BIOTIC AND TAPHONOMIC RESPONSES TO LAKE LEVEL FLUCTUATIONS IN
THE GREATER GREEN RIVER BASIN (EOCENE), WYOMING

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ABSTRACT

The Eocene Green River Formation (USA) is one of the best known and most extensively studied *Konservat Lagerstätte* in the world. While most studies have focused on the fossil fish and plants, few studies have examined the invertebrates, particularly the ostracodes of this renowned fauna. Six species of ostracodes (*Hemicyprinotus watsonensis*, *Candona pagei*, *Cypridea bisulcata*, *Metacypris paracordata*, *Potamocypris williamsi*, and *Procyprois ravenridgensis*) were recovered from 18 intervals within a 154 meter section of the Laney Member in the Washakie Basin. The ostracode species recovered comprise a variety of biological niches including plant and mud dwellers as well as nektonic lifestyles. These ecological tolerances were used to reconstruct environmental conditions of the lake through its history.

The taphonomic mode of the ostracodes varied with lithology and depositional setting. Ostracodes were commonly found recrystallized or as molds within the kerogen-rich micritic layers. There were also four coquinas within the section. In some of the micritic layers, the ostracodes were splayed along bedding planes, indicating possible post-burial deformation. The recrystallized shells often appear flattened and compressed. In the coquinas, the valves were unaltered and separated with no apparent orientation within the beds, possibly representing deflation surfaces along the lake margin.

Diversity analyses indicate that the ostracodes recovered from the Lower and Upper Laclede Beds of the Laney Member reflect lake level fluctuations consistent with

the balanced-filled and overfilled model (*sensu* Carroll and Bohacs) that has been constructed for the Washakie basin, based on stratigraphic, isotopic, and sedimentological data. The ostracode response to the changing lake conditions within the Laney Member demonstrates an environmental tracking of the balanced-filled to overfilled basin conditions. In addition, the similarity of ostracodes faunas between the Laney Member and those reported from the Uinta Basin supports the possible paleo-hydrologic connections of the various basins within the Green River Formation, related to the tectonic uplift and concomitant climatic change during the Eocene Thermal Maximum. The establishment of these connections has important implications for determining the overall tectonic and climatic history of this region.

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CHAPTER I

INTRODUCTION

The Eocene Green River Formation (GRF) is one of the most famous lacustrine *Konservat Lagerstätte* in the world (Roehler, 1991). Spanning three states (Colorado, Utah, and Wyoming) (Figure 1), the GRF represents the evolution of large lake systems during one of the most climatologically unique periods in Earth's history. This is because the early and middle Eocene represent one of the warmest times of the entire Cenozoic (DeConto and Pollard, 2003; Ivany et al., 2003; Zachos et al., 2003; Diekmann et al., 2004). While lake levels can often respond to climate change, levels within the lakes of the GRF may also have been influenced by tectonic uplift of the Absaroka Range as well as the Sevier and Laramide Orogenies (Pietras et al., 2003).

Throughout the ~20 million year history of the GRF, several tectonic and hydrologic regimes can be identified and characterized by the various resulting sedimentary facies. As the overall history of the GRF becomes better refined and understood (Bradley, 1964; Bradley and Eugster, 1969; Surdam and Stanley, 1979; Surdam et al., 1980; Carroll and Bohacs, 1999; Pietras et al., 2003), improved understanding of the biologic response to these changes can be made. Documenting this response is critical to understanding lacustrine speciation rates, colonization mechanisms, and species longevities.

Figure 1. Map illustrating the location of the three major basins of the Eocene Green River Formation.

While the GRF is best known for the exceptional fossil fish and plant fossils (McGrew, 1975; Grande, 1984; Grande and Buchheim, 1994; Ferber and Wells, 1995; Grande, 1999), few studies have been conducted on the invertebrate faunas of this basin (Swain, 1949, 1956, 1964; Kaesler and Taylor, 1971; Swain et al., 1971; Taylor 1972; Swain, 1999). Little is known about the preservational patterns of various invertebrates such as ostracodes (Class Crustacea), or their diversity dynamics, or how they might respond to paleoenvironmental changes within a lake basin such as the Green River.

Because ostracodes have specific environmental tolerances, abundant distribution, and are typically well preserved (Swain, 1964; Swain et al., 1971; Taylor, 1972; Wells et al., 1999; Frenzel and Boomer, 2005), they provide an effective means by which to evaluate the biologic response to known and documented lake level changes, as well as hydrologic connections and drainages of the various basins in the area.

Lake Basin Types and Biotic Response

Lake basins and their depositional sequences can be classified into a tripartite sequence-stratigraphic model developed by Carroll and Bohacs (1999) (Figure 2). This model classifies various lake stages with respect to climate (water/sediment supply) and tectonics (basin subsidence) (Carroll and Bohacs, 1999; Bohacs et al., 2000; Carroll and Bohacs, 2001). The three types of lake basins: underfilled, balanced-filled, and overfilled, can be seen in the members of the GRF. A typical overfilled deposit in the GRF consists of marlstones containing freshwater fossils from supralittoral to profundal paleoenvironments (Bohacs et al., 2000; Carroll et al., 2002, 2005). Balanced-filled deposits in the GRF are dominated by calcitic marlstones with beds commonly containing stromatolitic limestones, oolitic grainstones, sandstones, and dolomitic marlstones and

Figure 2. Carroll and Bohacs lake basin-type model used to classify lacustrine deposits in this study. The horizontal axis relates to potential accommodation space (tectonics), and the vertical axis represents the sediment and water supply (climate) which links precipitation and evaporation. The various members of the GRF are indicated as they have been interpreted to be related to this model. Modified from Carroll and Bohacs (1999).

are recognized as fluctuating from freshwater to saline-alkaline conditions (Bohacs et al., 2000; Carroll et al., 2002, 2005). Underfilled deposits in the GRF contain evaporites and dolomitic marlstones deposited under alternating non-saline and saline conditions (Bohacs et al., 2000; Carroll et al., 2002, 2005) (Figure 2). Since deposits in the GRF have been characterized according to the Carroll and Bohacs model, questions regarding the biotic response to these changing lake conditions can be addressed. In models of marine faunal change the role of sea level fluctuations resulting from tectonic or climatic change have been shown to have enormous influence on alpha and beta diversity in shallow marine settings (Brett et al., 1996; Ivany, 1996; Miller, 1996). Whether or not lacustrine diversity responds in a similar manner to basin dynamics has not been previously addressed. Do lacustrine faunas track lake level changes in the same way as the marine shallow shelf communities track sea level changes? This question can only be addressed in lake basins of sufficient duration and preservation to allow these changes to be recorded.

The GRF has produced a highly resolved history spanning a long period of time (Cohen, 2003) and therefore, provides the opportunity to apply this marine-based concept to the continental realm. The documentation of these patterns of environmental tracking can also provide critical information about the nature and extent of the basinal changes due to the extrinsic forces of climate and tectonics.

Testing Environmental Tracking

Environmental tracking, particularly in the marine realm, has been referred to by some as coordinated stasis (Brett et al., 1996; Holland, 1996; Ivany, 1996; Miller, 1996). Coordinated stasis is defined as long stable periods of species occurrences in the

fossil record that are separated by episodes of abrupt environmental changes (Brett et al., 1996; Ivany, 1996; Miller, 1996). A continuous and chronologically extensive stratigraphic record is necessary to test the hypothesis that faunal composition and diversity tracks environmental perturbations such as sea or lake level change. In addition, the record should have punctuated change (Lieberman and Dudgeon, 1996) as well as the preservational potential to record all species occurrences without large taphonomic biases (Baumiller, 1996). Without these elements the model cannot be rigorously tested. Thus, most continental depositional settings prove difficult in this respect and are not appropriate for study. Fortunately, the GRF provides both the temporal and preservational constraints to examine this phenomenon on an intra- and inter-basinal level.

Testing Paleohydrologic Connections

Based upon the size and relative locations of the various GRF basins, it is reasonable to suggest that different paleohydrologic connections existed throughout their existence. Paleohydrologic connections between the various basins of the GRF have been suggested and supported using various proxies. Roehler (1992) suggested that Lake Gosiute and Uinta were contemporaneous and periodically connected to the east of the Uinta Mountains. The supporting evidence used by Roehler (1992) was based on the correlation of lithologies, dated tuff beds, and recorded climate and salinity changes by flora and fauna. Furthermore, Surdam and Stanley (1979) argued that during Laney Member high stands, Lake Gosiute spilled over into the Sand Wash Basin and subsequently the Piceance Basin. Most recently, work concerning the paleohydrologic connections of the GRF has focused on landscape evolution using strontium isotopes and

tephra geochronology (Pietras et al., 2003; Rhodes et al., 2002; Smith et al., 2003). In order to determine whether or not ostracodes can be linked with paleohydrologic connections between basins, ostracode species must be documented to occur simultaneously within basins, and then shown to disappear after the basins are no longer connected. This coincidence in distributional timing could indicate that ostracode distribution reflects the regional paleohydrology.

CHAPTER II

STRATIGRAPHY AND PALEOENVIRONMENTAL CHANGES

The Greater Green River Basin (GGRB)

The geologic history of the Greater Green River Basin (GGRB) is related to several tectonic events. This foreland basin developed during the Laramide Orogeny (late Cretaceous to middle Eocene time) and occupies approximately 52,800 km², mainly within southwestern Wyoming, but also northeastern Utah and northwestern Colorado (Roehler, 1992). The basin is divided in half by a north–south trending anticline known as the Rock Springs Uplift (Roehler, 1992), and is further divided into sub-basins by various structural features (Figure 3). The Uinta Basin to the south is separated from the GGRB by the Uinta Mountains, Cherokee Ridge Uplift, and Sand Wash Basin Syncline.

Laney Member (LM)

Lake Gosiute was an ancient lake that occupied the GGRB and is responsible for the lacustrine deposits of the Laney Member (LM) (Figure 4). Recent geochronologic data suggest that deposition of Lake Gosiute occurred between 53.5 Ma and 48.5 Ma (Smith et al., 2003). The LM of the GRF represents the final stage of Lake Gosiute (Eugster and Surdam, 1973; Surdam and Stanley, 1979; Surdam et al., 1980; Carroll et al., 2002) and is thought to have been the longest phase of Lake Gosiute, lasting approximately 2 myr (Eugster and Surdam, 1973; Smith et al., 2003) (Figure 4).

Figure 3. Map of the tectonic features that divide the Greater Green River Basin into different sub-basins. The sub-basin of this study is the Washakie Basin, which is bounded by the Rock Springs Uplift to the east, the Wamsutter Arch to the north, and the Cherokee Ridge Uplift to the south. Modified from Roehler (1992).

Figure 4. Simplified stratigraphy of the Washakie Basin. Lake basin-type is represented to the right (OF = overfilled, BF = balanced-filled, UF = underfilled). The Laney Member represents the final extent of Lake Gosiute, and the transition between the balanced-filled Lower Laclede Bed and the overfilled Upper Laclede Bed. Modified from Carroll and Bohacs (1999).

Within the lowest part of the LM is the Laclede Bed (LB) which is typically divided by the “Buff Marker Bed” (BMB) into the Lower (LLB) and Upper (ULB) Laclede Beds respectively, and is overlain by the Sand Butte Bed (SBB) (Roehler, 1993; Carroll et al., 2002). The Laney Member is significant because it represents a transition from saline to freshwater conditions as represented by the Lower Laclede Bed (LLB) to the Upper Laclede Bed (ULB) (Surdam and Stanley, 1979; Surdam et al., 1980; Carroll et al., 2002). A shift in the overall climate from hot and arid to warm and humid is the probable mechanism for this transition (Roehler, 1993; Carroll et al., 2002). Furthermore, the Laney Member represents a threshold between a balanced-filled and an overfilled lake (Carroll et al., 2002).

Lower Laclede Bed (LLB)

The Lower Laclede Bed (LLB) typically contains lacustrine cycles or depositional sequences of laminated mudrock, dolomicritic marlstone, and stromatolites (Surdam and Stanley, 1979; Surdam et al., 1980; Roehler, 1993; Carroll et al., 2002). Four depositional cycles have been identified in the LLB, and these cycles are directly overlain by the BMB in most areas (Carroll et al., 2002). These cycles are currently interpreted as expansions and contractions of Lake Gosiute, typifying a balanced-filled lake in which the basin varied between open and closed hydrologies (Carroll et al., 2002). Large mudcracks (1-3 m) are present above the last depositional sequence, representing a large desiccation event below the BMB (Carroll et al., 2002). Roehler (1973) first described the BMB because it was easily identified in the field due to its buff color. The BMB caps the LLB and consists primarily of volcanoclastic material (Roehler, 1973; Carroll et al., 2002).

Upper Laclede Bed (ULB)

The ULB is poorly exposed in most areas and is sometimes classified as a “covered interval” (Carroll et al., 2002). However, the lowest portion of the ULB displays depositional sequences similar to those of the LLB (Carroll et al., 2002). The return to balanced-filled lake conditions after the BMB demonstrates that the lake may have been re-stabilizing after a large perturbation (volcanic event) (Carroll et al., 2002). The rest of the ULB is classified as a typical overfilled lake, and is composed mainly of shales, siltstones, and marlstones before the SBB. The capping SBB is composed of volcanoclastics and sands that are interpreted to be deltaic in origin, and are typical of an overfilled lake (Surdam and Stanley, 1979; Surdam et al., 1980; Roehler, 1993; Carroll et al., 2002).

Washakie Basin at Antelope Creek

The Washakie Basin (WB) is bounded by the Rock Springs Uplift to the west, the Wamsutter Arch to the north, the Sierra Madres to the west, and the Cherokee Ridge Anticline to the south (Roehler, 1992). The WB is shaped like a square bowl and is approximately 80 km in diameter and occupies nearly 7,770 km² (Roehler, 1992). Within the WB lies the Antelope Creek section (AC) of the Laney Member. This outcrop is located in the northeastern portion of the WB (Figure 5). The AC section has been the focus of numerous studies (e.g. Surdam and Stanley, 1979; Carroll et al., 2002, 2005) because of the exceptional exposure of the depositional cycles of the LLB and the BMB (Figure 6). The ULB is represented as a covered interval at this section, while the SBB is well exposed.

Figure 5. Distribution of the Laney Member in the Greater Green River Basin, including the Washakie Basin, along with the location of the Antelope Creek outcrop (AC). Modified from Surdam and Stanley (1979).

Figure 6. Photo showing depositional cycles of the Lower Laclede Bed at the Antelope Creek outcrop. Blue triangles represent individual lake cycles. White lines trace the various beds of the lake cycles. Scale as indicated.

Surdam and Stanley (1979), and Roehler (1993) suggested that the transition from the balanced-filled LLB to the overfilled ULB resulted from a shift in the climate from arid and dry to more wet and humid conditions. Furthermore, the timing and effect of the various tectonic events that took place during LM deposition are currently being investigated. Therefore, the changing facies of the Laney Member demonstrate the sensitive nature of this system in response to climatic and tectonic forcing (Carroll et al., 2002). Furthermore, these various lithologies have been an important means for correlating the three basins of the GRF. Therefore, the faunal composition of the Laney Member facies may be significant in correlating ostracode species within the other basins of the GRF and may provide more insight into the regional paleohydrologic connections.

CHAPTER III

METHODS

Sampling

Detailed stratigraphic sections at Antelope Creek (AC) were measured and described for the LLB (28 m) and the ULB (126 m). In order to accurately describe and sample the section, the “covered interval” of the ULB was trenched at 0.5 meter intervals. Intervals containing ostracodes were sampled consecutively at a one centimeter scale. Eighteen of the total facies sampled contained ostracodes.

All samples were examined under a binocular dissecting microscope for the presence of ostracodes. Since species of ostracodes were randomly distributed on the surface (Figure 7), a 1 cm x 1 cm grid was placed on the sample surface to randomly sample the ostracodes that could not be removed from the matrix. The surfaces were photographed and analyzed using Image-Pro ® Plus v. 4.1 software. Various filters, including best fit equalization, sharpen, HiPass, and HiGauss, were applied in order to accentuate morphological features of the valves. The most common filters were used to sharpen the images and equalize the light and dark colors. Ten percent of the samples were resampled in order to assure the random distribution and effectiveness of laboratory sampling.

Figure 7. Distribution of various ostracodes on the bedding surface of a sample from the Lower Laclede Bed at Antelope Creek. A) *Hemicyprinotus watsonensis*, B) *Candona pagei*, and C) *Procyprois ravenridgensis*.

Abundance and Taphonomic Analyses

The distribution of ostracode species appeared randomly distributed throughout the Laney Member at Antelope Creek. Therefore, the sample and the replicated counts were performed by placing a 1cm x 1cm grid on various locations of the sample bedding surfaces in order to evenly represent the faunal composition of the six identified species. Rarefaction (Sanders, 1968; Krebs, 1989) and jackknife statistical tests (Krebs, 1989) were performed to ensure that rare species were adequately sampled (Appendix D).

The maximum sample size counted was 133 individuals and the smallest was sixteen. Samples were recounted to ensure counting accuracy, however, it should be noted that some of the smaller samples fell below the statistically significant number of 100 individuals, according to the rarefaction analysis and twenty-four individuals according to the jackknife statistical tests (Appendix D).

The sampling method provided a more evenly-spaced sampling interval and a normalized comparison of valves per square centimeter. The percent relative abundance of a species within specific layers or populations was calculated using the equation $D = (n / N) * 100$, where n is the total number of organisms of a particular species in a given bed and N is the total number of organisms of all species in a given bed. The percent relative abundance of each species compared to itself was calculated using the equation $S = (n / N_n) * 100$, where n is the total number of organisms of a particular species in a given bed, and N_n is the total number of organisms of that species throughout the entire section. The two types of abundance measures were compared to see if they correlated to lake basin types. Jaccard coefficients were calculated using the formula: $S_j = (a / a + b + c)$ where a = the number of times two species being compared are both present, b = the

number of times the first species is present and the second species is absent, and c = the number of times the second species is present and the first species is absent (Kaesler and Taylor, 1971). In addition, a Bray-Curtis single linkage cluster analysis (Everitt, 1993) was performed using BioDiversity Professional Software (v. 2) on species distributions per facies to assess the similarities throughout the section.

Preservational mode (i.e. cast, mold, unaltered, recrystallized) of the valves was also recorded. Dominant modes of preservation throughout the LLB and ULB were compared to determine if a taphonomic signature between the lake basin types was present. In order to calculate potential preservation, a 1 cm x 1 cm grid was placed on the sample surface at approximately 3-4 random locations and the number of valves/cm² was calculated. After counts were made, the numbers were averaged and correlated to specific beds to see if any biases existed among apparent kerogen- or carbonate-rich facies. These facies were correlated to those previously analyzed by Surdam and Stanley (1979), Carroll et al. (2002, 2005).

Diversity Analysis

The diversity changes throughout the LM at Antelope Creek was analyzed using the Simpson's index of diversity $1 - D$, where $D = \sum (n/N)^2$, n = total number of organisms of a particular species, and N = total number of organisms of all species (Simpson, 1949). Simpson's index of diversity provides the probability of any two individuals drawn at random from an infinite community to belong to different species (Simpson, 1949).

Lithologies and other proxies were used to determine the nature and extent of the environmental changes throughout the stratigraphic section, while the ostracode diversity

and distribution results were used to document faunal changes. By comparing these results, the determination of whether or not alpha and beta species diversity tracked lake level changes within the GGRB could be assessed.

The ostracodes were then compared to previously described faunas from the Gosiute Basin (Kaesler and Taylor, 1971; Taylor 1972), and Uinta and Fossil basins (See Figure 1) (Swain, 1956, 1964; Swain et al., 1971; Swain, 1999).

CHAPTER IV

RESULTS

The Lower Laclede Bed at Antelope Creek (AC) measured approximately twenty-eight meters thick and contained four distinct depositional cycles that consisted of stromatolites and kerogen-rich laminated and non-laminated mudrocks. The cycles are similar to those described by Surdam and Stanley (1979) and Carroll et al. (2002, 2005) and are interpreted as lake level fluctuations. While the lowest cycle was not completely measured, the average thickness of each sequence is approximately 3.5 meters. The stromatolitic layers commonly contained ostracodes, peloids, and infilled mudcracks. These layers are interpreted as periods of contraction and or desiccation within the lake. The laminated mudrocks represent a profundal setting or a relatively deep and low energy environment. The LLB was dominated by laminated micrite or lacustrine mudrock and kerogen-rich shales (Figure 8). The BMB at AC was approximately ten meters and was composed predominantly of volcanoclastics. Mudcracks interpreted by Carroll et al. (2002, 2005) were observed and described at the base of the BMB, representing a significant desiccation event prior to the deposition of volcanoclastics. Within the LLB and BMB, eleven of the thirty-four facies sampled and described contained ostracodes including one ostracode coquina. The LLB at this outcrop was deposited in a balanced-filled lake. The measured portion of the ULB at AC was approximately 126 meters. The base of this unit contained three depositional cycles similar to the cycles in the LLB. The

Figure 8. Stratigraphic column of the Lower Laclede Bed of the Laney Member at Antelope Creek. Four depositional cycles are represented with facies containing ostracodes and mudcracks. The picture represents the fourth depositional cycle and is overlain by a kerogen-rich shale. Bed A is a stromatolite that forms the base of each cycle. Bed B is a laminated mudrock. Bed C is an oolitic grainstone.

cycles were typically comprised of marlstones and siltstones grading into ostracode coquinas and tufas, and indicating the re-establishment of balanced-filled conditions after the large desiccation and volcanic events associated with the BMB. The rest of the ULB consisted of shales, siltstones, claystones, ashes, and a wackestone containing abundant gastropods (Figure 9). Of the nineteen different samples described from the ULB, nine contained ostracodes. The shift towards more siliciclastic facies directly above the depositional sequences has been interpreted by Carroll et al. (2002) as overfilled lake deposits. Thus, a threshold (climatic, tectonic or both) was crossed to cause this transition of lake basin type to occur.

Ostracode Taphonomy

The dominant taphonomic mode of ostracode preservation throughout the LM at AC is calcite recrystallization. This is most likely due to the fact that the lake was oversaturated with respect to carbonate during this time. The greatest abundance of ostracodes in the LLB was preserved within the lacustrine marlstone facies. Species were rare in the highly kerogen-rich shales and stromatolites. Where the more kerogen-rich layers in the LLB contained ostracodes, they were preserved via molds and casts. The stromatolitic layers had few ostracodes, and they were recrystallized with silica. The silica may have been derived from the volcanic ash that is commonly reworked into the deposits. In addition, the valves of the LLB commonly were splayed and not fully intact and the overall quality of preservation was moderate to low. The average number of valves preserved / cm² in the LLB was approximately 9 valves / cm². Within the ULB, the average number of valves / cm² was 14 valves / cm². The dominant mode of

Figure 9. Stratigraphic column of the Upper Laclede Bed of the Laney Member at Antelope Creek (see Figure 5). Three depositional cycles are represented with facies containing ostracodes, tufas, and mudcracks. Photo shows contact between Upper Laclede and Sand Butte Bed.

preservation did not change in the ULB, but the quality of preservation did. The valves in the ULB were typically whole and intact with no splaying.

Ostracode Distribution

Six species of ostracodes were identified throughout the Laney Member (Figure 10), including *Candona pagei*, *Procyprois ravenridgensis*, *Hemicyprinotus watsonensis*, *Potamocypris williamsi*, *Metacypris paracordata*, and *Cypridea bisulcata*. These species have varying morphological characteristics and associated ecologic tolerances that generally overlap with minimal variation (Table 1). *Candona pagei* is interpreted to be a plant dweller that thrives in conditions with both high organics and carbonates (Swain, 1956, 1964; Swain et al., 1971; Taylor, 1972). *Hemicyprinotus watsonensis* is also considered to be a plant dweller and is regarded as having the highest environmental tolerance of the six species present; *H. watsonensis* commonly occupied all nonmarine environments (Swain, 1956, 1964; Swain et al., 1971; Taylor, 1972). The distribution of *H. watsonensis* becomes less important in determining environmental tracking because it is a eurytypic species. *Procyprois ravenridgensis* is a nektonic species that could survive in saline to freshwater; however, it is suggested that this species thrived in evaporative and stagnant waters (Swain, 1956, 1964; Swain et al., 1971; Taylor, 1972). Swain (1964) and Swain et al. (1971) reported that *P. williamsi* was a nektonic species that is commonly found in limestones and argillaceous rocks of the GRF. The presence or absence of *M. paracordata* is probably the most important indicator with respect to paleoenvironmental reconstructions and environmental tracking because this species typically inhabited environments that were brackish or estuarine in the GRF (Swain, 1956, 1964; Swain et al., 1971). Finally, *C. bisulcata* was rare in most areas sampled in

Figure 10. Five of the six species found in the Laney Member. *Cypridea bisulcata* is not featured because it appears as a singleton and is poorly preserved.

Ostracode Species	Ecological Tolerances	Occurrence in GRF			
		Fossil Basin	Gosiute Basin	Uinta Basin	
<i>Candona pagei</i>	Plant dweller; occupies carbonate rich environments that are both low and high energy. Cosmopolitan species.	X	X	X	Plant Dwellers
<i>Hemicyprinotus watsonensis</i>	Plant dweller; typically occupies carbonate rich environments. However, this species is found in the widest variety of environments. Cosmopolitan species.	X	X	X	
<i>Procypris ravenridgensis</i>	Nektonic or free swimming; well adapted to occupy shallow stagnant waters that are high in both carbonate and organics.		X	X	Nektonic
<i>Potamocypris williamsi</i>	Nektonic or free swimming; high tolerance for most environments. However, most commonly found in argillaceous rich sediments		X	X	
<i>Metacypris paracordata</i>	Mud dweller; typically found in stable environments that are brackish, estuarine, or nearly fresh water.		X	X	Mud Dwellers
<i>Cypridea bisulcata</i>	Mud dweller; typically found in carbonaceous shales, species most abundantly found in environments with well-circulated waters.	X	X	X	

Table 1. Ostracode species from the Laney Member with species' ecologic tolerances and distributions in the Green River Formation. Ecologic tolerances determined from previous studies of Swain et al. (1971) and Taylor (1972).

the GRF; this species was associated with fresh circulating waters that were saturated with respect to Ca^{2+} and CO_3^{2-} and mud (Swain, 1956, 1964; Swain et al., 1971; Taylor, 1972).

Abundance and Diversity Changes within the Laney Member

The distribution of these six ostracode species become important in interpreting the paleoecologic settings of the two lake basin types represented by the Laney Member at AC. Although all six species were present throughout the section as a whole, all six species never appeared in the same bed. The LLB was dominated by three species (*C. pagei*, *P. ravenridgensis*, and *H. watsonensis*). Within the ULB, only four (*C. pagei*, *P. ravenridgensis*, *P. williamsi* and *M. paracordata*) of the six species were recorded. At most, three species appeared together in a sampled facies.

The diversity and distribution of the six ostracodes species in the LM was distinctly different with respect to the LLB and the ULB. The diversity of the LLB was high (.76), with all six species appearing at least once within the section (Figure 11, 12). Each bed typically contained three to four species. The diversity of the LLB was dominated by three species that all favor carbonate-rich environments: plant dwellers *C. pagei*, *H. watsonensis*, and nektonic *P. ravenridgensis*. *Potamocypris williamsi* and *M. paracordata* only appear in the uppermost portions of the last depositional sequence of the LLB. These species are more likely to favor brackish, argillaceous settings. This portion of the LLB had the highest diversity (.72) and was significant because it was the first appearance of these species. *Metacypris paracordata* is typically found only in brackish environments. Therefore, the sudden presence of these species may demonstrate that the transition from the saline LLB to the fresher ULB occurred before the BMB.

Figure 11. Ostracode species abundance within individual beds of the Lower Laclede (bar graph), and species relative abundance throughout the entire section at Antelope Creek (solid line), Wyoming.

Figure 12. Absolute species abundance/cm² within individual beds of the Lower Laclede (bar graph), vs., species relative abundance throughout the entire section at Antelope Creek (solid line), Wyoming.

Cypridea bisulcata, on the other hand, had the lowest abundance appearing in only one layer of the LLB. The fact that *C. bisulcata* only appeared in one layer could have significant meaning concerning the depositional and ecological setting of that specific facies. However, because of its rarity, it is not significant to this analysis.

Diversity in the ULB (.65) was lower than the LLB (.76), with only four of the six species occurring within the section. *Candona pagei* appeared as a singleton in the lowest portion of ULB (Figure 13, 14), and *H. watsonensis* and *C. bisulcata* did not appear at all, possibly due to the large dessication event, and the volcanics associated with the deposition of the BMB. The ULB was dominated by one of the three main species of the LLB, nektonic *P. ravenridgensis*. The distribution of this species was consistent throughout the LM with little or no response to any apparent environmental fluctuations. The mud dwellers *P. williamsi* and *M. paracordata* appeared to replace the plant dwellers *C. pagei* and *H. watsonensis* in the ULB. The replacement of species and decrease in diversity from .76 LLB to .65 correlated with the change in lake basin type from balanced-filled to overfilled. The relative distribution of the species with respect to themselves correlated to the absolute distribution within individual facies. This supports the idea that the distribution reflected in the LLB and the ULB was not a taphonomic artifact.

A Bray-Curtis single linkage cluster analysis was used to determine the similarities among ostracode distribution in various facies. The distinct clusters that occurred separating the LLB from the ULB based on their ostracode occurrences further demonstrates that after the deposition of the BMB there was a distinct change in the lake basin type. Clustering the species composition of the various beds resulted in a clear

Figure 13. Ostracode species abundance within individual beds of the Upper Laclede (bar graph), and species relative abundance throughout the entire section at Antelope Creek (solid line), Wyoming.

Figure 14. Absolute species abundance/cm² within individual beds of the Upper Laclede (bar graph), vs., species relative abundance throughout the entire section at Antelope Creek (solid line), Wyoming.

division of the LLB and the ULB (Figure 15). Thus, the ULB and LLB can be divided or distinguished based solely on faunal composition. There were two distinct faunal compositions throughout the LM of the GRF that represented at least 2 million years of basin history. The four depositional cycles of the LLB recorded the lake level fluctuations, resulting from either climatic or tectonic perturbations. These lake level fluctuations in the LLB could have produced different ostracode faunas, but did not. Instead, the species tracked the lake level changes by increasing or decreasing in abundance. Thus, the faunal composition of the LLB maintained a period of stasis throughout the sequence and was dominated by three species (*C. pagei*, *P. ravenridgensis*, and *H. watsonensis*). The lake level fluctuations in the LLB had no apparent influence over the faunal composition (Figure 11, 12). Instead, there was a distinct faunal turnover after the BMB was deposited. The large volcanic and desiccation events associated with the BMB indicate that this dramatically changed the lake and resulted in a reassembly of the fauna. Within the ULB, two of the three species that dominated the LLB went extinct at or near the BMB. *C. pagei* and *H. watsonensis* were replaced by *P. williamsi* and *M. paracordata*. The extinction and reorganization of the fauna stabilized in the ULB and never returned to the characteristic faunal composition of the LLB.

GGRB Ostracodes vs. Ostracodes in GRF Basins

While the Colton Green River Transition Beds (CGRTB) in the Uinta Basin had a high ostracode species richness containing eighteen different species (Swain, 1956, 1964; Swain et al., 1971) (Table 2), the Laney Member in the Washakie Basin had only six species. Swain et al. (1971) described various zones throughout the Uinta Basin based on

Figure 15. Bray-Curtis single linkage cluster analysis the Laney Member based on ostracode faunal composition. The facies cluster together demonstrating the similarity of the fauna of the Lower Laclede Bed (LLB) and the Upper Laclede Bed (ULB).

the abundance of particular ostracode species. The major ostracode zones defined in the Uinta Basin correlate to the ostracodes that are most abundant in the LLB of the Washakie Basin: *C. pagei*, *H. watsonensis*, and *P. ravenridgensis* (Swain et al., 1971). These three species dominated both the CGRTB and the LLB bed and may be representative of the typical fauna associated with balanced-filled deposits in the GRF.

The six species preserved in the Laney Member at Antelope Creek have been found in other beds of the Uinta, Fossil, and Greater Green River Basins. All have been identified in the Colton-Green River Transition Beds of the Uinta Basin by Swain (1956, 1964) and Swain et al. (1971). Swain et al. (1971) recognized the appearance of numerous ostracodes in Fossil Basin including *C. pagei*, *H. watsonensis*, and *C. bisulcata*. Kaesler and Taylor (1971) identified five of the six species described in the LM (excluding *P. ravenridgensis*), in the Luman Tongue/Tipton Member (LT/TM) to the east of the Rock Springs Uplift in the Greater Green River Basin. Taylor (1972) proposed that *H. watsonensis* was the only species that appeared in the LM from those described in the LT/TM. However, this study proves that the distribution of ostracode species in the LM is higher than the previous studies suggested.

Ostracode Species	Fossil Basin	Gosiute Basin		Uinta Basin	
	Fossil Basin	Green River Basin	Washakie Basin	Uinta Basin	Piceance Basin
<i>Candona pagei</i>	x	x	x	x	x
<i>Candoniella whitei</i>				x	x
<i>Ilyocypris arvadensis</i>				x	x
<i>Ilyocyprimorpha linodosa</i>				x	
<i>Cypridea bisulcata</i>	x	x	x	x	x
<i>Cyprois ephraimensis</i>	x			x	x
<i>Scottia subquadrata</i>	x			x	x
<i>Hemicyprinotus watsonensis</i>	x	x	x	x	x
<i>Hemicyprinotus reniformis</i>					x
<i>Heterocypris whiteriverensis</i>					x
<i>Procyprois ravenridgensis</i>		x	x		x
<i>Stenocypis sinuata</i>					x
<i>Potamocypris williamsi</i>		x	x		x
<i>Advenocypris umbonata</i>					x
<i>Candona artensis</i>					x
<i>Tuberocypris centronotus</i>					x
<i>Metacypris paracordata</i>		x	x		x
<i>Heterocypris riflensis</i>					x
<i>Limnocythere sp.</i>					x

CHAPTER V

DISCUSSION

Results of this study indicate several important relationships regarding ostracode valve taphonomy and diversity as it relates to the Carroll and Bohacs sequence stratigraphic model and the Laney Member of the Green River Formation. Furthermore, this study uses ostracode distribution to support the regional paleohydrologic connections among the three basins of the GRF.

Taphonomic Signatures

The biotic and taphonomic responses associated with changing lake basin types in the GRF suggest that the three lake basin types (overfilled, balanced-filled, and underfilled) (Carroll and Bohacs, 1999; Bohacs et al., 2000; Carroll and Bohacs, 2001) may have specific biotic and taphonomic signatures. There are distinct differences in faunal composition of the balanced-filled LLB compared with the overfilled ULB in the Washakie Basin. Unfortunately, none of the prior Green River Formation ostracode studies discussed taphonomic patterns. However, a taphonomic signature between lake basin types existed in the Laney Member at Antelope Creek.

In the balanced-filled LLB, the quality of preservation is moderate to low, while the overfilled ULB displays a higher preservational quality. In a balanced-filled lake setting, the preservation will be more degraded and external morphologic features less recognizable. Fewer ostracodes also appear to be present in these types of deposits. The

deterioration in preservation of ostracode valves may be a result of both the fluctuating hydrology and the instable chemistry associated with a balanced-filled lake.

Furthermore, soft sediment deformation or other post-depositional disturbances can be expected based on the large number of ostracodes that were splayed in these balanced-filled lake settings.

In the overfilled deposits of the ULB, the preservation of ostracode valves increases in both abundance and quality. This is probably characteristic of this lake basin type, based on the influx of water and sediment being deposited. The lake chemistry of an overfilled lake is considerably more stable or consistent than that of a balanced-filled lake. The taphonomic biases of ostracodes in these lake basin types can hinder investigations because of the difficulty of species identification.

Lower Laclede Bed Ostracode Distribution

The facies within the LLB are consistent with a balanced-filled lake that fluctuates between being open and closed hydrologically. The patterns within the Lower Laclede Bed demonstrate that the distributions of Laney Member ostracode species do not directly correlate to lake level fluctuations (Figures 10, 11). The distribution of species remained fairly consistent throughout the depositional cycles of the LLB. Species richness remained relatively constant throughout the deposit peaking just below deposition of the Buff Marker Bed (Figures 10, 11). The distribution and diversity is correlative to the ecologic tolerances/preferences of the ostracode species. The three dominant species are plant dwellers (*C. pagei*, and *H. watsonensis*) and nektonic (*P. ravenridgensis*). All three of these species are geographically widely distributed however, they prefer carbonate-rich environments. Therefore, the distribution of the

ostracodes of the LLB were controlled by sediment type, geochemistry and the corresponding lake basin type.

Upper Laclede Bed Ostracode Distribution

The prevalent ostracode species of the Upper Laclede Bed are much different than the species found within the LLB. The three main species of the ULB are nektonic (*P. ravenridgensis*, *P. williamsi*) or mud dwelling (*M. paracordata*). These species' ecologic preferences are more specific than the species of the LLB. *Metacypris paracordata* and *P. williamsi* (excluding *P. ravenridgensis*) are commonly found in argillaceous-rich estuarine to brackish environments. The transition to more siliciclastic sediment in the ULB than the LLB and the abundance of these species represents the changing lake basin type from the saline balanced-filled LLB to the fresher conditions of the overfilled ULB.

Diversity Comparisons

The high quality of preservation of the Laney Member ostracodes allowed for the hypotheses of environmental tracking to be tested. The pattern of ostracode distribution in relation to lithologic changes demonstrates that fauna respond differently to abiotic changes in continental systems than in the marine. The ostracodes of the LM in the Washakie Basin respond more directly to large scale shifts resulting in lake level and lake basin type changes. Ostracode distribution and diversity in the GRF is controlled by, or reflects, lake basin type, because lake basin type influences the ecologic setting.

Gierlowski-Kordesch and Park (2004) suggested that diversity may be controlled by lake basin type, and that balanced-filled lakes would result in high diversity due to alternating hydrologic conditions. The ostracodes from the LM at Antelope Creek support the hypothesis of Gierlowski-Kordesch and Park (2004) concerning lake-basin type and

diversity: a higher diversity is associated with the balanced-filled LLB (six species), and lower diversity in the overfilled ULB (three species). An underfilled lake deposit was not investigated. However, lower diversity is assumed in an underfilled lake setting. Other factors controlling deposition and the overall nature of paleolacustrine deposits are still poorly understood and need to be further investigated.

Potential Paleohydrological Connections (Gosiute-Uinta Basins)

The distribution of these ostracode species provides biological evidence supporting the paleohydrologic connections among the three major basins of the GRF (Swain et al., 1971; Taylor, 1972) (Table 2). Lithologic and stratigraphic evidence suggests that during high stands of the LM, Lake Gosiute spilled over into the Piceance Creek Basin (PCB), a sub-basin of the Uinta Basin (Surdam and Stanley, 1979; Roehler, 1993) (Figure 12). The ostracodes present in the LM support this interpretation because all six species found in the Laney Member were also identified in the PCB by Swain (1956, 1964) and Swain et al. (1971). Swain et al. (1971) described *P. ravenridgensis* as a localized species of the Uinta Basin specifically to Raven Ridge, Utah, but the species may have originated in the Gosiute Basin and spilled over into the Uinta Basin during a high stand.

The six species identified in the LLB at Antelope Creek were also identified in the lower Eocene Colton-Green River Formation Transition Beds (CGRTB) of the Uinta Basin (Swain, 1949, 1956, 1964; Swain et al., 1971). The beds were described as being predominantly lacustrine shales and limestones, suggesting a balanced-filled lake setting. The species richness and diversity of the balanced-filled LLB and the CGRT are higher in

Figure 15. Possible locations of paleohydrologic drainages within the GRF basins. Arrows represent direction of drainage (darker arrows represent larger quantities of water). (A) Represents drainages during a balanced-filled lake (LLB). (B) Represents drainage during an overfilled lake (ULB). Modified from Smith et al., 2003.

comparison to the overfilled upper Laclede and Luman Tongue/Tipton Member (LT/TM) (Kaesler and Taylor, 1971).

The overfilled deposits of the ULB in the Washakie Basin and LT/TM in the Green River Basin are correlative based on faunal composition similar to those of the balanced-filled deposits. Two of three species that dominated the overfilled ULB of the LM (*M. paracordata* and *P. williamsi*) were also the most abundant species in the LT/TM (Taylor, 1972), with the only difference being that the fauna of LT/TM also contained *C. bisulcata* as a significantly abundant species (Taylor, 1972). In the ULB of the Washakie Basin, *P. ravenridgensis* was abundant rather than *C. bisulcata*. *Cypridea bisulcata* was rare throughout the LM and only appeared in one sample at Antelope Creek. Furthermore, this species was regarded as “sparingly distributed” in the Uinta Basin (Swain et al., 1971). The overall diversity of these overfilled deposits is moderate to low in comparison to a balanced-filled setting.

Further investigations of underfilled lake deposits in the GRF are necessary to confirm correlation of ostracode diversity and distribution to lake basin type; however, it is expected that the faunal diversity would be low (Gierlowski-Kordesch and Park, 2004) and only species with stagnant and saline ecological tolerances would be present. The boundaries and transitions between lake basin types need further investigation because they demonstrate significant thresholds being crossed, resulting in water and sediment (climate) input exceeding or outpacing the accommodation space (tectonics) (Carroll and Bohacs, 1999; Carroll et al., 2002).

Potential Paleohydrologic Connections (Fossil-Gosiute Basin)

There is little evidence linking Fossil Basin and Gosiute Basin. The presence of the same ostracode species in both basins provides biologic evidence for a connection at some point during the Eocene. Obviously, specific connections between basins cannot be proposed based solely on the presence of ostracode species. However, dispersal of ostracode species via birds, wind, and rain is very unlikely (Jenkins and Underwood, 1998). Therefore, ostracodes may provide a more accurate proxy of the biological interactions between the basins than the fossil fish fauna because ostracodes are typically well preserved, abundant, and most species have ecologic specific tolerances.

Thus, the ostracodes of the Laney Member indicate the importance and necessity to further investigate ostracodes in the Green River Formation. The ostracodes reveal information about the different taphonomic signatures associated with the Carroll and Bohacs sequence stratigraphic model. Also, the ostracodes can provide better insight into how faunal composition and diversity are associated with changing lake basin types. Because ostracodes are widely distributed and have specific environmental tolerances, they are valuable proxies for more than just paleoecology. Ostracodes of the GRF can provide insight and information regarding the paleohydrologic connections throughout the GRF basins that other fauna may not.

CHAPTER VI

SUMMARY

- A detailed faunal list of the ostracodes present is provided for the Laney Member at Antelope Creek. This faunal list can now be used to identify or correlate ostracode species throughout the various basins of the Green River Formation.
- The faunal composition, abundance, diversity, and taphonomy were documented. Analyses of how they varied between lake basin-types in the Laney Member at Antelope Creek were performed. The variations in ostracode distribution and richness are based upon lake basin type. Furthermore, specific ostracode species in the Green River Formation may be associated with or characteristic of lake basin types.
- A possible biological proxy for suggesting or correlating possible hydrologic connections that existed between the three basins of the Green River Formation is provided.

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APPENDICES

APPENDIX A

DIVERSITY AND FAUNAL COMPOSITION DATA

	<i>C. pagei</i>	<i>P. ravenridgensis</i>	<i>H. watsonensis</i>	<i>P. williamsi</i>	<i>M. paracordata</i>	<i>C. bisulcata</i>	Tot. Valves
1	18	2	11	0	0	0	31
Species/cm2	3.60	0.40	2.20	0.00	0.00	0.00	
%Avg. in Facies	58.06	6.45	35.48	0.00	0.00	0.00	
%Avg. of Self	17.00	1.50	17.50	0.00	0.00	0.00	
3	6	2	8	0	0	0	16
Species/cm2	1.50	0.50	2.00	0.00	0.00	0.00	
%Avg. in Facies	37.50	12.50	50.00	0.00	0.00	0.00	
%Avg. of Self	5.71	1.50	12.70	0.00	0.00	0.00	
7	9	4	3	0	0	0	16
Species/cm2	3.00	1.33	1.00	0.00	0.00	0.00	
%Avg. in Facies	56.25	25.00	18.75	0.00	0.00	0.00	
%Avg. of Self	8.57	3.01	4.76	0.00	0.00	0.00	
9	11	3	8	0	0	0	22
Species/cm2	2.20	0.60	1.60	0.00	0.00	0.00	
%Avg. in Facies	50.00	13.64	36.36	0.00	0.00	0.00	
%Avg. of Self	10.48	2.26	12.70	0.00	0.00	0.00	
11	5	5	9	0	0	0	19
Species/cm2	1.67	1.67	3.00	0.00	0.00	0.00	
%Avg. in Facies	26.32	26.32	47.37	0.00	0.00	0.00	
%Avg. of Self	4.76	3.76	14.29	0.00	0.00	0.00	
15	2	13	0	0	0	6	21
Species/cm2	0.67	4.33	0.00	0.00	0.00	2.00	
%Avg. in Facies	9.52	61.90	0.00	0.00	0.00	28.57	
%Avg. of Self	1.90	9.77	0.00	0.00	0.00	100.00	
23	7	9	3	8	0	0	27
Species/cm2	2.33	3.00	1.00	2.67	0.00	0.00	
%Avg. in Facies	25.93	33.33	11.11	29.63	0.00	0.00	
%Avg. of Self	6.67	6.77	4.76	4.28	0.00	0.00	
24	30	40	16	47	0	0	133
Species/cm2	6.00	8.00	3.20	9.40	0.00	0.00	
%Avg. in Facies	22.56	30.08	12.03	35.34	0.00	0.00	
%Avg. of Self	28.57	30.08	25.40	25.13	0.00	0.00	
27	12	0	5	23	2	0	42
Species/cm2	3.00	0.00	1.25	5.75	0.50	0.00	
%Avg. in Facies	28.57	0.00	11.90	54.76	4.76	0.00	
%Avg. of Self	11.43	0.00	7.94	12.30	1.74	0.00	

	<i>C. pagei</i>	<i>P. ravenridgensis</i>	<i>H. watsonensis</i>	<i>P. williamsi</i>	<i>M. paracordata</i>	<i>C. bisulcata</i>	Tot. Valves
36	5	16	0	0	14	0	35
Species/cm2	1.00	3.20	0.00	0.00	2.80	0.00	
%Avg. in Facie	14.29	45.71	0.00	0.00	40.00	0.00	
%Avg. of Self	4.76	12.03	0.00	0.00	12.17	0.00	
38	0	3	0	11	8	0	22
Species/cm2	0	0.75	0	2.75	2	0	
%Avg. in Facie	0.00	13.64	0.00	50.00	36.36	0.00	
%Avg. of Self	0.00	2.26	0.00	5.88	6.96	0.00	
40	0	2	0	5	11	0	18
Species/cm2	0.00	0.50	0.00	1.25	2.75	0.00	
%Avg. in Facie	0.00	11.11	0.00	27.78	61.11	0.00	
%Avg. of Self	0.00	1.50	0.00	2.67	9.57	0.00	
42	0	3	0	9	16	0	28
% Species/cm2	0.00	0.75	0.00	2.25	4.00	0.00	
%Avg. in Facie	0.00	10.71	0.00	32.14	57.14	0.00	
%Avg. of Self	0.00	2.26	0.00	4.81	13.91	0.00	
43	0	8	0	16	26	0	50
% Species/cm2	0.00	2.00	0.00	4.00	6.50	0.00	
%Avg. in Facie	0.00	16.00	0.00	32.00	52.00	0.00	
%Avg. of Self	0.00	6.02	0.00	8.56	22.61	0.00	
46	0	4	0	38	8	0	50
% Species/cm2	0.00	1.33	0.00	12.67	2.67	0.00	
%Avg. in Facie	0.00	8.00	0.00	76.00	16.00	0.00	
%Avg. of Self	0.00	3.01	0.00	20.32	6.96	0.00	
48	0	3	0	3	10	0	16
% Species/cm2	0.00	0.75	0.00	0.75	2.50	0.00	
%Avg. in Facie	0.00	18.75	0.00	18.75	62.50	0.00	
%Avg. of Self	0.00	2.26	0.00	1.60	8.70	0.00	
49	0	9	0	4	5	0	18
% Species/cm2	0.00	2.25	0.00	1.00	1.25	0.00	
%Avg. in Facie	0.00	50.00	0.00	22.22	27.78	0.00	
%Avg. of Self	0.00	6.77	0.00	2.14	4.35	0.00	
50	0	7	0	23	15	0	45
% Species/cm2	0.00	2.33	0.00	7.67	5.00	0.00	
%Avg. in Facie	0.00	15.56	0.00	51.11	33.33	0.00	
%Avg. of Self	0.00	5.26	0.00	12.30	13.04	0.00	
Total Valves	105	133	63	187	115	6	609 valves

APPENDIX B REPLICATE COUNTS

Samples	Ostracode species					
	<i>C. pagei</i>	<i>P. ravenridgensis</i>	<i>H. watsonensis</i>	<i>P. williamsi</i>	<i>M. paracordata</i>	<i>C. bisulcata</i>
1	16	3	11	0	0	0
Species/cm2	3.20	0.60	2.20	0.00	0.00	0.00
%Avg. in Facies	53.33	10.00	36.67	0.00	0.00	0.00
%Avg. of Self	15.50	2.26	17.50	0.00	0.00	0.00
15	2	13	0	0	0	6
Species/cm2	0.67	4.33	0.00	0.00	0.00	2.00
%Avg. in Facies	9.52	61.90	0.00	0.00	0.00	28.57
%Avg. of Self	1.90	9.77	0.00	0.00	0.00	100.00
24	30	40	15	45	0	0
Species/cm2	6.00	8.00	3.00	9.00	0.00	0.00
%Avg. in Facies	23.08	30.77	11.54	34.62	0.00	0.00
%Avg. of Self	28.57	30.08	24.19	24.30	0.00	0.00
48	0	3	0	3	10	0
% Species/cm2	0.00	0.75	0.00	0.75	2.50	0.00
%Avg. in Facies	0.00	18.75	0.00	18.75	62.50	0.00
%Avg. of Self	0.00	2.26	0.00	1.60	8.70	0.00

APPENDIX C

FIELD MEASUREMENTS AND DESCRIPTIONS

Sample #	Thickness(m)	Facies Description
1	0.51	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray, small interbedded siltstones are present (below this facies the section is covered).
2	0.03	Ash interbedded in sandstone, fine to medium sand, poorly sorted, sub-rounded to rounded, mostly quartz, some feldspars (the ash is most likely reworked).
3	0.45	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray, small interbedded siltstones are present, more kerogen-rich than 1.
4	0.01	Ash interbedded in sandstone, fine to medium sand, poorly sorted, sub-rounded to rounded, mostly quartz, some feldspars (the ash is most likely reworked).
5	0.02	Laminated micrite less kerogen-rich than 1 and 3, small gypsum layer at the base of the unit. Abrupt contact with overlying stromatolite.
6	0.2	Stromatolite fresh light gray to buff, weathers orange to buff, mound growths are 8-11 cm in diameter, prominent undulating bed.
7	0.66	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray, small interbedded siltstones are present, with some kerogen-rich shale interbeds that are around 1 cm thick.
8	0.01	Ash interbedded in sandstone, fine to medium sand, poorly sorted, sub-rounded to rounded, mostly quartz, some feldspars, the ash is reworked into a more indurated sandstone.
9	0.3	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray.
10	0.57	Reworked ash, mudcracks are present along with secondary gypsum at the base.
11	1.75	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray.
12	0.14	Stromatolite fresh dark gray to tan, weathers orange to buff, mound growths are 35 cm in diameter, prominent undulating bed.
13	0.14	Ash poorly indurated, fresh light brown, weathers light brown to light orange.
14	0.04	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray.
15	0.47	Laminated kerogen-rich shale, fissile.
16	0.03	Ash well indurated, fresh light gray to orange weathers dark orange to brown, prominent marker bed.
17	0.94	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray.
18	0.01	Ostracode coquina, poorly sorted, conglomeritic, fresh buff to tan, weathers to rusty brown.

19	0.21	Ash reworked, fresh white to light gray, weathers buff to light orange. Capped by a laminated micrite with large mudcracks.
20	0.02	Ash very similar to sample 2.
21	1.78	Laminated micrite that is kerogen-rich, fresh surface is light brown to brown and weathers to light gray to gray, with ash and sheet sands.
22	0.19	Stromatolite light gray to gray, weathers to buff, domes 4 cm, secondary chert and CaCO ₃ .
23	4.1	Laminated micrite interbedded with paper thin kerogen-rich shales.
24	0.03	Laminated micrite, well indurated, prominent marker bed, fresh light gray to buff, weathers dark gray.
25	0.21	Oolitic limestone, very undulating surface, fresh light gray to brown, weathers orange to brown, some hematite staining.
26	0.06	Laminated micrite, well indurated, fresh light gray to gray, weathers rusty brown, mudcracks .
27	2.6	Laminated kerogen-rich shale, interbedded with siltstones and sandstone.
28	0.32	Laminated micrite interbedded with paper thin kerogen-rich shales.
29	2.15	Ash, fresh yellow to rusty orange, weathers dark orange, interbedded with dark black to gray kerogen-rich shales.
30	0.06	Ash, fresh white, weathers orange to brown, well indurated prominent marker, no apparent bedding.
31	1.7	Laminated kerogen-rich shale, interbedded with siltstones and sandstone
32	1.65	Sandstone, fresh buff to tan, weathers orange, fine grained, rounded, well-sorted, mostly quartz and feldspar, mudcracks.
33	2.25	Interbedded siltstone and shale, fresh tan to buff, weathers light brown to orange, poorly indurated.
34/35	3.65	Similar to sample 33, however contains organic/kerogen-rich shales that are very fissile, facies change every 2-3 m shale-siltstone, abrupt contact with overlying sandstone marker bed(top of BMB).
36	11.42	Interbedded kerogen-rich shales, clay/marlstones, paper thin kerogen-rich shale, fresh gray to brown, weathers pale yellow brown. Claystone, fresh light olive gray, weathers yellow gray.
37	2	Interbedded paper thin shales and siltstones, fresh grayish orange, weathers very pale orange, fining upwards.
38	2.66	Ostracode coquina, poorly sorted, conglomeritic, fresh buff to tan, weathers to rusty brown, tufa layer on top of coquina.
39	8.6	Interbedded paper thin shales and siltstones, fresh grayish orange, weathers very pale orange, fining upwards.
40	0.5	Ostracode coquina, poorly sorted, conglomeritic, fresh buff to tan, weathers to rusty brown, tufa layer on top of coquina.
41	8.7	Interbedded paper thin shales and siltstones, fresh grayish orange, weathers very pale orange, fining upwards.
42	6.04	Ostracode coquina, poorly sorted, conglomeritic, fresh buff to tan, weathers to rusty brown, tufa layer on top of coquina.
43	11.92	Paper thin kerogen-rich shales, fresh dark yellow, weathers dark yellow orange, ostracodes present.

44	6.64	Interbedded siltstone and shale, fresh moderate yellow to brown, weathers dark yellow orange to gray orange.
45	3.92	Paper thin shale with reworked ash, fresh gray orange, weathers dark orange.
46	2.21	Interbedded paper thin shales and siltstones, fresh grayish orange, weathers very pale orange, fining upwards.
47	18.26	Claystone, fresh moderate yellow brown, weathers very pale orange, slightly laminated, no ostracodes.
48	4.98	Paper thin kerogen-rich shales, fresh dark yellow, weathers dark yellow orange, Fe concretions present, ostracodes, fish.
49	6.94	Calcareous arenite, fine grained, fresh gray black, weathers pale brown, planispiral gastropods, ostracodes.
50	1	Paper thin kerogen-rich shales, fresh dark yellow, weathers dark yellow orange, abundant ostracodes.
51	6.09	Bedded ash, fresh dark yellow brown, weathers yellow gray.
52	9.3	Bedded ash, fresh dark yellow brown, weathers yellow gray
53	11.62	Bedded ash, fresh dark yellow brown, weathers yellow gray, even further reworked than 51 and 52.
54	3.32	Interbedded siltstone and claystone, fresh dark yellow orange, weathers gray orange, extends to the base of the Sand Butte Bed.

APPENDIX D
SAMPLING STATISTICS