

**SEQUENCE STRATIGRAPHY AND PALEOECOLOGY OF THE LATE  
MISSISSIPPIAN LITTLE STONE GAP MEMBER IN THE  
APPALACHIANS OF WEST VIRGINIA**

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## **ABSTRACT**

The upper Mississippian (Chesterian) Little Stone Gap Member of the Hinton Formation in southern West Virginia was evaluated for its lithofacies and faunal composition. Petrographic and multivariate analyses were used to provide a better understanding of the ecological factors and sequence stratigraphic processes that controlled taxa ordinations and spatiotemporal shifts in facies. Six carbonate and three siliciclastic facies occur within the study interval and these facies stack into two distinct parasequence types. Siliciclastic facies were deposited in continental, low-energy lagoonal and marginal marine environments. Carbonate facies record variable energy conditions in lagoonal, shoal, shoal flank and open marine settings. Parasequence stacking patterns are interpreted as resulting from regional fifth-order glacioeustatic sea-level changes consistent with established age constraints for fourth-order sequences. Detrended Correspondence Analysis (DCA) of paleontological bulk samples produced similar differentiation of habitats into carbonates and siliciclastics thereby demonstrating the importance of interpreting ordination patterns within a facies framework. The combined DCA analysis of samples and taxa indicates that bryozoans, crinoids and rugose corals preferentially occur in carbonate facies whereas brachiopods, the most dominant taxon, are abundant in both. Results suggest the presence of significant paleoenvironmental gradients in fossil associations that correlates to changes in hydrodynamic conditions and substrate composition across the depositional system.

## **DEDICATION**

This thesis is dedicated to God Almighty for the grace He has given me to achieve this important milestone in my life; and to my family, most especially my loving husband for his support and numerous words of encouragement.

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## 1. INTRODUCTION

Studies of paleoenvironmental controls on the distribution of fossils mostly involve the interpretation of lithofacies changes (Bayer and McGhee, 1985; Patzkowsky, 1995) as well as variations in faunal compositions (Springer and Bambach, 1985; Miller, 1988; 1997; Brett, 1998; Holland et al., 2001). Hence, current research trends have emphasized the increased importance of combining stratigraphic and paleobiologic patterns to yield valuable insights into past depositional conditions (Holland, 1995; Scarponi and Kowalewski, 2004). Most of the paleontological studies have focused on well-bedded shale-limestone successions with well-preserved fossil assemblages on bedding planes. This study attempts to perform the same analysis on poorly-bedded limestone and lesser shale successions. Here, multivariate methods have been combined with stratigraphic interpretations to explore for and quantify environmental signatures contained in the faunal assemblages of Little Stone Gap (Avis Limestone) Member of the Hinton Formation.

The Little Stone Gap Member of the Appalachian Basin offers an opportunity to examine the influence of major paleoenvironmental controls on the distribution of fossils. The Little Stone Gap (Avis Limestone) Member is an anomalous unit characterized by fossiliferous marine carbonates occurring within predominantly siliciclastic calcareous shales, red mudstones and subordinate sandstones of the Mauch Chunk Group. It defines a regional marine transgression within the 3<sup>rd</sup>-order composite sequence of the Hinton Formation (Miller and Eriksson, 2000). Chesterian Series (upper Mississippian) is dominated by terrigenous facies deposited in the central Appalachian foreland basin during the early stages of Alleghanian orogeny. It outcrops in southern West Virginia (Fig. 1) and extends into parts of Virginia and Kentucky in the subsurface (Miller and Eriksson, 2000).

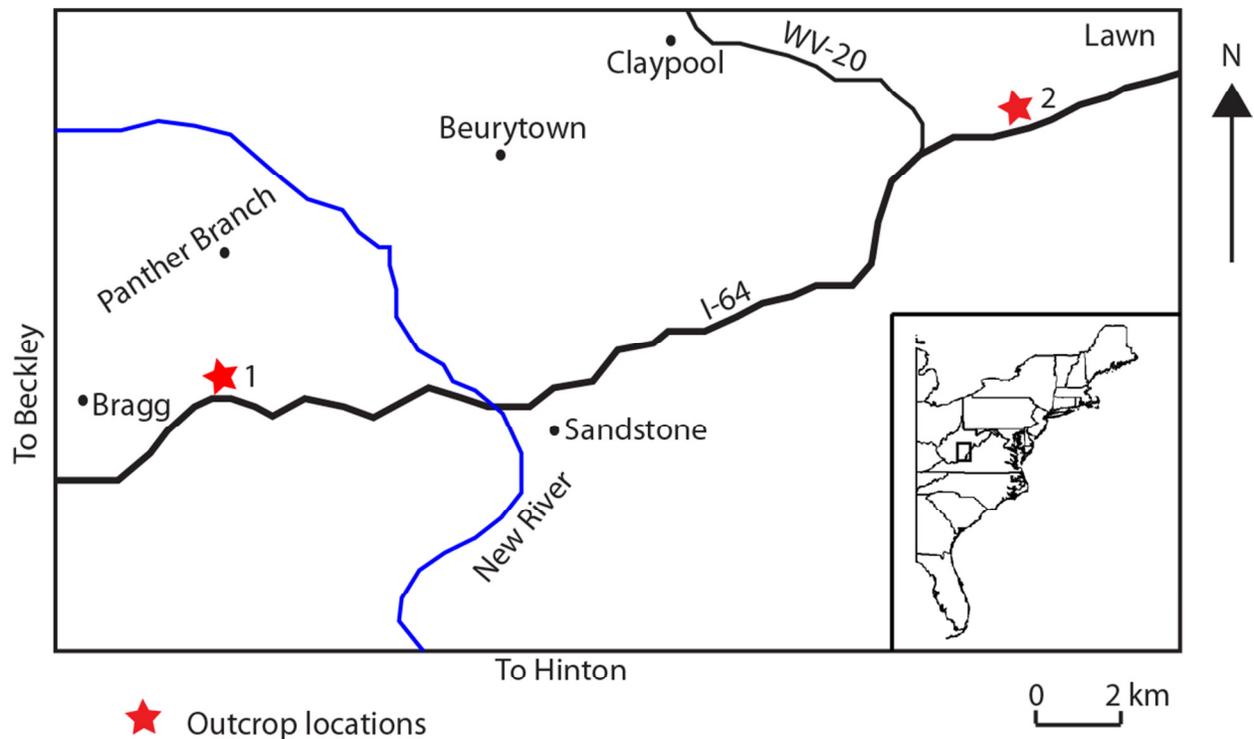


Figure 1. Map of study area showing outcrop locations in southern West Virginia.

The present study utilizes sedimentological and paleontological approaches to evaluate the environmental factors responsible for the deposition of the Late Mississippian (c. 325 Ma) Avis Limestone. Multivariate methods were employed to detect possible patterns in the fossil distributions, and to relate fossil ordinations to similar paleoenvironmental conditions necessary for meaningful paleoecologic interpretations. While rich faunal assemblages have been reported in the study interval (Henry and Gordon, 1992; Perry and Matchen, 2007), this is the first study to attempt a quantitative paleoecological analysis of this stratigraphic unit.

Fourth-order glacioeustatic controls on sequence development in the Mauch Chunk Group were previously recognized by Miller and Eriksson (2000) but this study discusses evidence of fifth-order glacioeustatic and other physico-chemical controls on sedimentation in the Little Stone Gap Member. In particular, the constituent lithofacies are described in terms of

changing depositional environments related to fluctuating sea-level cycles. The objectives of this study are to: (1) provide a detailed sedimentary facies analysis and account for possible vertical and lateral facies changes; (2) interpret the depositional environments in relation to generic fossil associations and facies characteristics; and (3) document the ecologic responses of fauna to flooding events by identifying possible paleoenvironmental gradients within the study area.

## **2. GEOLOGICAL SETTING**

### **2.1 Generalized Lithostratigraphy**

The Late Mississippian Mauch Chunk Group consists predominantly of siliciclastic rocks that make up four formations including the Bluefield, Hinton, Princeton, and Bluestone formations (Fig. 2). The Mauch Chunk Group is a westward-tapering wedge with a maximum thickness of over 900m (3000 ft) in southeastern West Virginia (Miller and Eriksson, 2000; Maynard et al., 2006). The Hinton Formation is a succession of predominantly non-marine strata, which are unconformably overlain by the Princeton Formation. Lithologically, the Hinton Formation consists of heterogeneous red beds (mudstone, siltstone and sandstone) intercalated with calcareous mudstones, gray to green shales and rare marine carbonates and black shales (Beuthin and Blake, 2004). Minor occurrences of coal beds have also been reported in the Hinton Formation (Englund et al., 1986).

The Stony Gap Sandstone at the base of the Hinton Formation conformably overlies the Bluefield Formation (Englund, 1979) although the character of this contact is controversial (Reger, 1926; Nolde, 1994). The Little Stone Gap Member at the top of the lower Hinton

Formation, an anomalous marine carbonate unit (Beuthin and Blake, 2004) is the focus of this study.

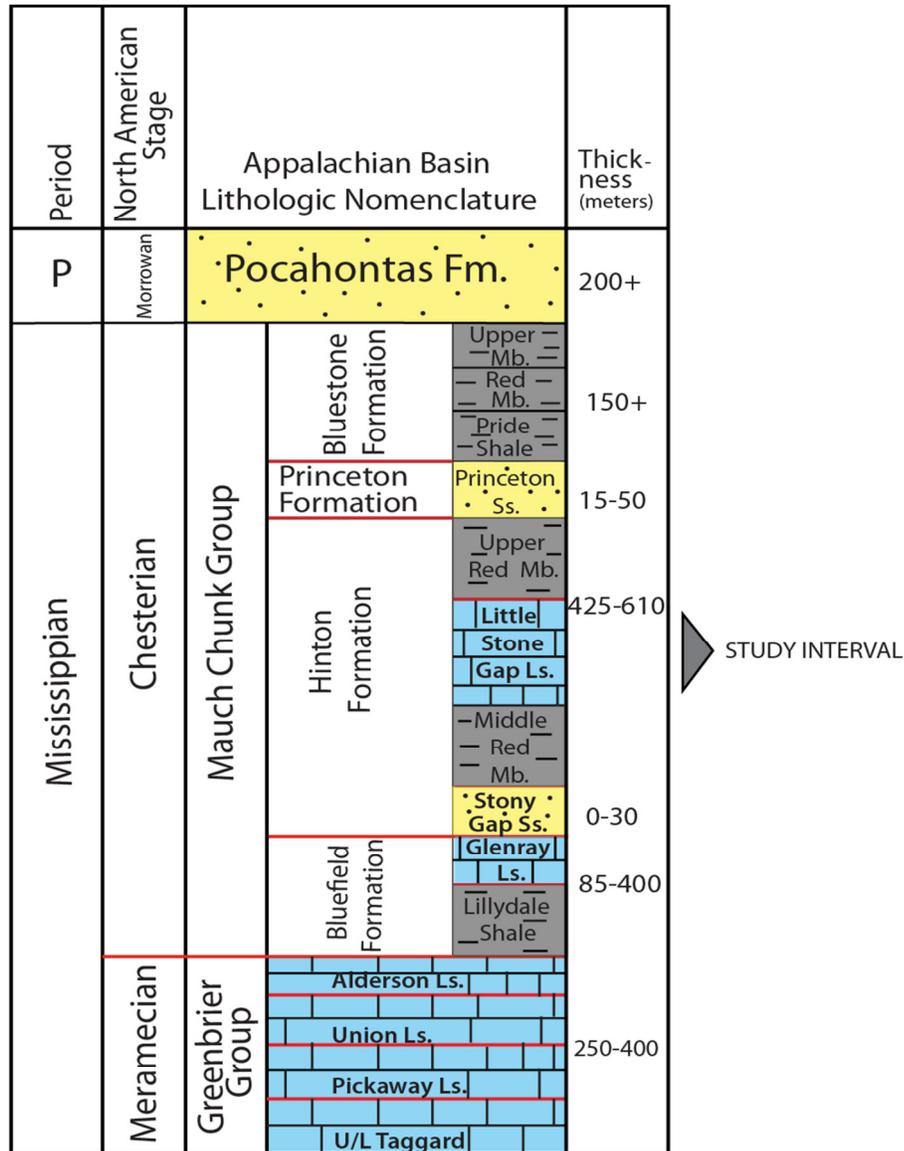


Figure 2. Study interval within the context of Mississippian lithostratigraphy (adapted from Al-Tawil and Read, 2003; Kahman and Driese, 2008)

## **2.2 Tectonic Setting**

The Hinton Formation occurs in the Central Appalachian Basin, which covers an area of about 73,000 km<sup>2</sup> in east-central United States. The Appalachian basin formed as a result of tectonic loading by thrust sheets related to the Taconic, Acadian, and Alleghanian orogenies (Quinlan and Beaumont, 1984; Hatcher, 1989). Tectonic loading created accommodation of up to 3,000m of Middle Ordovician to Pennsylvanian foreland-basin strata (Ettensohn, 2004). Penecontemporaneous tectonism and faulting are evidenced by Meramecian-early Chesterian carbonate seismites (Greb, 2002; Al-Tawil et al., 2003). Flexural tectonic models (Ettensohn, 1994; Ettensohn et al., 2002) and the preserved Mississippian rock record in the Appalachian basin suggests that regional deepening was succeeded by progradation of early Mississippian (Tournaisian-early Visean) and late Mississippian (Serpukhovian) clastics during thrust loading associated with the Acadian Orogeny.

## **2.3 Paleoclimate and Paleogeography**

The stratigraphic succession of the Hinton Formation can be viewed as a record of paleoclimate change linked to the onset of the Late Paleozoic ice age (LPIA) and the assembly of the Pangea. Migration of tectonic plates is hypothesized to have been one of the primary causes of climate change in the Carboniferous (Cecil, 1990). At the end of the Acadian Orogeny and throughout the Mississippian Subsystem, North America (Laurentia) and Western Europe were united as the Laurasia land mass. During the late Mississippian, latitudinal migration of the North American plate positioned the Appalachian basin at approximately 10-20<sup>0</sup> south of the paleoequator (Scotese and Barrett, 1990). As Laurasia drifted northward during the collisional

assembly of Pangea, the climate changed from arid in the early Mississippian to semi-arid in the middle Mississippian as indicated by extensive red bed paleosols in the Hinton and Bluestone formations to alternating semi-arid and seasonally wet conditions in the later Mississippian to humid conditions in the early Pennsylvanian (Miller and Eriksson, 1999; 2000; Al-Tawil and Read, 2003). Reduced circulation resulting from the closure of the intercontinental seaway separating Laurasia and Gondwana caused a buildup of large continental ice sheets in the southern polar region (Crowley and Baum, 1991; Frakes et al., 2005; Rygel et al., 2008). Resulting glacioeustatic changes exerted a strong control on late Mississippian sedimentation in the Central Appalachian Basin (Cecil, 1990; Maynard et al., 2006).

During the late Mississippian interval, the Appalachian highlands were rebounding after unloading in the middle Chesterian (Ettensohn et al., 2002). Basin infilling sediments were sourced from these highlands due to a rapid increase in size of the source area associated with this isostatic uplift (Brezinski, 1989).

## **2.4 Late Mississippian Sequence Stratigraphy**

The Mauch Chunk Group has been interpreted to represent a second-order highstand systems tract within the Mississippian Supersequence, the top of which is marked by the Mississippian–Pennsylvanian unconformity (Al-Tawil and Read, 2003). Up to seventeen high-frequency, fourth-order (~400 k.y.), unconformity bounded transgressive-regressive sequences occur within the Mauch Chunk Group, twelve of which have been assigned to the Hinton Formation (Miller and Eriksson, 2000). Fourth-order sequences have been related to glacioeustatic sea level changes on the order of tens of meters and are stacked into third-order composite sequences displaying retrogradational-aggradational and progradational stratigraphic

stacking patterns. Third-order transgressive systems tracts consist of fourth-order sequences stacked into a retrogradational-aggradational sequence set. Fluvial influx was sufficiently high during the entire relative sea level rise to have resulted in the aggradation of the coastal plain. Third-order highstand deposits consist of fourth-order sequences stacked into a progradational sequence set. The Hinton Formation consists of a complete third-order composite sequence whereas the Princeton and Bluestone Formations define transgressive systems tracts truncated at the Mississippian-Pennsylvanian boundary.

Based on sequence-stratigraphic relationships, the Little Stone Gap Limestone is interpreted as a fourth-order marine-dominated sequence. It is bounded by thick paleosols and defines a third-order maximum flooding surface within the Hinton composite sequence (Miller and Eriksson, 2000).

## **2.5 Biostratigraphy and Age Constraints**

Regional biostratigraphy of the Mississippian in Virginia and West Virginia is given in (Reger, 1926), (Wells, 1950), and (Rice et al., 1979). Advances in conodont (Nemyrovska, 2006; Richards, 2007), brachiopod (Gordon et al., 1982) and ammonoid (Ramsbottom and Saunders, 1985; Cossey and Adams, 2004) biostratigraphy have placed the Hinton Formation in the early Serpukhovian stage (lower Namurian A) (Powell, 2008) (Fig. 3) whose base is defined by *Lochriea nodosa* (Gradstein et al., 2004). Weller et al. (1948) and Englund and Henry (1984) correlated the Hinton Formation with the Pennington Formation. The top of the Hinton Formation in southern West Virginia is equivalent to the top of the Degonia Sandstone (Jones, 1996) and the Clore Limestone (Davydov et al., 2004) in the type Chesterian Series in the Midcontinent. The approximate time span of the Serpukhovian is 8 Myr (Somerville, 2008) but

that of the Hinton Formation is less than 2 Myr (324-326 Ma) and probably no more than 400 kyr (Miller and Eriksson, 2000). Conodont dating reveals that marine units in the Hinton Formation correlate with the Kinkaid and Menard Limestone of the midcontinental Chesterian type section (Sando, 1985; Henry and Gordon, 1992; Menning et al., 2006).

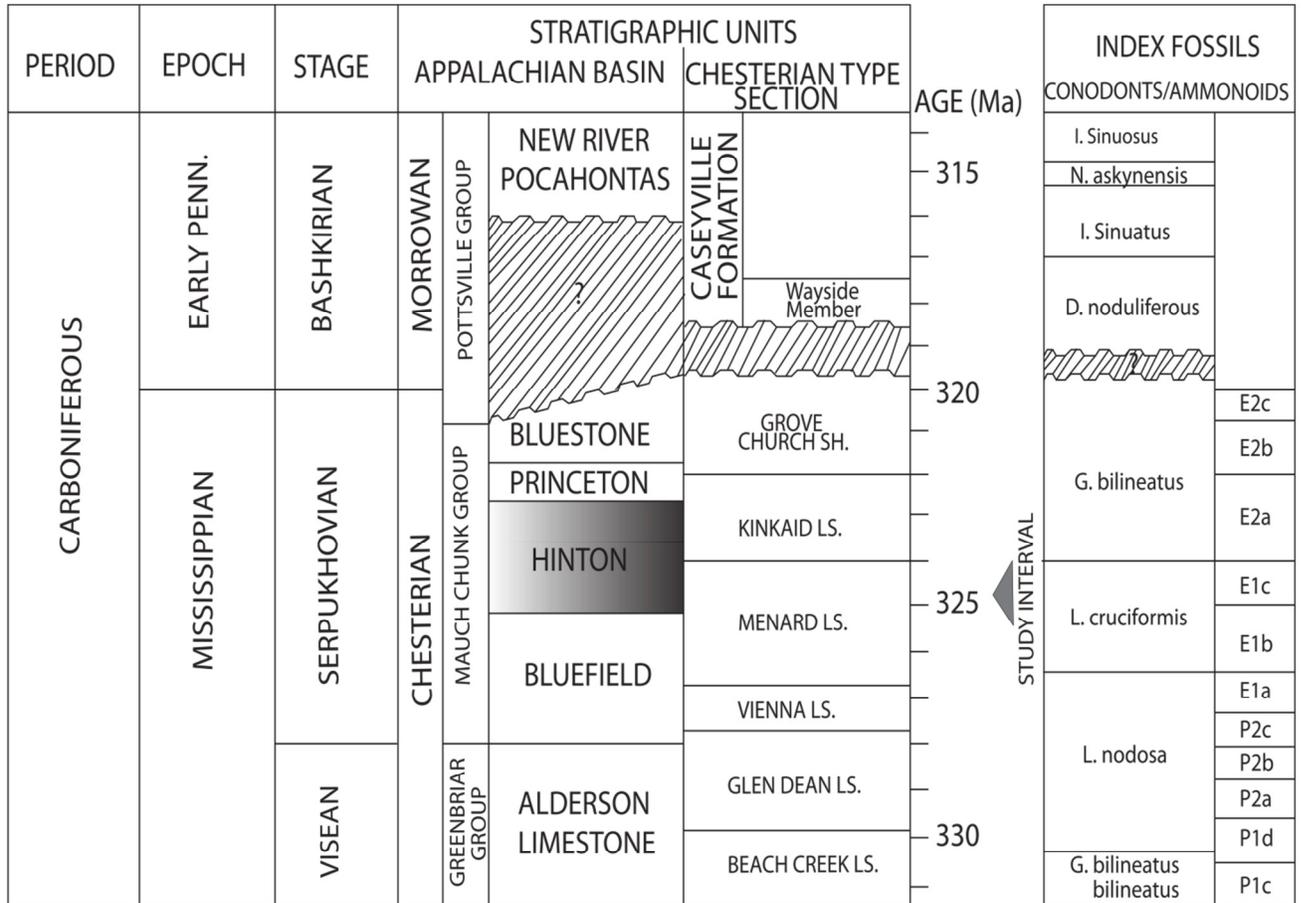


Figure 3. Correlation chart showing biostratigraphic and geochronologic constraints for the study interval (adapted from Cossey and Adams, 2004; Menning et al., 2006; Haq and Schutter, 2008)

### 3. Previous Work

Previous studies of the Bluefield Formation have described the lithology of the exposed rocks including the fossil species (Campbell, 1896; Reger, 1926; Reger and Price, 1929; Price and Heck, 1939; Thomas, 1966; McKinney and Gault, 1980; Gordon and Henry, 1981; Humphreville, 1981). Whisonant and Scolaro (1980) in a study of part of the Bluefield Formation exposed in Munroe County concluded that the sediments were deposited in tide-dominated intertidal to shallow subtidal environments. Earlier studies conducted by Manspeizer (1980), however, inferred a marine-neritic environment for the Lillydale Shale-Glenray Limestone stratigraphic interval. Sequence stratigraphic interpretations reveal that the Bluefield Formation is a tectono-eustatic third-order (2-4 Myr) composite sequence made up of lower-frequency fourth-order (0.1-0.5 Myr) glacio-eustatic sequences which, in turn, contain fifth-order (50-100 ky) upward-shallowing parasequences (Maynard et al., 2006). The Lillydale Shale member represents a second-order maximum flooding surface between the transgressive Greenbrier Group and the highstand Mauch Chunk Group (Reger, 1926; Nolde, 1994; Ettensohn and Greb, 1998; Greb et al., 2002). Red bed paleosols, coals, intercalated mudstone-siltstone, sandstone-mudstone (rhythmites) and carbonates were distributed in a wide range of depositional environments that vary from coastal-plain to open marine (Maynard et al., 2006).

Paleoecological analyses of the Bluefield Formation (Christopher, 1992) indicated the existence of six fossil communities distributed from intertidal to open marine environments. Marine invertebrate fauna in the Bicket Shale contains euryhaline taxa such as the gastropod *Bellerophon* and many other genera of bivalves including *Ectogrammysia* and *Phestia* that are indicative of bay or estuarine conditions. In contrast, the Reynolds Limestone contains a stenohaline, open marine fauna consisting of abundant brachiopod genera such as

*Anthracospirifer*, *Composita* and *Diaphragmus*, together with fenestrate bryozoans, crinoids and solitary rugose corals (Kammer and Lake, 2001). The Bluefield Formation contains the oldest record (Namurian) of amphibian vertebrates, *Hylopus hamesi*, in the eastern United States (Sundberg et al., 1990).

The Stony Gap Sandstone at the base of the Hinton Formation was initially interpreted as a series of marine bars (Englund, 1979) and later as a fluvio-estuarine deposit with inclined heterolithic units interpreted as tidally influenced point bar deposits (Miller and Eriksson, 2000). The Little Stone Gap Member, previously referred to as the Avis Limestone, has been identified as the only regional transgressive event in the Hinton Formation (Reger, 1926; Miller and Eriksson, 2000; Beuthin and Blake, 2004) and contains a diverse marine fauna dominated by brachiopods and bryozoans, as well as bivalves, corals and crinoids (Henry and Gordon, 1992). Recent studies (Beuthin and Blake, 2004; Cawthern, 2007; Vance, 2007) have also identified two regional marine zones in the Fivemile and Eads Mill Members of the upper Hinton Formation which consists of transgressive-regressive cycles of deposition (Miller and Eriksson, 2000).

The Princeton Formation is a conglomeratic unit consisting of two facies associations namely: polymictic conglomerate and conglomeratic sandstones (Miller and Eriksson, 2000). Heterolithic units exhibiting varying thicknesses, together with paleovertisols, also occur in the upper Princeton Formation. The depositional environment of the Princeton Formation has been variously interpreted as barrier beach (Weems and Windolph, 1986), delta (Schalla, 1984), braided river (Pinnix, 1992) and fluvio-estuarine (Miller and Eriksson, 2000).

Two marine zones are recognized in the Bluestone Formation, namely the Pride Shale Member and the Bramwell Member (Miller and Eriksson, 2000). The Pride Shale Member is a coarsening upward succession displaying rhythmic laminations of shale, siltstone and sandstone

deposited in a tide-dominated delta (Miller and Eriksson, 1997). Fossils are sparsely distributed and include bivalves, arthropods and carbonaceous material. Plant fossils and bioturbation have also been reported from the Pride Shale Member and some zones contain disarticulated brachiopod, bivalve, cephalopod and crinoid remains. Evidence of stenohaline marine conditions is well preserved in the Bramwell Member in the form of the bryozoan *Fenestella* and the brachiopods *Orthotetes* and *Ovatia* (Henry and Gordon, 1992). Abundant bivalve genera are also present and many correspond to those in the underlying Bluefield Formation.

Whereas the Mauch Chunk Group and its constituent formations are relatively unfossiliferous, faunas from the Bluefield and Bluestone Formations and the Little Stone Gap Member contain many invertebrate taxa throughout the Chesterian, and their occurrences were predicated upon tolerance to salinity in the depositional environment (Kammer and Lake, 2001).

## **4. METHODS**

### **4.1 Field Observations, Sampling and Petrography**

Initial field studies involved evaluation of potential outcrops between May and August 2010. Two completely exposed sections were identified (Fig. 1), logged on a cm-by-cm scale and sampled for petrographic and paleoecologic studies. Two sections with thicknesses of 70 and 50 feet, respectively, were measured at Bragg and at Lawn in southern West Virginia (Figs. 1 and 4). Observations included lithology, color, fossil content, sedimentary and pedogenic structures (Appendix A) and any other characteristics useful for facies analysis. A photomosaic of the portion of the Bragg section was prepared to evaluate the lateral continuity of facies (Fig. 5). Representative samples of each facies were collected and their stratigraphic position noted.

Petrographic studies were conducted on representative samples to assess the relationship between the sedimentology and paleoecology of the studied rocks. Twelve thin sections were prepared for petrographic analyses. Major textural components and diagenesis were observed in both transmitted and reflected light of a microscope. Individual facies were further characterized with photomicrographs.

Based on field, hand specimen, thin section petrographic and paleontological observations, nine dominant facies were identified in the Little Stone Gap Limestone Member. These facies are stacked into disconformity-bounded upward-shallowing parasequences capped by flooding surfaces. Parasequence sets were correlated between the two sections using similar lithologic and paleontologic characteristics (Fig. 4).

## **4.2 Bulk Sampling**

Logging of sections was followed by the collection of bulk samples from fossiliferous horizons (limestones and shales) in March, 2011 since few bedding planes were present. Samples were obtained with rock hammer and chisel from *in situ* outcrops. Resulting rock slabs were placed in sample collection bags and labeled according to their outcrop locality and stratigraphic position. In order to minimize the effect of small scale heterogeneity that can cause wide variation in biodiversity from bed-to-bed and to ensure detection of all taxa present, multiple (2-4) bulk samples were collected with a horizontal spacing of 10m or less. Such replicate sampling has been described by (Bennington, 1995; 1996) as a means of counteracting the patchy distribution of animals observed in most living marine communities.

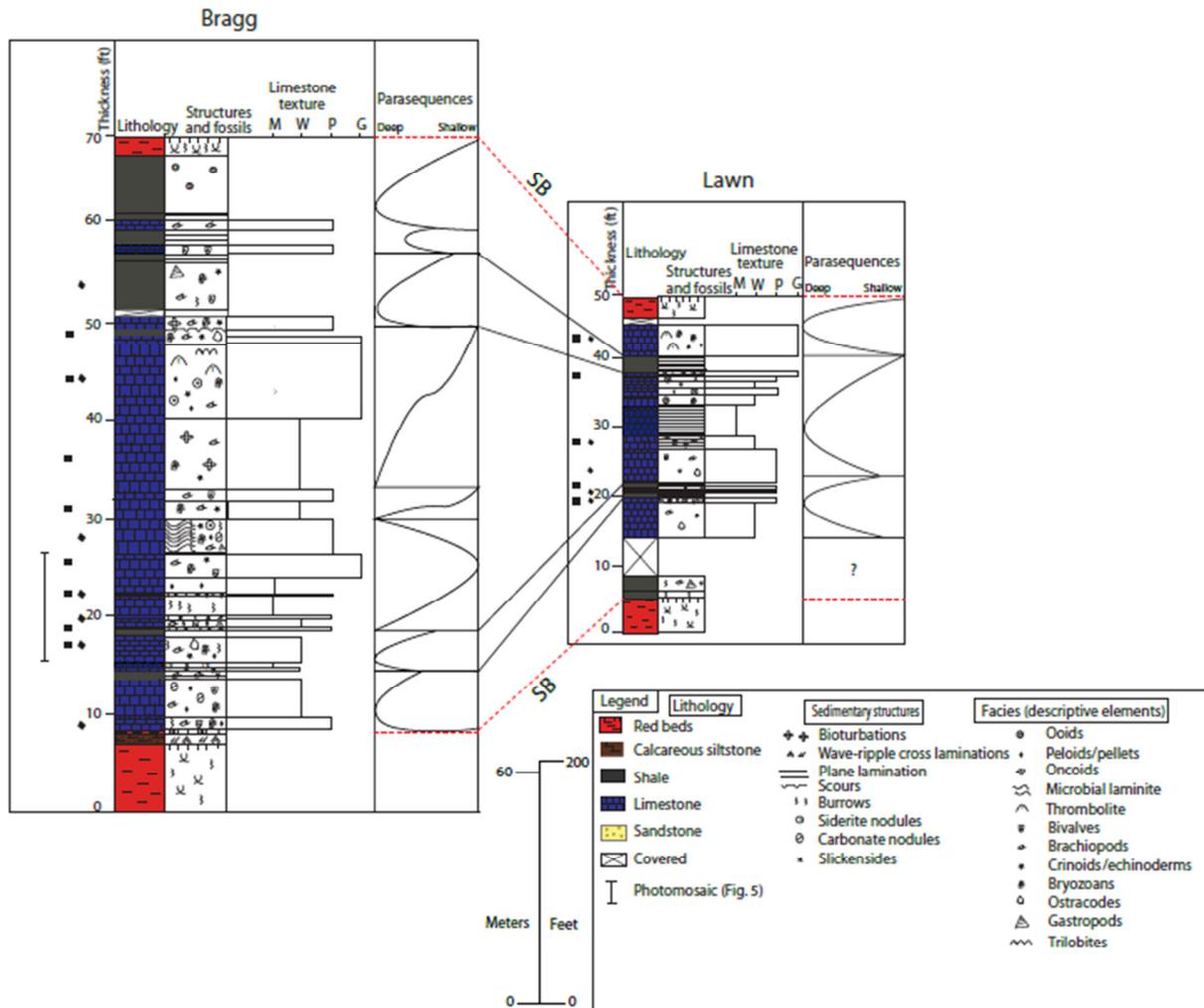


Figure 4. Measured sections and correlation of parasequence between sections. M= calcareous Mudstone, W= wackestone, P= packstone, G= grainstone. SB= sequence boundary  
◆ and ■ indicate units where petrographic and bulk samples were collected respectively.

### 4.3 Laboratory Methods

In the laboratory, each specimen was identified primarily to the genus level, except for bryozoans and crinoids. Genus level identifications were deemed adequate for paleoecological analysis as the ecologic differences between genera tend to be much more significant than those between congeneric species. In addition, the generally poor preservation of specimens created

ambiguity in species level identification which is more susceptible to taxonomic errors (Kammer and Lake, 2001). Also, the preservation of fossils used for this study is characteristically poor which greatly distorts proper identification of specimens to the species level. Many of the fossils are preserved as molds of former aragonitic shells resulting in high taphonomic loss of taxonomic information and observed biodiversity. Brachiopods and bivalves occur largely as molds of partially dissolved shells whereas the brachiopods *Composita* and *Wilkingia* preserve ample detail of skeletal structure. *Wilkingia* is invariably found articulated, closed and commonly retains life orientation in the measured sections. Conversely, crinoids, fenestrate bryozoans and dendritic bryozoans preserve remains of isolated fragments and usually do not permit assignment to a genus but only to a higher taxonomic level.

Individual bulk samples were weighed prior to disaggregating and slabbing in order to account for variations in sample size with respect to differences in rock volume. Limestone slabs were washed and the fossils on the outer surfaces counted and recorded. Poorly indurated shale and limestone samples were broken into smaller pieces and all observed taxa in the molds were tallied. Specimens tallied in this study are subsets of outcrop or thin section taxa. Laboratory identification of specimens derived from disaggregated samples and those exposed on slabs began in early June 2011 with the assistance of Dr. Robert Peck of Concord University. Fossils were identified with the aid of microscope, hand lens and reference materials in order to correctly identify each specimen to the genus level. The following references were used in the identification of each specimen: brachiopods (Muir-Wood and Cooper, 1960; Moore, 1965; Henry and Gordon, 1992) and bivalves (Moore and Teichert, 1969; Busanus and Hoare, 1991; Hoare, 1993).

#### **4.4 Counting Procedures**

Brachiopod and mollusk fossil counts were derived using the MNI (minimum number of individuals) method for fragmentary remains (Gilinsky and Bennington, 1994). Since isolated bryozoan and echinoderm fragments could not be assigned to a specific taxon (a), counts were made using the XNI (maximum number of individuals) method. Isolated fragments of crinoids and colonial bryozoans were included in the fossil counts because they constitute a significant proportion of the faunal content and are important environmental indicators. These approaches can result in either an underestimation (MNI), or overestimation (XNI) of the number of individuals. The use of both methods in this study could therefore lead to an overestimation of the number of bryozoan and crinoid individuals in comparison to brachiopods and bivalves. Overall, approximately 4148 fossil specimens were counted (Table 1) from a total of 45 bulk samples each weighing 3-5 kg.

#### **4.5 Multivariate Techniques**

The fossils of the Little Stone Gap Member are abundant but low in diversity. Their low taxonomic diversity (five taxa in all are encountered in this study) can be attributed to clastic influx to the Appalachian Basin following the isostatic uplift of adjacent highlands. Grouping of taxa into *a priori* defined ecological guilds (Bambach, 1983; Dodd and Stanton, 1990; Kammer and Lake, 2001; Lebold and Kammer, 2006) would further reduce the dimensionality of data (Gauch, 1982) and was not implemented here. Instead, each taxon/genus has been treated as a variable to yield a total of ten variables.

Once specimens were properly identified and counted, samples were standardized by transforming the raw data to percent abundance data (Table 2). Environmental controls on fossil distributions were evaluated by conducting multivariate analyses on occurrence (binary count) data (Tables 3 and 4) and percent abundance data using the PAST software. Both types of data yielded relatively similar results likely reflecting the strong underlying paleoecologic signal (Kammer and Lake, 2001). The data set of all the sampled units (21) and identified taxa/genera (10) was compiled in Excel, and three multivariate analyses were subsequently carried out. Extremely rare taxa occurring in only one sample were later removed from the data in order to reduce noise in the resulting patterns. This culling resulted in a final sample size of 4,136 (Table 5).

Table 1. Original abundance data of all genera obtained from every sampled unit. Sample lithologies and taxa are denoted by the following abbreviations.

Sh – Shale, Wkst – Wackestone, Pkst – Packstone, Grst – Grainstone, Brach – Brachiopod, Gastro – Gastropod, pel – pelmatozoan, col – columnals. Sample numbers correspond to sampled unit in the stratigraphic sections

Taxa		Brach	Brach	Brach	Brach	Brach	Brach	Bryozoan	Bivalve	Crinoid Pel. & Col.	Gastro	Bivalve	Ostracode	Corals	
Genera		Diaphragmus	Inflatia	Composita	Spirifer	Eumetria	Orthotetes	Indet	Phestia		Indet	Indet	Indet	Rugosa	
Sample ID	Lithology														Total
DS5	Wkst	39	10	0	0	0	0	0	0	5	0	0	1	0	55
DS6	Pkst	82	21	0	0	0	0	0	4	0	1	1	0	0	109
DS8	Pkst	0	0	2	0	0	0	7	0	0	0	0	0	0	9
DS11	Sh	63	14	0	0	0	0	0	0	0	0	0	0	0	77
DS13	Wkst	69	0	34	21	0	4	45	0	20	0	0	0	0	193
DS16	Grst	35	0	122	20	2	21	66	0	151	0	0	0	0	417
DS18	Grst	29	0	161	45	0	22	49	0	100	0	0	0	0	406
SS6	Sh	96	1	67	14	0	0	0	0	5	0	0	0	0	183
SS9	Wkst	285	30	8	27	0	0	0	0	0	0	1	0	0	351
SS11	Pkst	52	0	104	113	1	3	141	0	98	0	0	0	0	512
SS13	Pkst	42	4	9	0	0	0	10	0	7	0	0	0	2	74
SS15	Pkst	32	0	74	0	0	21	100	0	66	0	0	0	0	293
SS17	Grst	99	0	47	38	0	16	41	0	36	1	1	0	0	279
SS18	Pkst	50	4	0	13	0	0	60	0	47	0	0	0	4	178
SS19	Wkst	25	0	4	9	0	2	8	0	25	0	0	0	0	73
SS20	Pkst	173	0	5	0	0	0	2	0	0	0	0	0	0	180
SS21	Wkst	5	0	5	2	0	0	1	0	15	0	0	0	0	28
SS22	Grst	0	0	0	0	0	0	2	0	5	0	0	0	2	9
SS23	Grst	22	0	167	23	0	216	19	0	154	0	0	6	0	607
SS24	Pkst	13	0	12	0	0	34	2	0	0	0	0	0	0	61
SS26	Sh	11	4	39	0	0	0	0	0	0	0	0	0	0	54
															4148

Table 2. Percent abundance data generated from the culled abundance data.

Sample ID	Taxa	Brach	Brach	Brach	Brach	Brach	Brach	Bryozoan	Bivalve	Crinoids	Corals
	Genera	Diaphragmus	Inflatia	Composita	Spirifer	Eumetria	Orthotetes	Indet	Phestia	Pel.&Col.	Rugosa
DS5		18.5	72.2	0.0	0.0	0.0	0.0	0.0	0.0	9.3	0.0
DS6		19.6	76.6	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0
DS8		0.0	0.0	22.2	0.0	0.0	0.0	77.8	0.0	0.0	0.0
DS11		18.2	81.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DS13		0.0	35.8	17.6	10.9	0.0	2.1	23.3	0.0	10.4	0.0
DS16		0.0	8.4	29.3	4.8	0.5	5.0	15.8	0.0	36.2	0.0
DS18		0.0	7.1	39.7	11.1	0.0	5.4	12.1	0.0	24.6	0.0
SS6		0.5	52.5	36.6	7.7	0.0	0.0	0.0	0.0	2.7	0.0
SS9		8.6	81.4	2.3	7.7	0.0	0.0	0.0	0.0	0.0	0.0
SS11		0.0	10.2	20.3	22.1	0.2	0.6	27.5	0.0	19.1	0.0
SS13		5.4	56.8	12.2	0.0	0.0	0.0	13.5	0.0	9.5	2.7
SS15		0.0	10.9	25.3	0.0	0.0	7.2	34.1	0.0	22.5	0.0
SS17		0.0	35.7	17.0	13.7	0.0	5.8	14.8	0.0	13.0	0.0
SS18		2.2	28.1	0.0	7.3	0.0	0.0	33.7	0.0	26.4	2.2
SS19		0.0	34.2	5.5	12.3	0.0	2.7	11.0	0.0	34.2	0.0
SS20		0.0	96.1	2.8	0.0	0.0	0.0	1.1	0.0	0.0	0.0
SS21		0.0	17.9	17.9	7.1	0.0	0.0	3.6	0.0	53.6	0.0
SS22		0.0	0.0	0.0	0.0	0.0	0.0	22.2	0.0	55.6	22.2
SS23		0.0	3.7	27.8	3.8	0.0	35.9	3.2	0.0	25.6	0.0
SS24		0.0	21.3	19.7	0.0	0.0	55.7	3.3	0.0	0.0	0.0
SS26		7.4	20.4	72.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3. Original binary data set of all identified fossil genera and sampled units. 1 indicates that the genus was identified in the sample and 0 indicates that it was absent.

Taxa		Brach	Brach	Brach	Brach	Brach	Brach	Bryozoan	Bivalve	Crinoid	Crinoid	Ostracode	Gastro	Bivalve	Corals
Genera		Diaphragmus	Inflatia	Composita	Spirifer	Eumetria	Orthotetes	Indet	Phestia	Pel.	Col.	Indet	Indet	Indet	Rugosa
Sample ID	Lithology														
DS5	Wkst	1	1	1	0	0	0	0	0	0	1	1	0	0	0
DS6	Pkst	1	1	1	0	0	0	0	1	0	1	0	1	1	0
DS8	Pkst	0	0	1	0	0	0	0	0	0	0	0	0	0	0
DS11	Sh	1	1	0	0	0	0	0	0	0	0	0	0	0	0
DS13	Wkst	1	1	1	1	0	1	1	0	1	1	0	0	0	0
DS16	Grst	1	0	1	1	1	1	1	0	1	1	0	0	0	0
DS18	Grst	1	0	1	1	0	1	1	0	1	1	0	0	0	0
SS6	Sh	1	1	1	1	0	0	0	0	1	0	0	0	0	0
SS9	Wkst	1	1	1	1	0	0	1	0	1	0	0	0	0	0
SS11	Pkst	1	0	1	1	1	1	1	0	1	1	0	0	0	0
SS13	Pkst	1	1	1	0	0	0	1	0	1	1	0	0	0	1
SS15	Pkst	1	0	1	1	0	1	1	0	1	1	0	0	0	0
SS17	Grst	1	0	1	1	0	1	1	0	1	1	0	1	1	0
SS18	Pkst	1	1	0	1	0	0	1	0	1	1	0	0	0	1
SS19	Wkst	1	0	1	1	0	0	1	0	1	1	0	0	0	0
SS20	Pkst	1	0	1	0	0	0	1	0	0	0	0	0	0	0
SS21	Wkst	0	0	1	0	0	0	0	0	1	1	0	0	0	0
SS22	Grst	0	0	0	0	0	0	1	0	1	1	0	0	0	1
SS23	Grst	1	0	1	1	0	1	1	0	1	1	1	0	0	0
SS24	Pkst	1	0	1	0	0	1	1	0	0	0	0	0	0	0
SS26	Sh	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Table 4. Binary data set generated after culling the original binary data

Taxa		Brach	Brach	Brach	Brach	Brach	Brach	Bryozoan	Crinoid	Crinoid	Corals
Genera		Diaphragmus	Inflatia	Composita	Spirifer	Eumetria	Orthotetes	Indet	Pel.	Col.	Rugosa
Sample ID	Lithology										
DS5	Wkst	1	1	1	0	0	0	0	0	1	0
DS6	Pkst	1	1	1	0	0	0	0	0	1	0
DS8	Pkst	0	0	1	0	0	0	1	0	0	0
DS11	Sh	1	1	0	0	0	0	0	0	0	0
DS13	Wkst	1	1	1	1	0	1	1	1	1	0
DS16	Grst	1	0	1	1	1	1	1	1	1	0
DS18	Grst	1	0	1	1	0	1	1	1	1	0
SS6	Sh	1	1	1	1	0	0	0	1	0	0
SS9	Wkst	1	1	1	1	0	0	1	1	0	0
SS11	Pkst	1	0	1	1	1	1	1	1	1	0
SS13	Pkst	1	1	1	0	0	0	1	1	1	1
SS15	Pkst	1	0	1	1	0	1	1	1	1	0
SS17	Grst	1	0	1	1	0	1	1	1	1	0
SS18	Pkst	1	1	0	1	0	0	1	1	1	1
SS19	Wkst	1	0	1	1	0	0	1	1	1	0
SS20	Pkst	1	0	1	0	0	0	1	0	0	0
SS21	Wkst	0	0	1	0	0	0	0	1	1	0
SS22	Grst	0	0	0	0	0	0	1	1	1	1
SS23	Grst	1	0	1	1	0	1	1	1	1	0
SS24	Pkst	1	0	1	0	0	1	1	0	0	0
SS26	Sh	1	1	1	0	0	0	0	0	0	0

Table 5. Raw abundance data generated after culling the original abundance data.

Sample ID	Taxa	Brach	Brach	Brach	Brach	Brach	Brach	Bryozoan	Bivalve	Crinoid	Corals	Total	
	Lithology	Genera	Diaphragmus	Inflatia	Composita	Spirifer	Eumetria	Orthotetes	Indet	Phestia	Pel.&Col.		Rugosa
DS5	Wkst		39	10	0	0	0	0	0	0	5	0	54
DS6	Pkst		82	21	0	0	0	0	0	4	0	0	107
DS8	Pkst		0	0	2	0	0	0	7	0	0	0	9
DS11	Sh		63	14	0	0	0	0	0	0	0	0	77
DS13	Wkst		69	0	34	21	0	4	45	0	20	0	193
DS16	Grst		35	0	122	20	2	21	66	0	151	0	417
DS18	Grst		29	0	161	45	0	22	49	0	100	0	406
SS6	Sh		96	1	67	14	0	0	0	0	5	0	183
SS9	Wkst		285	30	8	27	0	0	0	0	0	0	350
SS11	Pkst		52	0	104	113	1	3	141	0	98	0	512
SS13	Pkst		42	4	9	0	0	0	10	0	7	2	74
SS15	Pkst		32	0	74	0	0	21	100	0	66	0	293
SS17	Grst		99	0	47	38	0	16	41	0	36	0	277
SS18	Pkst		50	4	0	13	0	0	60	0	47	4	178
SS19	Wkst		25	0	4	9	0	2	8	0	25	0	73
SS20	Pkst		173	0	5	0	0	0	2	0	0	0	180
SS21	Wkst		5	0	5	2	0	0	1	0	15	0	28
SS22	Grst		0	0	0	0	0	0	2	0	5	2	9
SS23	Grst		22	0	167	23	0	216	19	0	154	0	601
SS24	Pkst		13	0	12	0	0	34	2	0	0	0	61
SS26	Sh		11	4	39	0	0	0	0	0	0	0	54
		Total	1222	88	860	325	3	339	553	4	734	8	4136
		Total %	29.55	2.13	20.79	7.86	0.07	8.20	13.37	0.10	17.75	0.19	

Ecological gradients were analyzed using a variety of multivariate methods including correspondence analysis (CA), detrended correspondence analysis (DCA) and non-metric multidimensional scaling (NMDS). Correspondence analysis which plots both the R-mode (taxa) and Q-mode (sample) ordinations together shows in space how closely related individual taxa are to specific samples. This technique ordines samples and taxa in the same space by maintaining correspondence between both. The Q-mode CA differentiates between samples based on the similarity of taxa contained in them; in the same way that R-mode CA enables taxa to be grouped together based on their occurrence in similar samples. To overcome the arch effect commonly experienced in correspondence analysis (Hill and Gauch, 1980), DCA is performed with the aim of normalizing the sample and taxon scores.

Non-metric MDS ordines the data in a low dimensional space such that approximated distances are preserved (Kruskal, 1964). It is assumed that a closer distance between groups indicates groupings that are more similar in contrast to those further apart (Lebold and Kammer, 2006). Stress index measures the goodness-of-fit of a particular map of similarities to a linear curve. Stress values range from 0 to 1, with low values indicating a good fit and high values (>0.40) indicating a poor fit (Rohlf, 1992; Lebold and Kammer, 2006).

#### **4.6 Diversity/Evenness**

Apart from taxonomic composition, another attribute of community that was investigated is community structure. Evenness of fossil assemblages is an important parameter of biodiversity that is becoming more relevant to the determination of community structure (Cotgreave and Harvey, 1992; Kidwell, 2001; 2002; Woodd-Walker et al., 2002), energy flow and productivity, (Drobner et al., 1998; Wilsey and Potvin, 2000), potential frequency and,

intensity and character of interspecific interactions (Cotgreave and Harvey, 1994; Stevens and Willig, 2000). Evenness can be defined as a summary statistics that reflects the distribution of individuals among taxa. In a perfectly even assemblage, all taxa are represented by the same number of individuals. Conversely, in a highly dominant assemblage, one taxon is dominant and all the remaining taxa have a single individual. The Shannon Weaver and Simpson evenness indices, computed using PAST, were used as a measure of evenness of samples in this study.

## **5. LITHOFACIES**

Lithofacies identified in the field and corroborated in thin sections are illustrated in Figure 4 which also shows correlations between the two measured sections. Most facies are developed in tabular units although a photomosaic of a portion of the Bragg exposure demonstrates a significant build-up of lime mud flanked by grainstones (Fig. 5). In the following sections, facies are first described and then related in stacking patterns (parasequences). Parasequences consisting of stacked facies are then interpreted in terms of depositional processes and paleoenvironments.

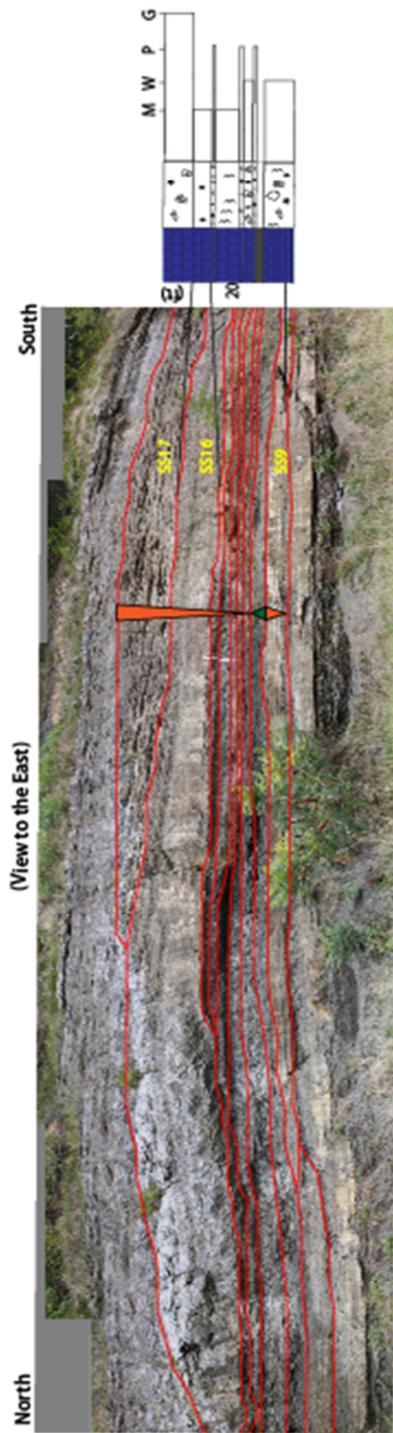


Figure 5. Photomosaic of Little Stone Gap Member exposed at Braggs, West Virginia. Lateral and vertical facies variations are outlined in red (measuring pole = 5 ft for scale). Parasequences are denoted with triangles.

## **5.1 Descriptions**

### **5.1.1 Red Mudstone**

This facies underlies and overlies the Little Stone Gap Member (Fig. 4) and is represented by vertic paleosols that display a range of pedogenic structures including mottling, extensive gleying, root traces or reduction haloes, slickensides and granular peds. Paleosols are silty to muddy, reddish, locally greenish-gray with abundant carbonate nodules, plant fragments and rhizoliths. The lower red mudstone facies is overlain by wave-ripple cross laminated calcareous siltstone whereas the upper red mudstone facies overlies an interval of skeletal grainstones and calcareous shales.

### **5.1.2 Calcareous Siltstone**

This is the least abundant facies and accounts for less than 3% of the section examined at Bragg and is conspicuously absent at the second study location (Fig. 4). At Bragg, it is restricted to the lower part of the section. The calcareous siltstone facies is approx. 1 ft thick, gray-green in color and intercalated with red beds. The facies exhibits a sharp basal contact and a gradational top. It is composed of well sorted, silt-size quartz grains cemented with calcite. Primary sedimentary structures include small-scale, ripple cross laminations. Fossils are lacking.

### **5.1.3 Gray Shale**

This facies is developed in the lower and upper part of the measured sections and constitutes about 16% of the sections. In the lower portions of measured sections, this facies pinches out laterally into wackestone. This facies is dark gray to olive-green in color, fine-grained, highly fissile and calcareous to chloritic with scattered silt-size quartz grains. It is

barren to variably fossiliferous with well sorted skeletal remains of molluscs, productid brachiopods (mainly *Diaphragmus* and *Inflatia* genus), bryozoans, echinoderms and crinoid ossicles. In the upper part of the Bragg section, this facies is developed in units up to 6 ft thick. Locally, this facies contain scattered plant fragments and spherical or irregularly rounded siderite nodules. Commonly, former aragonitic skeletal grains are replaced by neomorphic calcite while still preserving original fabric (Fig. 6a). Rare burrows are filled with sparry calcite and microspar (Fig. 6b).

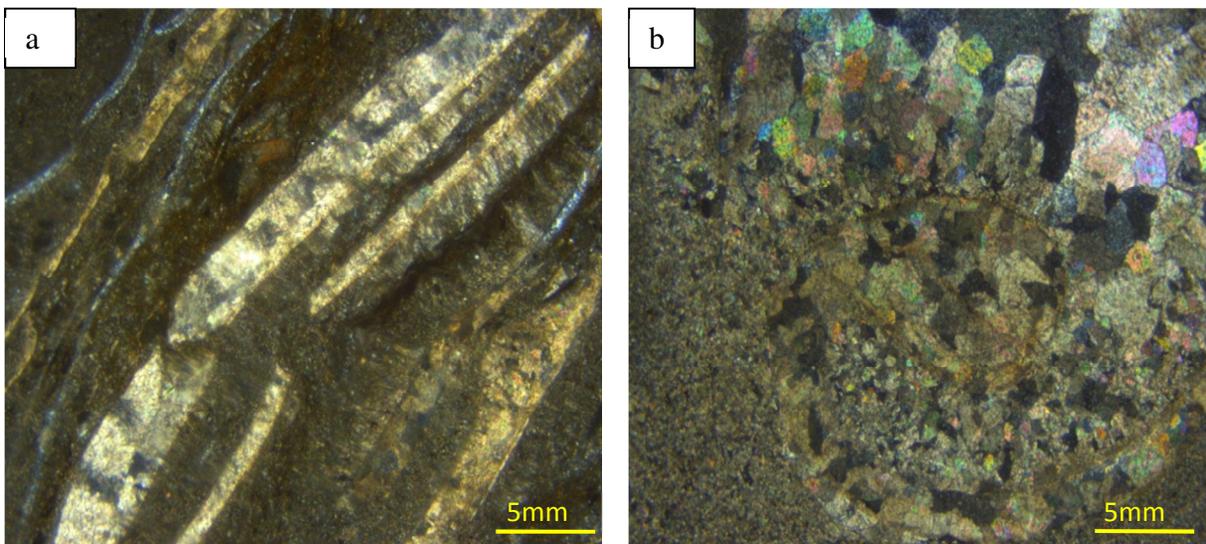


Figure 6. Photomicrographs of representative shale facies. a-Neomorphic recrystallization of brachiopod shells. b- Burrow filled with sparry calcite

#### **5.1.4 Peloidal/Bioclastic packstone**

This is the dominant facies in the study area making up 30% of the measured sections (Fig. 4). This facies makes up tabular units that persist laterally over tens of meters before pinching out or grading into adjacent facies (Fig. 5). This facies is randomly distributed within the measured sections and is commonly associated with lime mudstones and skeletal wackestones. Packstones occur in sharp-based beds between 1 and 3 ft interbedded with gray

shale facies in the upper portions of the measured sections (Fig. 4a). Packstones are massive, bioturbated, heavily burrowed, and composed of fine to medium sand-sized, well to moderately sorted, angular to subrounded, skeletal peloidal/oolitic grains with varying amount of mud. Skeletal grains consist of whole or fragmented mollusks, brachiopods, (Fig. 7a) ostracodes, large fenestrate bryozoans, echinoderms and crinoids. Several genera of brachiopods are identified in hand specimens including *Diaphragmus*, *Inflatia*, *Composita*, *Spirifer* and *Orthotetes*. *Trepostome* and *Cheilostome* bryozoans (Fig. 7b) have also been identified in thin sections. Ooids have cores consisting of sparry calcite and generally poorly developed radial fabric also made up of calcite (Fig. 7c). Cement-filled molds of mollusk fragments consist dominantly of microspar, fibrous and sparry calcite. Mud matrix in this facies is locally recrystallized to neomorphic calcite which also infills moldic porosity within skeletal grains. Microbial laminites (Fig. 7d) occur as yellow alternating millimeter-thick laminae of carbonate silt and mud. Light gray and yellow, horizontally stratified siltstone and fine grained mudstone laminae up to 1.5 cm occur locally within this facies and contain display convex-up shell concentrations.

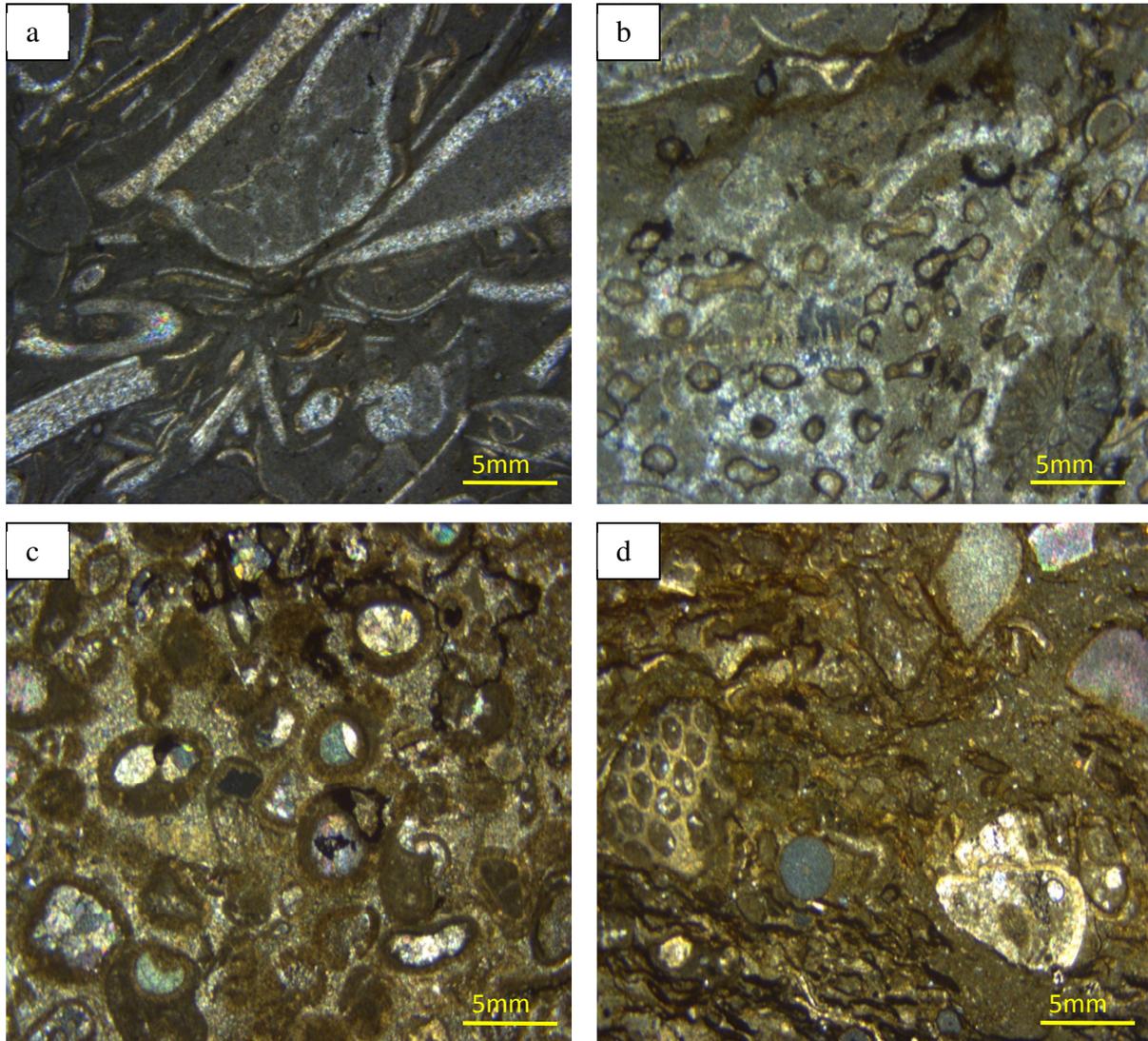


Figure 7. Photomicrographs of typical packstone facies. a-Fragments of brachiopods and bivalves in micrite. b-Bivalves, bryozoans and partially micritized brachiopods in micrite that is partially recrystallized to sparry calcite. c-Bryozoan fragments and poorly developed rounded to subrounded calcitic ooids. d-Crinoids and bryozoans in a microbially laminated packstone.

### 5.1.5 Lime Mudstone

Lime mudstone is the second least abundant rock type and makes up approximately 8% of the measured sections. It is common in the midsection as well as the upper parts of the measured sections. This facies can be traced across the exposures in beds up to 1.5 ft thick and

locally thickens into mound-like structure up to 4.5 ft thick (Fig. 5). Lime mudstone is dark gray, fine-grained, peloidal, laminated and commonly argillaceous to silty. Mudstones contain less than 10% mud-supported grains consisting, in order of abundance, of well to moderately sorted ostracodes, unidentified bivalves (Fig. 8) and gastropods. Most of the fossils have been diagenetically altered by neomorphism and micritization. This facies is characterized by high mud content although the lime mud or micrite is rarely recrystallized to microspar as evidenced by the close association of microspar with micrite. Small scattered burrows are abundant, allochems are barely deformed while undulatory, discontinuous, and millimeter scale microbial mats remain intact.

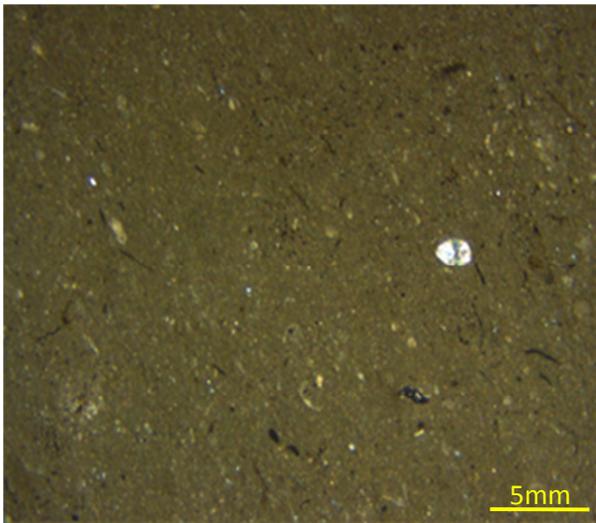


Figure 8. Photomicrograph of lime mudstone containing a small bivalve that is replaced by calcite.

#### **5.1.6 Peloidal/Bioclastic wackestone**

This facies constitutes about 20% of the measured sections (Fig. 4). It is randomly distributed throughout both sections although it is more common in the lower half of the Bragg exposure (Fig. 4a). This facies is dark gray, locally argillaceous, fine grained and thin- to

medium-bedded. It contains abundant well sorted peloids in addition to fragments of echinoderms, bivalves, crinoids, ostracodes and productid brachiopods. Large portions of the grains have been micritized (Fig. 9a) and replaced by microspar though some of the shells possess a primary fibrous calcite layer. Stylolite seams are developed within the microcrystalline mud (Fig. 9b). This facies typically is interbedded with bioclastic packstones.

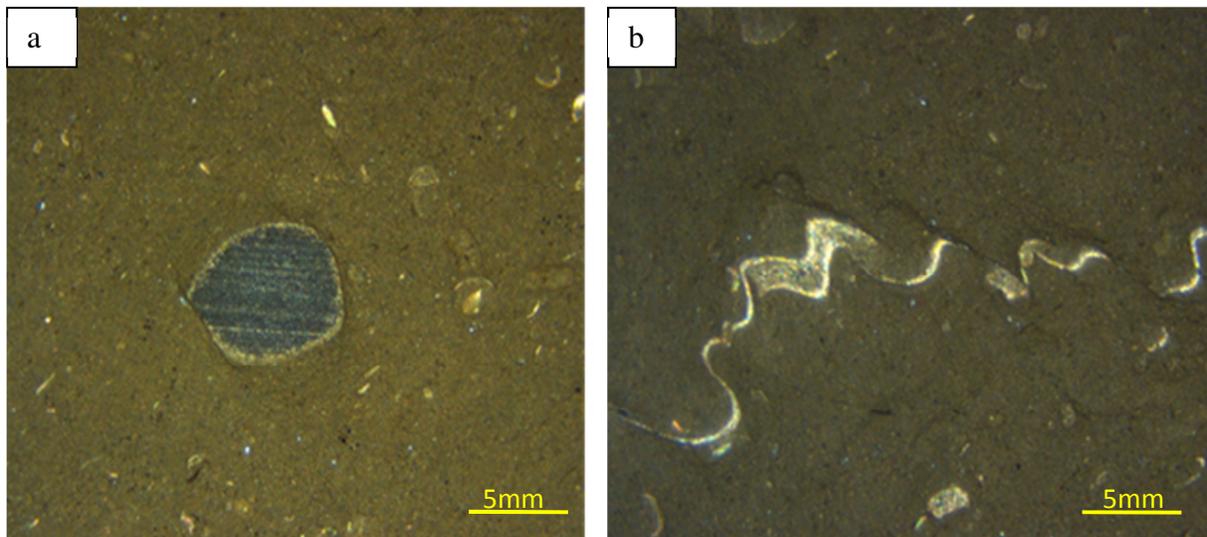


Figure 9. Photomicrographs of peloidal/bioclastic wackestone. a- Micritized bivalve with thin rim of calcite. b- Stylolite seams developed around brachiopod fragments.

### **5.1.7 Peloidal/Bioclastic grainstone**

This facies is developed mostly in the upper parts of the measured sections and comprises about 10% of the sections. Beds are characteristically discontinuous and pinch out against mudstone mounds (Fig. 5). This facies is composed of well sorted coarse-grained ooids, as well as brachiopods, bivalves, bryozoans, ostracodes, echinoderms (Fig. 10a), trilobites (Fig. 10b) crinoids and peloids. Framework grains are cemented with sparry calcite (Fig. 10c). Many of the fossils, including ooids, are abraded and fragmented. Peloids consist of angular to subrounded

micritized skeletal grains (Fig. 10d). Thrombolites consisting of clotted accretionary structures formed by calcareous blue-green algae, occur together with rare oncoids.

#### **5.1.8 Intramicritic/Bioclastic Wackestone and Grainstone**

This facies makes up about 4% of the measured sections and is restricted to the upper portions of the Lawn section (Fig. 4b). Beds range from 4.4 to 4.5 ft in thickness and are discontinuous laterally. This facies contain well-sorted, pebble- to sand-sized, elongate micritic intraclasts incorporated into bioclastic wackestones and grainstones. Framework grains are closely packed resulting in the development of stylolite seams around intraclasts (Fig. 11a-c). Although clasts show well-preserved cloudy outer rims, considerable parts of the grains have undergone silica replacement (Fig. 11c). Grains are dominated by ooids, peloids and fecal pellets (Fig. 11d). The latter are spherical to ellipsoidal, well sorted aggregates of organic matter. Locally, microquartz crystals replace the carbonate mud matrix. Microspar and sparry calcite occur as intragranular fills of highly leached, micritized or fractured skeletal grains of echinoderms, crinoids, brachiopods and bryozoans.

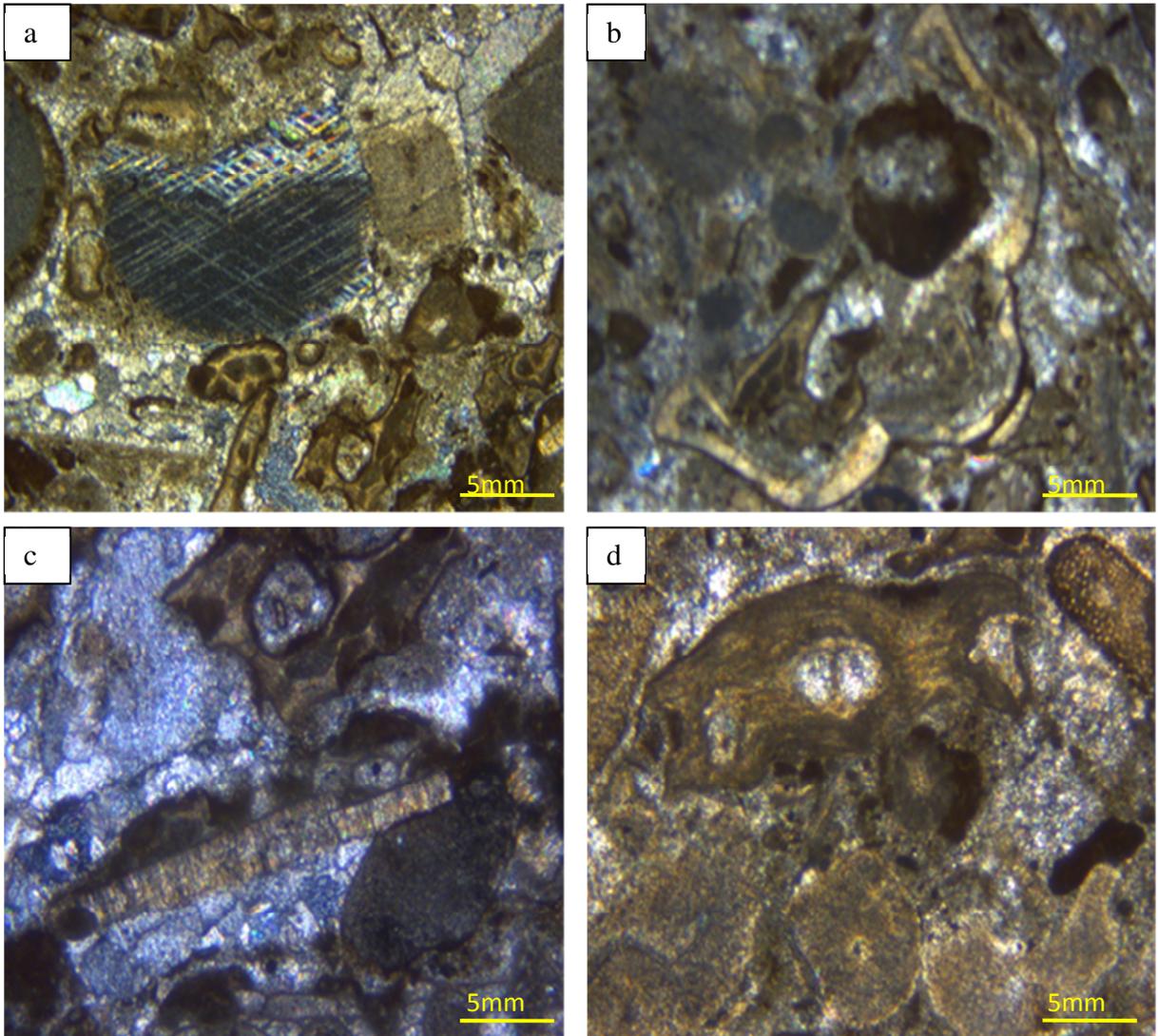


Figure 10. Photomicrographs of peloidal/bioclastic grainstone. a- Echinoderm, crinoid and bryozoans fragments in sparry calcite cement. b- Peloids, trilobite and bryozoan fragments in sparry calcite cement. c- Peloids, bryozoans and bivalve fragments in sparry calcite cement. d- Angular to subrounded micritized crinoids and brachiopod fragments in sparry calcite cement.

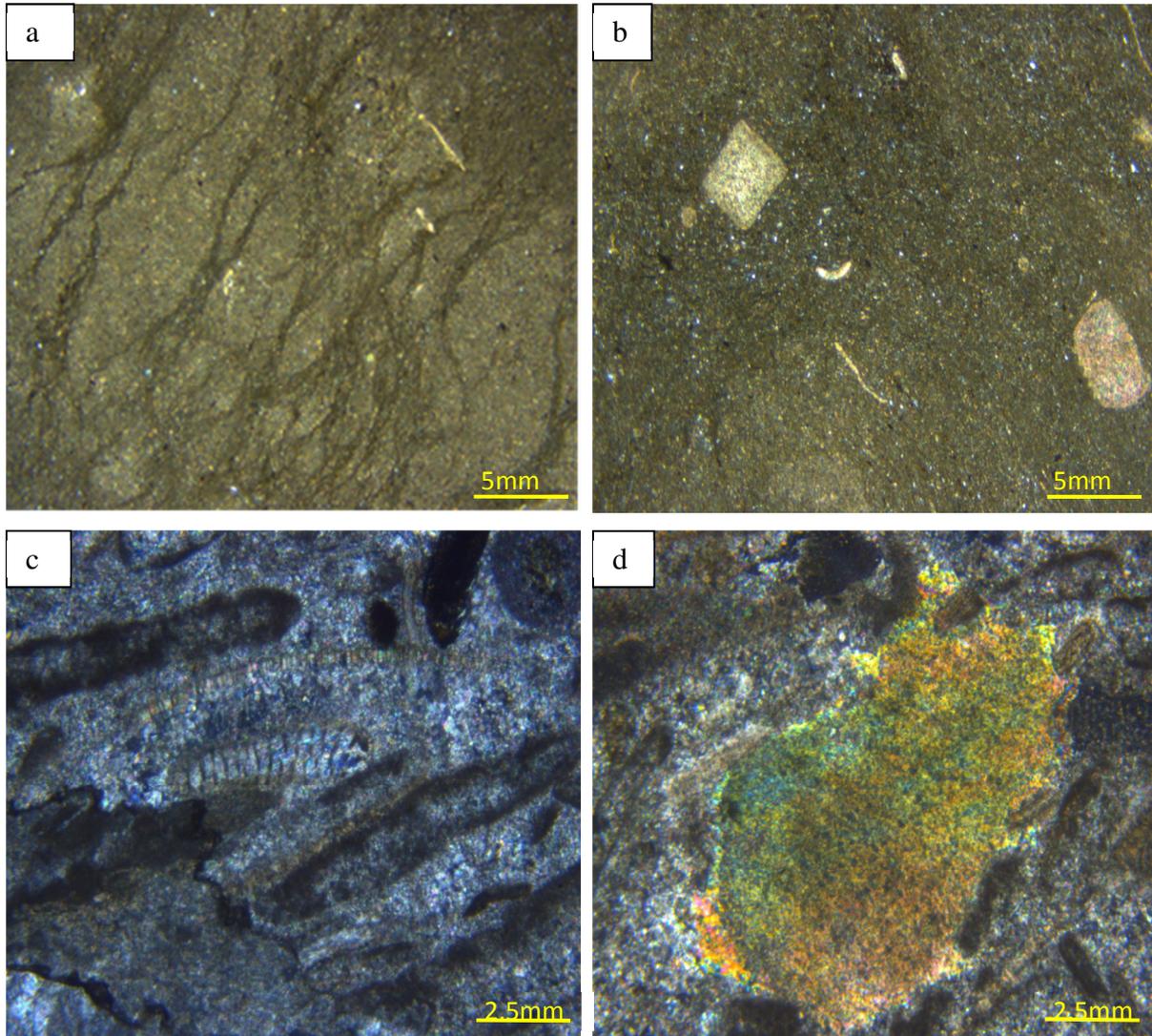


Figure 11. Photomicrographs of intramicritic/bioclastic wackestone and grainstone. a- Wackestone with stylolite seams around micrite intraclasts. b- Wackestone containing crinoids and bivalve fragments. c- Grainstone containing mollusk fragments and intraclasts with neomorphic replacement and stylolites. d- Spherical to ellipsoidal fecal pellets surrounding an echinoderm grain in sparry calcite cement.

### ***5.1.9 Interbedded Limestone and Shale***

This facies is confined to the upper portions of the measured sections (Fig. 4) and occurs as beds that can be traced across the exposure (Fig. 4; at Bragg: 57 to 61 ft; Lawn: 19-22 ft).

This facies consists of interbedded, 0.1 to 0.2 ft-thick gray limestone and up to 0.7 ft thick dark

gray, calcareous shale layers. They occur up section where they are overlain by red beds and gray shale. Limestones are poorly sorted, coarse grained packstones and grainstones consisting of angular skeletal particles cemented with calcite. Packstones are tabular with flat bases containing small gutter casts. Bioclasts include well preserved taxa including mollusks, ostracodes and (*Diaphragmus*, *Composita*, and *Spirifer*); mollusks and brachiopods typically display a convex-up orientation. Shales are fine grained, laminated and exhibit a characteristic yellowish-brown tan color.

## **5.2 Parasequence Stacking Patterns**

Lithofacies within the Little Stone Gap Member are stacked into parasequences bounded by flooding surfaces (Van Wagoner et al., 1990). Individual parasequences in the Little Stone Gap Member range in thickness from 3-20 ft. Two types of facies stacking patterns are recognized (Fig. 12); these are considered to be end members of a spectrum of siliciclastic- and carbonate-dominated parasequences.

### **5.2.1 Limestone-to Gray Shale-to Red Mudstone Parasequence**

This parasequence type ranges in thickness from 10 to 20 ft and consists of basal limestone, overlain by interbedded shale and limestone followed by gray shale and, rarely, capped by red mudstone (Fig. 12). Basal limestone facies consist of packstones and wackestones at Bragg and packstones and grainstones at Lawn and range from 1.2 to 4.5 ft in thickness. Interbedded grey shale and limestone facies consist of grey, calcareous shale beds up to 0.5 ft in thickness with interbeds of packstones and grainstones 0.1 to 0.2 ft thick. Overlying grey shale

facies are up to 6 ft thick, fissile, calcareous, fossiliferous or barren and contain siderite nodules. Capping red mudstone facies are pedogenically altered and contain calcium carbonate nodules.

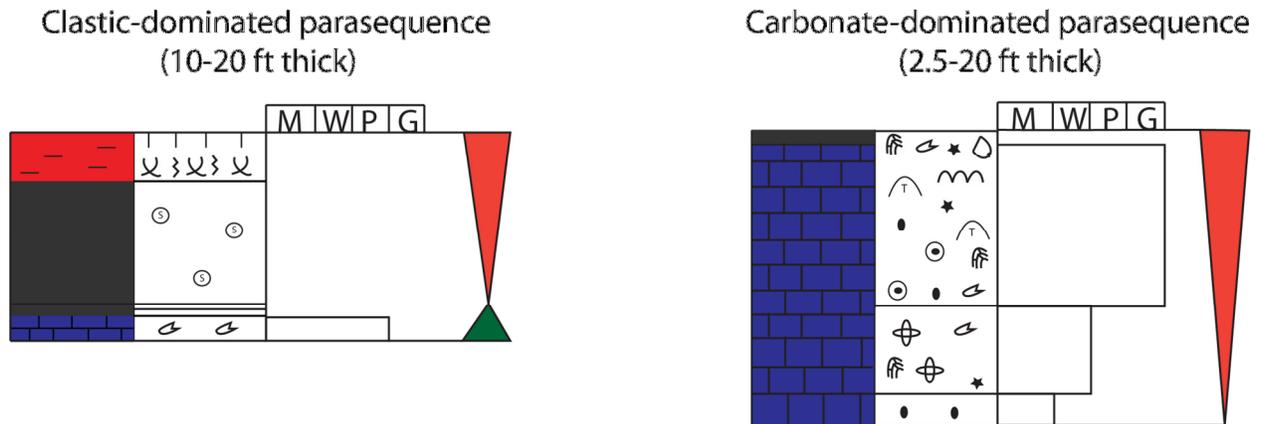


Figure 12. End-member parasequence types in the Little Stone Gap Member. Triangle demarcates deepening upward and inverted triangle shallowing upward. Refer to legend on Figure 4.

This parasequence records a transition from high-energy to low-energy carbonate-rich settings upward to low-energy lagoonal and continental/subaerial environments (Fig. 13). Skeletal grainstones within the basal limestone interval formed on high-energy shoals in water depths of a few to 20 meters. They could also have formed as extensive sheets within lagoons affected by low to moderate reworking (Al-Tawil et al., 2003; Wynn and Read, 2008). Skeletal argillaceous packstones and wackestones in the basal limestone interval developed offshore from grainstone shoals below fair-weather wave base and above storm wave base in water depths of about 20 to 60 meters (Purser and Seibold, 1973) though this range could be lower in the Appalachian Basin due to strong winds that blew across the basin (Golonka et al., 1994). Packstones at the top of the limestone intervals may represent condensed sections or hardgrounds as indicated by the presence of mixed, open-marine and shallow-marine taxa and intense

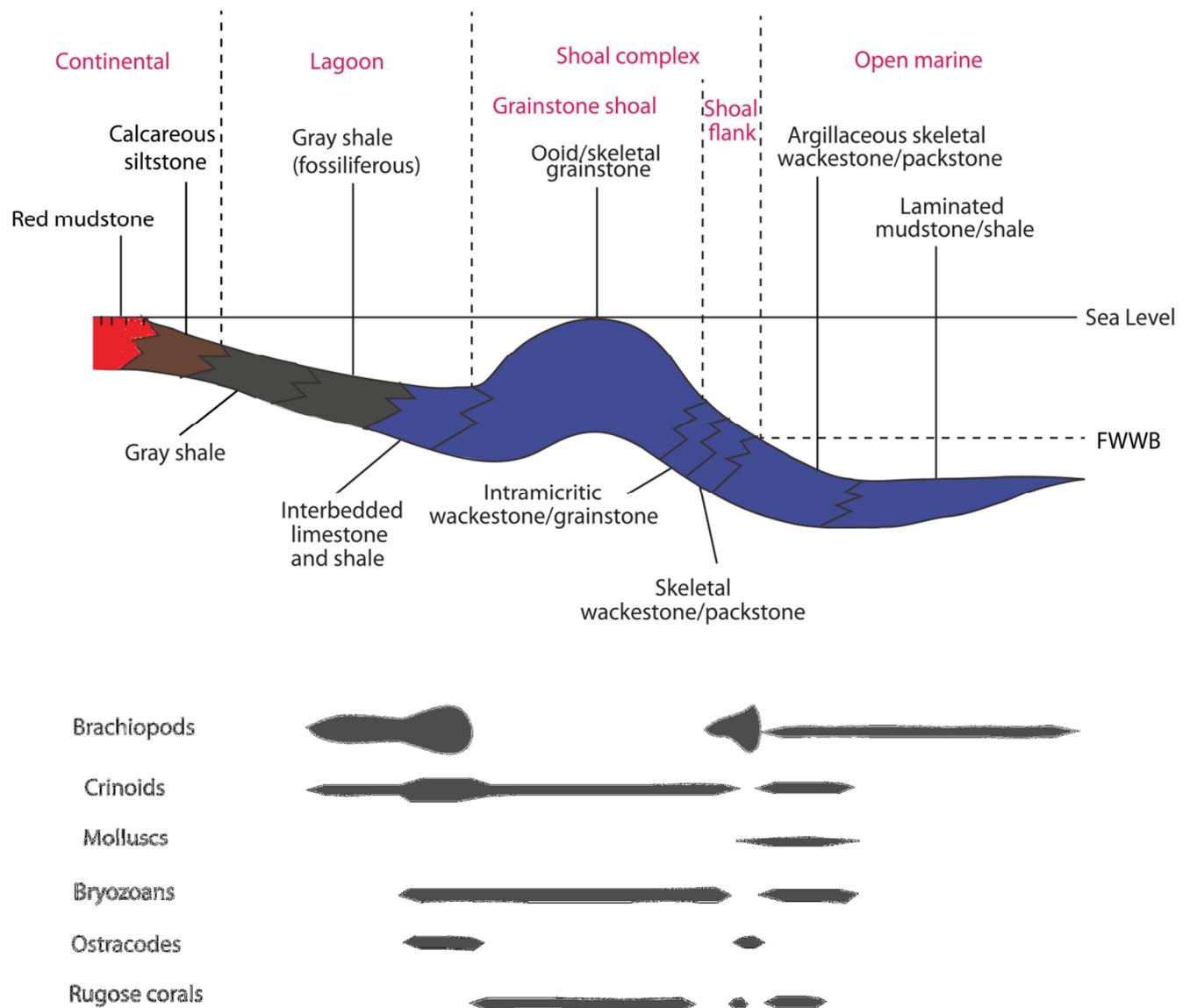


Figure 13. Schematic facies profile for the Upper Mississippian Little Stone Gap Member in the Appalachian Basin. Also shown are relative abundances (abundant, common, rare, and absent) of the dominant fossils.

burrowing. Interbedded limestone and shale (Fig. 4) developed in restricted lagoonal settings landward of carbonate banks. The presence of benthic organisms (i.e. *Diaphragmus*, *Composita*, *Spirifer*, bryozoans and crinoids) within the limestones supports normal salinity and dysoxic (2.0-0.2 m/l D.O) conditions in the shallower part of the lagoon (Tyson and Pearson, 1991). In contrast, the lack of fossils in the gray shales could be related to high sediment influx or adverse salinity conditions related to seasonal flooding. Abundant evidence exists in the Mauch Chunk

Group for monsoonal climatic conditions in the form of vertisols and annual, climate forced tidal rhythms (Miller and Eriksson, 2000). Overlying non-fissile, green/gray shales are also interpreted as lagoonal facies formed under variable salinity conditions (Smith and Read, 2001; Wynn and Read, 2008). This interpretation is bolstered by the lack of marine fossils and the association of this facies with red mudstones (Treworgy, 1985; Smith and Read, 2001). The presence of siderite nodules in the gray shales lends support to the prevalence of freshwater which tended towards reducing conditions as a result of degradation of organic matter (Postma, 1982; Bailey et al., 1998). Red mudstone that caps the uppermost parasequence indicates prolonged subaerial exposure typical of arid or monsoonal, semiarid climatic conditions (Ambers and Petzold, 1992) and which promoted the precipitation of carbonate nodules within the soil profile (Blodgett, 1988; Cecil, 1990; Caudill et al., 1996; Miller and Eriksson, 2000). The siliciclastic-dominated parasequences (Fig. 12) record drowning with deposition of carbonates in clear-water, shelfal settings followed by progradational outbuilding of gray, lagoonal mudstones and continental red beds.

### **5.2.2 Lime Mudstone to Grainstone Parasequence**

This parasequence type ranges in thickness from 2.5 to 20 ft and is typically upward coarsening at Bragg and upward fining to upward coarsening at Lawn (Fig. 4). Complete upward-coarsening parasequences consist of lime mudstone grading upwards into skeletal wackestone, skeletal packstone and skeletal to oolitic grainstone whereas the lower portion of symmetrical parasequences fine upwards from packstone to wackestone to mudstone followed by the same upward-coarsening trend. Parasequences rarely display upward fining in their uppermost portions or are capped by gray shale (Fig. 12). Lime mudstone facies are 1.5-4.5 ft

thick, dark gray, fine grained, argillaceous rocks that are rarely fossiliferous. Skeletal wackestone facies are 1-7.5 ft thick, dark gray, fine-grained and micritized. Bioclastic packstone facies are 1-5 ft thick, unlaminated, bioturbated and deeply burrowed. Grainstones facies are 4-8 ft thick, coarse-grained, micrite-free and commonly contain ooids, peloids in addition to fossils. Rare grey shale facies at the top of parasequences are dark gray, fine-grained and calcareous with skeletal grains that have been recrystallized to calcite.

This parasequence type records a transition from low-energy, open-marine conditions to moderate/high-energy, ooid shoals and shoal flanks and, locally, to lagoonal conditions (Fig. 13). Massive lime mudstone formed in a low-energy, offshore open-marine environment beyond the influence of siliciclastic influx (Smith and Read, 2001; Al Tawil et al., 2003; Wynn and Read, 2008). Wackestones and packstones formed on shoal flanks and record progressive shallowing of the shelf to clear, warm, shallow high energy ooid shoals developed above and adjacent to skeletal banks that may earlier have occurred as topographic highs (Harris and Fraunfelder, 1993). Poorly developed ooids, however, suggest moderate energy or sheltered shoals in water depths estimated to have ranged from the intertidal zone down to 10 meters (Keith and Zuppman, 1990; Kelleher and Smosna, 1993; Al-Tawil et al., 2003). This depth range is supported by the coexistence of thrombolites and oncoids in the oolitic grainstones, that are indicative of the photic zone which would be very shallow in such a muddy basin (Ginsburg et al., 1971). Gray shales that locally cap carbonate-dominated parasequences represent lagoonal facies and provide a link between the two end-member parasequence types. Carbonate-dominated parasequences record either rapid drowning followed by overall shallowing from offshore carbonate mudstones to ooid and skeletal shoals or, for the symmetrical parasequences, slower transgression followed

by shoaling. In common with the first parasequence, packstones locally define condensed sections or hardgrounds.

### **5.3 Sequence Stratigraphy**

The limestone to gray shale to red mudstone and lime mudstone to grainstone parasequences (Fig. 12) represent, respectively, more proximal and siliciclastic-dominated, lagoonal and more distal and carbonate-dominated, shelfal depositional systems. A summary of the interpreted depositional environments is given in Table 6. Thus, the Little Stone Gap Member records overall deepening from the basal red mudstone followed by shoaling into the overlying red mudstone (Fig. 4). This general trend is considered to be related to a fourth-order eustatic rise followed by fall as recorded by the Little Stone Gap Member (Miller and Eriksson, 2000). Based on available age constraints, fourth-order glacioeustatic fluctuations in the Mauch Chunk Group are of ~400 kyr duration (Miller and Eriksson, 2000). Individual parasequences in the Little Stone Gap Limestone record higher-frequency sea-level fluctuations and are interpreted to have been driven by fifth-order (~ 40 kyr) glacioeustatic changes.

Table 6. Summary of interpreted depositional environments for individual lithofacies of the Little Stone Gap Member.

Lithofacies	Description	Biota	Depositional environment
Red mudstone	Red or green-gray; mottled mudrocks, silty, massive, gleyed clay, slickensides, reduction haloes and carbonate nodules are common.	Root and burrow traces; plant fragments. Lacks fossils.	Subaerial/Continental
Calcareous siltstone	Gray-green; well-sorted grains of quartz; wave-ripple cross laminations occur locally.	None	Continental
Gray shale	Dark-gray to olive green; clay-size well-sorted angular quartz, chlorite and skeletal grains; locally interbedded with packstone or grainstone. Very fissile to massive, barren to moderately fossiliferous; siderite nodules occur in barren facies.	Small mollusks, fragments of brachiopods, bryozoans, crinoids and echinoderms; few plant fragments.	Lagoonal
Lime mudstone	Dark gray; fine-grained, argillaceous, silty, peloidal and pyritic.	None to sparse; may contain ostracodes and mollusks. Abundant burrows and well-developed microbial and plane laminations.	Low-energy and deep open marine

Lithofacies	Description	Biota	Depositional environment
Peloidal/bioclastic wackestone	Dark gray; fine-grained, argillaceous, thin- to medium-bedded, well-sorted peloids and skeletal grains; stylolite seams present; usually interbedded with packstones.	Contains fragments of echinoderms, bivalves, crinoids, ostracodes and productid brachiopods.	Shoal flank to shallow open marine
Peloidal/bioclastic packstone	Dark-gray; fine to medium grained, argillaceous; angular to subrounded, well to moderately sorted peloids and ooids.	Highly fossiliferous with whole and fragmented mollusks, brachiopods, ostracodes, bryozoans, echinoderms and crinoids. Burrows, bioturbations, and microbial laminites occur locally.	Shoal flank to shallow open marine
Peloidal/ bioclastic grainstone	Gray; well sorted large ooids, angular to subrounded peloids; thrombolites and oncoids present.	Abraded and fragmented skeletal grains such as brachiopods, bivalves, bryozoans, trilobites, ostracodes, crinoids and echinoderms.	High-energy ooid/grainstone shoal
Intramicrotic wackestones and grainstones	Gray; pebble to sand sized, well sorted, elongated micrite intraclasts, biotite, quartz, chlorite, pyrite, ooids, peloids and fecal pellets.	Micritized and fractured skeletal grains including echinoderms, crinoids, brachiopods and bryozoans.	Shoal flank
Interbedded limestone and shale	Gray; coarse grained, poorly sorted, limestones; fine grained, fissile, argillaceous shales. Displays gutter casts and concentrated shell beds.	Angular skeletal particles such as mollusks, ostracodes, to brachiopods.	Lagoon

## 6. PALEONTOLOGY

### 6.1 Data

A total of 4148 identifiable fossil specimens (Table 1) were collected from the Little Stone Gap Member. They included brachiopods, bryozoans, bivalves, gastropods, ostracodes, crinoids and rugose corals. This list does not include those taxa (e.g. trilobites) that were only observed in thin section. Due to poor preservation, species level identification was rarely possible: specimens were identified to genus level when possible or assigned to higher taxa when morphological details were inadequate for systematic diagnosis.

The most abundant and diverse taxa were brachiopods, which represented six genera, and occurred in all of the 21 sampled units. The brachiopod genera included *Spirifer*, *Eumetria* and *Orthotetes*. The most abundant brachiopods (Fig. 14) are *Diaphragmus* (29.6%) and *Composita* (20.8%). In fifteen samples, brachiopods were found in association with stenotopic taxa (crinoids, rugose corals and bryozoans). The non-brachiopod taxa recorded in substantial quantities included crinoids (17.8%), which were represented by pelmatozoans and columnals preserved as disarticulated stem pieces, and bryozoans (13.4%). Mollusks (0.1%) and rugose corals (0.2%) were infrequent (Fig. 14).

### 6.2 Multivariate Analyses

The detrended correspondence analysis (DCA) was applied to ordinate samples and taxa to reduce multivariate data to a few dimensions. The first two axes accounted for 38.7% variation in the data, thus capturing a notable fraction of the variation in the data. DC1 axis primarily represents changes in dominant brachiopod genera (Fig. 15): samples with low scores

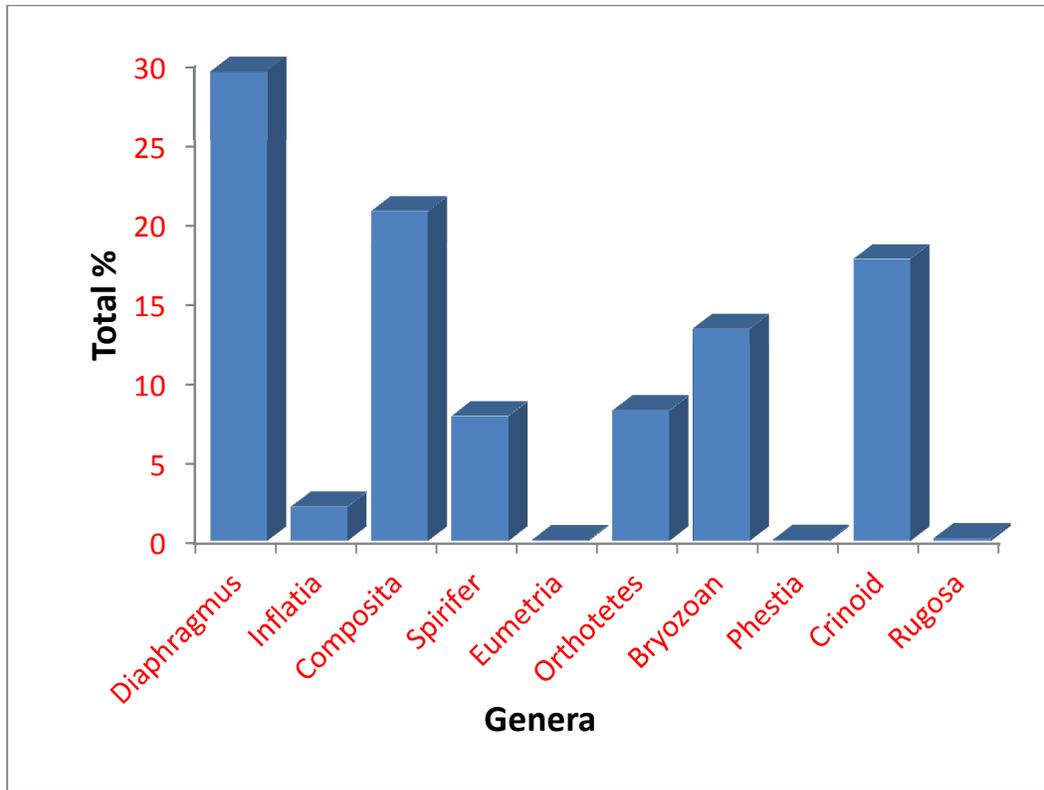


Figure 14. Percentage distribution of individual taxon/genus obtained from both localities.

are dominated by *Eumetria*, *Orthotetes* and *Spirifer* whereas those with high scores are dominated by *Diaphragmus*, *Inflatia* and *Composita*. DC2 axis represents a gradient from brachiopod-rich associations (low-to-intermediate DC2 scores) to bryozoan-crinoid-coral dominated assemblage (high DC2 scores) (Fig.15).

When grouped by lithology, the samples show distinct facies-related grouping in the ordination space, with carbonates and fine-grained siliciclastic samples clearly separated (Fig. 16). Shales dominate at high DC1 and low DC2 scores whereas carbonates tend toward low-to-intermediate DC1 scores and low-intermediate DC2 scores. Within carbonate facies, packstones exhibit highly variable DC scores. The brachiopod genera *Diaphragmus*, *Inflatia* and *Composita* appear to be primarily occurring in fine-grained shale samples. The remaining brachiopods

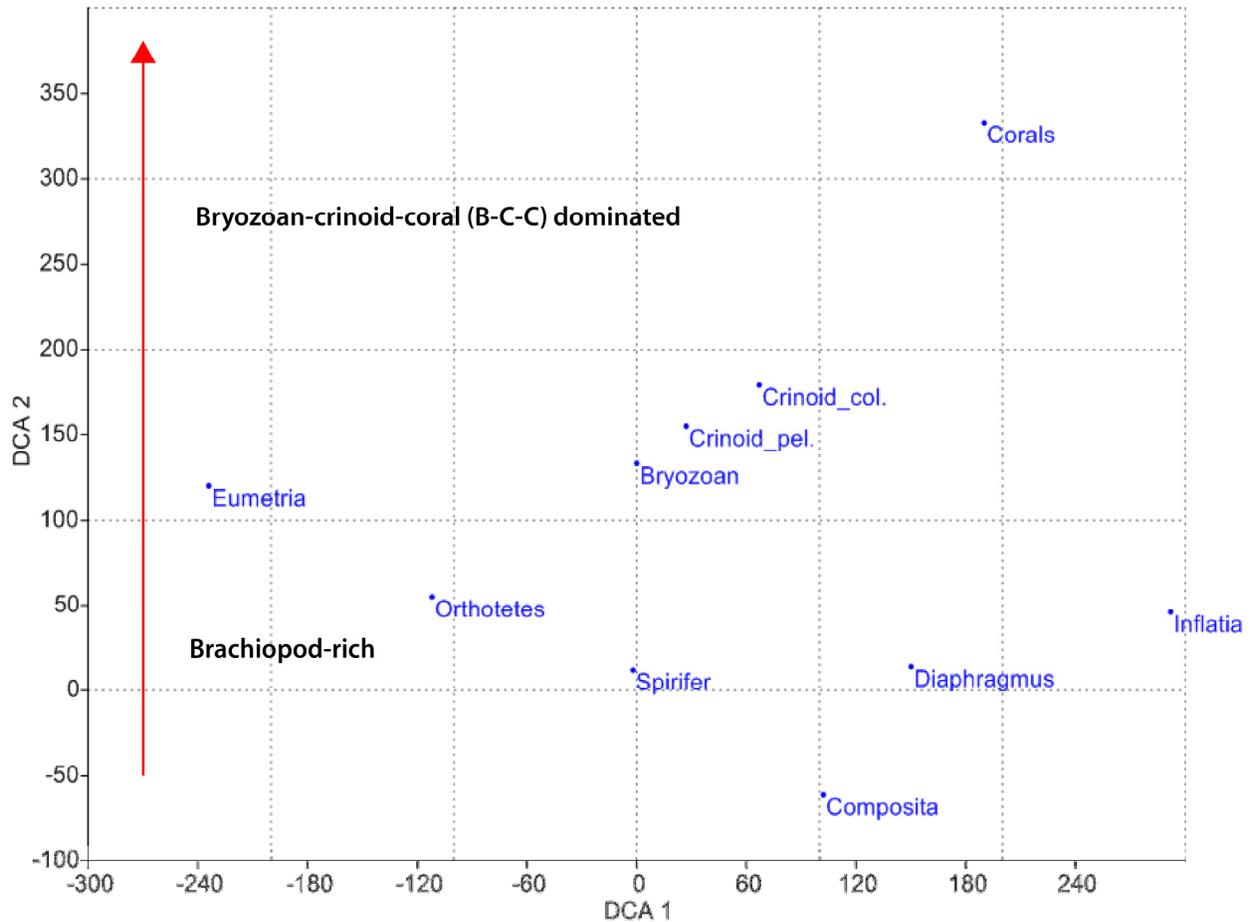


Figure 15. Detrended correspondence analysis ordination of taxa/genera (R-mode data) of the Little Stone Gap Member. First two axes explain 38.7% variance in data (DC1 = 25.2%, DC2 = 13.5%).

(*Eumetria* and *Orthotetes*) appear to be preferentially occurring in carbonates. *Spirifer* occurs predominately in carbonates, including all three types of limestones. Bryozoan-crinoid-coral assemblage occurs preferentially in carbonate-rich samples (Fig. 17).

The sample DC scores were also plotted by lithology (Fig. 18), grain size (Fig. 19), stratigraphic position (Fig. 20) and locality (Fig. 21). These plots reveal a gradual increase in grain size from fine grained shales to coarse grained carbonates towards the top of the section. Near-complete overlap in grain size trends was observed when the DC scores were plotted by locality.

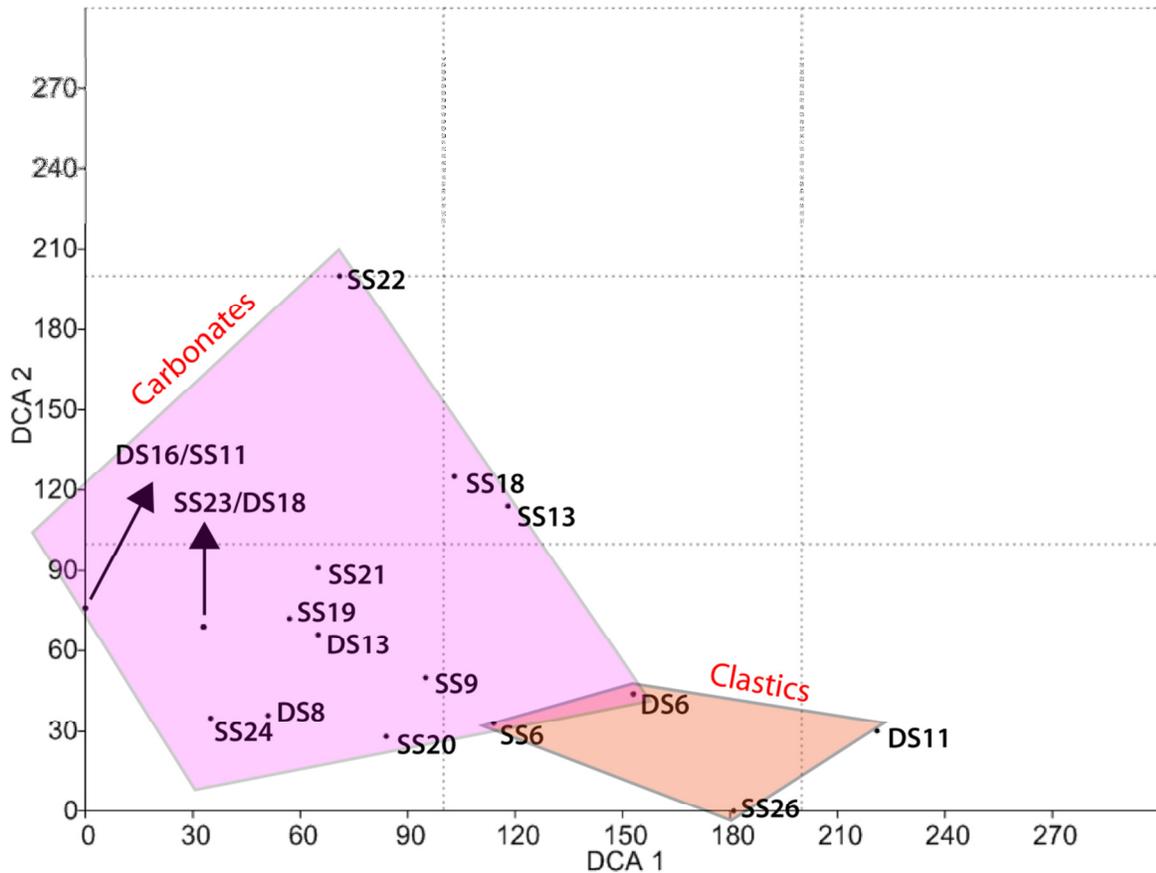


Figure 16. Detrended correspondence analysis ordination of samples (Q-mode data) of the Little Stone Gap Member

The results obtained for Correspondence Analysis and non-metric Multidimensional Scaling of the binary data yielded results consistent with those reported above for DCA. Namely, these other approaches were also successful in discriminating between brachiopod-dominated units and bryozoan-crinoid-brachiopod assemblages (Appendix B). In all ordination methods, the separation between the two major facies types is clearly observed, but delineation of individual carbonate subfacies is not manifested unambiguously in the ordination patterns (Fig.18).

The Shannon-Weaver and Simpson indices were calculated from abundance data for each sample. Marked variations in evenness were observed from facies to facies (Fig. 22): for the

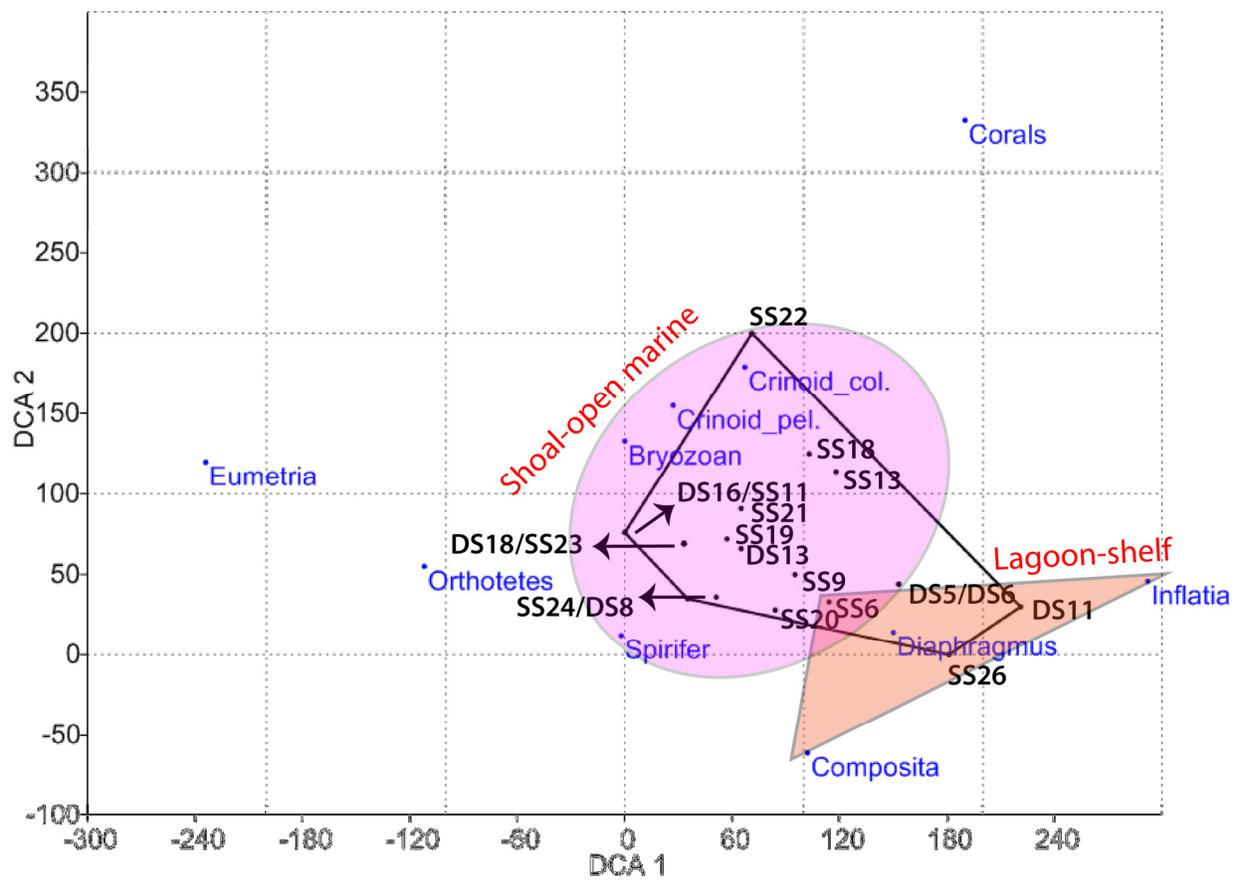


Figure 17. Combined detrended correspondence analysis of the Little Stone Gap member.

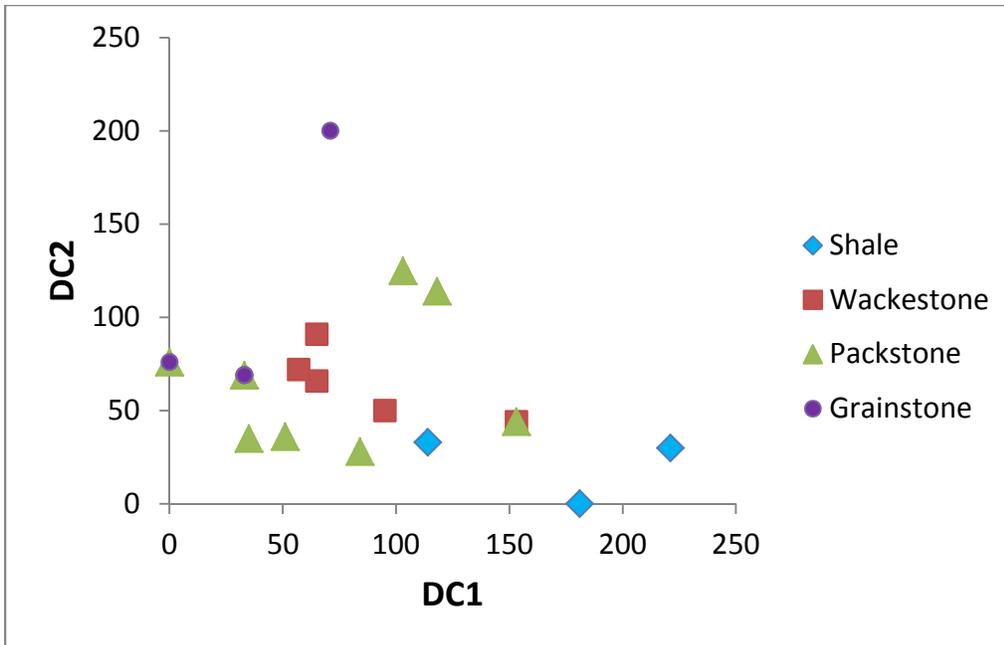


Figure 18. Sample DC scores for Little Stone Gap Member plotted by lithology show a gradation in grain size from shale to grainstone. Note the wide distribution of packstones.

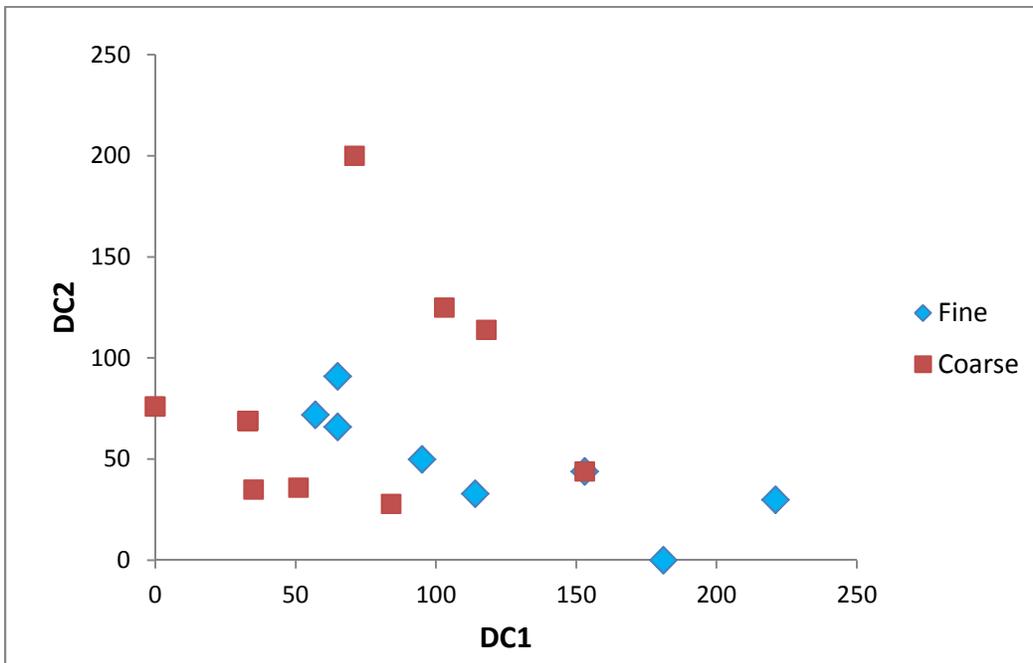


Figure 19. Sample DC scores for Little Stone Gap Member plotted by grain size showing a significant overlap. Also, DC2 does not appear to be influenced by grain size variation.

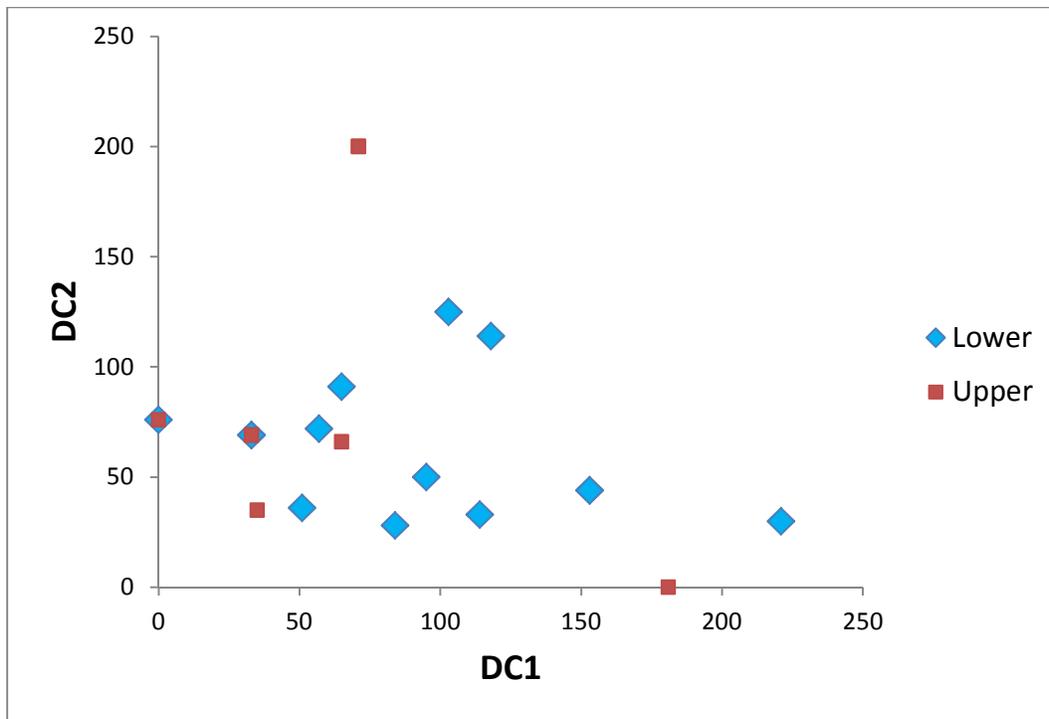


Figure 20. Sample DC scores for Little Stone Gap Member plotted by stratigraphic position and supporting generally shallowing-upward parasequences.

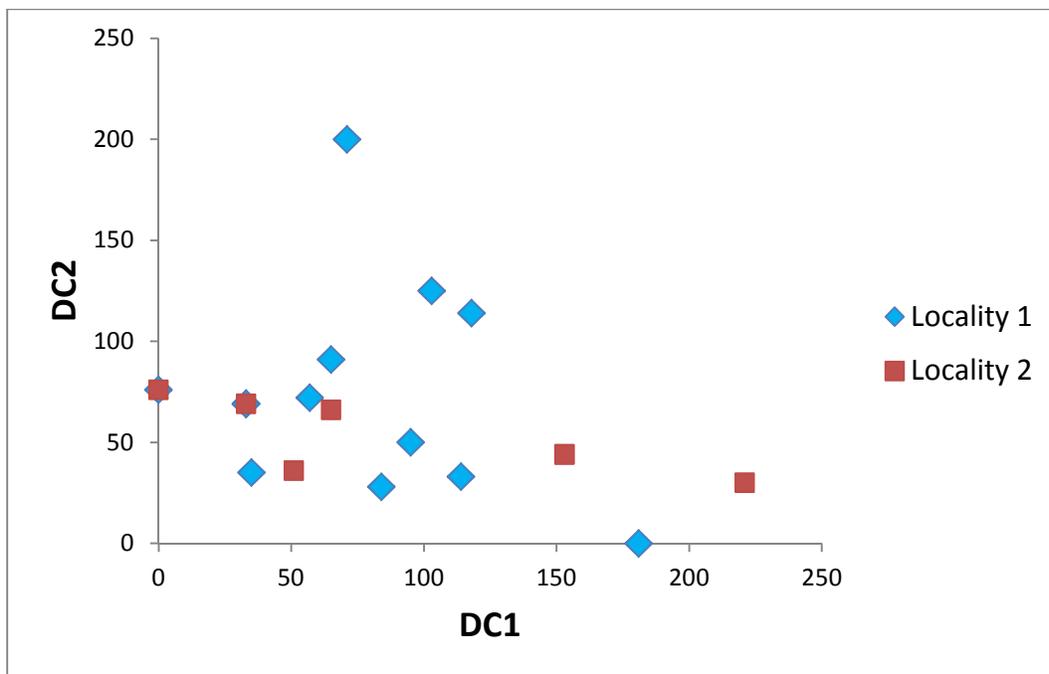


Figure 21. Sample DC scores for Little Stone Gap Member plotted by locality showing considerable overlap and indicating the occurrence of similar facies at both localities.

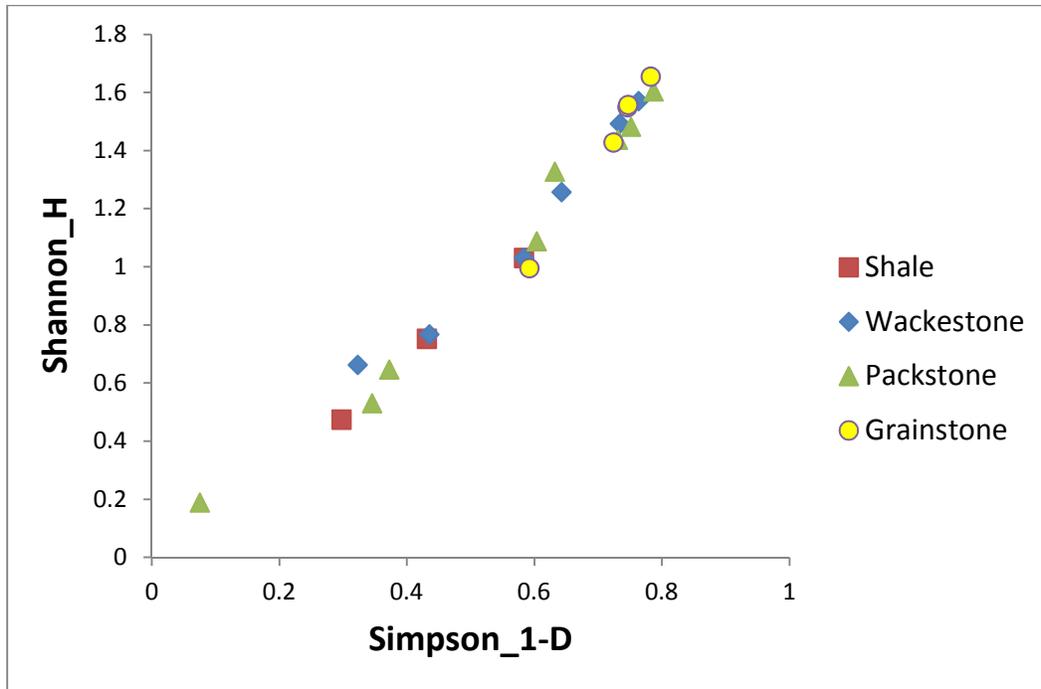


Figure 22. Variations of evenness within samples of the Little Stone Gap Member showing that grainstones exhibit unusually high evenness.

Shannon-Weaver index, evenness values range from 0.19 to 1.65 for carbonates and 0.47 to 1.03 for shales. In the case of the Simpson index, carbonates range from 0.08 to 0.79 whereas shales range from 0.30 to 0.58 (Table 7). It should be noted that grainstones, in particular, tend toward maximum evenness relative to other facies. Further, the magnitude of the variance in evenness was observed to be smaller in deep-water shaly environments.

### 6.3 Discussion

Except for *Orthotetes*, all taxa present in the samples represent genera (or higher taxa) that represent fully marine organisms (Kammer and Lake, 2001). The ordination gradient (Fig. 17), however appears to primarily reflect a transition from fine-grained siliciclastic-dominated, lagoonal, low-energy settings to carbonate-dominated low-high energy shelfal settings. Namely,

Table 7: Measured diversity indices (Shannon Weaver and Simpson) for lithofacies of the Little Stone Gap Member.

Sample ID	Lithology	Shannon_H	Simpson_1-D
DS5	Wackestone	0.7677	0.4355
DS13	Wackestone	1.57	0.7638
SS9	Wackestone	0.6619	0.3231
SS6	Wackestone	1.03	0.5841
SS19	Wackestone	1.492	0.7345
SS21	Wackestone	1.257	0.6429
DS11	Shale	0.4741	0.2975
SS6	Shale	1.03	0.5841
SS26	Shale	0.7519	0.4314
DS6	Packstone	0.6464	0.3728
DS8	Packstone	0.5297	0.3457
SS11	Packstone	1.603	0.7872
SS13	Packstone	1.327	0.6322
SS15	Packstone	1.481	0.7519
SS18	Packstone	1.437	0.7314
SS20	Packstone	0.1877	0.07537
SS24	Packstone	1.087	0.6041
DS16	Grainstone	1.549	0.7463
DS18	Grainstone	1.557	0.7472
SS17	Grainstone	1.654	0.7825
SS22	Grainstone	0.995	0.5926
SS23	Grainstone	1.428	0.7242

samples with high DC1 scores and low DC2 scores represent lagoonal settings whereas more distal carbonate-dominated settings are characterized by samples exhibiting widely variable DC1 scores and low-intermediate DC2 scores.

The energy-related onshore-offshore gradient observed in the paleoecological ordination of the analyzed samples is not surprising: both depth and substrate characteristics tend to control the distribution of benthic taxa on shelves (Ellingsen, 2002). Also, the onshore-offshore gradient observed in the ordinations of Paleozoic samples e.g., this study and Miller et al. (2001) have

been reaffirmed by quantitative tests carried out for late Quaternary depositional systems (Scarponi and Kowalewski, 2004).

Generally, the carbonate habitat was subject to higher water-energy conditions and contained firmer substrate than the fine-grained siliciclastic habitat. Low-energy, lagoonal environments are dominated by the brachiopods *Diaphragmus*, *Inflatia* and *Composita*. Their presence supports the hypothesis that spines may provide support on softground or soupground (Leighton, 2000). Common taxa in high-energy firmer substrate environments include the brachiopods *Anthracospirifer*, *Eumetria* and *Orhotetes* together with bryozoans, crinoids and rugose corals. Environmental interpretation of fenestrate bryozoans is notoriously difficult given their ability to occur in a wide range of habitats (McKinney and Gault, 1980; Bonelli and Patzkowsky, 2008). The occurrence of fenestrate bryozoans in carbonate facies reported here supports their broad environmental tolerances. It can be suggested that these bryozoans inhabited moderate-high energy waters possibly near shoals and sheltered mud bottoms. Thick-walled rugosan corals, preferentially occurring in packstones and grainstones facies represented fixosessile forms (Neuman, 1988) with preference for high-energy environments (Gomez-Herguedas and Rodriguez, 2009) such as in calcareous/oolitic sand shoals exhibiting constant rate moderate to high energy.

Plots of sample DC scores by stratigraphic position (Fig. 20) suggest a shallowing-upward trend within the parasequences, which is consistent with previous facies interpretations of the Little Stone Gap Limestone (Neal, 1989; Place and Beuthin, 1998). The overlap observed for the two localities in the plot of sample DC scores by locality (Fig. 21) is not unexpected since there is little or no difference in facies composition at both localities. Packstones greatly overlap with other limestones (Fig. 18) because they correspond to maximum flooding surfaces that

exhibit environmental condensation. This type of condensation is characterized by mixing of organisms that lived in different environments (Fursich, 1978). This is indicated here by the co-occurrences of deeper water brachiopods and shallow water taxa such as bryozoans, crinoids and rugose coral.

The dearth of mollusks in the faunal assemblage could be due to either taphonomic or ecologic factors. A taphonomic bias toward the elimination of aragonitic skeletal infauna is supported by a minimal silicification. Thin sections of bivalves examined under the microscope, however, show an appreciable replacement of dissolved skeletal grains by neomorphic calcite. The low abundance of mollusks especially in the count could also be due to the elimination of most bivalves as a result of slicing through them during the preparation of slabs. Hence, bivalves which were generally observed in thin sections could not be accounted for in bulk samples. Hardgrounds, which are characteristic of packstone facies in the Little Stone Gap Limestone, indicate early diagenesis (lithification) at shallow depths followed by local exhumation (Cherns, 1983). This interpretation is supported by abundant elongated micrite and partly siliceous intraclasts contained in limestones (wackestones and grainstones). The taxonomic and numerical underrepresentation of mollusks in Little Stone Gap Limestone could also be related to dissolution in marine waters during very early shallow burial. The depositional environment was starved of siliciclastic input during the deposition of the Little Stone Gap Limestone than for the remainder of the Hinton Formation due to a significant third-order tectono-eustatic sea level rise (Miller and Eriksson, 2000; Maynard et al., 2006).

The observed variations in evenness (Fig. 22) cannot easily be attributed to sample size, lithology, or other sample characteristics. Going by their strongly lithified nature, grainstones are prone to larger size fractions and apparently low evenness caused by the removal of some

common taxa (Kidwell, 2001; Peters, 2004). Grainstone facies in this study, however, exhibit a slightly different relationship between sample size and evenness. This relation indicates that while evenness patterns are driven by sample-size effects, other factors such as taxonomic composition could be responsible for the observed trend. This is best explained by the fact that grainstone samples are mostly dominated by genera from different higher taxa compared to the remaining facies that are co-dominated by taxa from the same class or order. For example, grainstones are dominated by brachiopods and crinoids while other facies contain equally large proportions of taxa belonging to the class of *Brachiopoda*.

Biotic controls (e.g. differences in body size, guild structure, and morphologic dissimilarity) are other possible principal contributors to variance in evenness. However, this could not be determined due to unavailable data on the morphological and ecological characteristics of the fossil specimens.

## **7. CONCLUSIONS**

1. The nine lithofacies encountered in the Little Stone Gap Member define five depositional environments that range from continental to nearshore to proximal settings of a marine shelf. These environments include continental red mudstone and calcareous siltstone; lagoonal gray shale and, interbedded limestone and shale; ooid/skeletal grainstone shoal; shoal flank, intramicritic wackestone/grainstone and skeletal wackestone/packstone; and open marine, argillaceous, skeletal wackestone/packstone and, laminated mudstone/shale which were arranged along ecological gradients defined by local and regional scale environmental variations.
2. The Little Stone Gap Member is composed of a succession of fifth-order parasequences that show upward-deepening and upward-shallowing trends. Two types of parasequence stacking

patterns are: carbonate-dominated and siliciclastic-dominated parasequences. Carbonate-dominated parasequences formed by rapid drowning followed by shoaling during periods of low clastic input. In contrast, siliciclastic-dominated parasequences record carbonate sedimentation during slower drowning followed by progradational outbuilding of lagoonal facies and subsequent subaerial exposure.

3. Fossils are abundant in the Little Stone Gap Member but exhibit low diversity. Overall, five taxa which are dominated by brachiopods were encountered in the study. Brachiopods occur in all of the twenty-one sampled units represented by six genera. Mollusks are generally scarce in this study due to taphonomic loss and ecological factors related to high clastic influx to the Appalachian Basin; and fracturing incurred during rock slabbing.

4. Multivariate techniques provide a viable means of evaluating ecological gradients across depositional systems. DCA ordinations indicate that taxa sort along preferred gradients that are defined by energy of deposition, substrate composition and distance from the shoreline. Bryozoan-crinoid-coral assemblages are best developed in open marine carbonate environments whereas brachiopods show preference for siliciclastic and muddy carbonate environments. The distributions of taxa and samples in ordination space reaffirm the categorization substrate into carbonates and siliciclastics and the need for using a quantitative approach for effective paleoenvironmental analyses.

5. Evenness values recorded by grainstone facies suggests that taxonomic structure as well as environmental and biotic factors are important and should be considered in the determination of evenness.

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## APPENDIX A: OUTCROP DESCRIPTIONS FOR THIS STUDY

Exposure 1 (Along I-64W; between Sandstone and Bragg)

Distance (ft)

- 0-7.0 Mudstone paleosol; reddish, massive, unfossiliferous, mottled and burrowed. Shows pedogenic slickensides and root haloes.
- 7.0-8.0 Calcareous siltstone; yellow-orange, massive and unfossiliferous. Displays stromatolites and wave-ripple cross laminations.
- 8.0-8.5 Mudstone paleosol; reddish, unfossiliferous, mottled and burrowed. Contains root traces and peds. This unit grades into the siltstone below.
- 8.5-9.7 Skeletal packstone; dark grey, chippy, massive, fine-grained. Contains abundant burrows, peloids, bryozoans, bivalves and brachiopods.
- 9.7-13.7 Skeletal wackestone; dark-grey, fine grained. Contains lots of peloids and few carbonate nodules. Consists of brachiopods, bivalves and bryozoans.
- 13.7-14.7 Shale; dark-grey, fine grained and fissile. Fossiliferous; contains brachiopods
- 14.7-14.8 Skeletal wackestone; dark-grey, fine grained. Contains bivalves and bryozoans.
- 14.8-15.5 Lime mudstone; contains pyrites and ostracodes.
- 15.5-18.1 Skeletal wackestone; contains abundant burrows, brachiopod spines, peloids, ostracodes, crinoid pelmatozoans and bryozoans.
- 18.1-18.7 Shale; dark-grey, fine grained, calcareous.
- 18.7-18.9 Skeletal packstone; grey, thin bedded, medium grained and burrowed. Contains bryozoans, brachiopods, crinoid pelmatozoans and columnals.
- 18.9-19.9 Skeletal wackestone; dark-grey, massive, fine grained. Contains ostracodes, bivalves and gastropod with abundant peloids.
- 19.9-20.1 Skeletal packstone; grey, medium bedded, medium grained, silty, burrowed. Contain bryozoans, crinoids and brachiopods.
- 20.1-22.3 Lime mudstone; dark-grey, massive, fine grained. Contains scarce burrows.
- 22.3-22.5 Skeletal packstone; grey, medium grained, burrowed. Contains microscours, peloids, fenestrate bryozoans, bivalves, brachiopods, ostracodes, crinoid pelmatozoans and columnals.

- 22.5-24.1 Lime mudstone; dark-grey, fine grained, massive. Argillaceous with characteristic yellowish tan. Contains peloids.
- 24.1-26.7 Skeletal grainstone; grey, medium to coarse grained, medium bedded, structureless. Contains brachiopods, gastropod, bivalves, bryozoans, crinoid pelmatozoans and columnals. Microscours occur 1.2 ft above the preceding lime mudstone.
- 26.7-30.2 Skeletal packstone; dark-grey with microbial laminations; burrowed; silty; argillaceous; contains calcite nodular concretions, ooids, peloids, bryozoans, brachiopods, echinoderms, gastropod, crinoid columnals and pelmatozoans.
- 30.2-32.2 Skeletal wackestone; dark-grey and fine grained. Contains bryozoans, brachiopods, crinoid pelmatozoans and columnals.
- 32.2-33.2 Skeletal packstone; grey, medium grained. Contains bivalves and brachiopods.
- 33.2-40.7 Skeletal wackestone; dark-grey, massive and bioturbated. Contains brachiopods, bryozoans, crinoid pelmatozoans and columnals.
- 40.7-48.4 Skeletal grainstone; grey with yellowish tan, coarse grained, argillaceous, peloidal, oolitic, thrombolitic. Contains fenestrate bryozoans, brachiopods, trilobites, echinoderms, rugose corals, crinoid pelmatozoans and columnals.
- 48.4-49.9 Skeletal grainstone interbedded with fossiliferous shale; contains brachiopods, bryozoans, ostracodes, crinoid pelmatozoans and columnals.
- 49.9-51.2 Skeletal packstone; grey, medium grained, scoured base and bioturbated. Contains brachiopods, crinoids and bryozoans. Displays alternating light and dark laminae.
- 51.2-51.7 Skeletal grainstone covered by scree.
- 51.7-56.7 Shale dark-grey, fine grained, fissile and burrowed. Fossiliferous; contains bryozoans, bivalves, brachiopods, gastropods and echinoderms.
- 56.7-61.7 Skeletal packstone interbedded with laminated shale. grey, medium grained. Contains bivalves and brachiopods.
- 61.7-67.7 Shale dark-grey, fine grained, calcareous, barren. Contains siderite nodules.

67.7-69.7 Mudstone paleosol; reddish, massive, barren, mottled and burrowed.  
Shows pedogenic slickenside, and root haloes.

Exposure 2 (Along I-64E; between Sandstone and Lawn)

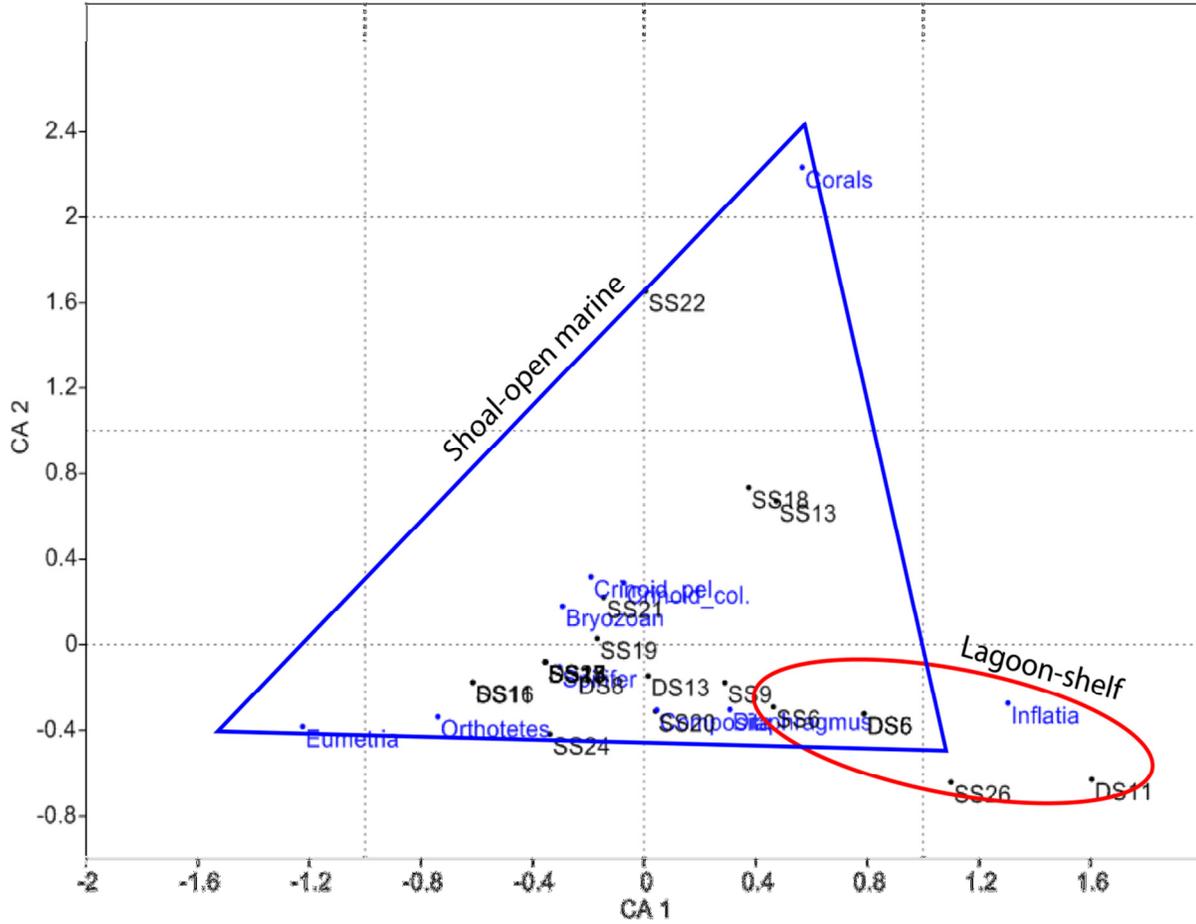
Distance (in ft)

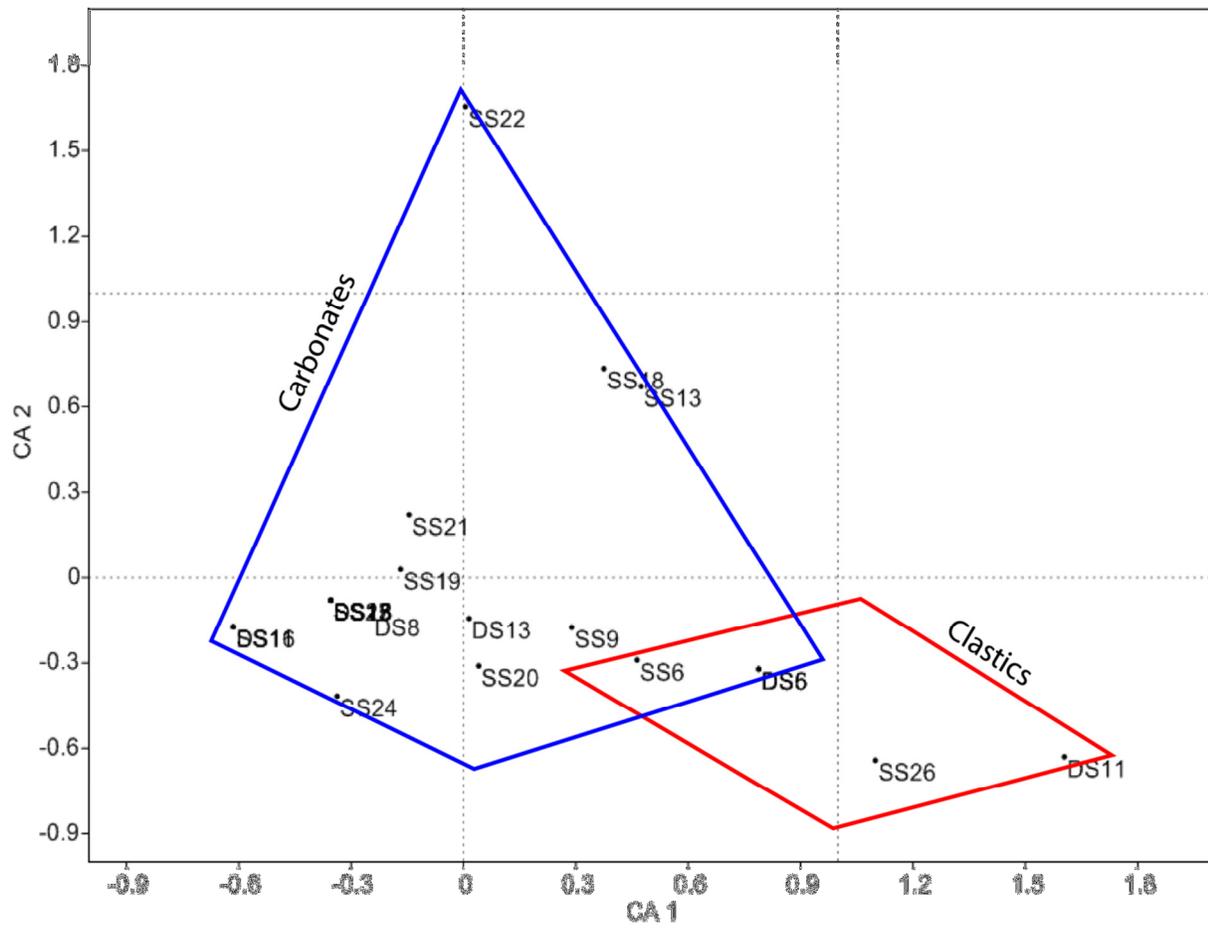
- 0-5.0 Mud paleosol; reddish, massive, barren, mottled and burrowed. Shows pedogenic slickensides and root haloes.
- 5.0-6.2 Shale; dark grey, fine grained, massive, and barren.
- 6.2-8.2 Shale; dark grey, fine grained, mottled, leached, burrowed, calcareous and fossiliferous with brachiopods, gastropods and crinoids.
- 8.2-13.8 Rock unit capped by talus
- 13.8-18.8 Skeletal wackestone; dark-grey, fine grained and massive. Contains brachiopods, ostracodes, and crinoid columnals.
- 18.8-19.6 Skeletal packstone; grey, medium grained. Contains peloids, fenestrate bryozoans, brachiopods, bivalves, gastropods, ostracodes, crinoid pelmatozoans and columnals.
- 19.6-20.3 Shale showing storm beds; dark grey, fine grained, fissile, grainy, calcareous and barren.
- 20.3-20.5 Skeletal packstone; grey, medium grained, thin bedded. Displays composite storm beds, peloidal, scour based. Contains fenestrate bryozoans, brachiopods and ostracodes.
- 20.5-20.9 Shale; dark grey, fine grained, calcareous, barren and laminated.
- 20.9-21.1 Skeletal packstone; grey, medium grained. Contains bryozoans and crinoids.
- 21.1-21.7 Shale; dark grey, fine grained, calcareous, and laminated. Contains brachiopods.
- 21.7-26.6 Skeletal packstone; dark-grey, fine grained and massive. Contains peloids, bivalves, brachiopods, ostracodes, echinoderms, crinoid pelmatozoans and columnals. Displays alternating light and dark laminae.
- 26.6-28.6 Skeletal wackestone showing tectonic compression; grey, medium grained, layered. Argillaceous with characteristic yellowish tan. Contains scour

- fills, brachiopod spines, bivalves, bryozoan fragments and crinoid columnals.
- 28.6-33.0 Intramicritic/skeletal wackestone; dark-grey, fine grained and laminated. Contains poorly sorted mud clasts, and few skeletal grains. Displays yellow weathering.
- 33.0-37.3 Skeletal packstone interlayered with wackestone; grey, medium grained, pellicitic and oolitic. Contains fine silt pellets, crinoid ossicles and lacy bryozoans.
- 37.3-37.8 Skeletal grainstone; grey, medium to coarse grained and laminated. Displays thrombolitic caps. Contains oncoids, brachiopods, bryozoans, crinoid pelmatozoans and columnals .
- 37.8-40.3 Shale; dark grey, fine grained, fissile and fossiliferous.
- 40.3-44.8 Intramicritic/skeletal grainstone; grey, medium to coarse grained and thrombolitic. Contains peloids/pellets, brachiopods, bryozoans, crinoid pelmatozoans and columnals.
- 44.8-45.8 Shale; dark grey, fine grained and fissile. Rock unit is capped by talus.
- 45.8-48.8 Mudstone paleosol; reddish, massive, barren and mottled. Shows pedogenic slickensides and root haloes.

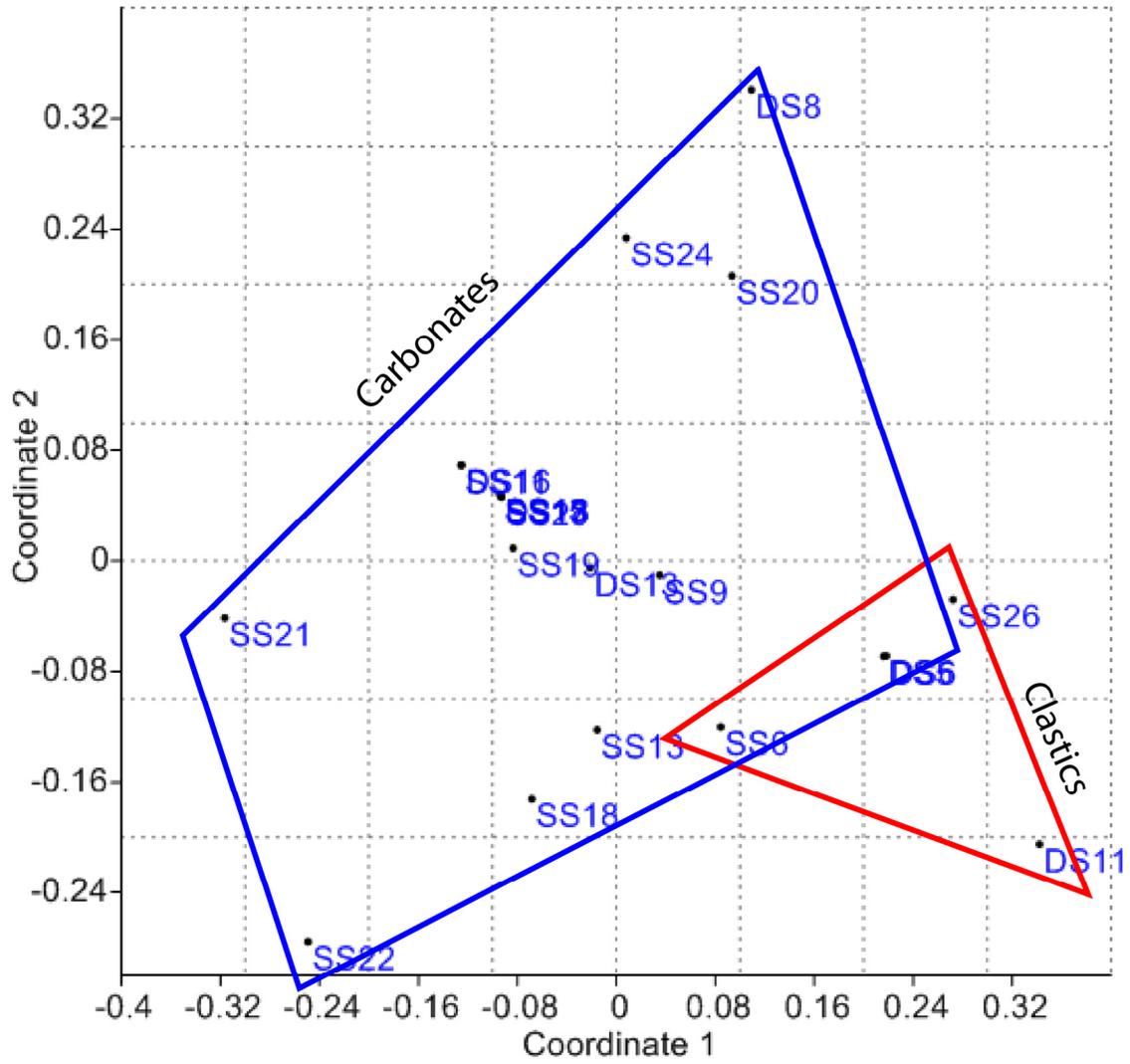
# APPENDIX B: CORRESPONDENCE ANALYSES AND NON-METRIC MULTIDIMENSIONAL SCALING

(a) Correspondence Analyses

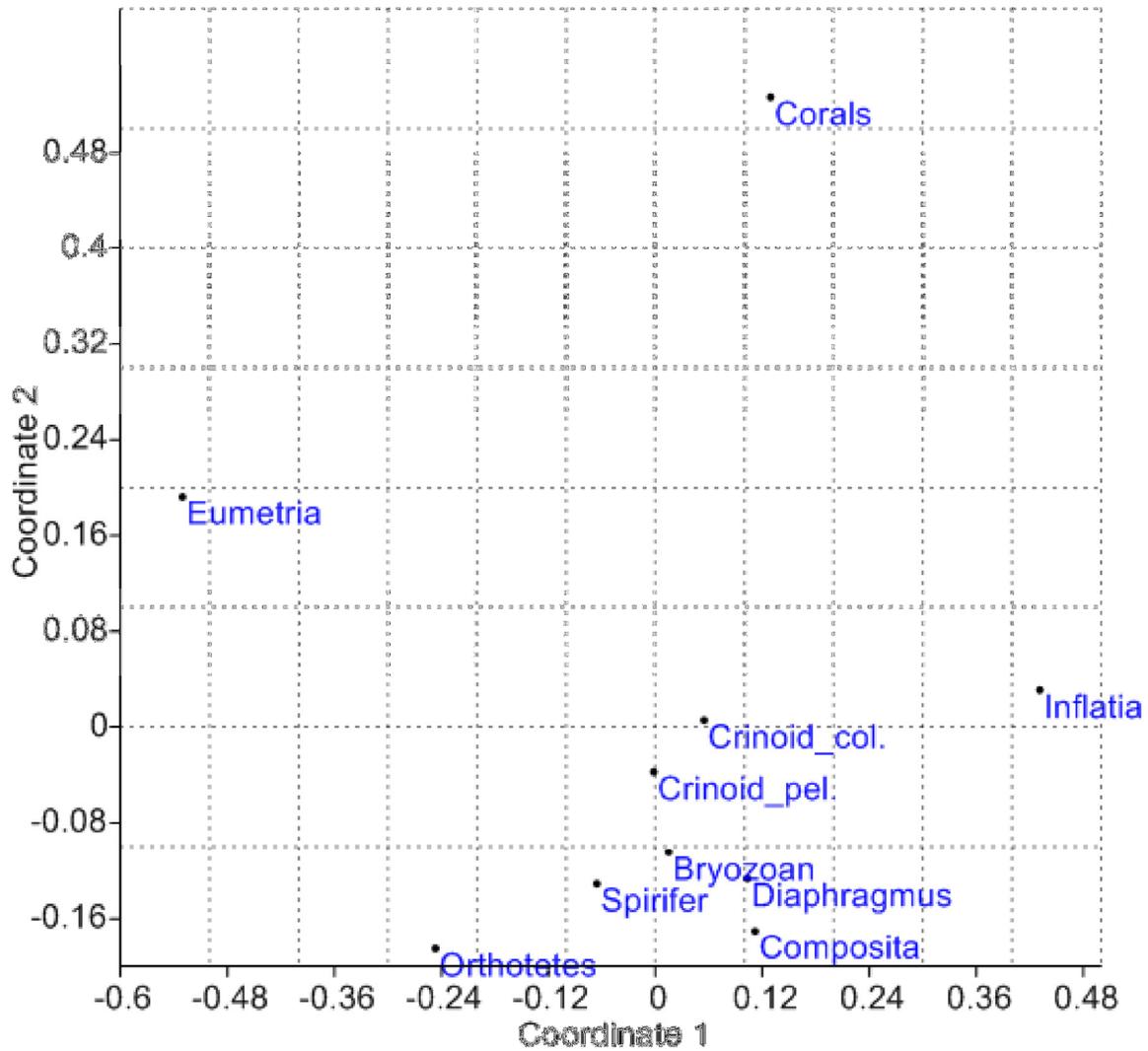




(b) Non-metric multidimensional scaling



Q-mode NMDS (Cosine); stress = 0.1566



R-mode NMDS (Dice); stress = 0.0898