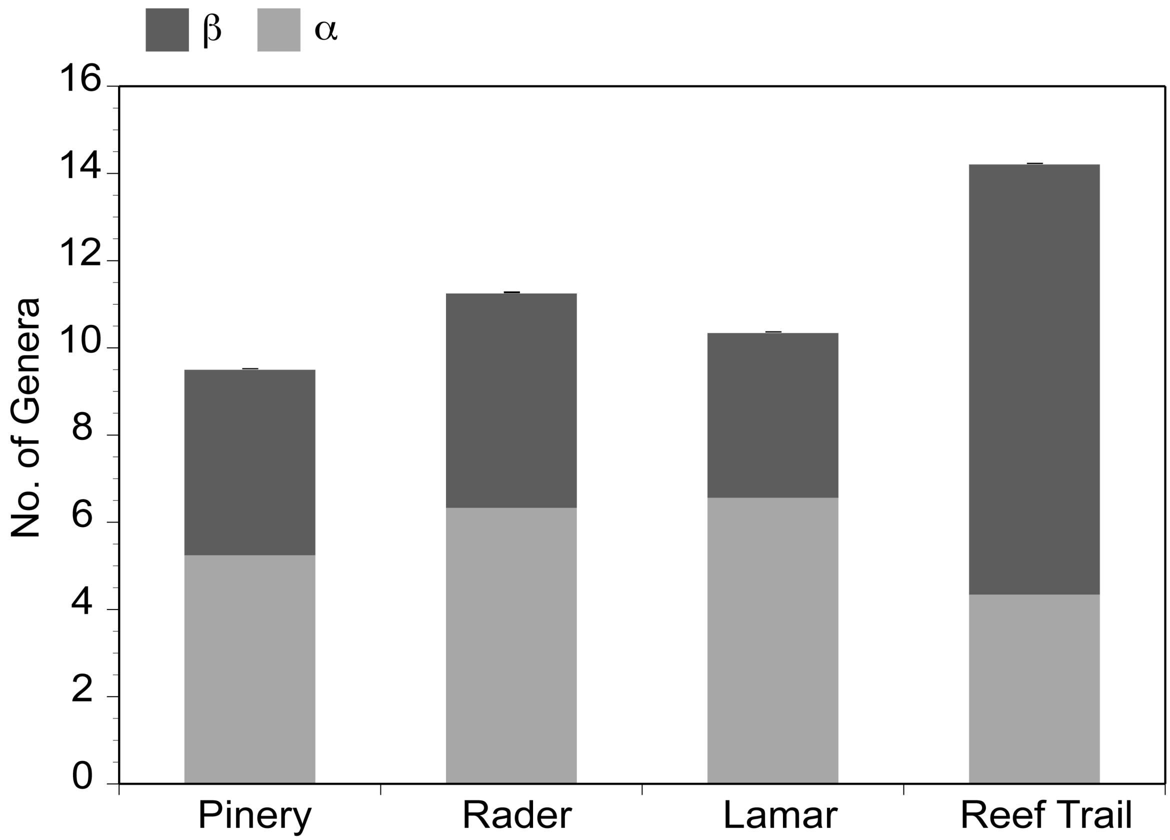


Figure 4.3–Brachiopod diversity partitioned into alpha and beta components for each member. Subsampled to the number of individuals in the Pinery Member (n = 772). Error bars are 95% confidence intervals.

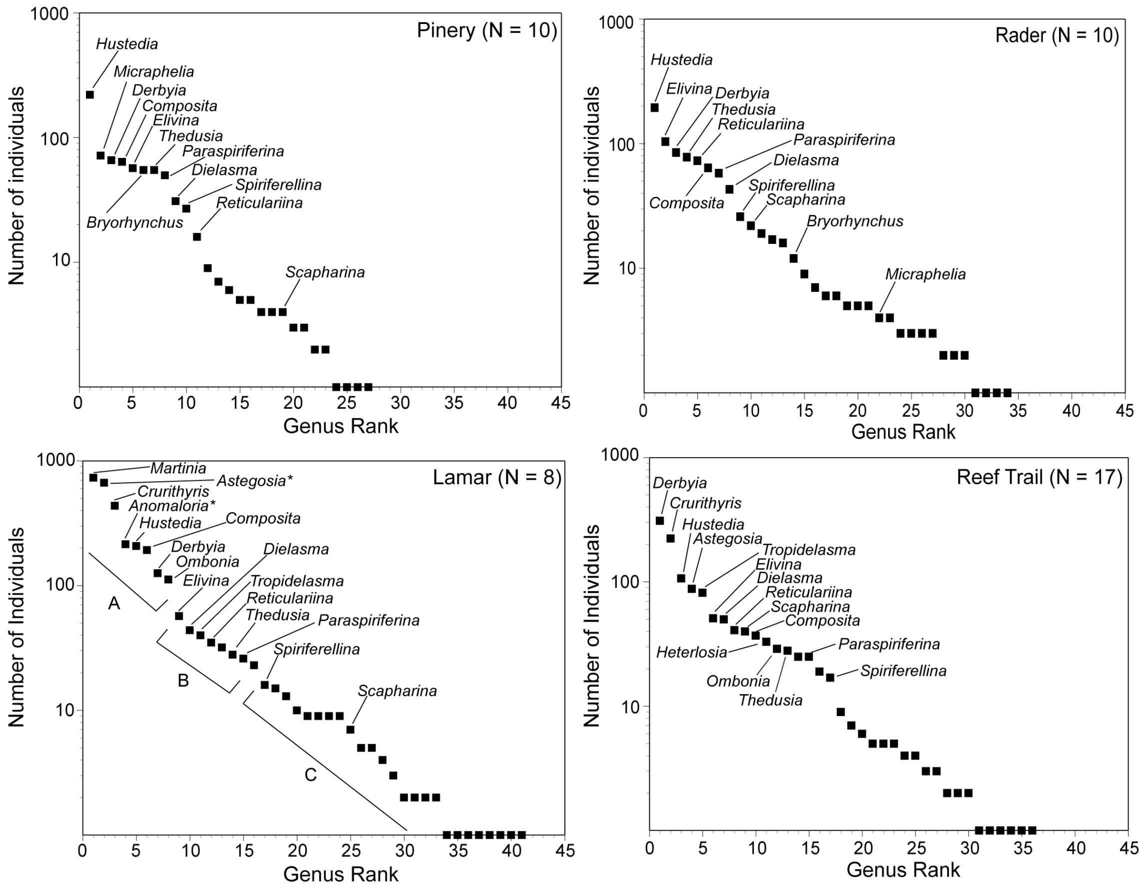


Figure 4.4–Rank abundance plots for each metacommunity at the member scale. The abundance of each genus is plotted against the genus rank on a logarithmic scale. Each plot includes all collections within the member. A = steeper segment; B = flatter segment; C = sharp decline segment. Asterisks denote the new genera entering the basin from outside North America.

Lamar Member. The Reef Trail Member displays an intermediate pattern in which the first five genera form a steep drop followed by a more gentle decrease in abundance.

The change in dominant taxa within the steeper segment of the Lamar Member results from the accommodation of new brachiopod genera at high abundances. Previously abundant brachiopods like *Hustedia*, *Derbyia*, and *Composita* remain abundant but they are joined by *Martinia*, *Astegosia*, *Crurithyris*, and *Anomaloria*. Two genera–*Astegosia* and *Anomaloria*–immigrate into the basin from outside North America and become prominent in the Lamar Member metacommunity. Within the study interval, *Martinia*, *Crurithyris*, and *Ombonia* occur for the first time in the Lamar Member collections. From their first appearance, they are abundant and occur in many collections. Although these genera were not found below the Lamar Member in this study, Cooper and Grant (1977) did report rare occurrences of these taxa in the lower Bell Canyon Formation. This assemblage of previously rare and immigrant brachiopods appear to be accommodated into the metacommunity without forcing other brachiopods to become extinct. In the Reef Trail Member, taxa that were dominant in the Pinery and Rader Members return to high abundance alongside new Lamar Member dominants incorporated into the metacommunity. These results indicate that composition and structure of metacommunities in the Bell Canyon Formation were not static over geological time scales.

Discussion

Drops in sea level may have influenced brachiopod diversity through time by the loss of connections among communities and decreasing the area of habitats occupied by brachiopods. In a previous analysis, compositional changes in the Lamar Member metacommunity relative to the Pinery and Rader Members was attributed to a disruption, possibly related to a change in sea level and dispersal (Fall and Olszewski in press). Decreasing beta values from the Pinery through the Lamar Member suggest that through this time, the local paleocommunities remained connected through dispersal. However, a larger disruption between the Rader and Lamar Members (CS13-CS14) allowed previously rare genera and new invaders to enter and take dominant positions in the metacommunity promoting a new configuration. With a higher level of dispersal in the Lamar Member, these faunas were able to reach most of the local paleocommunities and actually become dominant taxa. The rank abundance distribution of the Reef Trail Member suggests partial recovery to pre-Lamar community state but with new genera in the dominant roles. The disruption preceding the Reef Trail Member could have reduced the size and increased the isolation of paleocommunities, making it difficult for brachiopods to reach suitable area for their occupation. The Reef Trail Member records the last normal marine conditions before deposition of evaporites of the Upper Permian Castile Formation. Factors that may have contributed to the difference between the Lamar Member and Reef Trail Member faunas include: decline of the shelf margin allowing more siliciclastic material to enter the basin and increasing evaporitic conditions within the basin (Wilde et al. 1999). Wilde et al. (1999) suggest that the reef was shutting down and becoming restricted during deposition of the Reef Trail Member, which would allow a greater volume of siliciclastic material to enter the basin. The increase in silt would cause marine water to become turbid, making it difficult for filter-feeding organisms. Extensive evaporitic salt deposits overlying the Bell Canyon Formation reflect very arid, hypersaline conditions hostile to normal-marine life (Sarg et al. 1999). These factors would destroy brachiopod habitat and therefore change patchiness in response to changing conditions in the basin related to the closing of the basin.

Conclusions

The metacommunities of the Bell Canyon Formation responded to environmental disruptions by changes in their abundance structure, composition, and diversity. Sufficiently large perturbations allowed previously rare taxa and invaders from outside the basin to become dominant in metacommunities. The change in dominant taxa indicates that high abundance or incumbency did not prevent replacement of dominant taxa, and the local communities accommodated the new taxa without forcing other taxa into extinction. After perturbations, a metacommunity did not return to the previous state, but rather to a state with new dominant taxa in place.

CHAPTER V

CONCLUSIONS

There are multiple, interconnected processes acting at different scales that influence the composition, diversity, and structure of communities. The main goal of this research was to understand how processes influenced the diversity of fossil communities in the Middle Permian. The research presented in this dissertation suggests that paleocommunities are influenced by multiple factors at different scales and are not stable over evolutionary time. Understanding the processes influencing fossil communities will improve our knowledge on what determines species diversity through geologic time.

There are four composite sequences within the Bell Canyon Formation that contain lowstand, transgressive, and highstand systems tracts. Three of these sequences were previously recognized from the shelf: CS 12 (includes the Pinery Member), CS 13 (includes the Rader Member), and CS 14 (includes the Lamar Member). A fourth composite sequence is proposed based on the sequence stratigraphic analysis in this study and includes the Reef Trail Member. Generally, brachiopods once living on the slope were commonly transported toward the basin by debris flows during highstand; however, transport of brachiopods is not restricted to this systems tract. Occasionally, debris flow with brachiopods also occurred within the lowstand and transgressive systems tracts.

The role of environmental disruptions, related to sea-level changes, plays a large part in governing the diversity of brachiopod metacommunities. It appears that brachiopods are not responding to environmental heterogeneity on the slope represented by systems tracts. For example, the Pinery and Rader Members have similar compositions and abundance structure, but they come from different systems tracts. Therefore, it is proposed that brachiopod metacommunities are responding to changes related to sea level disruptions represented by unconformities, and that not all disruptions are of the same magnitude. The Lamar Member shows a dramatic change in the composition and structure of the metacommunity. The change in composition accompanies the disruption between CS 13 and CS 14, suggesting a larger magnitude disruption than that between CS 12 and CS 13. Within the Lamar Member, previously rare taxa and immigrant taxa from outside the basin replace the dominant taxa of the Pinery and Rader Members, suggesting that the incumbent taxa of the Pinery and Rader Members could not prevent the new taxa from colonizing and becoming abundant. Additionally, the replacement of dominant taxa does not cause extinctions of the incumbent taxa. The composition and abundance structure of the Reef Trail Member metacommunity returns to a similar state as the Pinery and Rader Members, but now includes the Lamar Member taxa. The metacommunity did not return to the previous observed state observed in the underlying members.

Using metacommunity theory, dispersal is invoked as an important ecological process for the distribution and diversity of Bell Canyon Formation brachiopods. Results from diversity partitioning indicate that dispersal was relatively higher in the Pinery, Rader, and Lamar Members compared to the Reef Trail Member. However, dispersal may have been affected by the disruptions, which would increase or decrease the area occupied by brachiopods making the slope more or less patchy in brachiopod distribution. The lowest beta value occurs in the Lamar Member, indicating that new brachiopods were able to reach and colonize most paleocommunities. Across the Lamar and Reef Trail contact, the beta values increased to the highest levels of the Bell Canyon Formation, suggesting patchy distribution of brachiopods on the slope. This change in patchiness could be a response to changing conditions in the basin related to the closing of the basin.

These findings indicate that environmental disruptions influence the dynamics of local paleocommunities, and at a larger scale, the metacommunity. Metacommunities are not static through this interval and can be perturbed into configurations with new dominant taxa. The dynamics within paleocommunities do not appear to prevent the replacement of the incumbent taxa with new taxa. The response of the metacommunity can be observed at the member level and over a ~5.4 Myr interval. Therefore, ecological responses of metacommunities are resolvable at the geological time scale.

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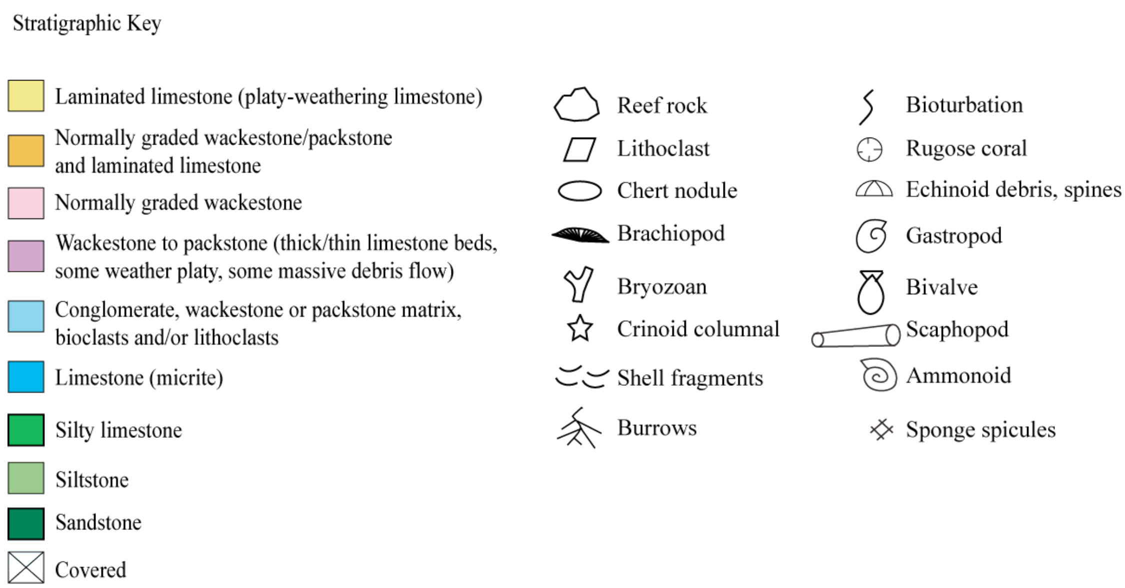
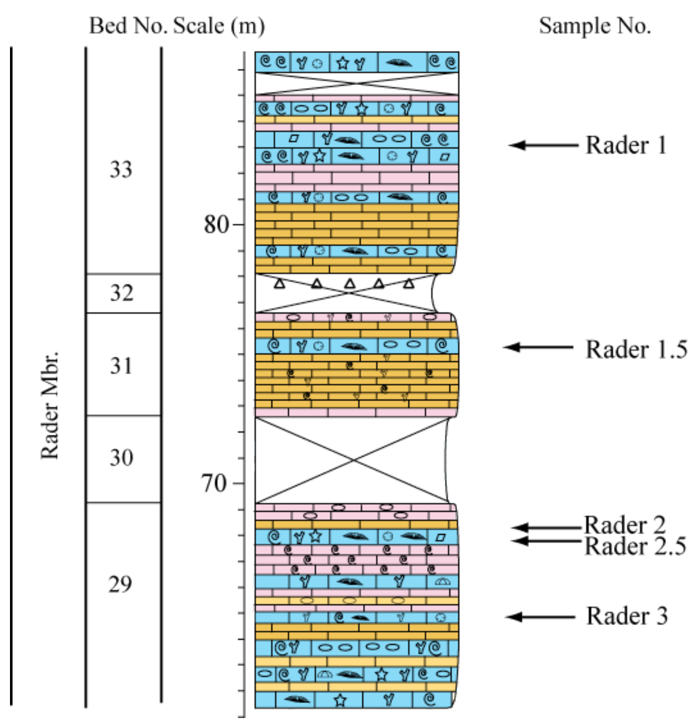
APPENDIX

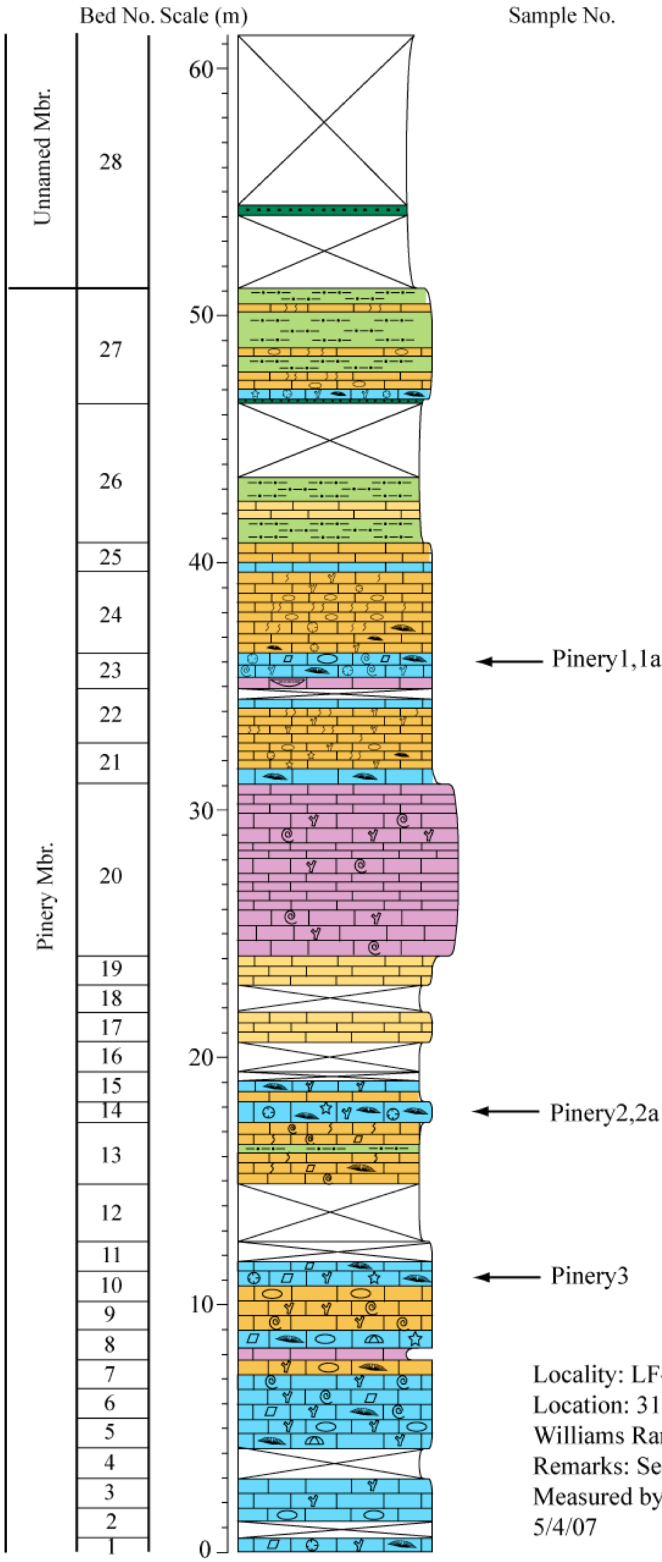
MEASURED SECTIONS

The following pages provide graphic measured sections and the sedimentological descriptions associated with the measured sections.



Locality: LF-BR (Back Ridge)
Location: 31°49.491 N, 104°52.508 W
Williams Ranch Road
Remarks: Section located to the west of Bell's SC2
Measured by: L. M. Fall and S. A. Marcus 5/2/07-5/4/07





Locality: LF-BR (Back Ridge)
Location: 31°49.491 N, 104°52.508 W
Williams Ranch Road
Remarks: Section located to the west of Bell's SC2
Measured by: L. M. Fall and S. A. Marcus 5/2/07-5/4/07

<u>LF-BR (Back Ridge)</u>

Bed 1: 57 cm – conglomerate, limestone, weathers massive to slabby on outcrop, N6 to N7, in places 10YR 7/4, weathered face, 5YR 6/1 fresh face, some large bryozoans here, coarse base and fine top, fossil seen include: rugose corals, brachiopods (disarticulated, cross-sections), bryozoans (ramose, fenestrate, *Domopora, Acanthocladia*), fossils and lithoclasts look oriented, lithoclasts look like some are derived from underlying material (same color as underlying bed), lithoclasts are between 10YR 8/2 and 10YR 7/4 in color, also grey (N6) lithoclasts, lighter color lithoclasts are rounded, oblong shape, 4.5 and 2.5 cm long, orientation is parallel to bedding planes, also see *Hustedia*, fossils seem to be in zone near top, before where bed becomes finer, not much in way, if any, echinoderm material and/or fusulinids in this bed

Bed 2: 120 cm – base is rubbled/covered, may contain some thinner (<10 cm) limestone beds, not coarse, may be grainer, top is thicker amalgamated limestone bed/beds, weather hackly to thin, slabby beds, has chert blebs in it, near middle of interval, these beds thicken and thin on outcrop, hackly weathering and are not easy to trace, beds have chert in them, nodular, may have been fossils at one point, very steep slope

Bed 3: 120 cm – conglomerate, limestone, several conglomeratic beds, near base there are zones of small chert blebs, bryozoans appear to be best-preserved fossils in these conglomerates but they are still sparse, one limestone bed thickens on strike to the NNW and thins out to SSE, chert in large nodules and layers, preserves some fossils, top of interval is ~45 cm thick, weathers differently from underlying hackly, lighter-weathering bed(s), underlying beds may be finer grains (cannot tell on fresh face), top of interval weathers darker, cannot see grains, may have some bioturbation on top

Bed 4: 120 cm – covered where measured, rubbly float, nothing on strike, may be silt?

Bed 5: 120 cm – base of interval is ~base of zone of conglomerates, base weathers massive to thin slabby to platy depending on where you are on strike then a hackly-weathering, chert-bleb conglomerate, bryozoans (*Domopora*, ramose) preserved in chert nodules too, not just weathered out single fossils, ?spirifer, note that base of interval has fine fossil grains including possible echinoderm debris, above these two beds it goes back to more platy/wavy/slabby weathering finer material, then top of interval is fine grey limestone with chert

Bed 6: 120 cm – base of interval is fine, grey limestone as below, then bed ~31 cm thick of fossil debris, weathers massive (not hackly), can see brachiopods in cross-section, disarticulated, fusulinids, few bryozoans, above this is a hackly-weathering conglomerate fairly thick, brachiopods, bryozoans, lithoclasts, several amalgamated conglomerates to top of interval, still see bryozoans, mainly with occasional brachiopods, hackly to the top of interval

Bed 7: 120 cm – base of interval is still hackly-weathering conglomerate with a zone of chert, preserves fusulinids, some bryozoans, lots of chert blebs, finer towards the top, see chert in nodules (may be after burrows?) and layers, finer material may be packstone or wackestone, rest of interval has limestone beds, finer fossil grains, chert, platy on top, platy below, noted petroliferous odor when platy bed was acidized, may have some silt in platy beds (platy interval ~10 cm) too, limestone bed contains brachiopods, bryozoans, chert, bed is fine, coarse, fine, coarse may scour into fine at base of bed, bed is ~15 cm thick, top of interval ~15 cm thick limestone bed, finer than bed below, chert zone at top and bottom

Bed 8: 120 cm – base of interval has thin limestone beds and possibly some silty beds, cannot tell if there are silty beds but it is very benched back below another conglomerate, base of conglomerate is chertified, see brachiopod shell, some bryozoans, bed is ~25 cm thick with 6 cm thick chert zone, very iron-stained chert, above this weathers platy/rubbly with no visible fossils, lots of chert, then a fine-grained conglomerate, see bryozoans, abundant crinoid columnal, few brachiopods, *Hustedia*, echinoid plate, possible spine, chert nodules, lithoclasts, still pretty fine-grained overall though

Bed 9: 120 cm – base of interval slightly covered, then up into thin, platy beds, then smaller limestone bed (~7 cm) with lots of chert, back to platy beds, then smaller limestone bed, possibly coarse/fine layers, lots of chert, then conglomerate, see brachiopods preserved in chert layer at base, fusulinids, *Domopora*, lots of chert blebs, top has large chert nodules, very weathered, iron-stained, preserve fossils (fusulinids), weathers massive to wavy/platy

Bed 10: 120 cm – base of interval has coarse/fine beds, several centimeter's thick and platy-weathering interbeds, coarse/fine beds have chert in zones and nodules, fine fossil grains in thicker beds, disarticulated brachiopods(?), very small bryozoans, *Derbyia*-like brachiopod, beds fine upward abruptly to fine cap, ~middle of interval is coarser conglomerate, weathers rubbly to massive, contains lithoclasts, brachiopods, bryozoans, rugose coral, crinoid columnal segments, lithoclasts are large (~10 cm length) in places, may cut into underlying bed, parts are very coarse, other parts seem to be finer, some lithoclasts have "Liesegang banding" weathering, little of everything in this bed, *Hustedia*(?), may be several conglomerates, see scattered whole brachiopods (spirifer pieces, *Hustedia c*ommon), note lithoclasts weather differently in places, some are weathering out in relief, *sample taken PS-Pinery3*

Bed 11: 120 cm – base of this interval is top of lithoclast conglomerate (~45 cm), covered for rest of interval, no beds noted on strike either

Bed 12: 232 cm – cover/rubble

Bed 13: 248 cm – contact with underlying beds is fairly sharp, strike 175° dip 18°, underlying beds appear to be silty, thick bed at base where measured is 13 cm, limestone beds are bioturbated, coarse/fine layers seen, small flows with chert layer, see fusulinids, lithoclasts, brachiopod(?), flow may scour into underlying platy beds, bed thickens and thins on outcrop, ~6 cm where measured, note platy beds above, weather expansively, may have some silt beds, coarse/fine layers, thicker beds appear to thicken and thin on strike, weather rubbly in places

Bed 14: 85 cm – thick conglomerate(s), coarse, weather hackly, massive, see lots of brachiopods (*Hustedia*, other brachiopods in cross-section), bryozoans; *Composita*?, spirifers, rugose corals, crinoid columnals, ramose bryozoans, bed thins on strike to the north, there are possibly three conglomeritic beds, some platy, rubbly, slabby beds between coarse fossil material in all conglomerates here, chert towards top of beds, one bed is very cherty, nodules and blebs, upper conglomerate/conglomerates may have more bryozoans, all thicken and thin on outcrop, note that underside of bed has fossils weathering out, *samples taken along strike BR-Pinery2 and 2a*

Bed 15: 120 cm – base of interval has platy and coarse/fine beds, then a smaller coarse conglomerate with chert at base and top, see bryozoans mainly, brachiopod(?) in cross-section, platy on top of bed, then cherty bed with possible fine cap, no fossils seen, rest of interval covered

Bed 16: 120 cm – covered, rubble with bioturbation, top has thicker limestone bed and thin platy limestone

Bed 17: 120 cm – base of interval platy-weathering limestone, then laminated limestone, slightly bioturbated in places, chert in layers and nodules, fresh, slightly petroliferous with acid applied, no fossils seen in these beds, laminated beds are crinkly, may be silty, above this is a small, finer grained conglomerate, see small fossil grains, mainly unidentifiable, can see *Acanthocladia*, some brachiopod shells, chert nodules, has fine top to bed, several limestone beds (most <10 cm), fine fossils at base, fine upwards, cherty, dark limestone in rest of interval, some iron-stained thin beds of limestone too

Bed 18: 112 cm – covered where measured, on strike, platy, thin-bedded limestone as below, also with some thicker limestone beds, laminated/bioturbated

Bed 19: 117 cm – thin platy/laminated limestone as below, some light/dark layers thicken and thin, coarse/fine beds with chert, slightly more resistant than below, less laminated, very thin light/dark beds (<1 cm), ends at cliff bench

Bed 20: 695 cm – thick/thin limestone beds that weather platy/slabby, some massive but fine-grained conglomerates, see fusulinids and bryozoans, looks like they are "floating" in this bed, thicker beds can be traced and thin along strike, weather hackly, chert in nodules and layers, three larger beds near base of unit where measured (~25 cm, ~30 cm, ~30 cm), these have fossils but are not coarse, thicken and thin on outcrop, layers near top, can see bioturbation on tops of beds, some darker beds too, there are chert layers and nodules, cliff-forming limestone benches back in places

Bed 21: 167 cm – base has conglomerate with chert, see whole brachiopods on to of bed, then coarse/fine and platy as below, dark/light layers, then coarser-grained conglomerate, weathers massive to wavy/slabby, see bryozoans, rugose coral, fossils weather out on base, disarticulated brachiopod shells, big chert nodules, crinoid columnals, thins on strike to the north, thickens/persists to the south, moved 1850 cm to the SSW along strike where measured, base of conglomerate coarsens, see lots more brachiopods, weathering is still strange, massive in places, platy/slabby along strike, fine top on conglomerate too

Bed 22: 229 cm – at base of interval, coarse/fine layer, cherty, weather platy/slabby/massive, thicken on outcrop on strike to SSW, cherty, on strike looks like slightly thicker, see bryozoans in bed, fossils are finer, chert on top of bed, bioturbation on top of bed, probably another small conglomerate, then rest of interval is covered

Bed 23: 143 cm – at base of interval, beds weather out as very thin slabs, wavy, very irregular, some silt in lenses?, thin limestone beds, may be some soft-sediment deformation, some probable fossil grains in lower beds, above this is a rubbly-weathering interval, full of fossils, see brachiopods, bryozoans, rugose coral, fusulinids, *Domopora*, *Acanthocladia*, *Hustedia*, chert in nodules and layers, not sure if these are some glide planes in these beds, cannot tell how many conglomerate beds are here either, very fossiliferous, there are lithoclasts in top of this bed, these may be finer beds, too, fossil-wise, *samples taken along strike BR-Pinery1 and 1a*, sample BR-Pinery1a was taken along strike to the SSW ~1756 cm

Bed 24: 327 cm – base of interval is coarse/fine beds, platy weathering limestone, bioturbated tops to beds, chert in zones and nodules, upper portion of bed weathers more resistantly, some coarser beds towards tops, fossil weather out on base of beds, see *Acanthocladia*, rugose corals, brachiopods, fossils are finer (smaller) than seen in conglomerate below, beds coarsen to SSW on strike, very bioturbated upper surfaces, see coarse/fine pattern again, with coarser bases, finer tops, chert on finer tops, unit weathers more cliff-like along strike, note that many of the traces are bivalve traces (*Lockeia* and *Uchirites*), even in cliff-like faces, platy limestone separates beds with coarser bases, finer tops

Bed 25: 118 cm – moved ~1250 cm along strike to the SSW again to move off edge of slope, outcrop area constricts uphill towards top of knob, platy/coarse/fine beds above conglomerate, like beds below

Bed 26: 581 cm – base of unit has thin limestone beds and silty beds, silt interbeds thicker (+1m), few small limestone platy, bioturbated beds crop out in the silt, rest of interval is sloped, covered with rubble, presumed silty interval, top 7 cm of interval is sandstone bed, indurated, very fine to fine sand, moderately well-sorted, iron-stained, calcite cement, grains rounded to subrounded, quartz, darker materials seen, sharp contact

Bed 27: 450 cm – first bed in interval is conglomerate, coarse base, weathers massive, ~36-37 cm thick where measured, see rugose corals, brachiopods, bryozoans on strike, may be two conglomerates, top also has fossils weathering out, crinoid columnal seen, note that along strike to the south beds rubble out on steep slope, above are coarse/fine beds, platy beds, and silt interbeds, beds are bioturbated at top again, still lots of bivalve traces, beds weather somewhat resistantly, chert in nodules and layers, this interval has more silt than below, otherwise, it's pretty similar, some beds weather much more platy/rubbly due to bioturbation

Bed 28: 1023 cm – mostly covered, small outcropping of fine/very fine sandstone seen, some mica(?) in sandstone, some darker grains, calcite cement, forms slope, mainly covered with limestone rubble from above

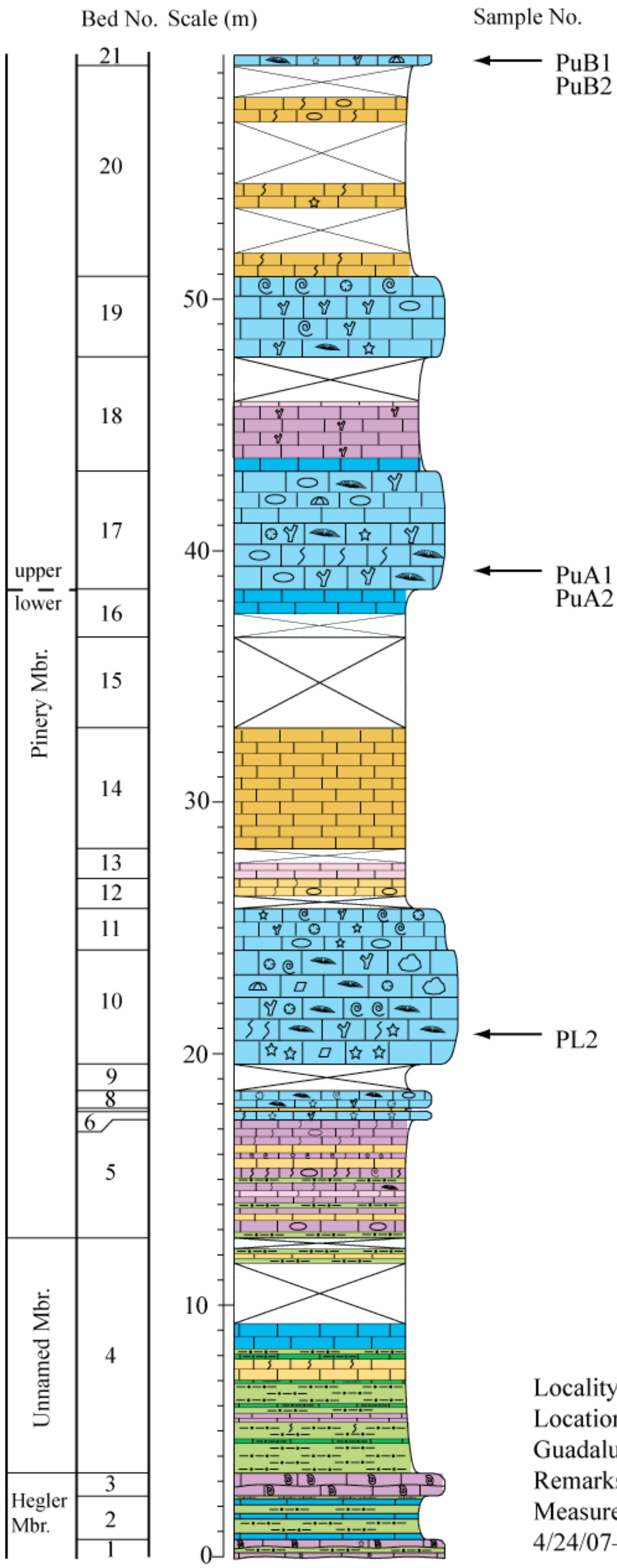
Bed 29: 786.5 cm – interbedded conglomerates and platy limestone, 46 cm conglomerate, sharp contact with underlying beds, bed has chert blebs, finer cap, traceable on strike, see brachiopods, shell pieces, coarser base, bryozoans in base, some crinoid or echinoid material in finer cap, weathers massive to hackly to platy, also see fusulinids at top in finer material, contact sharp with above platy beds, 38 cm platy interval, beds weather very thin/platy, chert in layers, some nodules, limestone is dark but not petroliferous, see small-scale coarse/fine intervals with tiny fossil grains, 22 cm finer conglomerate(s), see *Domopora*, *Acanthocladia*, small brachiopods, rugose coral, lots of fusulinids but just weathering poorly to be definite, some echinoderm pieces, chert in layers, bioturbated top but not like Pinery below (i.e., not distinct traces), 10 cm platy with thin limestone, thins and thickens on outcrop, chert in very thin layers, coarse/fine seen in thin limestone bed, fossil grains in coarse portion, 25 cm conglomerate, coarse base, *Domopora*, fusulinids, fossils weather out on underside of bed, fenestrate bryozoan, this may be up to three amalgamated conglomerates, chert in large nodules and layers, weathers massive in places, almost platy in other areas, hackly in portions too, 120 cm coarse/fine beds and platy limestone, some of the coarser beds thicken and thin on outcrop, lots of chert in layers in these beds, beds look dark/light because of the chert here, some very fine fossil debris in coarser intervals, 38 cm coarser conglomerate, fine upwards, scours into underlying beds, lots of bryozoans (*Acanthocladia*, *Domopora*) brachiopods (seem to be articulated but broken), rugose corals, few fusulinids seen but not abundant like below, chert nodules (small) in some places at the base, weathers hackly/rubbly/massive, thins on strike somewhat to the NNW, *sample taken here BR-Rader3*, 26 cm thicker coarse/fine bed, fine fossil grains at base, fine cap, lots of chert in bands and nodules, 44 cm platy limestone, then several limestone beds, some thicker, really see coarse/fine intervals, do not see bioturbation, seem less silty than in the Pinery Member below, lots of chert too, some chert makes very fine layers following bedding, stringers and nodules too, 11.5 cm coarse/fine bed, fine fossil debris at base where measured, along strike amalgamates and thickens and gets more coarse, 17 cm conglomerate, fossils at base, see brachiopods disarticulated, chert in layer, fossils still small overall, few meters to SSW on strike these beds are ~40 cm thick, may be separated by a stylolite on strike, hard to trace, 55 cm conglomerate, gets coarse, see *Domopora*, brachiopods, ramose bryozoans, fusulinids, abundant fusulinids at base of interval, coarse base, gets finer at top, lots of *Domopora*, big echinoid plate, brachiopods are large and articulated, chert nodules, rugose corals, note that there is a ramose bryozoan that may be *Cladopora* (large zooecia) that is common here, not too much chert overall in the bed compared to the coarse/fine and platy beds at least, traceable on strike, thins slightly to NNW, 2 cm limestone bed with chert layer between conglomerate and coarse/fine bed, 18 cm coarse/fine bed, coarser at the base, possible echinoid spine, mainly chopped-up shell bits in this flow, fine cap, 140 cm, first 50 cm of the 140 cm are coarse/fine beds with chert, fine caps, <10 cm thick, tops weather platy, then the two beds with fusulinids, note that there is some fine platy material between these two beds, upper bed with lots of fusulinids may have a rippled cap, note fusulinids in lower bed are aligned almost due E/W, they may be slightly WWN, above these two beds it is coarse/fine and platy, note in these two beds there is crinoid material, bryozoans, these beds have lots of chert, bryozoans are *Domopora* and *Cladopora*, maybe crinoid plate(?), 25 cm coarse/fine bed, lots of fusulinids in base, chert blebs at base, fine top, one *Domopora*, mainly fusulinids, fine cap, 17 cm platy limestone, weathering expansively, 48 cm this bed may be several conglomerates, base is coarse, see bryozoans, crinoid columnal, fusulinids (lots), lithoclasts, crinoid arm piece (just one plate), large *Acanthocladia*, *Domopora*, there are lots of brachiopods but hard to identify these, weathers very wavy/slabby, see rugose coral too, *sample taken here BR-Rader2.5*, 17 cm platy and coarse/fine interbeds, 19 cm large coarse/fine bed, fine fossils, chert, fine cap, 30 cm conglomerate, coarse base, fine top, flow has large chert nodules, large bryozoans, lots of brachiopods, rugose coral, *Domopora*, *Cladopora*, lots of shelly debris, fine cap, *sample taken here BR-Rader 2*,18 cm coarse/fine bed, fine fossil hash at base, fine top, chert in bed, nodules and lenses

Bed 30: 335 cm – 120 cm covered/rubbled out, 120 cm may have conglomerate but slumped on outcrop, covered/rubbled out, 95 cm covered/rubbled out, may have some coarse/fine beds

Bed 31: 402 cm – 22 cm first has coarse/fine layers at base, coarser middle portion but note that coarser portion here is very fine pieces of fossils, may have a few more coarse/fine layers at top, top of bed has pyrite on it (limonite after pyrite?), 208 cm interval of thicker beds, four thicker beds at the base of interval are coarse/fine with chert, thinner beds between are platy-weathering, (1) ~18 cm coarse/fine bed at base, (2) ~6 cm thinner beds above with cherty layers, these all have fine fossil debris, (3) a fifth coarse/fine bed is ~26 cm thick, still not very many coarse fossils, very large chert nodules, *Domopora*, above this is platy-weathering interval again, (4) then ~25 cm thick coarse/fine bed, see fusulinids and finer shell hash, chert nodules, very fine top again, coarser portion thickens and thins on outcrop, then smaller coarse/fine, then platy beds, then another coarse/fine bed with brachiopod spine and fusulinid at top of coarse/fine bed, 66 cm conglomerate, lots of fossils seen, abundant bryozoans, fusulinids, *Domopora*, some chert nodules, conglomerate has finer top, brachiopods, rugose coral, *Hustedia*?, see lots of shelly scraps too, note that finer beds above also contain unidentifiable fossil grains, chert near top of bed too, *sample taken here BR-Rader1.5*, 82 cm coarse/fine beds and platy-weathering beds, lots of chert, coarse/fine beds are thinner here ~4-6 cm thick, 24 cm coarse/fine bed here, see chopped up brachiopod shells, bryozoans, *Acanthocladia*?, *Domopora*, may be some fusulinids, chert nodules throughout, preserve fossils in this bed

Bed 32: 154 cm – covered bench, note this bench contains bentonite chips plus where measured a very serious cairn

Bed 33: 857 cm – interbedded conglomerate, coarse/fine, and platy limestone, 46 cm coarse/fine and platy beds, chert as below, note some fossils are somewhat coarser, 23 cm conglomerate, loaded with fusulinids, some chert nodules, see brachiopods, *Acanthocladia*, rugose coral, weathers very nodular/rubbly at base, *Cladopora*, brachiopod shell pieces, fine cap on bed, fine cap has very small fossil pieces too, 60 cm coarse/fine beds/platy beds, note that these beds weather flaggy and into sharp pieces (like Rader on McKittrick Canyon Rd), 25 cm conglomerate, coarse, abundant fusulinids, chert nodules preserve fossils, *Domopora*, rugose coral, ramose bryozoans, very hackly weathering, brachiopods shells, *Acanthocladia*, may be some orientation to fossils, 194 cm coarse/fine beds, one lower bed has fusulinids, otherwise these beds are very fine to base of massive conglomerate, 3-6 cm scale is thickest, 70 cm massive conglomerate, has chert band near top, chert nodules preserved fossils, *Domopora*, *Cladopora*, crinoid columnals, *Acanthocladia*, lithoclasts, rugose coral, brachiopod shells, weathers massive to hackly, note this bed scours into underlying beds, *sample taken here BR-Rader1*, 10 cm coarse/fine to platy beds, chert, same as below, 28 cm conglomerate, coarse base, bryozoans (*Domopora*, *Cladopora*, *Acanthocladia*), fusulinids, chert nodules, very small brachiopod shell, fines upward (borderline), 14 cm coarse/fine bed, chert in two layers, continuous on outcrop, very fine fossil hash, 5 cm platy limestone, as described below, 170 cm massive conglomerate, thins on strike, very hackly weathering, see some bryozoans, lots of chert nodules, may have lithoclasts, weathers very poorly to identify fossils, has fusulinids near top on strike, crinoid columnals, rugose corals fossils look like they are “floating”, 41 cm coarse/fine beds, as below, 90 cm cover, huge boulders, 80 cm conglomerate, fusulinids, crinoid columnals, *Domopora*, *Cladopora*, rugose coral, scraps of brachiopods, fusulinids are aligned at top of bed almost E/W, massive hackly weathering, few brachiopods seen, dominated by fusulinids and bryozoans here



Locality: LF-PS (Pine Springs)
Location: 31°54.004 N, 104°49.344 W
Guadalupe Mountains National Park Visitor's Center
Remarks: Pinery Member type section
Measured by: L. M. Fall and S. A. Marcus
4/24/07–4/26/07

<u>LF-PS (Pine Springs)</u>

Bed 1: 68 cm –interbedded with nodular limestone and siltstone, sharp and wavy/undulatory lower contact, nodular limestone at base, N7 weathered face, N6 fresh face, calcitic fossils present, fossils weather poorly and mostly are unidentifiable, crinoid columnal segment seen, molds/impressions of ammonoids are common and all appear to be oriented on bedding planes on their lateral/medial sides, may be some bioturbation, upper 15 cm of bed less rubbly/nodular, thickens and thins along outcrop, N7 weathered face, N6 fresh face, some fossils observed, probably calcitic, poor preservation, top of bed is bioturbated, burrows look like they pipe silt down from above, pyrite (or limonite after pyrite) crystals scattered on the surface, voids lined with calcite present

Bed 2: 173 cm – interbedded silty limestone and siltstone, siltstones above the limestone bed near base, no fossils seen, limestone beds are approximately ±5–8 cm thick along strike, two limestone beds (±6 cm) seen along strike (SE), one in center of bed and one near base of overlying bed, mostly covered interval

Bed 3: 90 cm – nodular limestone, beds weather more massive compared to lower nodular limestone but some beds weather rubbly, wavy lower contact, N6 to 10YR 8/2 weathered face, N6 fresh face, ammonoids common mainly observed in rubbly beds with some oriented on bedding planes on their lateral/medial sides and some oriented perpendicular to bedding, some grainy patches (calcitic fossils?) in rubbly-weathering beds, otherwise not many fossils seen, some calcite-lined voids, some iron-rich areas

Bed 4: 935 cm – interbedded siltstone and limestone, bed divided into 120 cm intervals, (1) 120 cm contains siltstone, covered, coarse silt to fine sand seen, calcite cement, weakly cemented, not obviously bedded, no sedimentary structures seen, silty/sandy interval weathers rubbly, some mica flecks, (2) 120 cm contains ~20 cm silty limestone at base, weathers resistantly, some iron staining, may be bioturbated, siltstone overlies silty limestone with no obvious bedding, a ~14 cm limestone bed with lots of iron-rich areas and not as silty, few scattered fossil grains near top, bioturbated at top, very thin to laminated siltstones, a ~±13 cm limestone, some fossil grains near top, bioturbated, some very iron-rich areas that maybe replacing burrows(?), burrows seen throughout bed, wavy tops to undulatory tops and bases of beds in this interval, (3) 120 cm contains siltstone at base, a ±9 cm silty limestone, weathered face has "ribbon-like" texture on outcrop, iron-rich areas, may be fine sand in limestone, gets very platy at top, very small branching burrows on top of bed, overlying this bed is another silty interval, calcite cemented, some mica flecks, coarse silt to fine sand, mostly covered, no bedding seen, another thin silty limestone (6 cm) with "ribbon" texture, may be bioturbated, another silty interval, siltstones are better indurated, parts are laminated, (4) 120 cm contains ~ 9 cm silty limestone, iron-rich areas, platy near top, platy to rubbly-weathering thin limestone beds overlie siltstone, bioturbated, fossil (brachiopod?) seen on bedding surface, very fine grains, iron-stained, near top of interval is a coarse to fine bed, bioturbated at top, platy interval of silty limestone, (5) 120 cm contains 4 cm siltstone, calcite cemented, more indurated, covered by platy interval, then another ~6 cm limestone, covered, ~19 cm thick limestone with chert nodules, not much else seen, small platy portion on strike near middle of bed, covered to top of interval, (6) 120 cm covered, (7) 120 cm covered, last interval is 95 cm covered at top, some siltstone and platy beds exposed

Bed 5: 470 cm – interbedded siltstone and limestone, ~17 cm thick limestone, sharp lower contact, N8 weathered face, 5YR 6/1 fresh face, bed has fossil hash at base, chert nodules, along strike (ESE) bed has parting and splits into two beds, parting is silty carbonate, bed has fossil grains (not identifiable) near top, bed laterally traceable on outcrop, along strike, beds below are thin limestone and siltstone beds, sharp contact with underlying beds, 23 cm platy limestone, mostly covered, 13 cm thick limestone, 10YR 8/2; 5YR 6/11, beds make subtle bench, laterally traceable, some fossil (?) grains seen, bioturbation on top, top of bed gets silty, 40 cm siltstones, covered, then thin limestone beds, coarse/fine layers seen, bioturbation on top of bed in finer material, weathers platy, siltstone interbeds, more coarse/fine limestone, bioturbation on top, cherty bed neat top too, 28 cm limestone, 10YR 8/2 weather face, 5YR 6/1to 5Y 6/1, top of bed highly bioturbated, horizontal burrows, bed makes bench on outcrop, grains in rock not identifiable, bioturbation may be through whole bed, brachiopod shell seen, some grainer patches, burrows may concentrate fossils, burrows (*Chondrites*) small to cm-scale, vertical, 75 cm siltstone at base, otherwise covered, 26 cm limestone, two (?) maybe three, tops and bottoms bioturbated, 10YR 8/2 weathered face, 5YR 6/1 fresh face, bottom bed is ~9 cm thick, upper bed is ~11 cm thick, bottom bed has large horizontal burrow visible on top bedding surface, interbeds silty(?), upper bed is fossiliferous, very grainy, fusulinids or foraminifers(?) seen on fresh face, both beds have zones of chert, weather to subtle benches, top of upper bed also bioturbated, 40 cm platy, thin-bedded limestone, may have one slightly thicker bed near base, mainly covered, 13 cm limestone, large chert zone at top of bed, 10YR 8/2 to 10YR 8/6, some N6, top of bed N7 weathered face, brachiopods scraps seen, N6 to N5 fresh face, abundant fusulinids, crinoid columns, few brachiopod shells, coarse below, finer above; bioturbated top; may have very small lithoclasts in coarse portion; bryozoan, possible microcrinoid cup (?), fossils are silicified, bed persists on outcrop, top has some large burrows, 6 cm platy limestone interbeds, mostly weathered back, 8 cm limestone bed, chert at top, 10YR 8/2 weathered face, 5YR 6/1 fresh face, grainy limestone, burrowed top, bed somewhat persistent on outcrop, fossils not apparent, 6.5 cm platy limestone interbeds, top is ~2 cm thick, no fossils seen, 22 cm limestone (?packstone), chert base, N6 to 10YR 7/4 weathered face, 5Y 6/1 fresh face, has some very small fossil grains on weathered face that are not identifiable, ?possibly crinoid columnal, can see some coarser/finer layers (large scale) on weathered surface, chert makes top of bed, 2.5 cm limestone then 7 cm limestone with a few chert blobs visible, bioturbated top, weathers blocky/rubbly, 15 cm limestone, chert nodules (large) at base and top, bioturbated at top, persists across outcrop, 10YR 8/2 and N6 weathered face, N6 to 5YR 6/1 fresh face, weathers as blocky bench, chert may be after burrows on top, grainy, like thicker bed below, 4 cm limestone, two 2 cm thin limestone beds as below, weather platy/wavy, 12 cm limestone, coarse at base (still very fine grains), finer near top, few fossils near base not identifiable, like beds described below, coarse layer only ~1.5 cm of bed at base, not cherty, 112 cm limestone with bioturbated tops and possibly platy interbeds in between

Bed 6: 35 cm – conglomerate, massive limestone, sharp lower contact, weathers as bench, 5Y 6/1 weathered face, N6 to N5 fresh face, siliceous fossils, fossils small, distributed throughout, abundant crinoid columnals, few bryozoans, where measured seems to be thicker than along strike in WSW direction, thickens to the ENE then rubbles out, echinoid plate in chert, top of bed is finer, slightly burrowed

Bed 7: 12.5 cm – laminated limestone, weathers platy, thin limestone with chert nodules, few very small fossil grains, may be coarse/fine layer

Bed 8: 68 cm – conglomerate, limestone, sharp lower contact, where measured may be three flows however hard to trace on strike as separate conglomerate beds, some possible platy units, scoured contacts, described the three conglomerates: (1) base of lower conglomerate is fine, chert layer overlies this preserves fusulinids, may show scouring at top, some brachiopods preserved, very coarse, crinoid columnals and rugose corals, local zone of this material, along strike ENE conglomerate remains fine at base, a very coarse, scoured top, fossils include: bryozoans, rugose corals, fusulinids, crinoid columnals/segments, big brachiopods, spirifer brachiopod, other scraps, *Domopora*, crinoid radial plate, *Hustedia*, all very fragmented/torn-up stuff, conglomerate thins along strike, still chert top with fusulinids and bryozoans; (2) middle conglomerate, contain fossils, smaller/larger at top, chert, crinoid columnals, bryozoans, *Hustedia;* (3) upper conglomerate, brachiopods, bryozoans, coarser material, makes consistent bench on outcrop, chert nodules, persistent chert layer on top, echinoid plate; some disarticulated ?brachiopods, thickens and thins a bit on outcrop, may scour

Bed 9: 106 cm – covered where measured, may have bed but cannot tell, rubbled out, along strike still rubbled out/talus covered

Bed 10: 453 cm – conglomerate, massive limestone, where measured limestone forms cliff, sharp lower contact, there are ~9 conglomerates, at base generally fine, have fine/cherty tops, at least one has a heavily bioturbated top, crinoid debris, fusulinids, some have lithoclasts, lithoclasts are rounded, shell fragments, rugose corals, echinoid plate, crinoid columnals seen on strike (WNW), brachiopod shells, microcrinoids, may pinch or thin out to the WNW on strike, reef rubble boulders (meter scale), upper conglomerate may be channelized because it thins on strike, other conglomerate are more-or-less continuous, one of the lower conglomerates looks like it is coarse at the base with a laminated/thinly bedded top, upper conglomerate reef clasts have lots of sponges and chert, very coarse conglomerate, brachiopods, echinoid plates, rugose corals, may have a *Coenocystis* (crinoid), spirifers, bryozoans, some brachiopods are articulated, fusulinids, sphinctozoan sponge, *Acanthocladia*, ?tabulate, *Derbyia*-like shell fragments, large crinoid columnals, noted stylolites too, fusulinids do not weather out very well but are abundant, abundant large bryozoans, large sponges, fine cap, *samples taken PS-PL2*

Bed 11: 165 cm – conglomerate, limestone, there are three fine conglomerates and one coarser conglomerate at top, chert nodules, crinoid columnals, finer fossils debris in lower beds, lower beds have finer caps, chert nodules and layers, fusulinids in top bed, top bed has bryozoans, crinoid columnals, on strike to the WNW of measured area another limestone with coarse base and fine top (thicker fine top than small, cm-scale as found below), ?pinches out where measured section is, coarse, upper bed where measured is loaded with fusulinids, crinoid columnals, rugose corals, bryozoans, brachiopod shells (scrappy), beds thicken and think on outcrop, make last benches for a bit

Bed 12: 120 cm – limestone beds within this interval, base is covered, half way through interval is 16 cm thick limestone bed with chert nodules, no fossils seen, bioturbated, light/dark areas, overlain by platy limestone, probably silty, weathers in thin (less than cm) plates, overlain by small set of beds (+5.5 cm), dark (N5) limestone with chert layers in it, little burrowing, overlain by platy beds (~7 cm), overlain by 8 cm thick limestone bed, lots of chert, bioturbated at top, these limestone beds weather rubbly/wavy, may be getting back to coarse/fine layers now, cm-scale, tiny grains

Bed 13: 120 cm – normally graded wackestone at base of interval, coarse/fine, bioturbated, chert in layers and nodules, some platy interbeds, no visible fossils on outcrop, about half way through to top is covered

Bed 14: 480 cm – normally graded wackestone/packstone and laminated limestone, cherty, thin limestone beds, bioturbated, coarse/fine layers, platy limestone interbeds, squashed brachiopods in float (road kill)

Bed 15: 360 cm – covered, talus/large slump blocks

Bed 16: 190 cm – at top, slightly thicker limestone beds, fine caps, weather slightly more blocky than below

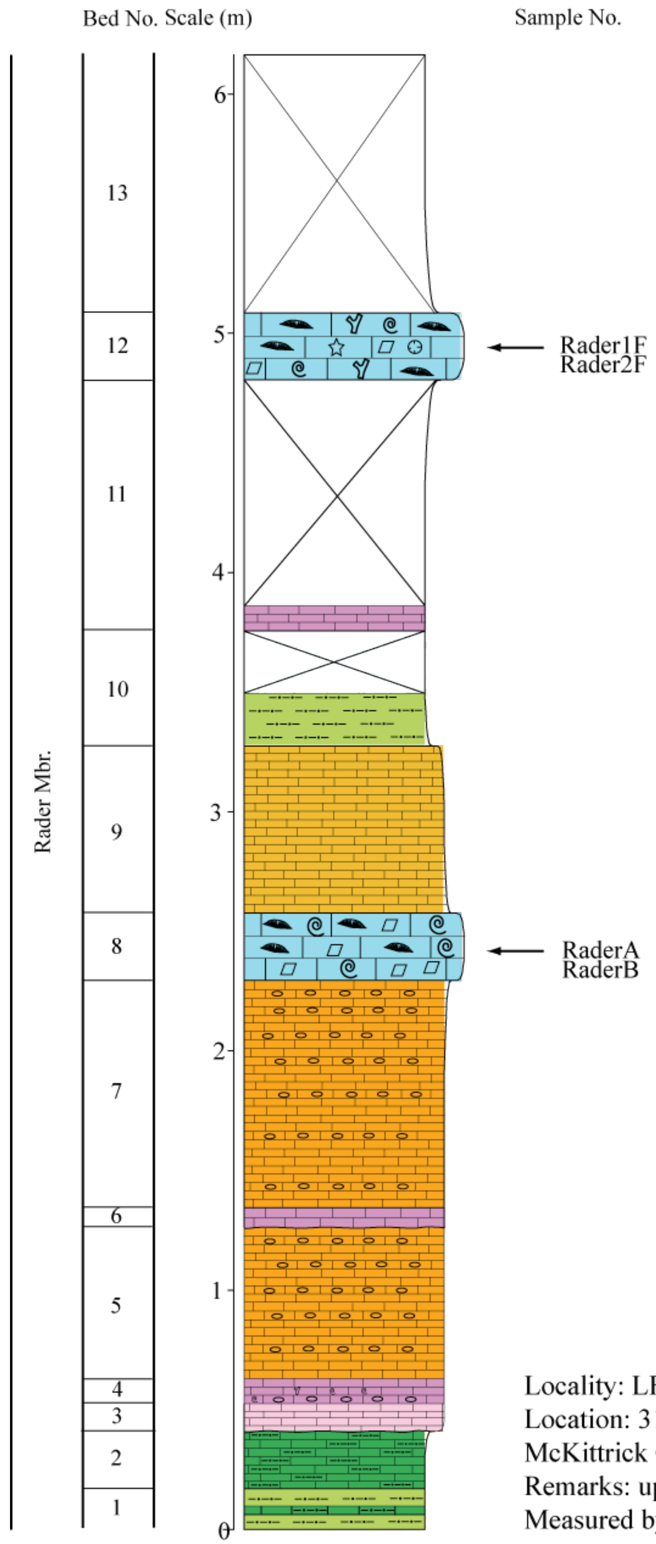
Bed 17: 470 cm – four conglomerate beds, (1) 112 cm conglomerate, massive limestone, makes bench on outcrop, note along strike (W) these beds are hard to distinguish, lots of rubble and cover, lots of chert, abundant bryozoans, *Acanthocladia*, middle/top of unit is bioturbated, weathers rubbly in places, can see burrows (vertical), fossils fine fragments throughout unit, see some brachiopods, one brachiopod articulated but most are scrappy pieces, on strike to W, looks like beds thicken and thin, basal limestone to the W from where measured gets thicker, coarser (whole brachiopod seen), see rugose corals, bryozoans (*Domopora*), *Hustedia*, Derbyia-type shell, spirifers, some echinoid spines seen along strike to the E and echinoid plate; (2) 85 cm conglomerate, limestone, chert layer, ?possible pectin in chert, echinoid spines, *Domopora*, disarticulated brachiopod shells, where measured not very coarse, crinoid material, fossils distributed throughout, echinoid plate, thins on strike to the W, chert in layers and nodules, not much brachiopod stuff, thin limestone beds (~110 cm), mainly not very fossiliferous; (3) 100 cm conglomerate, limestone, chert where measured, fossils weather out in middle of bed, *Acanthocladia*, fossils concentrated above chert in zone ~8 cm thick, lots of bryozoans in this, tiny *Hustedia*, brachiopod shell pieces mainly, few are whole, fenestrate bryozoans, in places bed weathers out so coarse portion is seen, rugose coral, fusulinids; (4) 45 cm conglomerate, limestone, cherty nodules and layers, limestone rubbles along outcrop, some fine fossil debris seen, benches back cannot see upper contact due to cover, may be sharp since this is a bench, *samples taken at base of bed PS-PuA1 and PuA2*

Bed 18: 453 cm – lots of cover/rubble, 55 cm thick limestone, very deeply weathered, no fossils seen, no chert noted, massive, 110 cm thick wackestone to packstone, makes up middle, middle of next intervals very deeply weathered, few fossils seen in lower portion where measured, bryozoans and finer fossils seen, fine top, 15 cm limestone bed on top, chert, looks like a coarse/fine bed here, pretty well covered in limestone/talus/grass

Bed 19: 322 cm – base of bed is 77 cm thick limestone, fossils seen include bryozoans, brachiopod pieces, fossils float in rock, crinoid columnal, fine-grained, ~223 cm thick conglomerate, limestone, massive, bed is continuous, weathers stair-stepped, around the corner of the hill to the west, this unit is a cliff-former, to the ENE the lower area rubbles out, fossiliferous units tend to weather hackly, some chert nodules, bryozoans – ramose, *Acanthocladia*, *Domopora*, rugose corals, brachiopods but few and far between, bryozoans dominate bed, fossils distributed throughout, see fenestrate bryozoan, in places nothing is on weather surface, fusulinid seen, brachiopod ?spirifer see on strike to the W, weathering on bed is very holey, hard to see fossils, zones with tons of fusulinids, to the W massive holey unit disappears

Bed 20: 840 cm – normally graded wackestone/packstone and laminated limestone, dark, weather blocky, make more gentle slope, see bioturbation in portions of unit on top of limestone beds, fine fossil debris in some beds, crinoid columnals, piece of rugose coral, some beds have chert layers on top, these may be like below coarse/fine layers, mostly cover with some small beds sticking out

Bed 21: 40 cm – conglomerate, limestone, coarse, brachiopods, bryozoans, rugose corals, fossils throughout, ?*Mesolobus*, some good brachiopods on top of bed, massive echinoid plates, crinoid columnals, contact with overlying unit is sharp (seen to W along strike), overlying unit is sand/silt, *samples taken PS-PuB1 and PuB2*



Locality: LF-ROTR (Rader on the Road)
Location: 31°56.799 N, 104°44.059 W
McKittrick Canyon Access Road
Remarks: upper Rader Member
Measured by: L. M. Fall and S. A. Marcus 5/7/07

<u>LF-ROTR (Rader on the Road)</u>

Bed 1: 17 cm – base of section floats; interbedded siltstone and limestone, 7 cm thick basal siltstone bed, calcite cemented, mica flecks, darker grains, fairly well indurated, weathered face is 10YR 8/2 to 10YR 7/4, N9 (caliche or efflorescent crust in places), fresh face is 10YR 6/2, massive bed due to weathering; 2 cm thick silty limestone bed, weathered face same as previous bed, fresh face is 5Y 6/1, somewhat indurated, mica flecks present; 8 cm siltstone bed fresh is 10YR 6/2, weathers as beds below, calcite cemented, slightly more recessive weathering than bed of silt below, otherwise, as basal bed

Bed 2: 24 cm – silty limestone beds, well-cemented, no obvious fossils, may be few fossil grains, iron-staining in bed, colors as beds below

Bed 3: 11.5 cm – normally graded limestone, with wavy, undulatory contact with beds below, bed varies in thickness, has chert near base, weathered face is N5, 10YR 8/2, 10YR 7/4, 10YR 8/6, fresh face is N4-N3, lithoclasts (small), shelly material at base, fine fossil remnants, fine limestone cap, 16 cm thick on strike, top of beds benches back/weathers recessively, may be platy between beds, might be silty

Bed 4: 10.5 cm – wackestone to packstone, cherty at the base, weathers 5YR 6/11, fresh face is 5Y 6/1 to 5YR 4/1, shelly material in bed, may be coarse near base of bed, fossil material preserved in the chert at the base, poor preservation, fines at top, identifiable fossils include: bryozoans, fusulinids

Bed 5: 63 cm – interbedded normally graded limestone and platy limestone beds, chert in layers, cannot identify beds in between, weathers expansively, layers are force apart by weathering and lichen, smaller limestone beds are ~4-6 cm thick, very planar beds, may have one bed that is slightly undulatory, beds may be coarse/fine, chert tends to be at top of beds

Bed 6: 8.5 cm – wackestone to packstone, base looks wavy, lots of chert in nodules, diffuse layers, weathered face is 10YR 8/2, N6, 10YR 6/2, fresh face is N4, petroliferous odor when acid is applied, fossil grains seen on fresh face, weathered face does not really show fossils, chert on top of bed, bed thickens and thins on outcrop; above this bed, outcrop gets rubbly/covered

Bed 7: 95 cm – normally graded wackestone/packstone and laminated limestone, lots of chert, chert in layers, beds between weather out, beds are planar on strike, lots of cover in this interval on strike

Bed 8: 28 cm – conglomerate, wackestone to grainstone matrix, productid brachiopod with spines near top, lithoclasts, identifiable fossils include: *Hustedia*, fusulinids, fossils are towards top of bed, on strike to the NNW beds rubble out get covered, walked several meters to the SSE to get more outcrop, bed has fine cap, *samples taken here ROTR-RaderA* and *RaderB*

Bed 9: 70 cm – normally graded wackestone/packstone and laminated limestone, chert in upper bed is more diffuse than in layered, very fine top to uppermost bed in interval, contact sharp with overlying bed

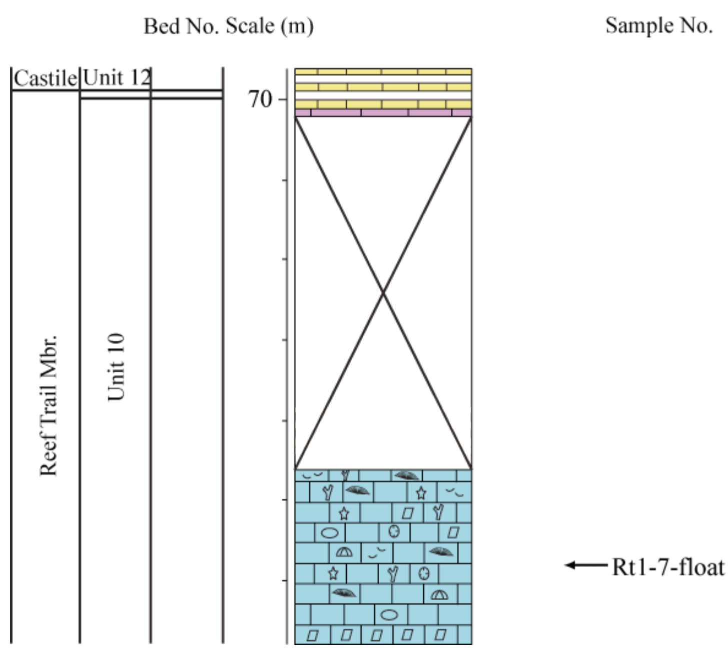
Bed 10: 48 cm – base of interval is ~27 cm of siltstone, somewhat indurated at base, not calcite cement, weathers to 10YR 7/4, fresh 10YR 6/2, mica fleck present, sharp contact

Bed 11: 105 cm – base of interval is +5.5 cm wackestone to packstone, sharp base and top, do not see chert, very fine grained, possible fossil grains, possibly brachiopod spines or sponge spicules, approximately middle of interval is ~10 cm thick very fine grained limestone bed, may have fossil bits but not identifiable, looks like may have coarse/fine layers, rest of interval is covered, see some silt chips, may be more silt in this covered interval

Bed 12: 28 cm – conglomerate, wackestone to grainstone matrix, very coarse base, identifiable fossils include: bryozoans, brachiopod shell pieces, rugose corals, *Acanthocladia*, ramose bryozoan, *Domopora*, crinoid columnals, dominated by bryozoans, top of bed is finer but still fossil hash including fragments of *Derbyia*-like sheets and *Hustedia*, bed traceable on strike, walked it to the SSE, noted fusulinids at base on float blocks, fenestrate bryozoans, crinoid columnals, maybe lithoclasts, *samples taken here ROTR-Rader1F and Rader2F*

Bed 13: 108 cm – covered, see fine-grained limestone float, some coarse/fine beds in float but the coarse fossiliferous material is gone

Locality: LF-LmRT1
Location: 31°49.894N, 104°52.081W
Williams Ranch Road
Remarks: Bell's SC1
Measured by: L. M. Fall and S. A. Marcus



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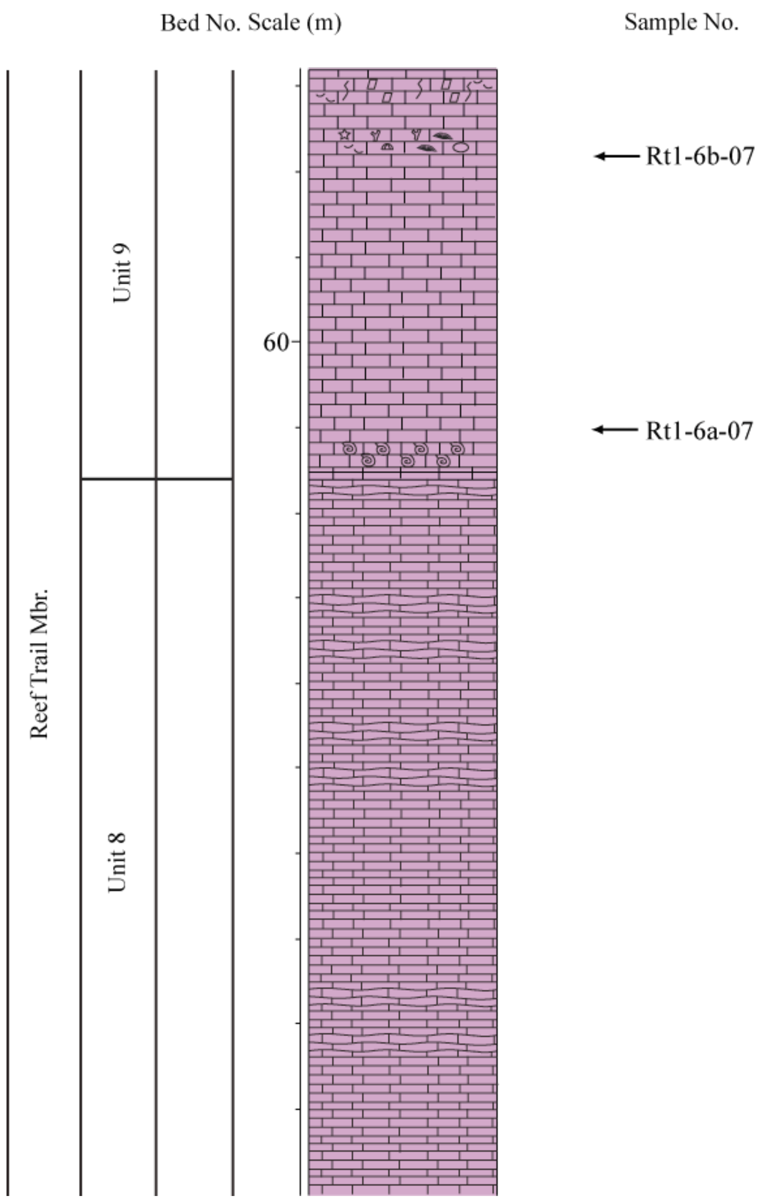

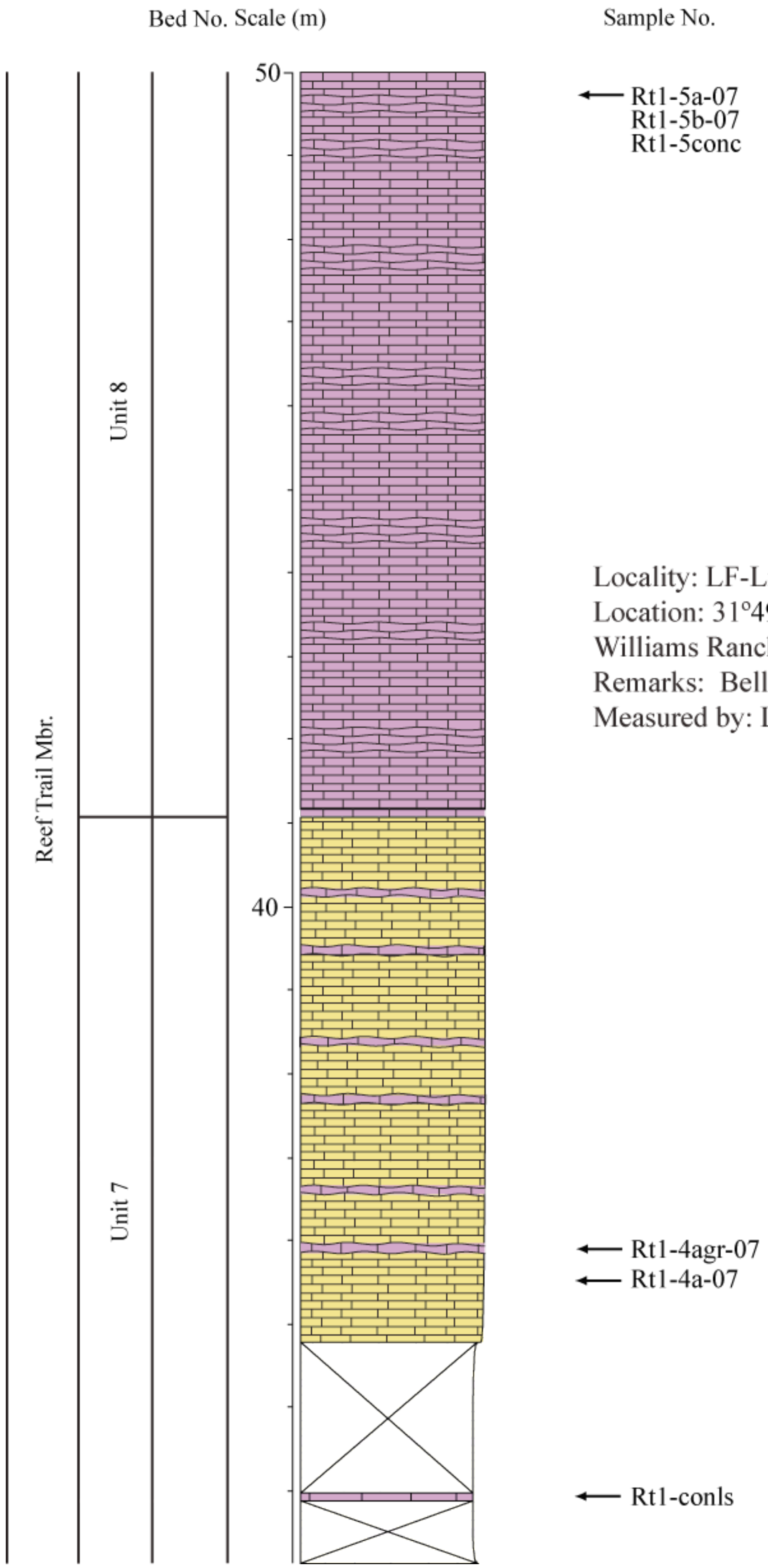

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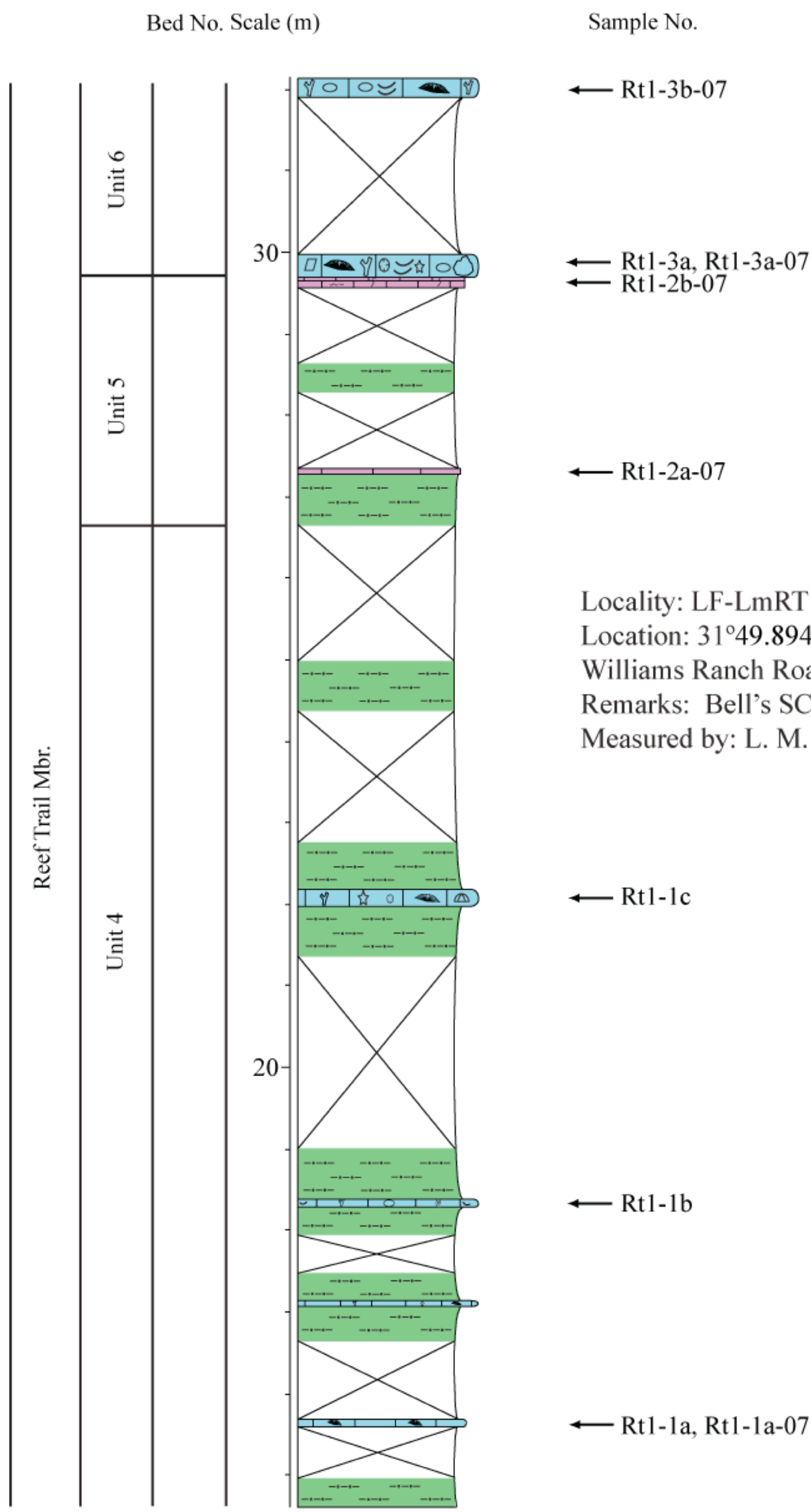

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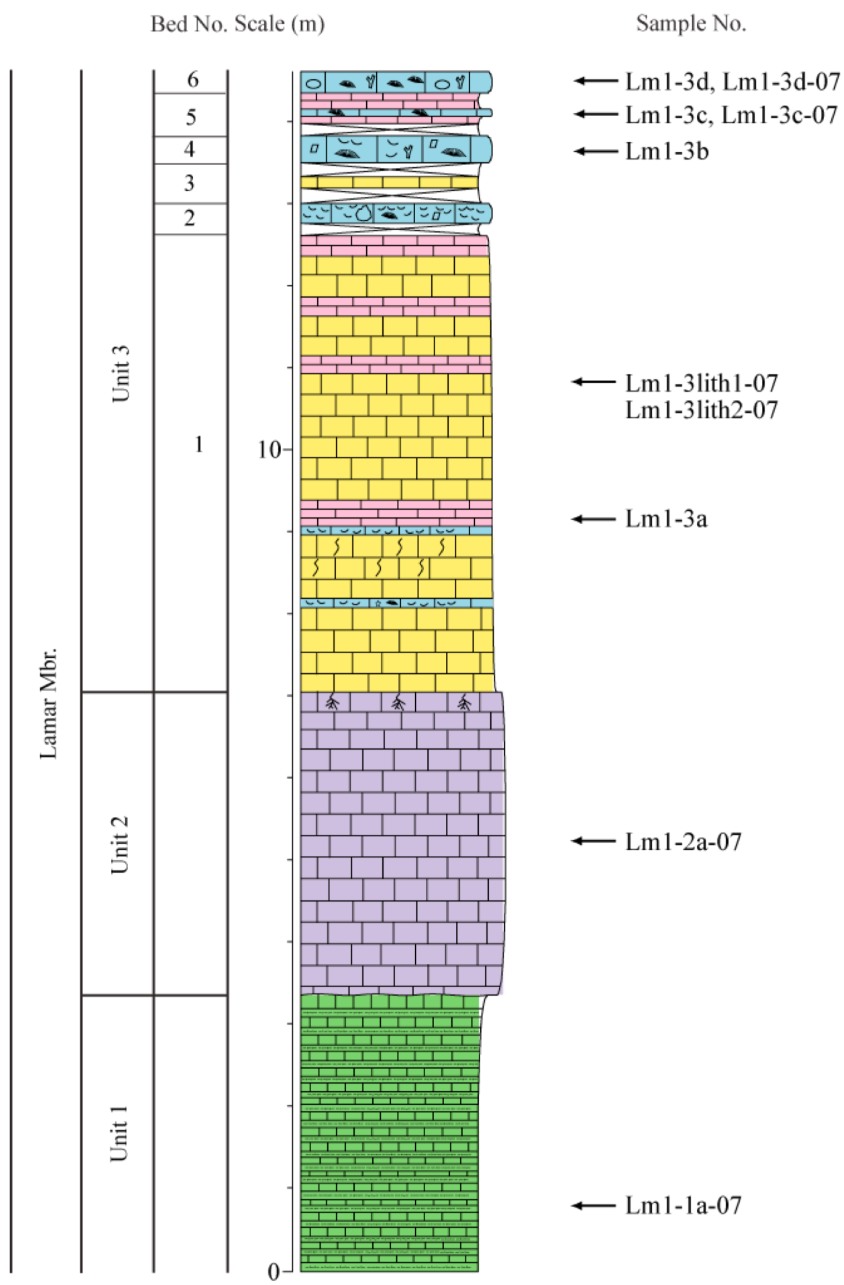


LF-BCLm1

Unit 1: 335 cm – interbedded limestones and siltstones, forms cliff where exposed well, becomes more carbonate dominated towards the top of the bed, chert appears in nodules and stringers throughout bed, siltstone is carbonate cemented, friable, weathers back in outcrop, weathers 5Y 8/1, fresh is same to 5Y 6/1, weathers redder, varies on outcrop, small beds may thicken and thin along strike, hard to trace, bed size: 6 cm, 2.5 cm, both carbonates and siltstones are not easy (or possible) to trace on outcrop, carbonate beds range in thickness: 5 cm, 7 cm, 12 cm, 2 cm, thicken upsection, limestone on weathered face is 5Y 6/1, fresh face is 10YR 6/2, no fossils noted on weathered faces at base of section, it is limestone, iron-stained, weathers platy to wavy weathering, ~6m along strike to the SW, strike N28º to 30º, dip 22º, upper part of unit is more massive, portions very iron-stained, has more iron-staining than at BCLm3, still cherty, noted small debris flow near top of unit, on few cm-scale, contact with overlying unit is sharp, but hard to trace on outcrop, contact seems wavy, *lithologic sample taken BCLm1-1a-07 ~240 cm below contact with Unit 2*

Unit 2: 370 cm – limestone, mudstone, much of contact with Unit 1 is covered, weathered 5Y 6/1, mottled weathering, cliff-former, areas 5GY 6/1, fresh is 5Y 6/1 to 5GY 6/1, chert near base, discontinuous bands, massive, very hard, near base, possible thin beds, weathers hackly, jointed towards middle of unit, 2-3 m long zone of chert (discontinuous), benches back in places along outcrop, larger burrows are visible, some chertified, burrows (3.6 cm long, diameter 0.7 to 1 cm, vary in size and shape) are penetrating sediment, also see some bioturbation ~middle of bed on benched back area, centimeter-scale burrows near very top of bed, uppermost bed is very small conglomerate, discontinuous, varies from 11 to 6 to 4 cm thick, one brachiopod weathering out (rhychonellid?), contact with next unit is sharp, *lithologic sample taken BCLm1-2a-07 ~185 cm above contact with Unit 1*

Unit 3

Bed 1: 555 cm – interbedded platy, laminated limestone and conglomerate, 210 cm above base there are a few centimeter-scale thicker beds, chert in layers, very cherty and iron-rich, note beds weather thicker but seem to be laminated when broken open, chert drops out somewhat and the "zebra stripes" pick up, *lithologic sample taken of "zebra stripes" BCLm1-3a*, these are laminations are more planar, still a little undulatory, may be small fining-upwards couplets, darker material looks more crystalline, then along strike to the NE, 8.5 cm thick conglomerate, looks more like turbidite deposit, some fossils seen, pinches out to the SW, mostly fragments, *Hustedia* seen, cherty, crinoid columnal, *Hustedia*, very small, chert preserves fossils, looks like packstone, grains are very small, 71 cm thick platy, laminated material overlies conglomerate, a bioturbated area seen in platy-weathering unit, also below conglomerate is a dark limestone layer that is 1-2 cm thick with a finer, lighter cap with bioturbation? at top, between these two conglomerates, it is dominantly laminated, but laminations are disturbed in places by burrows, vertical seen where burrows show up, *two lithologic samples taken ~3 meters below top of*

Unit 3 BCLm1-3lith1-07 and BCLm1-3lith2-07, 6.6 cm thick conglomerate, conglomerate has lots of grains but most are not identifiable, lots of chert, more continuous on outcrop, see bioturbation in float, burrows that look horizontal or very slightly vertical in laminated unit, have sponge spicules and very small grains in them, may also have bioturbation in tops of conglomerate, not as sharp a contact as seen in other sections, thin-bedded, less bioturbated limestone, one thicker bed with chert at the base, ~5.5 cm thick, fine-grained, cherty, fine cap that is bioturbated, most dark/light couplets do not look like the grain size changes, then up to thicker beds, wavy dark/light beds that look like “ribbon rock” in places, beds are thick/thin, pinch out on outcrop in <1m, may be bioturbated in places,

Bed 2: 24 cm – thick, where measured, there is layer of coarser conglomerate (or lens), unit is traceable to the NE, rubbles out to the SE, mainly grainy, fossil hash, traced along strike to the NE to see if anything weather out, fossils more distributed (packstone), still not whole weathers as a bench, jointed top, some lithoclasts of lightly material, long and skinny, may be silty, they are very soft, one brachiopod seen, *Composita*?, <u>small reef-rubble clast</u> (36 cm x 42 cm) seen along strike to NE, conglomerate seems to rubble out to NE, too

Bed 3: ~52 cm – platy-weathering limestone, mostly covered

Bed 4: 32 cm – conglomerate, see *Derbyia*, *Hustedia*, may be amalgamated beds, looks like two beds, dark/light layers, *sample taken here BCLm1-3b*, along strike, this bed rubbles out, very few portions where the fossils are coming out, cherty portions show shell fragments that are mainly not identifiable, ?rhynchonellid, bryozoan, disarticulated shells, some lithoclasts, *Composita*?, more brachiopods than ~1-2 m below, but patchy distribution, along strike to NE

Bed 5: ~54 cm – interbedded normally-graded wackestone and conglomerate, mainly covered, 10 cm thick conglomerate, has a fine cap, this bed has whole brachiopods where measured, lithoclasts, rugose corals, *Hustedia*, clasts and brachiopods look aligned, cherty, ?*Composita*, *sample taken here BCLm1-3c*, high-graded in area with brachiopods, two pieces taken here too, *sample taken ~50 cm from 2006 sample BCLm1-3c-07 ~105 cm below top of Unit 3*

Bed 6: 25 cm – conglomerate, chert layers and chert nodules, below chert, bed is grainer, weathers rubbly, chert thickens and thins, see bryozoans, disarticulated brachiopods, small lithoclasts, finer above chert, along strike to NE, beds below crop out, coarse/fine layers with chert nodules in them, grainer, *Domopora*, lots of brachiopod shells in rubbly weathering stuff, thins to NE, but is consistent across outcrop and traceable, *sample taken here BCLm1-3d*, *sample taken from top BCLm1-3d-07*, *sample from small conglomerate ~100 cm above the top of the Lamar (Lamar/Reef Trail transition) BCRt1-1z-07 (below Rt1-1a of 2006)*

<u>Unit 4</u>

1260 cm of siltstone and conglomerates, silt, 10YR 7/4, ~3.6 m up is conglomerate in siliciclastic recessive unit, also ~6.6 m is another good-sized conglomerate, forms small bench, (1) conglomerate, 120 cm above top of Unit 3 (Lamar/Reef Trail contact), bed weathers resistant on outcrop, 5Y 6/1 on weathered face, some on fresh surface, packstone-to-grainstone, fossils are silicified, weather resistantly bed is ~4.7 cm thick in area of measured section, 5.5 cm along strike to the SW, 4.5 cm to the NE, bed can be traced along strike for ~12 m, big clasts (10-20 cm scale), clasts oblong, some are rounded, look micritic, fizz on outcrop, abundant, clasts weather different colors, 5Y 6/1, 10YR 8/2 to 10YR 7/4 to 10YR 8/6 (pale yellowish-orange), grays to orange, clasts are centimeter to 10's of centimeter in scale, do not appear to be oriented, noted leptodid brachiopod, ?*Punctospirifer*, lots of brachiopods, fines along strike, lithoclasts and fossils become more oriented, see fining along strike to SW and NE, fossils seen on outcrop include: *Composita, Domopora*, brachiopod spines, echinoid spines, brachiopod shell fragments, fenestrate bryozoans, crinoid columnals, echinoid plate, *Derbyia*, rhychonellid, *Crurithyris*, found bivalve in float here, *sample taken here BCRT1-1a*, *sample taken ~1.5 m along strike to the NE from 2006 sample BCRt1-1a-07*, (2) conglomerate, 3.6 m up from base of section, very fine grained, chert in zones and nodules in limestone, finer-grained, N7 to 5Y6/1 on weathered surface, found bivalve in float here too, 5Y6/1 on fresh face, ?packstone to grainstone, very fine debris, includes fusulinids, several cross-sections in rock face, bryozoans also present, some fossils are silicified, weather out, beds are thicker here, ~10cm thick, range to 5 cm thick, 6 cm thick along strike, 13.5 m of section is traceable along strike, echinoid spine ("war club"), plate, fine debris mainly, fine limestone (micritic) bed above, chert zone locally between fossil hash and find cap, walked along strike to NE and stays fine-grained, *sample taken here BCRT1-1b*, (3) conglomerate, ~360 cm above second conglomerate, very thick, weathers as subtle bench, ~20 cm thick bed, coarser layer from 6 cm, 6-7 cm thick, coarser layer on top too, 16 cm thick along strike, traceable for ~17.7 m along strike, coarsens somewhat to the NE, 5Y61 on fresh and weathered surface, larger grains overall again, packstone to grainstone, brachiopod or bivalve shells seen on fresh surface with mineral oil, along with foraminifer (miliolid?), ?ostracod, lots of coarser fragments, in top coarse bed, bivalve is weathering out, on weathered surface: echinoid spines, rugose coral, brachiopod shells, bryozoans, in coarser portions, fragments up to centimeters long, whole brachiopods seen, fossils silicified, whole echinoid spines (common), plates, *Hustedia*, clasts, *Domopora*, crinoid columnals, few more bivalves seen weathering out, clasts not consistent, sharp upper and lower contact, *sample taken here BCRt1-1c*

<u>Unit 5</u>: 240 cm – interbedded limestone and siltstone, limestone weathers platy near base, two beds of limestone 7.2 cm and 5.1 cm thick, 5Y6/1 for fresh face, weathered too, beds difficult to trace along strike, very fine-grained in portions, ?wackestone, grains in top of bed are not identifiable beyond fragments, coarse and fine layers, hard to tell if coarse to fine or coarsening upwards, have limonite in places, limonite comes in layers, ?replacing pyrite and fossils, portions possibly fining-upwards, forms subtle slope between beds, coarser grains, chert nodules, overall package coarsens upward platy on surface, grains in upper portion mostly not identifiable, brachiopod shells, disarticulated, bryozoans, in packstone, gets bioturbated towards top, burrows sparse, cut vertically and horizontally, some chertified, some areas of horizontal bioturbation are very intense, other areas have

discrete burrows, mainly horizontal at top of unit, burrows are *Chondrites* and *Planolites*, also vertical burrows seen, very little vertical burrowing, these are seen in float blocks from underlying conglomerate, possible *Uchirites* seen in float piece, bed gets bioturbated near the top below upper contact, contact with overlying unit sharp, *lower limestone sampled BCRT1-2a-07, upper limestone sample d–LF-BCLm1-2b-07*

Unit 6: 246 cm – conglomerate with siltstones?, two conglomerates bound unit, between these units it is covered, (1) 29 cm thick lower conglomerate, weathers 5Y6/1, fresh face is the same, no orientations to fossils, upper part of bed fine in places, along strike thickens and thins, see echinoderm fragment on fresh face, packstone to grainstone, other fragments seen not identifiable, on weathered surface, *Domopora*, crinoid columnal, rugose coral, shell fragments, along strike, bryozoans, clasts noted, lithoclasts, ?*Hustedia*, ramose bryozoans, abundant bryozoans, more crinoid columnals, along strike to the NE is a large lump of reef rubble, 1.6 m high by 3.6m long, weathers with "classic" reef-rubble texture, just lots of chert, few bryozoans seen, farther along strike conglomerate thickens to 43cm, see brachiopods, crinoids, lots of fragments and coarse grains, see ?bivalve fragment, more brachiopods (*Hustedia* again), *Domopora* again, *Composita*, rugose coral, chert nodules, very grainy, thins again along strike, *sample taken here BCRT1-3a*, *sample taken ~275 cm along strike to SW of reef-rubble clast BCRT1-3a-07*, (2) ~25cm thick upper conglomerate, parts finer-grained than basal bed, 5Y6/1 on weathered face, same for fresh face, iron stains on fresh and weathered face, it is limestone, rock is slightly more friable in places than unit below, cemented more poorly than below, grains not identifiable on fresh face with mineral oil, ?fusulinids (if so, small), packstone to grainstone, along SW strike, gets grainer, see brachiopods (rhynchonellid) weathering out, bryozoans, thins along strike to the NE, ~13 cm thick, gets less grainy, still see lots of chert, see shell fragments, disarticulated brachiopod shells, thins to 7 cm just about above the reef rubble, thickens again to 21 cm, coarsens again, see brachiopod shells, abundant bryozoans, one piece is weathering out, several cm long ramose bryozoans, brachiopod shells, gastropod, 24 cm thick bed along strike, bryozoans, brachiopods (strong ribs), coarse at base, fine at top, contact with upper unit is sharp, may be 1-2 very small limestone beds before overlying platy unit kicks in, *sample taken along strike near SW end of outcrop BCRT1-3b-07*

Unit 7: ~818cm – limestones, thin-bedded to laminated, contact with underlying unit is sharp and laterally traceable and continuous, ~8.5 cm thick small limestone bed, discontinuous on outcrop, petroliferous, N4 on fresh face, 5YR 6/1 to 5Y 6/1 on weathered face, small fossil grains seen on weathered face, bryozoan, brachiopod shell fragment, most too small to identify on outcrop, looks almost concretionary in places, very dense limestone, platy-bedded, thin limestone with lenses of grainy sediments, beds are weathering in an expanded fashion (i.e., they are not in a resistant unit and are expanded on bedding planes), weathers to 10YR6/2, fresh is N4 (platy stuff), slightly petroliferous, laminated, weathers to very thin plates, at base, thick/thin couplets, coarse/fine layers, coarse layer has very small grains is darker, finer material is light, *sample taken of coarse/fine layering BCRT1-4a-07*, flattened brachiopods (sparse) seen in platy float here, ?*Composita*, at 3.15m, a grainer, slightly resistant unit is weathering out, grainer portion is 5YR5/2, weathers to N4, petroliferous, incorporates clasts of what appears to be laminated beds (lighter weathering), has lots of smaller fossil fragments, see shell fragments, packstone, some lithoclasts have very fine fossil debris in them, fossils are silicified, bed is up to 8.7 cm thick on strike, thickens and thins on outcrop, *sample float piece taken of grainer bed BCRT1-4a*, noted possible crinoid columnal, sponge seen (fairly complete ?sphinctozoan), note clasts can be up to ~10cm long, ?fishbones may be from above, small crushed *Composita* seen on platy-weathering material below grainy unit, also see bryozoan fragment in grainy unit, noted a few thick/thin beds below grainy unit, including a very thin (~1cm) grainy unit, virtually nothing seen in the platy-weathering stuff, saw fish bones in grainer portion, clasts are like surrounding seds?, noted spinctozoan sponge, fish bones, squashed brachiopod, echinoid spine and base, possible pectin, fossils are concentrated in some areas, possible burrows, in some cases patchy distribution of grainer portions, some fossils are widely dispersed in this little zone/lens, not seemingly oriented, also they weather brownish on outcrop not like silicified fossils in conglomerates below, grainer patches really do not have much identifiable fossils, *sample taken of laterally persistent but partially discontinuous grainy bed with large lithoclasts (cm-scale) BCRT1-4agr-07*, *sample is float/unoriented pieces BCRT1-4adissolve-07, sample collected BCRT1-4a-float-07*, *possible pectin BCRT1-4a-Bi*, gradational contact

Unit 8: ~1732 cm – platy to wavy-weathering limestone, there is a gradational change upsection, near base of unit, platy weathers to 10YR6/2, same fresh, may be slightly darker (closer to 5/2?), thicker bed, not as petroliferous as below, fresh surface is 5YR4/1 to N4, grainer in places, thin-bedded, not laminated, "pie-crust" texture noted, some beds weather thicker (cm scale), grainer units: seen gastropod (high-spired), fishbones, ?spicules, shell hash (very weathered!), grainer areas near base have shell fragments, grainer areas are not really bedded, more like stringers and surfaces that may have been a little reworked, note that platy units may be getting some silty interbeds and may be incorporated into grainer units, found brachiopods on slab, disarticulated spiriferids or rhynchonellids, beds that are not grainy are barren on surface, grainy beds/surfaces appear all along outcrop, but not in continuous beds, found very large fragment of *Acanthocladia* 5 cm in length, branches, again in grainer portion of section, complete echinoid spine, scaphopod, these are half way through section here, may be getting larger fossil debris up section?, seeing more-bedded pieces where fossil grains are making up the thicker portions of the beds, still "pie-crust" weathering, picking up concretions with bluish chalcedony weathering, thin concretions, weather lighter, hackly in outcrop, seeing some debris-rich areas with lithoclasts, larger fossils in places going upsection, whole crushed probable brachiopods, scaphopods, *Composita*, crinoid columnal, some parts of beds seen in float show alignment of fossil grains, gastropod, *Domopora*, echinoid spine, all seen in ~same unit that is ~3/5 up section, spine is several centimeter long, fossil distribution is scattered and concentrated, also see rhynchonellid, more flattened *Composita*, nice branching bryozoan, *Acanthocladia*, moving up section, conglomerate with (9.5 cm) large scaphopods, lithoclasts, ?brachiopods, echinoid spines, weathers to 10YR 4/2, fresh face is 5YR 4/1, petroliferous, see large shell preserved as calcitic in this bed, bed is ~872 cm above base of bed, *three float blocks taken here BCRT1-5a*, just above another concretion zone, too, note fish bones seem to drop out up section, get another conglomerate, ~3-5 cm thick, with lithoclasts, shelly debris, crinoid columnals, bryozoans, ?bivalves, crushed brachiopods, very large sponge spicule, *two float blocks collected closer to top of bed BCRT1-5b*, also may have bivalves too, near top of section is zone of concretions with chalcedony, these are weathering as described above, then more platy units, contact with next unit is sharp, note this combines Gorden Bell's units 11 and 12, note that dips change as does attitude upsection, *two oriented lithologic samples taken in this bed BCRT1-5a-07 and BCRT1-5b-07, sample of concretion below fossiliferous layer 5a and probably below "pie-crust" lithologic sample 5b BCRT1-5conc*, concretion is ~1m x 1m, weathers hackly on surface, has areas of chalcedony, can see edge of concretion where it abuts adjacent sediments, has a light zone around concretion, can also see some fossils but not identifiable

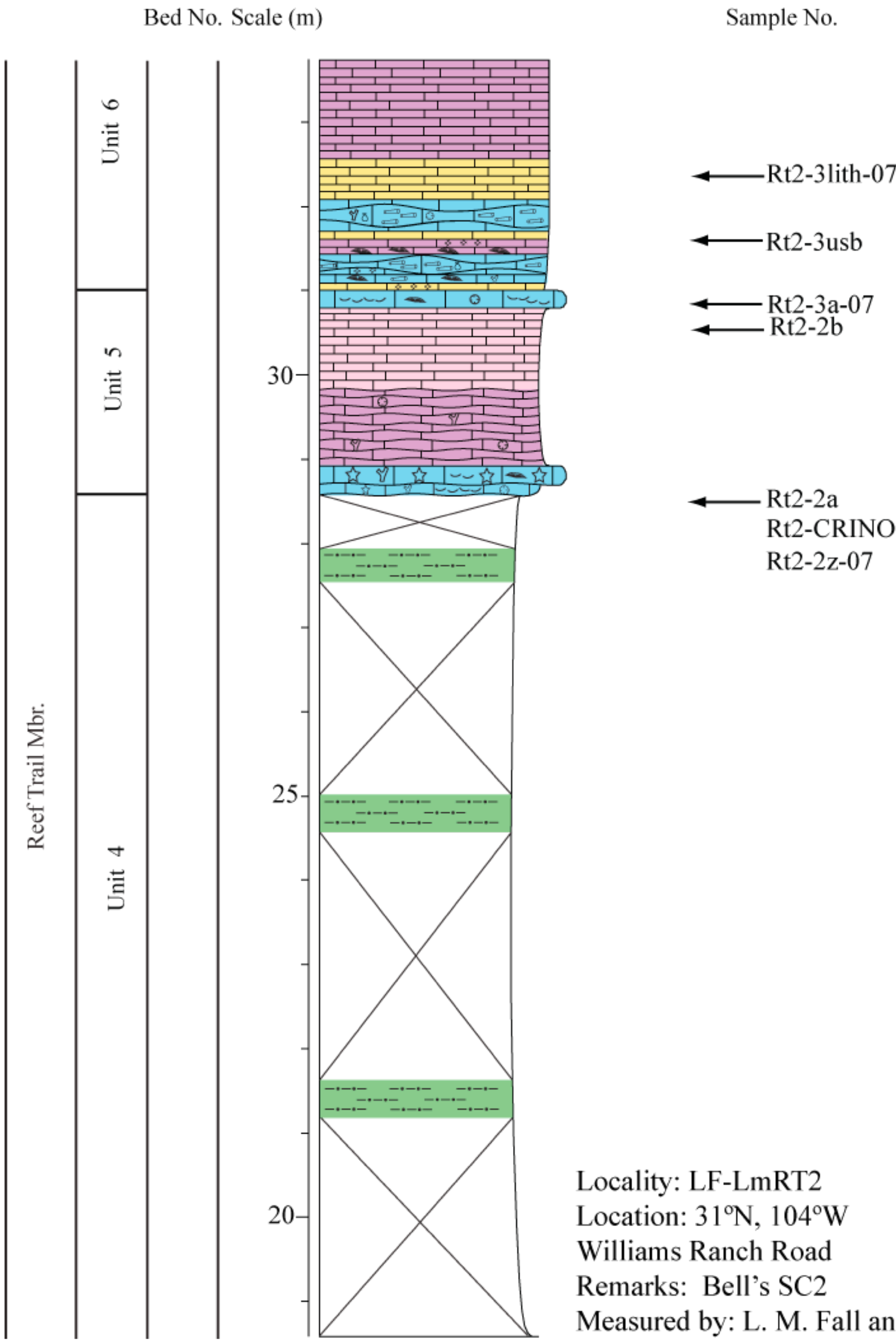
<u>Unit 9</u>: 480 cm – limestone, light gray at base, weathered surface is 10YR 8/2, fresh surface is N6 to N7, petroliferous, chert (or silica-replaced limestone) with fossils, ammonites, ammonite bed is the base of this bed, ammonites from mm to cm scale on outcrop, patchy distribution of ammonites along strike, ammonites disrupt bedding, beds are laminated, radiolarians in laminations, ?sponges, hackly weathering, then into a small covered interval, then debris flow with lithoclasts, fenestrate bryozoan, lots of shelly debris, some inclasts, several different clast lithologies, ?fish bits, large shells possibly brachiopods, *samples taken to show lithologies (two float and one oriented) BCRt1-6a*, areas of possible bioturbation where second sample taken*, sample taken BCRt1-6a-07*, fossiliferous portions of this bed, echinoid plates, brachiopods (whole), bryozoans (*Domopora*), lithoclasts 1-2 cm in scale, subangular, fenestrate bryozoan, crinoid columnal, chert, possible coral, very localized zone, looks like it sits on a concretion, there are areas of grainy fossiliferous material that come and go, then to top of bed, which is a light gray limestone that looks like base of unit, ammonite seen on outcrop, bioturbated slightly, burrows concentrate fossils, top of bed is conglomerate with huge (10's of cms) lithoclasts, lots of lithologies, different color patches, clasts are rounded to sub-angular, some grainy areas look like they are concentrated in burrows, weathers to 5Y 8/1, some very sparse whole fossils, in places lenses of fossils, see brachiopod fragments, crinoid columnals, bryozoans in grainer portions, contact with overlying unit is questionable, next unit is a conglomerate that has large lithoclasts in the base, these may be part and paired of the same event, *sample taken BCRt1-6b-07*, contact is sharp on outcrop

<u>Unit 10</u>: 218 cm – conglomerate, limestone, fresh is N8, weathers to 10 YR8/2 to N6, massive, lots of fossils on outcrop, base of unit has lots of lithoclasts, exhibits

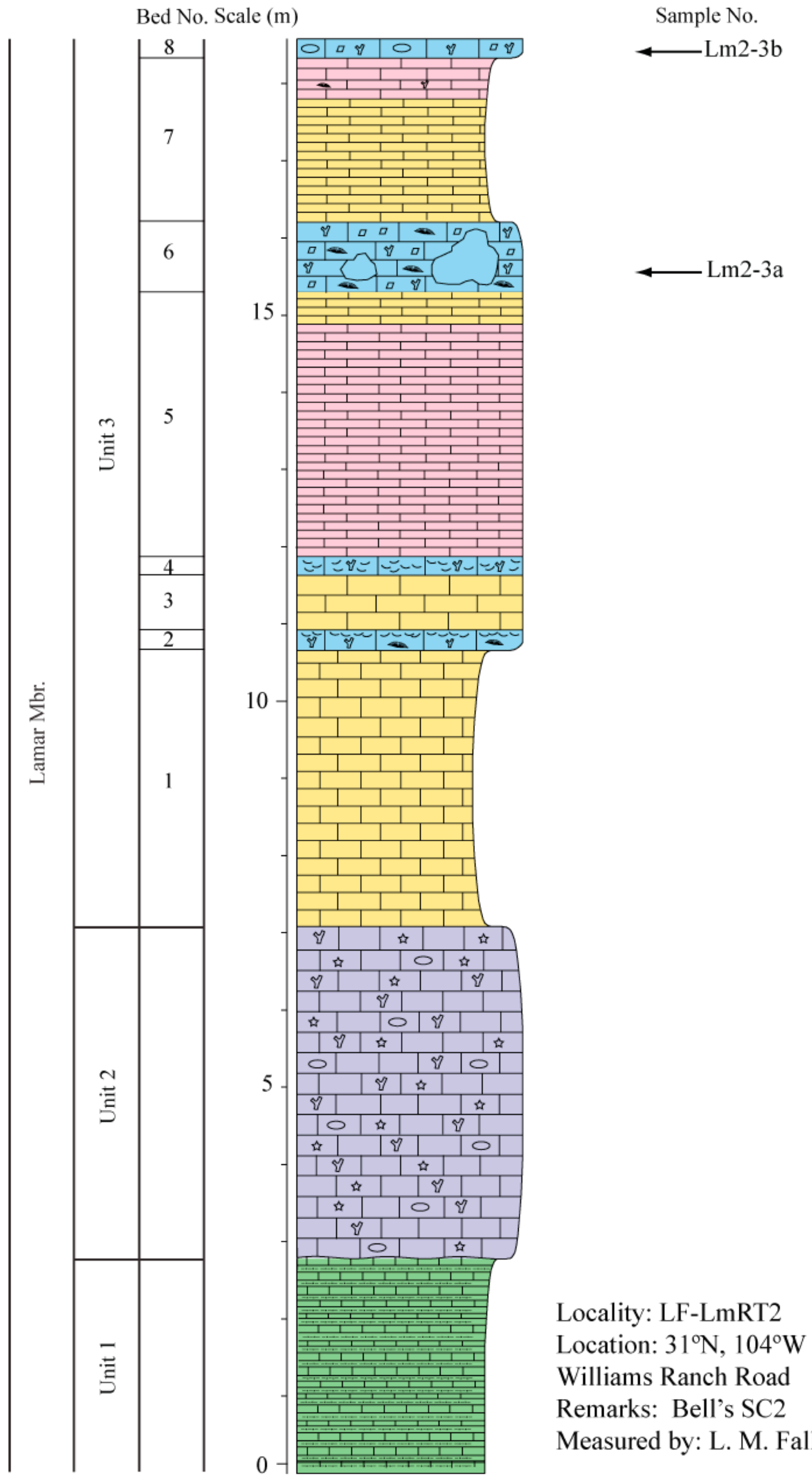
different lithologies in clasts, some are finer-grained, some coarser, see *Domopora*, bryozoans, *Derbyia*, *Composita*, *Hustedia*, these are in upper flow portion, where lithoclasts decrease in size and many more fossils, see echinoid spine, rugose coral, bivalve, areas of darker lithoclasts, fossils are silicified, sponge?, ?myalinid, fossil layer may scour into/be amalgamated into the underlying unit with the lithoclasts and "Liesegang banding" weathering, very hard to sample, very massive beds here, 443 cm of covered interval, *sample taken here BCRt1-7-float*

Unit 11: 8.8 cm – limestone, packstone, weathers to N5, fresh face is N5, petroliferous, weather out as a resistant, massive bench, has chert nodules, little iron-staining, weathers hackly and jointed, bed has fossil grains in it, may be recrystallized, brachiopod fragments, shell fragments, crinoid columnals, smaller lithoclasts, some larger, walked outcrop to the NE on strike, beds stays very consistent along strike, can see upper contact with the Castile Formation very well, chert in bed may be a layer, persists across outcrop, *sample taken BCRt1-8a*, contact with overlying unit is sharp, somewhat wavy

Unit 12: Castile Formation, base is reddish (iron-rich) limestone, at contact, it is iron-stained, weathers to 10YR 6/2, fresh face is N4, can see iron-layers, laminated, very consistent on outcrop, this is the "paper limestone" (overlain by Tessey)



Locality: LF-LmRT2
Location: 31ºN, 104ºW
Williams Ranch Road
Remarks: Bell's SC2
Measured by: L. M. Fall and S. A. Marcus



Locality: LF-LmRT2
Location: 31ºN, 104ºW
Williams Ranch Road
Remarks: Bell's SC2
Measured by: L. M. Fall and S. A. Marcus

<u>LF-BCLm2</u>

<u>Unit 1:</u> 278 cm – interbedded limestone and siltstone, contact between with underlying sandstone is sharp, sharp across outcrop, sharp contact with overlying unit, wavy across outcrop, cherty, iron-stained layers, limestone layers are 1.7 cm, 2.7 cm, 1.5 cm, silty interbeds still evident near top of unit, some silt beds are laminated, silt weathers recessive, some very small fossil grains seen in slightly coarser layers, not identifiable, packstone, chert is preserving some fossils in layers (chert is more layered than nodular in the bed), underlying very fine sandstone is 10YR 7/4 on weathered surface, same on fresh face, quartzose, calcite cement, thin bedded, recessive weathering, silt interbeds (in Unit 1) are 10YR 7/4 near the base, weather recessive, silt is coarse, iron-rich unit weather 5R 5/4, slightly more indurated, fresh face is mottled, 5R 6/6 to 5R 5/4 to 10YR 8/6, limestone is N5 on weathered face, fresh is N4, *sample taken BCLm2-1a*

<u>Unit 2</u>: 430 cm – massive-weathering cliff-forming limestone, wackestone to packstone chert in nodules, fossils in outcrop seen, including bryozoans, lots of crinoid debris, ?fusulinids, some stringers of layer shelly debris, fossils difficult to see, abundant crinoid columnals, weathered face is N6 to 10YR 7/4, fresh is 10YR 6/2, fossils seem to be in vague layers, may have slight orientations, *sample taken* near base *BCLm2-2a*, bryozoans include *Domopora*, ramose bryozoans, they are chertified and weather out well, chert nodules, may still be somewhat layered, contact overlying unit is sharp

<u>Unit 3</u>

Bed 1: 358 cm – platy-weathering, laminated limestone at base of unit, strike 12ºN, dip 18º, some laminations are iron-rich, laminations are crinkly, looks like "zebra-stripe" at Lm1, also some thin beds (5 mm) near base of unit, weathered beds are 5YR 6/6, fresh 5R 5/4 in iron-rich area, weathered 10YR 7/4, fresh is 10YR 6/2 in non-iron-rich areas, no silt noted in limestone interlayers, recessive up to overlying bed

Bed 2: 27 cm – conglomerate, very discontinuous on outcrop, cannot be traced more than a few meters, above is covered, actually it may be a turbidite flow, it has a coarse base and fine top (~1 cm), fossils are coarse/large, fossils seen include: *Hustedia*, bryozoans, *Domopora*, ramose form of "*Domopora*" [Plate 22, Fig. 21 in Permian Reef Complex], ?richthofenid brachiopods, ?*Acanthocladia*, *Composita*, lots of shell fragments

Bed 3: 70 cm – laminated limestone

Bed 4: 25 cm – conglomerate, finer-grained, see shell fragments, bryozoans.

Bed 5: 342 cm – normally-graded wackestone, some areas are debris-rich and look more like conglomerates, some of the coarser unit pinch out laterally, chert layers and nodules in these beds, some of the coarser units (darker) scour into underlying lighter units, return to much thinner-bedded platy weathering limestone has some iron-staining, ?may be laminated, petroliferous, *sample taken few meters to the south BCLm2-3lith1-07 and second sample taken a little north along strike and below BCLm2-3lith2-07*

Bed 6: 91 cm – conglomerate, contains at least two reef clasts where measured, large reef clast is 337 cm across, conglomerate looks like mostly brachiopod shells (disarticulated), few *Domopora*, lithoclasts, see *Hustedia*, other disarticulated brachiopods, looks like two conglomerates where the reef clast is not sitting in the upper part of the unit, *samples taken from two areas of the outcrop at base and top ~2 meters to the north BCLm2-3a*, forms small bench/small cliff on outcrop and persists on strike, parts are loaded with brachiopods, *sample taken here BCLm2-3a-07*

Bed 7: 212 cm – recessive weathering unit, normally-graded wackestone, some platy-weathering beds that look like stuff below conglomerates, few thicker beds that have chert, some fossils but mainly disarticulated, sparse whole fossils, *Hustedia*?, *Domopora*, very small (~2 mm) *Hustedia*

Bed 8: 25 cm – conglomerate, below this conglomerate brachiopods are visible on bedding planes but not identifiable because they are crushed, capping conglomerate has bryozoans, lithoclasts, chert nodules, coarse at base, finer top, gets covered and hard to trace along strike, *sample taken here BCLm2-3b in 25 cm thick part of bed*, contact with overlying bed is sharp, visible whole brachiopods on top of bed, *Hustedia*, bryozoans, chert nodules, *sample taken ~same place as 2006 BCLm2-3b-07*

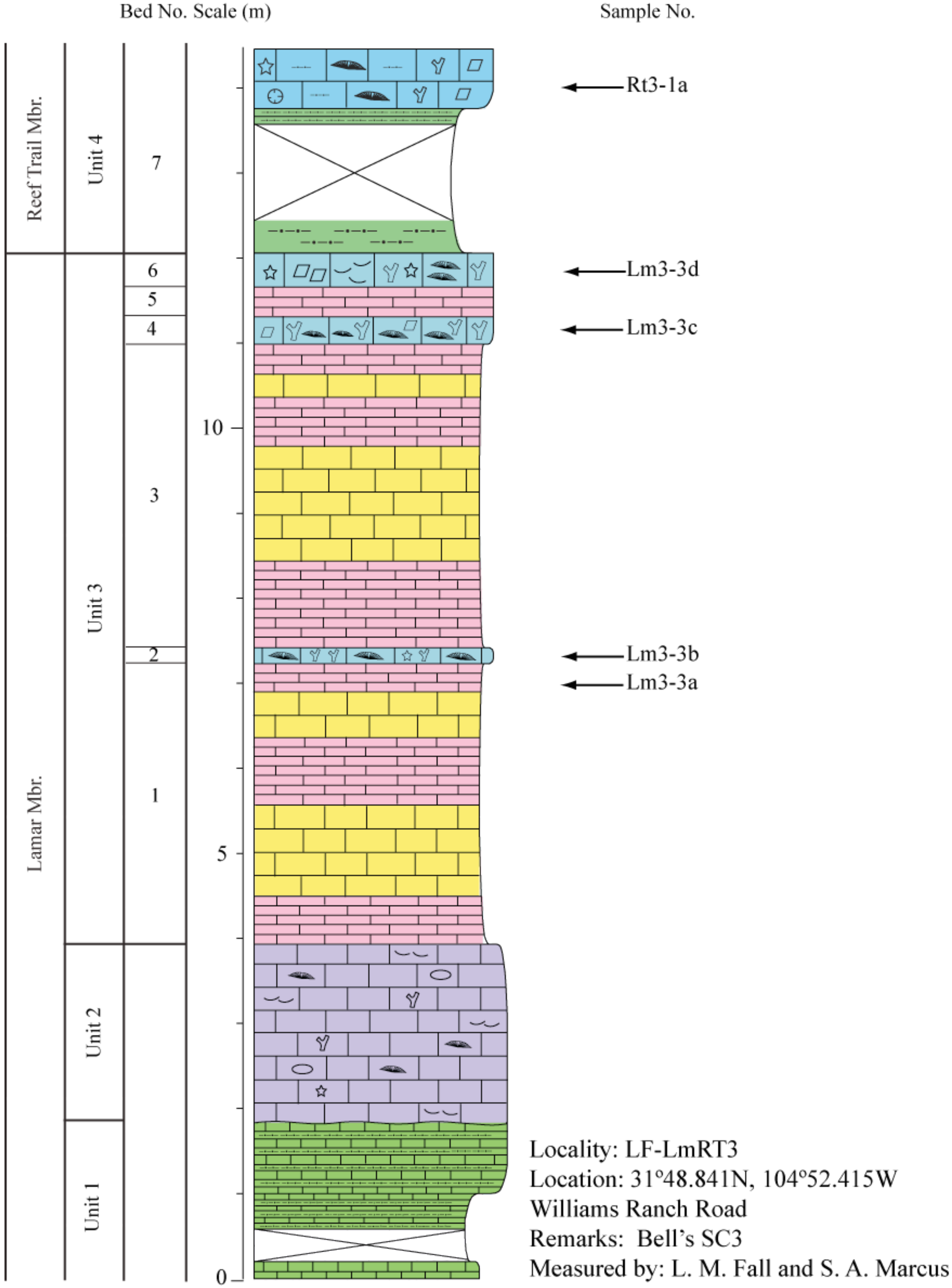
<u>Unit 4</u>: 1000 cm – siltstone, mainly covered interval, float blocks of limestone, but nothing is traceable on outcrop, float blocks with limonite replacing pyrite, siltstone from gopher hole is 10YR 7/4 on weathered surface, 10YR 6/6 on fresh surface, calcite cemented, weathers into a soft slope, even along strike cannot find anything that looks in place, contact with overlying unit is sharp, and placed at point where carbonate beds pick up again

<u>Unit 5</u>: 267 cm – conglomerate, two conglomerates bounding the unit, 34 cm from base of unit to top of first conglomerate, base consists of several beds ranging in thickness from 2 cm to 6.2 cm to 1.2 cm thick with platy beds in between, beds are coarse/fine units, petroliferous, chertified at base, finer at top, wavy (thickens and thins), cannot see grains in places, possible bioturbation, beds are not flat lying (also may be soft-sediment deformation), some fossils in thicker, grainer parts of beds, including rugose coral, shell fragments, crinoid columnal, bryozoan, weather to N6, fresh face is N6, (1) first conglomerate may be several amalgamated flows, 22 cm thick where section measured but 41 cm thick on strike to the north, thins to the south along strike, crinoid columnals, *Domopora*, *Litocrinus*? (microcrinoid), *sample taken here BCRT2-2a*, also saw *Codiacrinoid*, popped off outcrop, anal plate preserved larger, med-bowl to vase shaped cup on outcrop seen, sample taken *BCRT2-CRINO*, may be a crinoid-dominated conglomerate, large columnals see, too, *Punctospirifer*? or rhynchonellid seen, not many brachiopods, *sample* taken *BCRT2-Crino and Crin2*, sparse whole brachiopods, lots of shell fragments, above conglomerate, bedding gets thinner, beds are wackestone, packstone, weather very wavy on outcrop, mostly smaller grains but a few larger fossils (rugose, bryozoan) seen, weathering thin-bedded, thicker coarse/fine beds (5 cm, 6.4 cm, 5.5 cm) underlie conglomerate, these weather more resistantly than underlying thinner (mm-

cm scale) beds, (2) second conglomerate, thins toward the south along strike, again may be amalgamated, 21 cm thick where section measured, along strike to the north, section thickens up, brachiopods seen: ?*Hustedia*, ?*Stenoscisma*, lots of debris, but not many whole brachiopods, beds (can see two on strike) have fine caps, 32 cm thick, along strike, beds of conglomerates become separated by several coarse/fine beds that show bioturbation, wavy contact starts these beds, now have 23 cm of coarse/fine beds, lower conglomerate thickens on strike to the north to 66 cm thick, full of fragmented fossils, still has fine cap, rugose coral seen, *Domopora*, lots of chert, thins and amalgamates along strike to the north again, sharp contact with overlying unit, moved ~36 m to the north along strike following upper contact of Unit 5 because the section became mostly covered, upper bounding conglomerate here is 125 cm thick and may be up to five amalgamated beds, thin partings that look like they bound conglomerates, soft-sediment deformation noted near top of upper debris flow(s) of possible flame structures, definite reef lithoclasts seen, sediments underneath are pinched and squished, can see *Archaeolithoporella* in one clast very well, conglomerate may cut into underlying sediments but very hard to tell if there is any scouring, contact sharp with overlying platy unit, *sample taken here BCRT2b*, *lithologic sample taken ~110 cm to the north and ~20 cm below base of upper conglomerate BCRT2-2lith*, small conglomerate underlies BCRT2-2a, *sample taken BCRT2-2z-07*

<u>Unit 6</u>: 375 cm – coarse-fine unit marks base of mainly thin-bedded limestone before slope gets covered, above coarse-fine layer (3.4 cm), limestone gets very thinly-bedded, 1-2 mm thick, petroliferous, weathers very platy, dark/light layers, light layers coarsens, approximate location of Rigby & Bell's (2005) sponge, fishbones and Rigby & Bell (2005) sponge are in laminated to very fine bedded material, see lots of fishbones, note: under Rigby & Bell (2005) sponge is a small conglomerate to the south along strike ~50 cm, incorporates the underlying thin-bedded material as clasts, coarser-grained, scaphopods, possible sponge, lots of lithoclasts, bryozoans, crinoid columnals, small lithoclasts, second thicker bed has scaphopods, bryozoans, lithoclasts, gastropod, these beds are packstones, above this is a smaller fossiliferous unit (conglomerate?) 6 cm thick, can see: bryozoans, scaphopods, chert, brachiopod fragments, disarticulated shells, probably packstone, *this is probably sample RT2-3-07*, overlain by a series of dark/light beds, pertroliferous, not planar across outcrop, grainy, chert in layers (in light layers), radiolarians in this?, productid brachiopod bed is found ~40 cm above top of Unit 5, has several productids exposed along bedding-plane surface, some productids have been flattened, some may still have some relief, one has spines on the hinge, bed is wavy, ~1 brachiopod thick, grainy, sub-cm scales, convex-side up, then back to platy-weathering, very thin bedded, petroliferous limestone, then a thicker-bedded (~10 cm thick) portion, this weathers to N4 and 5Y 7/2, bed has bedding somewhat interrupted (?bioturbation), stringers of chert, chalcedony, grainer patches with shell fragments, large sponge in base of bed, lots of large hexactinellid spicules, back to very thin beds, beds < 1mm in places, some iron-rich layers, then back to several thicker beds (1 cm, 1.5 cm, 2.5 cm) that thicken and thin along strike, thicker beds

have disarticulated brachiopod shells, sponge or bryozoan, scaphopods, sphinctozoan sponge, bryozoan, lots of fragments, thinly-bedded above these beds, there is a lens of scaphopod-rich (9.3 cm) material that looks like it fines upwards (this is probably the upper scaphopod bed), *sample taken BCRT2-3USB-07*, see lots of scaphopods, some with geopetals, bryozoan, gastropods (low-spire), rugose coral, lens thickens and thins on outcrop in ~ 1m, may be two beds, brachiopod shell (small), brachiopods seen on top of bed, crushed, not identifiable, lithoclasts/stringers of finer material, scaphopods appear to be oriented, none seem to be vertical, other fragments are not oriented, note that scaphopods are in lenses along outcrop and are not in continuous beds, larger beds (thicker) to north along strike, above scaphopod bed, there are several lenses that pinch out and thicken and thin on outcrop, bed to south has lots of scaphopods, chert, very rubbly weathering, appears to have oriented scaphopods, 9 cm thick, draped by thin-bedded, platy limestone, which is above and below these lenses of fossils, laminated in places, dark/light on weathered faces, radiolarians again?, grainy, cannot see difference in grain-sizes for dark/light stuff, lens has lithoclasts, 9.6 cm thick, draped by finer beds, clasts do not look like underlying material, gray-weathering, bed weathers rubbly, lots of unidentifiable fragments, brachiopod or bivalve shell, scaphopod, not continuous on outcrop, ?coral, wavy base, above is platy with some thick-thin beds, petroliferous, weathers N4 (thicker bed 5 mm), also some iron-rich beds, at 259 cm above base is 116 cm thick package of wavy-bedded, thin limestone beds, fresh is N3, petroliferous, weathers to 10YR6/2, beds are grainy in places, lots of fossils, but not in large flows, fossils are fragmentary, shelly material, disarticulated, flattened, see fishbones, brachiopods, wackestone to packstone here, covered above but there are float blocks of coarser, fossiliferous material, and not much else to see in place, conglomerates not in place, grainy areas are in patches and stringers, *sample taken of brown grainy deposit with light ?lithoclasts (very similar to deposit seen in BCRT1) BCRT2-3lith-07 it is ~265 cm above the top Unit 5*



Locality: LF-LmRT3
Location: 31°48.841N, 104°52.415W
Williams Ranch Road
Remarks: Bell's SC3
Measured by: L. M. Fall and S. A. Marcus

<u>LF-BCLm3</u>

<u>Unit 1</u>: 183 cm – interbedded limestone and siltstone, first bed is limestone of 3.6 cm thickness, then recesses back into siltstones, gets more massive, cherty, iron-stained near top, from base, limestone beds first thin (1.1 cm) weathers platy near base, then the limestone becomes more massive, silts are calcite cemented, some friable, weathers to 10YR 7/4, fresh is same, limestone beds are weathered to 5Y 6/1, fresh face is same, some platy weathering near top, 9.4 cm thick beds, beds are wavy, *Hustedia* seen in chert (7 cm) layer near top, rugose coral, shell fragments, crinoid columnal, ?*Composita*, fenestrate and ramose bryozoans, again all very close to top, but not in same layer as *Hustedia*, 14.5 cm from contact, fossils sparse, beds mostly planar but some beds are possibly deformed, small 30 cm thick conglomerate, siltstones may be deformed around bed, thins to 17 cm, thickens to ~32 cm, sharp contact with underlying silts, bed pinches and swells along outcrop, upper contact varies between sharp and wavy, subtle undulations

<u>Unit 2</u>: 210 cm – limestone, massive weathering, some chert nodules, not as layered as in Unit 1, nodules appear to be not oriented, may possibly be replacing burrows in places(?), weathers N6, fresh is N7, sparse fossils include: bryozoans (ramose) and *Domopora*, same iron-staining, brachiopod shell, productid(?), crinoid columnal, tiny *Hustedia*, shell fragments, fenestrate bryozoan, on very weathered surfaces can see coarse/fine layers, contact with overlying unit is sharp

<u>Unit 3:</u>

Bed 1: 330 cm – platy-weathering, thin-bedded to laminated limestone, slightly petroliferous, laminated limestone weathers 10YR 8/2, fresh 10YR 6/2, laminations not straight (crinkly), alternate dark and light, are various thicknesses (still mm to sub-mm), chert in some thicker beds of darker limestone (1.8 cm), some thicker beds with very fine limestone grains in them (2.8 cm), chert, a few grainer beds seen, bryozoan, coarse to fine cycles seen in fresh face, *lithologic sample taken here BCLm3-3a*, sampled beds are 4.3 cm thick, bed continuous on outcrop, several coarse/fine beds overlie where sample was taken

Bed 2: 19 cm – conglomerate, weathers hackly, forms resistant bench, continuous across outcrop, lower contact is undulose and sharp to scoured in areas, walked out bed to the WSW to where it pinches out on outcrop, has a channel-form appearance, has areas of very large fossils, may be amalgamated, looks like there is a fine parting between flows in places, fossils seen on outcrop include: high-spired gastropod steinkern, whole brachiopods including *Martinia*, *Leptodus*, *Composita*, *Hustedia*, *Derbyia*, productid with spines, *Meekella*?, *Domopora*, ramose and fenestrate bryozoans, ?*Punctospirifer*, lots of shelly debris, scaphopod, bivalve, *Reticulariina*, ?*Rhombopora*, rhychonellid, spines (brachiopod or echinoid), finer portions have *Domopora*, crinoid columnals, lots of brachiopods from a coarser portion of the flow, weathering at the base of the debris flow on the underside, bed is 19 cm (where sampled) but thickens to 29 cm and 40 cm on strike, upper contact is wavy/undulose, subtle waves/swells (mm to cm scale), *sample taken here BCLm3-3b*

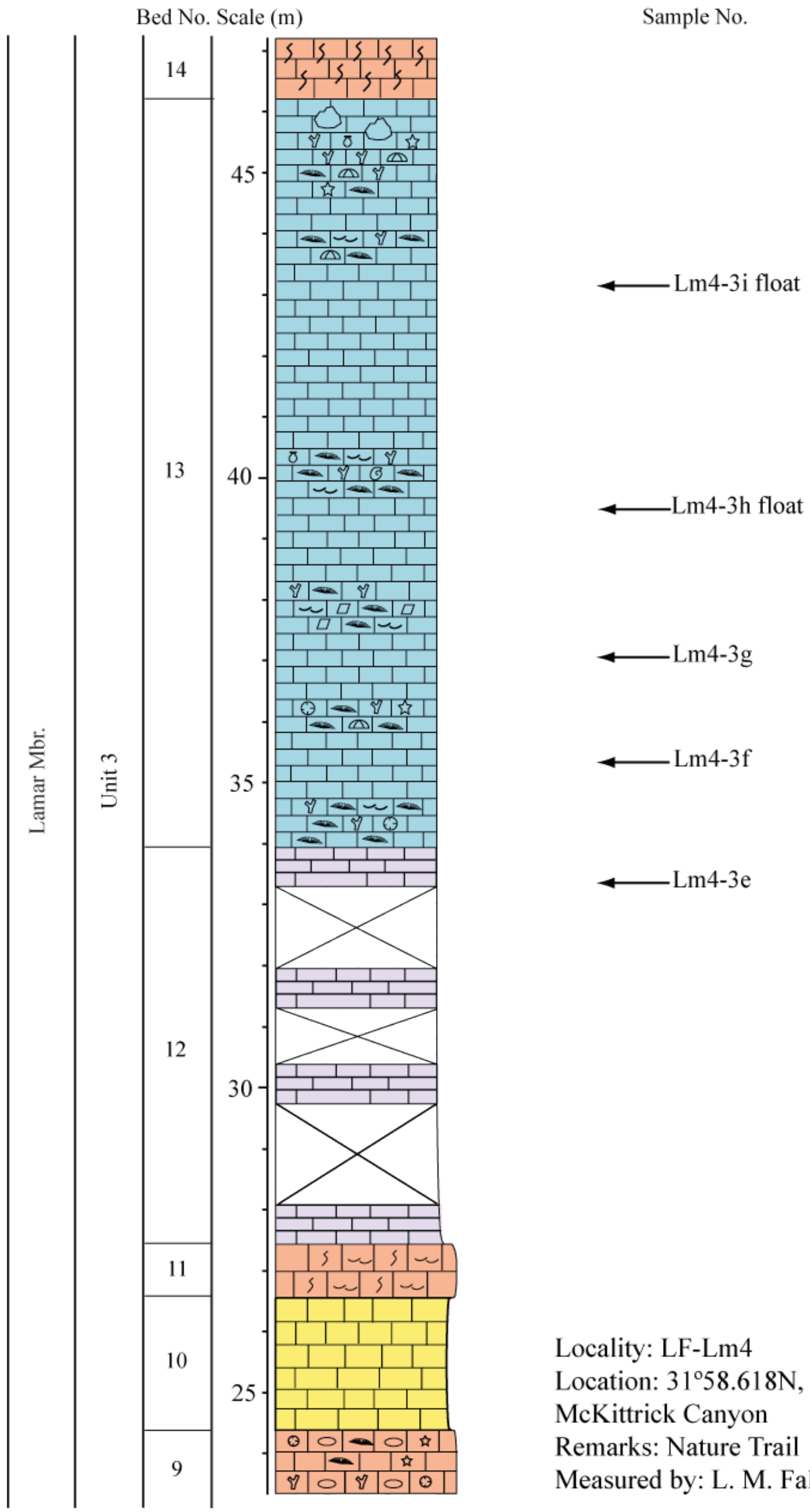
Bed 3: 357 cm – platy-weathering limestone, there are some smaller, fine-grained conglomerates (9.5 cm thick), chert nodules in nodules and stringers, get several thicker conglomerates upsection, some beds are thicker (16.3 cm), coarser, there are very chertified fossils, *Domopora*, shell fragments (8.2 cm thick), chert nodules, echinoid plates, *Domopora*, crinoid columnal, disarticulated brachiopod debris in the second of these two minor conglomerates that are close together, slightly petroliferous, also have clasts/stringers of finer material, overlying beds have very fine calcitic grains (packstone), seem to be coarse/fine couplets, weather platy, may be wackestone, chert layers here, fossils weather out of these, very small fragments, see brachiopod shell fragments, echinoid plate, dark layers are coarser, see very minor scour into underlying light layers, a medium-sized conglomerate which thickens and thins (7.8 cm thick), weathers prominently, grains larger than the smaller conglomerate below, Note: smaller is not thickness, the grains are smaller and they are not prominent on the outcrop, whole bryozoans (ramose, *Domopora*), brachiopod fragments, echinoid and brachiopod spines, chert nodules, ?fusulinid, ?*Composita*, fenestrate bryozoan, rhychonellid?, beds above this conglomerate go back to coarse/fine thick and then to very platy and thin-bedded, back to sub-mm scale, not like laminations below, slightly petroliferous

Bed 4: 32 cm – conglomerate, bed thickens and thinks on outcrop, pinches out on outcrop to the SW, looks superficially like a channel, very coarse where measured, bed to the SW-NE thickens from pinch-out to 3 cm to 17 cm to the NE to 32 cm where measured, seen on outcrop: clasts, abundant *Domopora*, large ramose bryozoans, disarticulated brachiopods, whole brachiopods include: *Hustedia*, *Composita*, *Reticulariina*, *Meekella*, *Punctospirifer*, *Chonetinetes*?, bivalves, areas of small brachiopods, *Acanthocladia, sample taken here BCLm3-3c*

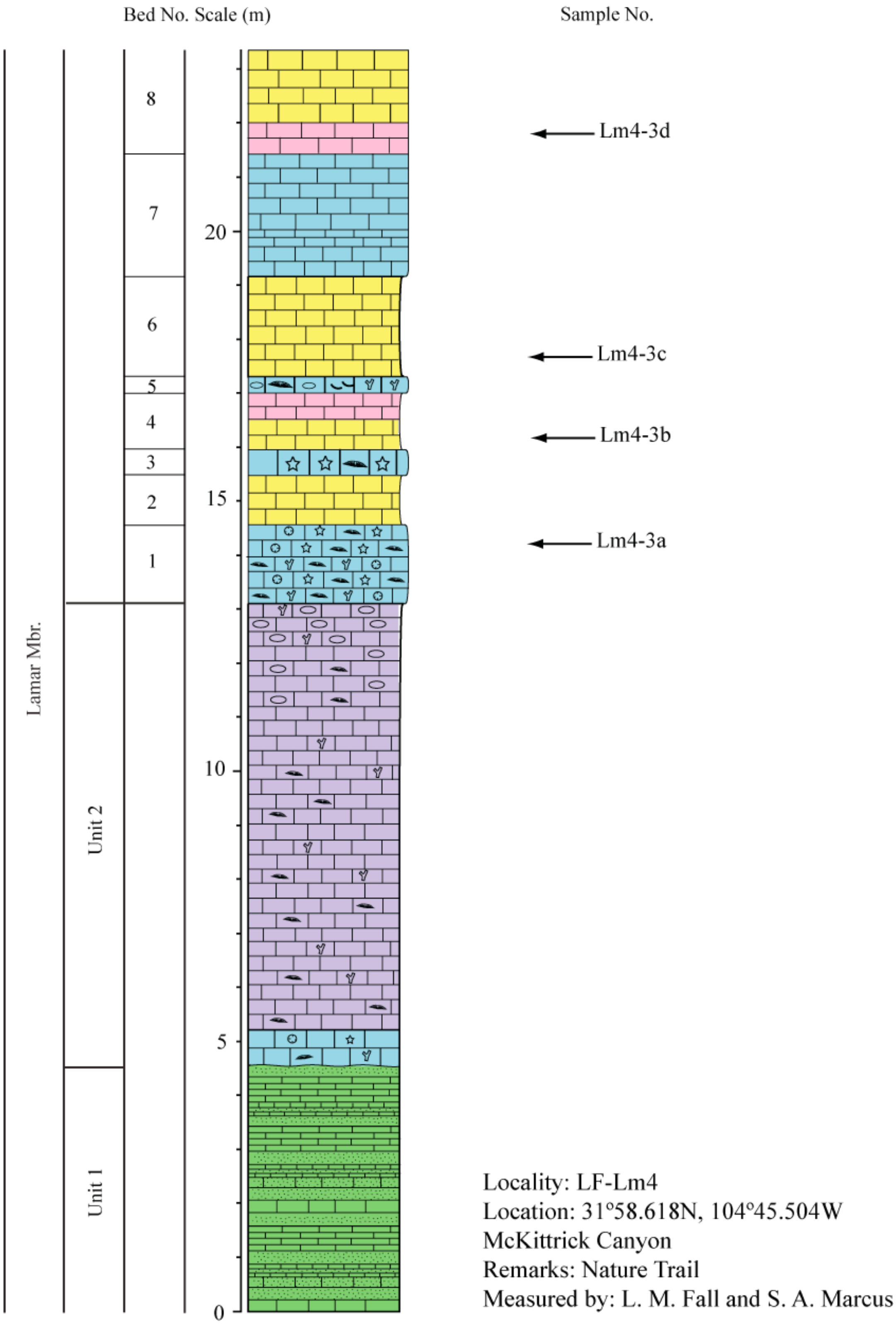
Bed 5: 35 cm – platy-weathering limestone, some thicker beds in section again, may be turbidite-style deposition with coarser beds, fining upwards, chert in this bed, replacing fossils, bed ~4 cm, persistent on outcrop (others pinch out?), very fine fossil fragments make coarser portion of bed, weathers slightly resistant, then, more very platy beds, then platy units drop almost totally below a 7.7 cm thick bed that is possibly a turbidite, chert in layer may be replacing fossils, shell fragments in bed (brachiopod bits), toward very top of Unit 3, there is a thicker (5.8 cm) conglomerate with larger fossils than below (except for other conglomerates), fossils seen include: *Domopora*, large spirifer, ?*Derbyia*, *Hustedia*, ramose bryozoans, large chert layers, getting close to top of outcrop, exposures getting limited due to fault and slumping

Bed 6: 40 cm – conglomerate, massive-weathering, thickness varies on outcrop, bed likely amalgamated, looks like parting between two conglomerate (fine layer), weathers hackly, jointed, N6 weathered in color, N6 to N7 on fresh, *sample taken here BCLm3-3d*, sampling upper part of debris flow, fossils seen on outcrop: crinoid columnals, ?*Derbyi*a, *Domopora*, many brachiopod shell fragments, lots of clasts (lithoclasts) in upper portion of unit, lots of chert, some bioturbation noted at top of bed, *Hustedia*, most brachiopods are disarticulated, bed fines upwards, echinoid spines

Unit 4: 410 cm – top floats, 170 cm covered/silt at base, weathers back as flat area, recessive weathering, 70 cm conglomerate, weathers massive as bench, these look like amalgamated flows with silty beds near the base, beds weather massive to rubbly, fossils include: *Domopora, Derbyia, Composita*, rugose coral, ?bivalve, lithoclasts, crinoid columnals, ?rhychonellid, *Martinia, Acanthocladia*, ramose bryozoans, *Hustedia*, spirifers, coarser at the base, finer at the top, fines into silt, bed varies in thickness to ~110 cm thick, conglomerates vary from place to place, bed is jointed, weathers to 5Y 8/1, fresh is 5Y 8/1 and N7, *sample taken here RT3-1a*



Locality: LF-Lm4
Location: 31°58.618N, 104°45.504W
McKittrick Canyon
Remarks: Nature Trail
Measured by: L. M. Fall and S. A. Marcus


Bed No. Scale (m)
Sample No.
Lamar Mbr.
Unit 2
Unit 1
8
7
6
5
4
3
2
1
20
15
10
5
0
Lm4-3d
Lm4-3c
Lm4-3b
Lm4-3a
Locality: LF-Lm4
Location: 31°58.618N, 104°45.504W
McKittrick Canyon
Remarks: Nature Trail
Measured by: L. M. Fall and S. A. Marcus

<u>LF-BCLm4</u>

<u>Unit 1:</u> 455 cm – interbedded sandstone and limestone, limestones may be sandy, thick bedded at base, resistant, forms bench above sandstone, beds at base are ~60 cm thick, amalgamated, first bed is ~34 cm thick where measured, limestone, has iron blebs (small nodules) scattered in bed, strikes N40º dips 6º, sandstone is 10YR 7/4, calcite cemented, limestone layers have stringers of iron and chert nodules, there are lenses of limestone in the sandstone, see some fossil grains: crinoid columnals and bryozoans, fossils are silicified, very fine fragments, the lenses are discontinuous on outcrop, can see what may be mica flecks but not individual sand grains so sandy limestone is our call, get limestone/sandstone interbeds, sandstone is bedded, calcareous, varies in thickness on outcrop, sandstone unit in ~middle of bed is ~80 cm where measured, has thinner beds (cm-scale) within, limestone stringers near top of sandstone bed, near top of bed limestone begins to dominate, pick up possible small conglomerate with lithoclasts, chert in small nodules, what probably were fossils, mainly not identifiable, see a few bryozoans (*Acanthocladia*), crinoid columnals, limestone units weather to N6-N7, on fresh face N6 to N5, wackestone, beds ends where last sandstone occurs under limestone, sharp and undulatory contact with overlying limestone, traced along strike (gets covered) resumed measuring ~6m north along strike to go up wash where more continuous outcrop is exposed, there is ~19 cm more of Unit 1 here below conglomerate that marks start of carbonate units above, uppermost beds of Unit 1 are carbonate beds, thin-bedded, may have sandy limestone, fossils in these beds, see bryozoan, fossil fragments, not identifiable

<u>Unit 2</u>: 855 cm – mainly massive limestone, mudstone to wackestone, base of unit is conglomerate, ~95 cm thick, cherty crinoid columnals, ramose bryozoans, rugose corals, *Domopora*, other bryozoans seen (common), brachiopod (?rhynchonellid), *Hustedia*, crinoid stalk pieces (several columnals), ?spiriferid, brachiopod spines, bryozoans and crinoid bits seem to be most abundant, limestone weathers at base to N5, bit of 10YR 7/4 and 10YR 8/2, fresh face is N6-N7, above this unit is massive limestone, , some sparse fossils (wackestone), slightly above conglomerate are some brachiopods weathering out (*Hustedia*, spirifers), several "floating" in ~same layer, sparse fossils in massive beds (bryozoans, brachiopod pieces), chert nodules, stylolites noted, also another rhynchonellid or spiriferid, chert nodules appear scattered and in zones, this bed weathers N6 to N5 here, some iron staining around cherty areas, fresh face 10YR 6/2 to N7/N6, limestone is mainly micritic, *Punctospirifer* noted, brachiopod fragment seen in chert nodule, towards top chert becomes more abundant, picking up possible bioturbation, top of unit is very similar to rest of unit otherwise, sharp contact with overlying unit, massive unit is a cliff former here, and overlying unit is more bedded and platy

<u>Unit 3:</u>

Bed 1: 146 cm – massive-weathering conglomerate on the trail, thinner-bedded limestones with platy-weathering intervals that have smaller-scale bedding, strike N315º, dip 12º, massive conglomerate thickens and thins on strike, can see zones of

more fossiliferous portions, fossils seen include: *Meekella*, large rugose corals, *Acanthocladia*, *Hustedia*, *Domopora*, crinoid columnals, cherty, *Rhychopora*?, lithoclasts (possibly underlying lithology), brachiopod shells, ?*Spiriferella*, ?richthofenid, stylolites where coarse layer meets finer, ?*Wellerella*, *Derbyia*, *Punctospirifer*, many different kinds of bryozoans, very diverse group of fossils, *sample taken* here *BCLm4-3a*

Bed 2: 92 cm – thicker, centimeter-scale limestone beds with chert layers, platy interbeds, then finer-grained beds, finer-grained bed has fossil fragments, bryozoan fragments are very fine, bed fines upwards

Bed 3: 47 cm – conglomerate, contains crinoid columnals, lower portion fines upwards, then there is a coarsening-upwards portion to the top, mainly crinoidal, see brachiopod shell, *Hustedia*, more brachiopods at base in coarse to fine, too, crinoid packstone in coarse upper layer, *sample taken* here *BCLm4-3b*

Bed 4: 105 cm – fine-bedded limestone, then another very fine crinoidal layer/bed, then fine limestone, platy-weathering beds, these beds are petroliferous, weather on millimeter scale in places, both thicker-bedded limestone and platy beds have chert in them, see crinoidal material and bryozoans in finer-grained conglomerate or coarse/fine layers, chert is layered in places, sharp and continuous contact

Bed 5: 35 cm – conglomerate, large chert nodule near top, crinoid columnals, ?*Composita*, shell fragments, bryozoans (*Domopora*), on fresh face can see more bryozoans and brachiopod shells but not identifiable, *Hustedia*, mainly incomplete brachiopod fragments, sharp contact, *sample taken here BCLm4-3c*

Bed 6: 185 cm – mainly laminated limestone, not petroliferous, laminae are alternating dark-light, some layers have very fine fossil fragments, noted crushed, road-kill brachiopods on some bedding surfaces, sparse where found, layers with chert, iron-staining, top of unit is more massive, not laminated, fossiliferous, *Acanthocladia*, chert nodules, *Domopora*, crinoid columnals, rugose coral, very small lithoclasts, see brachiopods in cross-section, ?*Composita*, *Hustedia*, contact with overlying beds looks gradational, may cut out some underlying laminated beds

Bed 7: 231? cm – 26 cm thick conglomerate, packstone, fairly fossiliferous, see bryozoans (*Domopora*, *Acanthocladia*), *Hustedia*, ?spirifer, encrusted *Hustedia*, crinoid columnals, rhynchonellid, larger brachiopod shell fragments, abundant bryozoans, may have finer base, chert nodules, larger at top of bed, 17 cm thick conglomerate, wackestone, has fewer fossils weathering out, *Acanthocladia*, *Domopora*, brachiopod in cross-section, chert in nodules near top, may be following burrows, bioturbation noted at top of bed, *Hustedia*, 15 cm finer limestone with possible dissolution seams, few bryozoans and shell fragments, 139 cm limestone, fine limestone with some fossils, fossils in lenses and patches, weathers different in places, soft-sediment deformation in one areas, in laminated zone that has gotten squeezed between layers, dark/light laminated layer lithology, conglomerate and fossils along strike, fossils include: large crinoid columnals, bryozoans abundant (*Domopora*), rhynchonellid, brachiopods are sparse, rugose coral, brachiopods in cross-section, chert nodules, there are stylolites, they may be zones of dissolution, has a few chert nodules, too, *sample taken here BCLm4-3d*

Bed 8: 192 cm – laminated limestone, weathers mostly massive but also a little platy, chert layers, some bedding planes expose crushed brachiopods that are not identifiable, laminations and very small scale bedding are dark/light in banding, petroliferous, very similar to bed measured lower in unit with same lithology

Bed 9: 105 cm – grainy limestone, several beds amalgamated together, massive amounts of chert near center of bed, see crinoid columnals, rugose corals, bryozoans (*Domopora*), brachiopod shells seen but not identifiable due to chert, spiriferid or rhynchonellid seen, in second area of grains, see crinoid columnals, stylolites seen, large chert nodules, not much else

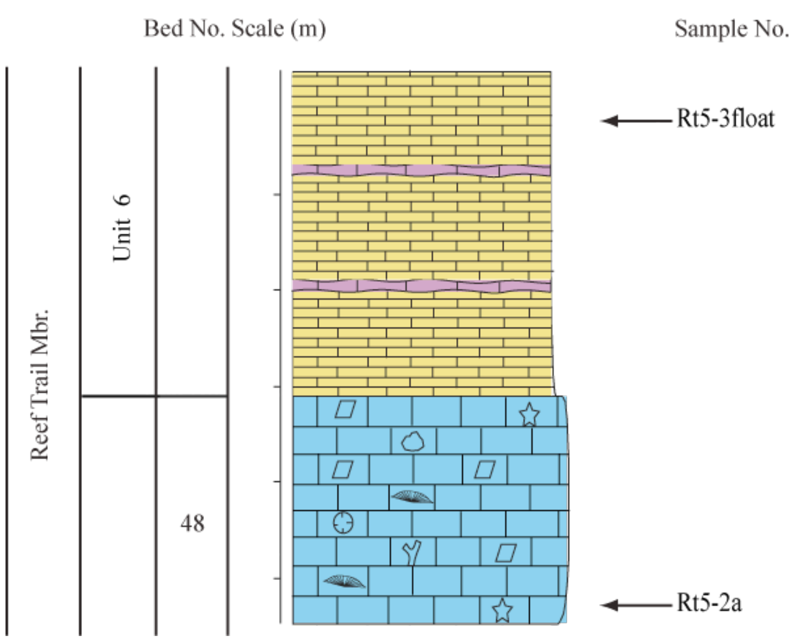
Bed 10: 217 cm – limestone, portions of bed are micritic and massive, laminated at base with dark/light laminae, goes into thicker-bedded "ribbon rock" look, lighter band 6mm, darker 2mm near base, stylolites, chert nodules on sub-millimeter scale, bands become wavy near top of unit, no fossils seen, strike 100°NE, dip 2°

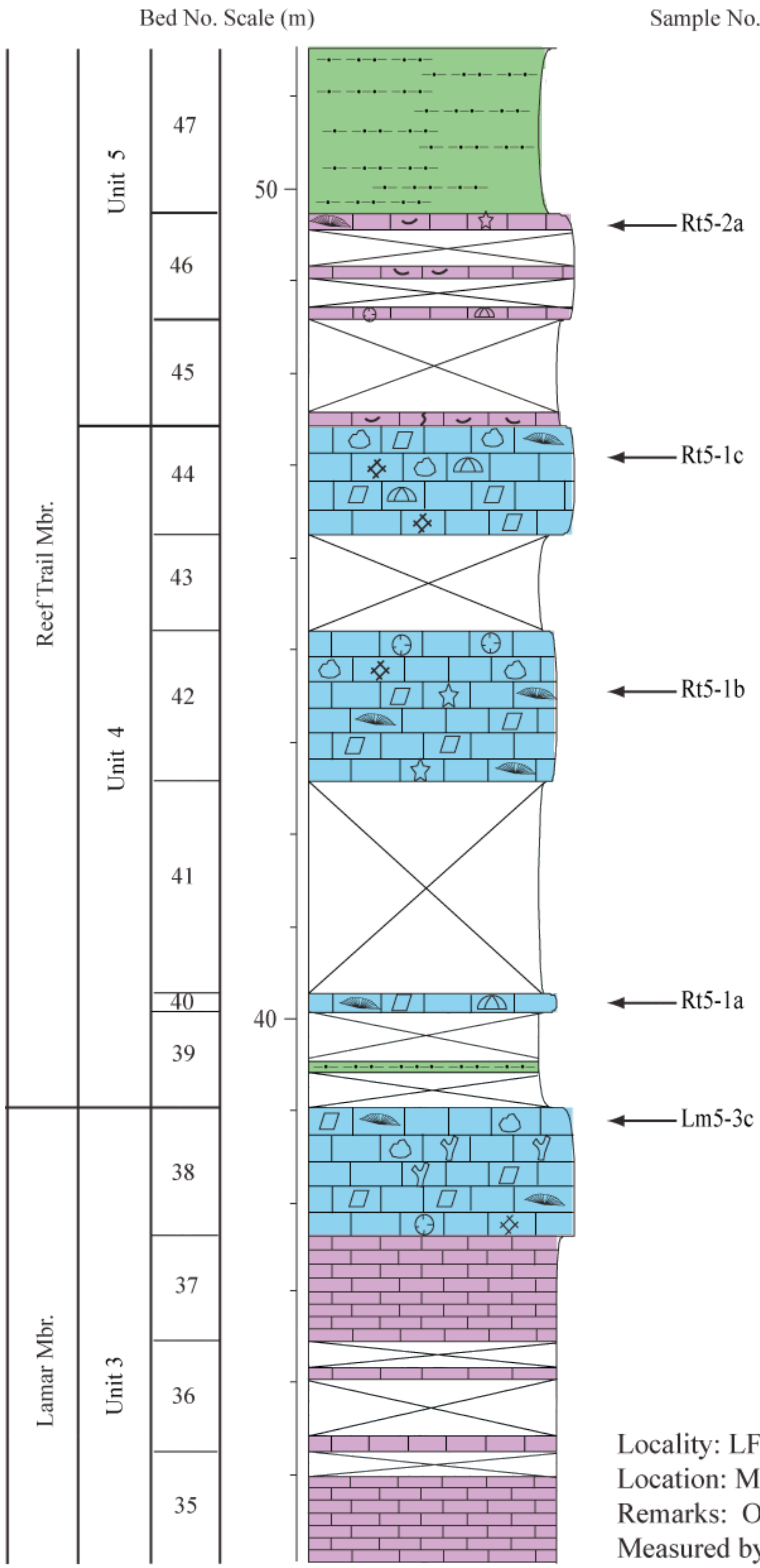
Bed 11: 88 cm – massive, with chert and fossils, very few at top of bed, bioturbated with burrows at top of bed, small chert nodules below at sub-millimeter scale, larger chert nodules at top, many follow burrows, few fossils floating in unit, weathers out as consistent bed/bench on outcrop, sharp upper contact, marked by bioturbation/chert

Bed 12: 650 cm – mainly thin, grainy beds with lots of chert, may be finer beds in between, mostly rubble, chert nodules large, shelly fragments of brachiopods, bryozoans, crinoids seen in thinner (~10 cm) grainy beds, finer beds seen in places overlying chertier, grainer beds, looks like it's draping grainy beds, grainy beds to from wackestone to packstone, most fragments are small, occasionally large fossils seen: *Composita*, *Domopora*, other bryozoans, crinoids seem to be less abundant here, beds not continuous on outcrop (hard to trace), thickness varies, grades upwards in thickness until a fairly continuous massive bed that thickens and thins on outcrop

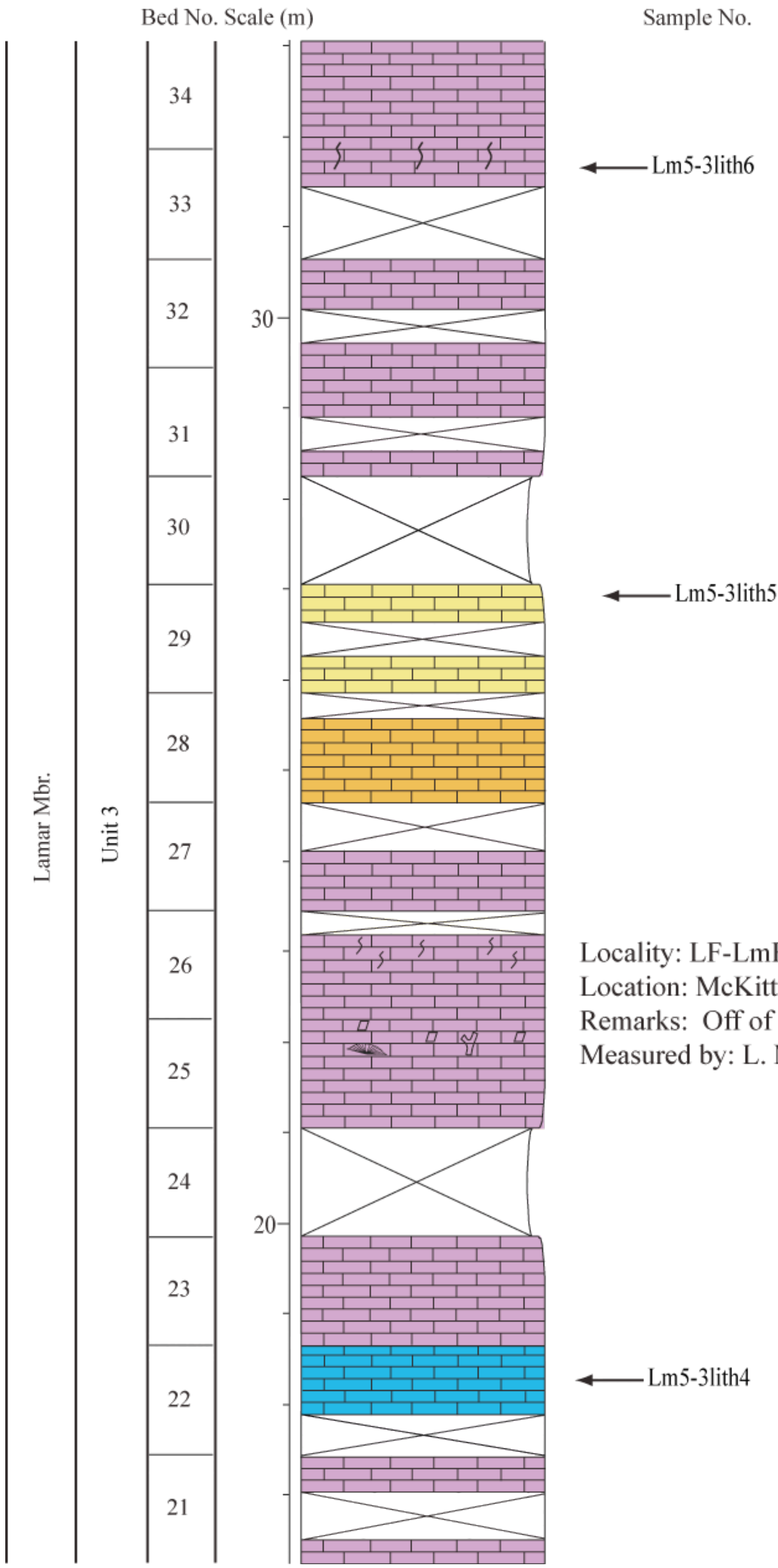
Bed 13: 1227 cm – 36 cm thick conglomerate, rhychonellids, rugose coral, crinoid columnal, *Domopora*, other byrozoans, *Martinia*, ?C*omposita*, echinoid plate, disarticulated brachiopod shells, parts grainer, *sample taken here BCLm4-3e*, 24 cm thick conglomerate, may be amalgamated, cherty, see *Martinia*, *Domopora*, rugose coral, crinoid columnals, unidentifiable brachiopod shells in cross-section, draped with fine bed that separates it from overlying conglomerate, also see large rhynchonellid, shell fragments, large echinoid plates ~1 cm across, spirifer, *Hustedia*, ?*Punctospirifer*, chert nodules are large, mainly near top, zone of brachiopods along strike (rhynchonellids, *Hustedia*, spirifers), *sample taken here BCLm4-3f*, xx cm thick conglomerate, lithoclasts of lighter sediment, large, mainly at top of bed, rugose coral, separated from underlying conglomerate by very small (centimeter scale) bed of fine material, bryozoan fragments (*Domopora*), brachiopod shells in cross-section, shell fragments, spiriferid or rhynchonellid pieces, *Derbyia*, echinoid plates, *Hustedia*, fossils come and go on outcrop, parts look brachiopod-rich, parts are bryozoan-rich, thickens off trail along strike to the southwest, fine bed above with cherty layer, see laminations in these lithoclasts, may be incorporating layered, finer sediments, see more brachiopods where sampled, *sample taken here BCLm4-3g*, remaining thickness is a zone of conglomerates, not traceable on outcrop, platy-to-slabby weathering limestone beds also in this interval that are not fossiliferous, where conglomerates are cropping out, there are pavements of fossils, described surfaces as move upsection, surface 1: *Hustedia*, *Domopora*, *Martinia*, *Punctospirifer*, ?*Stenoscisma*, brachiopod fragments, rhynchonellids, *Composita*, lots of large, weathered brachiopods, float pieces have possible bivalves, *sample taken here BCLm4-3h (float)*, higher up, see spirifers, zone of bivalves, first gastropod?, *Meekella*, rhynchonellids, *Martinia*, small brachiopods seen also, spirifers, *Composita*, *Acanthocladia*, crinoid columnals, *Hustedia*, *Derbyia*, whole weathered brachiopods in this zone, platy-weathering beds have zones of laminations, stringers of fossils with finer grains, few millimeters to centimeters thick, fossils not see on platy surfaces (above and slightly up-dip from surface 1), mold of butterflied bivalve in platy bed, not sure if same as in brachiopod beds, bivalves may increase in abundance as move upsection, abundant brachiopods, reef rubble (possibly not in place), sample taken here BCLm4-3i (float), zones of very coarse fossil debris that weather out as spectacular brachiopods and other fossil pavements, some pavements show echinoid spines that look aligned, crinoid columnals, *Acanthocladia*, brachiopods are mainly fragments, echinoid spines and plates are abundant, also can see coarse/fine beds but not like turbidite-style deposition, can see stringers of fossils in finer material and finer material worked into coarser material, 115 cm thick conglomerate on top of the overall conglomerate bed contains many whole brachiopods, dip-slope exposure, *Martinia*, *Lissochonetes*, rugose coral, *Domopora*, crinoid columnals, *Hustedia*, large ramose bryozoans, disarticulated brachiopods, *Reticulariina*, *Punctospirifer*, *Composita*, *Acanthocladia*, bivalves, *Derbyia*, bored *Martinia*, clasts of reef rubble, bioturbated unit that probably correlates across canyon overlies bed

Locality: LF-LmRT5
Location: McKittrick Canyon
Remarks: Off of Permian Reef Trail
Measured by: L. M. Fall and S. A. Marcus

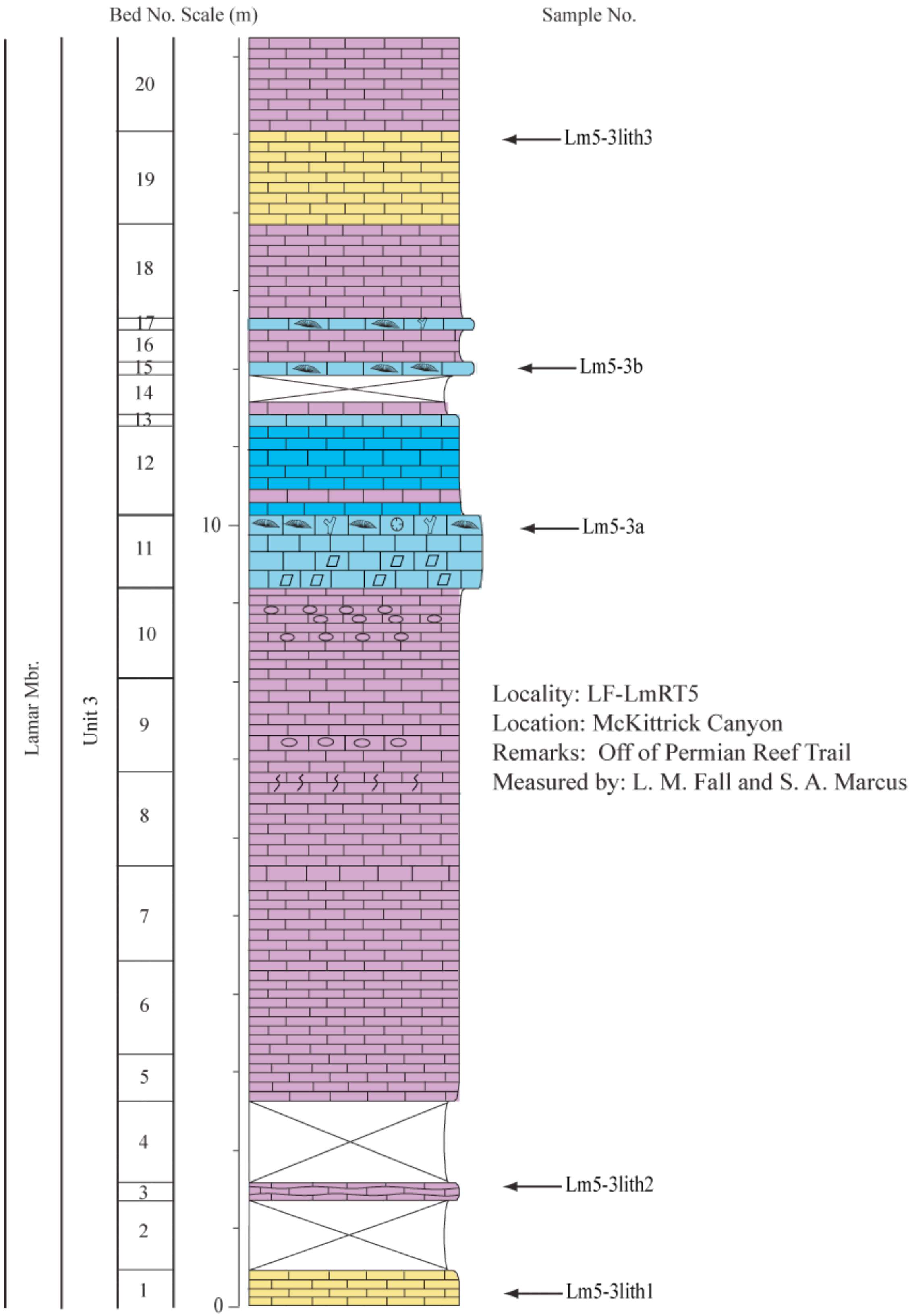




Locality: LF-LmRT5
Location: McKittrick Canyon
Remarks: Off of Permian Reef Trail
Measured by: L. M. Fall and S. A. Marcus



Locality: LF-LmRT5
Location: McKittrick Canyon
Remarks: Off of Permian Reef Trail
Measured by: L. M. Fall and S. A. Marcus



Bed No. Scale (m)
Sample No.
Lamar Mbr.
Unit 3
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
10
0
Lm5-3lith3
Lm5-3b
Lm5-3a
Lm5-3lith2
Lm5-3lith1
Locality: LF-LmRT5
Location: McKittrick Canyon
Remarks: Off of Permian Reef Trail
Measured by: L. M. Fall and S. A. Marcus

LF-BCLm5

Unit 3

Bed 1: 45 cm – slabby-weathering limestone beds, 2-3 cm thick, capped with 9 cm thick beds, limestone on weathered face is between N4-N5, petroliferous, no visible grains seen on outcrop or broken surface, fresh face is between 5YR6/1 and 5Y6/1, *lithologic sample taken here Lm5-3lith1*, thin chert layers present in beds, ~6-7 mm in thickest area, 1-2 mm where thin, tops of bed weather smooth, upper bed (thicker bed) discontinuous but traceable along strike, ~5-10 m, basal beds are ~45 cm thick

Bed 2: 90 cm –covered

Bed 3: 23 cm – platy-weathering limestone, resistant, consists of base benched back, then 4.7 cm, 2.8 cm, 3 cm thick beds, wavy contacts, where amalgamated, bed is thicker (23 cm), weathered surface is 5Y6/1, thin stringers of chert, some beds weather very thin-bedded (almost laminated), some very fine grains seen in upper portion of bed, not seen in fresh face, fresh face is 5Y6/1, slightly petroliferous, *lithologic sample taken from top of bed Lm5-3lith2*

Bed 4: 105 cm – covered/slumped.

Bed 5: 60 cm – massive to platy-weathering limestone, very platy on outcrop, weathered surfaces show laminations, bed is discontinuous on outcrop, some chert in thin, discontinuous layers, looks like previous described bed, weathered face 5Y 6/1, no visible grains in fresh face, fresh face 5YR 6/1

Bed 6: 120 cm – massive to platy-weathering limestone, small bed included

Bed 7: 120 cm – massive to platy-weathering limestone, massive bed at top with chert, still looks like lower beds

Bed 8: 120 cm –bioturbated limestone, bed is 4.5 cm thick, burrows are mainly vertical, exposed well on outcrop tops of bed, can trace bed on strike, slightly petroliferous, burrows are centimeter scale, can see horizontal, possibly branched burrows in float

Bed 9: 120 cm – massive to platy-weathering limestone, thick bed of limestone, chert on top and some nodules, possibly fossil seen on outcrop, thinner beds and platy beds weather out, there is a lot of cover

Bed 10: 115 cm – beds up to base of conglomerate show very similar features to beds previously described, some areas of laminations, some thicker-weathering, chert in layers/nodules, some beds up to ~+20 cm thick, possibly some burrows

Bed 11: 95 cm– conglomerate, contact is sharp with underlying unit where seen on outcrop, massive weathering, abundant fossils, large, white brachiopods seen, crinoid columnals, chert nodules, *Hustedia, Crurithyris,* ?*Crenispirifer*, *Domopora*, rugose coral, echinoid plate, *Martinia*, brachiopod dominated, lots of disarticulated shells in some areas seen inside view, see *Composita*, *Martinia* dominated, see large spirifers, *Derbyia*-like brachiopod, small spirifers, *Thedusia*, branching bryozoans, *Acanthocladia*?, one flat gastropod? *Euomphalus*. very continuous to the NE along strike, it changes and has a thinner brachiopod-dominated top, and a thicker unit with lithoclasts and much sparser fossils at the base, lithoclastic unit has lithoclasts on several cm-scale, rounded clasts, see crinoid debris, echinoid spine, fenestrate and ramose bryozoans, few brachiopods *Hustedia*, overlying brachiopod-rich bed may scour into the lithoclastic unit, *sample taken ~where section is measured bed is massive and hard to find a place to sample BCLm5-3a (three pieces, fourth piece was taken ~50 cm a way)*, bed where sampled is ~95 cm thick, weathered face of debris flow is covered with brachiopods where measured, mottled, N5, 10YR 7/4, N6, fresh surface N6-N7

Bed 12: 113 cm – smaller limestone beds, 11 cm lime mudstone, small conglomerate/coarse layer above fine layer, brachiopods, gastropods, mainly smaller grains, may have some whole brachiopods, whole brachiopods seen, some fossils may still be calcite-preserved darker, some are silicified, bed is ~7.5 cm thick, another bed of lime mudstone, ~7.5 cm thick, no fossils seen, 10 cm thick bed of lime mudstone in this interval near top, no fossils seen, between beds and along outcrop is slumped, covered, assume these beds are actually continuous and in contact

Bed 13: 15 cm – conglomerate, thickens along strike to the NE, there seem to be several conglomerates along strike, hard to trace small, individual beds, where measured, 15 cm bed that has fossils at the base and a fine cap, brachiopods?, fossils not oriented, whole and disarticulated, *Domopora*, *Martinia*? in base of layer

Bed 14: 50 cm –limestone and covered interval, within interval is another brachiopod-rich conglomerate, see spirifer, ?*Crenispirifer*, *Martinia*?, silicified brachiopod that looks like bivalve, ?*Composita*-like brachiopod, not oriented, finer cap

Bed 15: 18 cm – coarser conglomerate, echinoid plate, *Domopora*, ?*Martinia*, fewer brachiopods than lower beds, some stylolites seen along strike, below coarse layers, moved NNE along strike because one or more of these brachiopod beds (likely top bed) gets a lot thicker, ~4-5 m on strike, bed is 45 cm thick, see spirifers, *Domopora*, crinoid columnal, chert, *Martinia*, not oriented, may have another conglomerate on top, ~12 cm thick, along strike, see echinoid plate, crinoid columnal (very rare), many brachiopods, up to ~58 cm thick, see ?*Leiorhynchus*, *Martinia*, lots of other brachiopods, spirifers, *Derbyia*?, not oriented, leptodid brachiopod, *sample taken near top of bed BCLm5-3b*

Bed 16: 40 cm – dark limestone, few fossils seen, 'floating' echinoid spine, contact with overlying unit is sharp, wavy/undulatory where seen, partly covered/slumped on strike, not traceable very far

Bed 17: 15 cm – conglomerate, very brachiopod-rich where measured, see bryozoans, ?*Martinia*, spririferids, not oriented (concave up and down), large brachiopods, disarticulated, fines along strike to the NE, top gets fine, see *Hustedia*, fossils floating in it along strike, not traceable for more than 12 above this bed

Bed 18: 120 cm – platy-weathering, dark limestone has some fossils that are larger, fossils are patchy/floating, chert nodule, bed is 13 cm thick, fossils are brachiopods, disarticulated, not oriented, very localized, bed not really traceable on strike

Bed 19: 120 cm – beds get darker, a few grains seen, weather rubbly/slabby, laminations are seen on float blocks, but not on fresh faces, or on most of the weathered outcrop, *lithologic sample taken at top of this measured interval BCLm5-3lith3*

Bed 20: 120 cm – massive to platy-weathering limestone, very top of bed is a very local fossil patch, ramose bryozoans, some broken brachiopod shells, no orientation, 5 cm thick, not traceable on strike

Bed 21: 120 cm – dark limestone, few floating fossils seen near base of this interval, mainly covered

Bed 22: 120 cm – mainly covered near bottom, dark, wavy-to-rubbly weathering limestone with caliche weathering and some chert, *lithologic sample taken here BCLm5-3lith4*

Bed 23: 120 cm – platy-to-rubbly weathering dark limestone, slightly petroliferous, in ~center of interval is a bioturbated unit, cherty, possible chert replacing burrows, gives rock mottle texture, not traceable on strike

Bed 24: 120 cm – covered, lots of float

Bed 25: 120 cm – near base has limestone that has an almost septarian nodule-like appearance in places, possibly a little fossiliferous area, cannot identify fossils, possible brachiopods, crinoid columnal?, above that may be burrowed, lots of chert, note some limestone weathers very hackly see lots of float of this, other beds weather very smooth, hackly looks darker, too, along strike see very small fossil grains in ~same bed as described above, see *Acanthocladia*, pieces of brachiopod shells, *Domopora*, lithoclasts all very small, lots of chert

Bed 26: 120 cm – at/near base has veined limestone (looks septarian again), few chert blobs, covered until just below top of interval, bioturbated near top

Bed 27: 120 cm – mostly covered, small dark limestone bed as described below with platy/rubbly weathering

Bed 28: 120 cm – darker limestone with bedding seen, beds/laminae or thick/thin or coarse/fine layers, very thin platy beds weathering out seen on outcrop here, possibly silt in these beds(?), mostly covered to top

Bed 29: 120 cm – very thinly laminated, platy-weathering beds near base, look like "zebra-striped" rocks, moved along strike to the SW several meters to see this bed, breaks along beddings, *small lithologic sample taken BCLm5-3lith5*, mostly covered, some hackly-weathering limestone, may be in place(?)

Bed 30: 120 cm – cover, same limestone kinds of float, hackly stuff and smooth stuff

Bed 31: 120 cm – few limestone beds outcropping, dark, possibly bioturbated, wavy-rubbly weathering, no fossils seen, lots of cover

Bed 32: 120 cm – same as last interval

Bed 33: 120 cm – covered near base, actual outcrop near top, bioturbation noted, some very fine fossil grains seen, possibly calcitic?, crinoid columnal, beds weather in the 10-12 cm thick range, *lithologic sample taken from slightly grainy bed BCLm5-3lith6*

Bed 34: 120 cm – platy-to-wavy dark limestone as previously described, dark/light layers on cm-scale, above is bioturbated, small local fossil areas, some larger brachiopods "floating" in bed, beds not traceable for long distance on strike (few meters), beds a little thicker (13-15 cm thick), local chert, much more bioturbation seen in places, picking up more fossils now

Bed 35: 120 cm – base mottled/bioturbated, dark limestone ~middle of unit is small bed with whole brachiopod valves (not oriented), other parts of this bed as traced on strike have "floating" shells, some along strike (NW) are smaller, oriented, chert in nodules and layers, bed is ~12 cm thick where measured, thickened on strike to NW, covered above this bed

Bed 36: 120 cm – near base of interval, fossiliferous bed benches out, has fine cap, brachiopods large, bed is ~ 25 cm thick above mostly covered may have one limestone bed

Bed 37: 113 cm – gray, pretty featureless limestone at top, covered up to that point, beds are massive (no bedding seen), platy to wavy limestone

Bed 38: 138 cm – conglomerate, lithoclasts of featureless limestone, reef-rubble clasts, broken-up scattered fossils, including brachiopods, bryozoans (ramose), sponges, crinoid columnal, lithoclasts are many different lithologies, bed thins on strike to the NW, fossils tend to be broken and not concentrated, one lithology has some calcite fossils and some silicified, fossil hash in places, bed is a real mish-mash, measured at 108 cm at NW end, lower portion has both silicified and possibly calcitic fossils, *Domopora*, lithoclasts, brachiopod shells, spirifer, lithoclasts 7.5 cm, rugose seen, scattered fossils, in one area, there are small brachiopods that look like they are possibly all the same and associated with a reef-texture area, also areas of sponges, still in reef clast too, NW end is 108 cm thick, SE on strike is 205 cm thick, top of bed has lithoclasts subrounded to subangular, sizes are 9 cm long and color is 10YR8/2, 3 cm (rounded) and 5Y8/1, 11 cm long and color is 10YR8/2 to 10YR8/6 (subangular), moving SE on strike, see brachiopods (*Hustedia*) mixed in with lithoclasts, also saw rugose coral, more sponges in reef lithoclast, more lithoclasts at top of bed here, more angular sizes are 8.3 cm long and N8 (angular/subangular), another ~5.5 cm long and N6, *sample taken at top of bed here in lithoclastic unit BCLm5-3c*

<u>Unit 4</u>

Bed 39: 102 cm – no outcrop exposed, but the rubble with caliche and silt areas

Bed 40: 19 cm – conglomerate, slumped along outcrop, traced ~12m on strike to the SE, makes small bench under junipers, bed has chert nodules, lithoclasts, 5Y6/1 for most of rock, lithoclast of 10YR8/6, rounded ~8.5 cm long, others ~4.0, others in 1-2 cm range, shell fragments seen, very large echinoid spines, (~6.8 cm long), lots of echinoid spines seen, one whole brachiopod on weathered surface, lots of small grains, not identifiable, a rugose seen, weather fairly smooth, SE on strike, *sample with some brachiopods snagged BCRT5-1a*, bed is slightly thinner here, too

Bed 41: 230 cm – rubbled-out slope, there may be small beds, but if so, they are not traceable, moved ~10-12 m SE along strike from where measuring base of overlying unit is rubbly and slumped, upper contact may be scoured into but very hard to tell

Bed 42: 163 cm – conglomerate, reef boulders, lithoclasts but hard to tell what's matrix versus clast here, some reef rubble looks like the more orange-weathering silt fills in portions, this conglomerate is just chopped up stuff, including brachiopods, crinoid columnals, rugose, lots of sponges, cherty, 10YR7/4 to 10YR8/6 on surface, also

10YR8/2, gray material is N6-N7 to N5, top of unit is fine in places, may be bioturbated, traced out to area with "Liesegang banding" weathering, persists around hillside and forms bench below trees at top of hill, see a few more brachiopods on strike to the NNW, *Hustedia*, spirifer pieces, ?*Martinia*, conglomerate has a coarser base (lithoclasts, lots of reef rubble) and a finer top, *sample taken BCRT5-1b*

Bed 43: 105 cm – covered where measured, ?silt, possibly limestone beds rubbled out, nothing in place

Bed 44: 117 cm – conglomerate, large lithoclasts, reef rubble near base, echinoid spines seen near top, sponges, top seems to be finer than base, walked out on outcrop, this is near top of the hill and is traceable, but very weathered, very similar to lower conglomerate just described, but not as massive at the base, few scattered brachiopods near top, *sample taken from upper portion BCRT5-1c ~96 cm above base conglomerate in area with some shelly debris visible*

<u>Unit 5</u>

Bed 45: 116 cm – cover and limestone rubble, bioturbation, looks like burrows were open, have cement in them, lots of limestone rubble in float, measured to possible base of grainy limestone bed, possibly has yellow silt(?) in places, bioturbation continues, grains in bed but not identifiable, mainly rubble, possible gastropod/ammonoid in the silty stuff?

Bed 46: 114 cm – three small limestone beds in this interval, base is coarser limestone, not sure where it is in place, rugose coral seen, lithoclasts, chert, grains mostly finer, possible brachiopod shell, lots of stuff but not identifiable, possible echinoid spine, and more rugose coral, above the grainy zone is a finer interval, float looks bioturbated, then there is small limestone bed that is ~6.5 cm that persists on outcrop with lithoclasts, some fossils that are much finer than below, little chert, bioturbated, limestone weathers blocky on outcrop, above this unit at top of interval is a coarser bed, ~12 cm thick, grainer again, can see fine/coarse/fine where measured, chert seen, smaller lithoclasts, bryozoan, crinoid columnal, *Hustedia*, spirifer, *sample taken at top of bed BCRT5-2a*

Bed 47: 180 cm – calcareous siltstone, weathers rubbly, 10YR7/4 on weathered, fresh is 10YR6/2, quartz grains, some shelly fragments, some areas weather into rounded cobbles, scattered fossil grains, *lithologic sample taken BCRT5-2lith*

Bed 48: 237 cm – conglomerate, fresh face is 5YR6/1, weathered is N6, weathers massive at base, rounded boulders, to a grooved flagstone-like surface at contact with brown platy unit, where conglomerate unit is finer, bed has some coarse/fine layers seen in places, *Hustedia*, spirifer pieces, chert nodules, grainy bed again, echinoid spine, lithoclasts smaller not reef material, one reef clast, rugose coral, see whole brachiopods in places, bryozoan, *Crenispirifer*?, crinoid columnal, not all that much is identifiable, fines near contact with brown platy material, *two samples taken where measured at/near base of unit in coarser portion of flow BCRT5-2b*

<u>Unit 6:</u> 340 cm – brown, platy limestone, same as at the Williams Ranch sections (Lm1 and Lm2), contact with underlying unit sharp, noted ammonites on contact bedding plane, fossils scattered on outcrop, above contact is mainly rubble out, fossils

scattered in areas, other areas look like grains are concentrated into small channels?, 10YR6/2 on weathered face, slightly petroliferous, 10YR4/2 on fresh face, weathers platy to slabby, in one portion of a grainer unit, we see a large crinoid columnal segment, a few small, scrappy reef-looking pieces, also see gastropod (higher spired), scaphopod, also noted brown, lithoclast-rich unit is present, see *Acanthocladia*, sponges (not hexactellind) Guadalupia ?(sp), fish bones seen, one small bed/area looks a lot like the ammonite bed at Lm1/RT1 section, weathers concretionary style, has fine layers preserved, not many/any seen, possibly radiolarians, *three float pieces here for dissolution/thin section at top of section BCRT5-3float*

VITA

Leigh Margaret Fall

Texas A&M University
Michael T. Halbouty Bldg.
College Station, TX 77843-3115
Office: (979) 845-2451; Fax: (979) 845-6162
lfall@geo.tamu.edu

Education

Ph.D. 2010, Geology, Department of Geology & Geophysics, Texas A&M University, College Station, TX

M.S. 2003, Geology, Department of Geosciences, Indiana University, Bloomington, IN

B.S. 1999, Geology, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM

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