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HIGH-RESOLUTION ESTUARINE SEA LEVEL CYCLES FROM THE LATE CRETACEOUS: AMPLITUDE CONSTRAINTS USING AGGLUTINATED FORAMINIFERA

NEIL E. TIBERT[1] AND R. MARK LECKIE[2]

ABSTRACT

Agglutinated foraminifera provide high-resolution proxies for relative sea level change in Late Cretaceous coal-bearing strata. Three foraminiferal assemblages are recognized where *Trochammina* (trochospiral) occurs in abundance with either one of the following: 1) *Miliammina* (quinqueloculine) associated with carbonaceous shale, interpreted as the marsh; 2) *Ammobaculites* (uncoiled) and estuarine ostracodes associated with shelly mudstones, interpreted as the central, muddy estuary; and 3) *Verneulinoides* and *Textularia* (serial) associated with gray mudstones, interpreted as distal estuary (open bay). The marsh represents 0–1 m water depth and this approximates absolute mean sea level, the central estuary represents 5–8 m water depth, and the distal estuary (open bay) represents water depths of 10 m or greater. Alternations between foraminiferal associations in a 25-m section of the upper middle Turonian Smoky Hollow Member, Straight Cliffs Formation, indicate sea level amplitude changes that ranged from 1–10 meters.

INTRODUCTION

Foraminifera can be used to constrain paleo-water depths for both shallow marine and deep-sea environments and there exists much potential to develop Cenozoic sea level histories for shelf deposits (e.g., Arnold, 1983; Culver, 1988; Zwaan and others, 1990; Abbot, 1997; Leckie and Olson, 2003). In contrast, foraminiferal bathymetric data in marginal marine settings are rarely reported with the exception of a few early descriptive works (e.g., Phleger, 1960, 1965). At its most fundamental level, two aspects of modern marginal marine foraminifera make them suitable for bathymetric inferences. First there are numerous modern ecological data sets from coastal marshes and estuaries around the world (e.g., Buzas, 1974; Scott and Medioli, 1980; Scott and others, 1980, 1991 1995, 1996; Scott and Leckie, 1990; De Rijk, 1995; Culver and others, 1996; Hayward and others, 1996; Goldstein and Watkins, 1998). Second, marsh foraminifera demonstrate distinct vertical partitioning where taxon associations can be used with remarkable precision to distinguish between high and low marsh (e.g., Scott and others, 1996).

The relationship between marsh assemblage and elevation with respect to mean sea level is a valuable datum to reconstruct sea level histories (e.g., Scott and Medioli, 1980). Remarkable is that the primary genera that dominate modern marsh and estuarine assemblages have persisted since the Carboniferous (Conkin and Conkin, 1982; Wightman and others, 1993, 1994; Tibert and Scott, 1999), and Mesozoic marginal marine strata yield superb examples of this (Eicher, 1965, 1966; Morris, 1971; Wall, 1976; McNeil and Caldwell, 1981; Wightman, 1990; Tibert and others, 2003a,b). This paper presents a model that uses uniformitarian comparisons between modern and ancient marginal marine foraminifera data to identify and construct a high-resolution sea level history for a fourth-order Late Cretaceous coal-bearing stratal sequence in southwest Utah.

Ice volume changes spanning the past several million years have contributed to an impressive record of sea level rise and fall that is preserved in both the stratal geometry of continental margin sequences and isotopes of deep-sea carbonates. To identify a comparable pattern in marginal marine deposits is far more problematical given that sedimentation and subsidence rates, the gradient of the coastal plain, and migration of the shoreline all impose significant control on relative sea level change (Collier and others, 1990). Essential to the success of spatial and temporal sea level models is the ability to identify an absolute reference point or Mean Sea Level (MSL) datum. In coastal settings, the marsh surface represents MSL and this fundamental principle has been used with reasonable success to develop Holocene sea level histories to within centimeters (e.g., Scott and others, 1996 and references within). Sea level amplitude studies with this resolution are certainly not viable for the Cretaceous given the high potential for taphonomic disturbance (Goldstein and Watkins, 1998). However, we can make inferences with respect to Mesozoic sea level change when we consider that the average marsh elevation is within approximately 1 m of sea level and that total foraminiferal populations of high and low marsh environments are taxonomically distinct (Scott and Medioli, 1980; Scott and others, 1980, 1991, 1995, 1996; Scott and Leckie, 1990; De Rijk, 1995; Culver and others, 1996; Hayward and others, 1996; Goldstein and Watkins, 1998).

Under favorable hydrologic and climatic conditions, a marsh will grow or aggrade with steady base level rise (McCabe, 1984). If rates of sea level rise increase or the basin compaction rates outpace peat accumulation rates, the marsh environment will be superceded by an advancing estuarine/bay facies and its associated foraminifera. A well-preserved ancient marsh sequence should therefore record alternations between coal beds containing marsh taxa and mudstones containing estuarine or shelf taxa depending on the magnitude of sea level rise. The resultant stratigraphic signature is marsh-estuarine couplets or small-scale relative sea level cycles.

We present a two-fold approach that uses the intimate relationship between the coal beds and foraminifera to estimate sea level amplitudes at meter and decimeter scales. We will provide two examples from the westernmost margin

[1] Department of Environmental Science and Geology, 1301 College Avenue, Jepson Science Center, Mary Washington College, Fredericksburg VA 22401. E-mail: ntibert@mwc.edu

[2] Department of Geosciences, 611 North Pleasant St., University of Massachusetts, Amherst MA 01003.

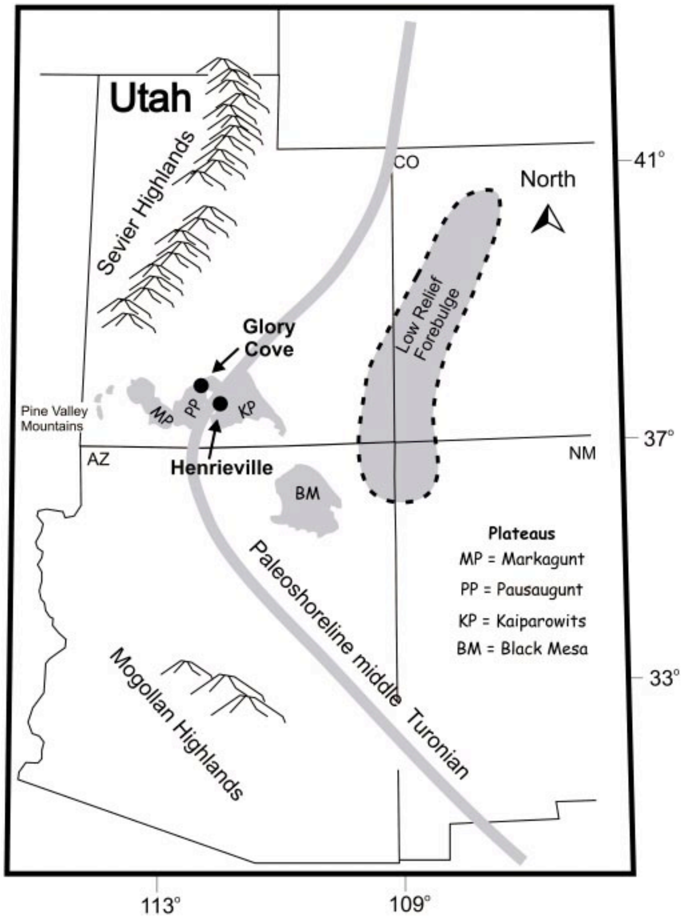


FIGURE 1. The study area and position of the middle Turonian (Late Cretaceous) shoreline, southwest Utah.

of the Cretaceous Western Interior Basin (WIB) located on Kaiparowits Plateau and Paunsaugunt Plateau in southwest Utah (Fig. 1) where middle Turonian coal-bearing strata contain abundant marginal marine foraminifera and ostracodes.

BACKGROUND

FORAMINIFERA

Agglutinated foraminifera occupy all marginal marine sub-environments (marsh, central estuary, lagoonal, and the open bay) and their population compositions are well known (e.g., Buzas, 1974; Scott and others, 1980; Scott and Leckie, 1990; De Rijk, 1995; Culver and others, 1996; Goldstein and Watkins, 1998; Sen Gupta, 1999). Because agglutinated foraminifera construct their tests of sedimentary particles, they are abundant in marsh environments and have a high potential for preservation. The dominant marginal marine foraminifera and their ecological ranges are listed in Table 1. Most of the primary genera that comprise the modern population data sets are widely reported in Cretaceous strata (Eicher, 1965, 1966, 1967; Bloch and others, 1999; Stritch and Schroeder-Adams, 1999; Tibert and others, 2003b).

One of the pioneering studies of marginal facies in Utah was that of Morris (1971) where he recognized a distinct lagoonal assemblage dominated by *Verneuilinoides* and *Trochammina*. He also reported a marsh association dominated by *Saccammina*. We believe that his figured specimens are in fact freshwater thecamoebians that belong to the families Centropyxidae and Difflugidae as illustrated from Cretaceous strata in western Canada (Medioli and others, 1990). Wall (1976) reported an association of agglutinated foraminifera from western Canada that he interpreted as marginal marine. Tibert and others (2003b) documented marginal assemblages from the transgressive Dakota Formation where *Trochammina* and *Verneuilinoides* occur in association with brackish bivalves (e.g., *Corbicula*), mudstones, and coal. This present study will build on the principles presented in these previous works to develop a high-resolution sea level record in coal bearing strata.

STUDY AREA

The Greenhorn Marine Cyclothem records widespread continental flooding of North America that extended from the Gulf of Mexico to the Arctic Ocean during the latest Cenomanian and early Turonian. Given the widespread geographic distribution of Cenomanian-Turonian strata, this interval has been scrutinized by researchers around the world. Several global events characterize the Cenomanian-Turonian boundary interval that include a $\delta^{13}C$ positive excursion attributed to ocean anoxia (Arthur and others, 1987; Schlanger and others, 1987), decreased $^{87}Sr/^{86}Sr$ levels in the ocean attributed to enhanced ocean volcanic activity (Bralower and others, 1997), benthic foraminiferal isotope values that suggest deep water temperatures were as high as 20° C (Huber and others, 1995, 1999), and a record of coastal onlap that indicates eustatic flooding of continental landmasses (Hancock and Kauffman, 1979; Haq and others, 1988; Sahagian and others, 1996; Robaszynski and others, 1998; Sageman and others, 1998).

The third-order (10^6 yrs) sea level cycles that punctuate Upper Cretaceous strata of the WIB (Kauffman, 1977;

TABLE 1. Modern marginal marine foraminifera and their corresponding ecological ranges.

Environment	Estuary	Lower salt marsh	Upper salt marsh	Fresh water marsh
Tidal range	Sub/inter tidal	0–70 cm above MSL	70–110 above MSL	Not applicable
Salinity	1–35 ppt	15–32 ppt	1–25 ppt	0 ppt
Microfossils	Agglutinated foraminifera	Agglutinated foraminifera	Agglutinated foraminifera	Arcellaceans (Thecamoebians)
Modern Protists	*Ammobaculites* *Ammotium salsum* *Eggerella advena* *Reophax* *Miliammina fusca*	*Trochammina inflata* *Miliammina fusca* *Ammobaculites* *Ammotium salsum*	*Trochammina inflata* *T. macrescans* *Tipotroncha comprimata* *Miliammina fusca*	*Centropyxis constricta* *Nebela collaris* *C. aculeate* *Difflugia*

TABLE 2. Depth and size of modern estuaries. Data provided from Nichols and others (1991), Boyd and Honig (1992), Morales (1997), Dalrymple and others (1992), and Penland and others (1988).

Estuary location	Depth	Tidal range	Length	Width
James Estuary Virginia, USA (Nichols and others, 1991)	5.8 m	0.7 m	161 km	5.1 km
Lawrencetown Lake Eastern Shore, Nova Scotia (Boyd and Honig, 1992)	1–3 m	0.9 m	6 km	<1 km
Guadiana River Southwest Portugal/Spain (Morales, 1997)		2.0 m	50 km	1 km
Mississippi (Penland and others, 1988)	5–8 m	0.3 m		
Cobequid Bar Salmon River Nova Scotia (Dalrymple and others, 1992)		12.0 m	40 km	0–12 km

Kauffman and Caldwell, 1993) have generated much interest with respect to their origins. The proposed depositional mechanisms for the higher frequency cycles that superimpose third-order cycles are disputed given the long standing debate between tectonic and eustatic advocates (e.g., Van Wagoner, 1995; Yoshida and others, 1996). Many authors agree, however, that the cycles formed in response to multiple forcing mechanisms (McCabe and Parrish, 1992; Leithold, 1994; Shanley and McCabe, 1995; Gardner, 1995a; Leckie and others, 1998; Leithold and Dean, 1998; West and others, 1998; Eaton and others, 2001). The Cenomanian-Turonian Greenhorn Marine Cyclothem (Kauffman, 1969) corresponds to a significant flooding event recognized around the world (Schwarzacher, 1994; Gale, 1995; Sahagian and others, 1996; Robaszynski and others, 1998; Gale and others, 2002). Of interest here are the fourth- (10^5 yrs) and fifth- (10^4 yrs) order cycles that superimpose the third-order Greenhorn Marine Cycle.

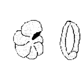
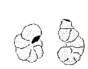
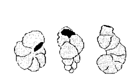
Recent studies of the marginal marine and open basin facies indicate oceanic/climatic control factored significant for the development of the high-frequency decimeter scale lithologic alternations recognized in the Bridge Creek Formation and western equivalents (Elder and others, 1994; Sageman and others, 1997, 1998; Tibert and others, 2003b). Chronology and correlation of the basin-wide rhythmic deposition was a primary focus for many of these studies and discussions regarding sea level amplitude were minimal. This is understandable given the difficulty to distinguish between the effects of basinal subsidence, eustasy, climate, and autogenic compaction in marginal marine strata. In siliciclastic facies, shoreline positioning traditionally relies upon geographic tracking the strandline via identification of upper and lower shoreface beach deposits (Collier and others, 1990). Unfortunately this method provides an approximate reference frame for sea level amplitude to within several tens of meters.

Coal-bearing strata accumulated during the Cenomanian-Turonian in southwest Utah (Ryer, 1984). The strata comprise in ascending order the Dakota, Iron Springs, and Straight Cliffs Formations. The three dimensional stratigraphy is well preserved on Kaiparowits, Paunsaugunt, and Markagunt Plateaus (Fig. 1) (Eaton, 1991; Elder and others, 1994; Eaton and others, 1997; Eaton and others, 1999; Eaton and others, 2001; Tibert and others, 2003a, b). Brackish water facies crop out at Glory Cove located 2 miles east of the town of Tropic on Route 12 and at the entrance to the Grand Staircase National Monument at Henrieville also on Route 12 (Fig. 1). The age of the Smoky Hollow Member is late middle Turonian based on recovered fossils assigned to the molluscan *Prionocylcus hyatti* Biozone (Eaton, 1991). McCabe and Shanley (1992) and Shanley and McCabe (1995) provided stratigraphic descriptions of the Straight Cliffs Formation at Henrieville where they recognized broad environmental associations that include upper and lower shoreface and fluvial facies. The coal-bearing interval was recently described as an estuarine-marsh transition deposited during the late regressive phase of the Greenhorn Marine Cyclothem (Coal Zone 9: Tibert and others, 2003b).

METHODS

The abundance and well-known ecological preferences of modern agglutinated foraminifera and the relatively fixed position of the marsh surface with respect to mean sea level are the basis for the model presented in this paper. Jones and Charnock (1985) highlighted the potential to make paleoecological inferences using agglutinated foraminifera that are differentiated into morphogroups. We have adopted this approach to facilitate comparison of Holocene with Cretaceous taxa where we categorize modern agglutinated taxa into the following morphological categories: trochospiral

TABLE 3. Sea level amplitude criteria based on foraminiferal population data.

Environment	Depth range	Predominant morphotypes		Modern genera	Ancient genera
MARSH	Meter-scale (~0–1 m)	Trochospiral Quinqueloculine		*Trochammina* *Miliammina*	*Trochammina* *Miliammina*
CENTRAL ESTUARY	Ten-meter-scale (~5–8 m)	Uncoiled Trochospiral		*Ammobaculites* *Ammoastuta* *Ammotium*	*Ammobaculites* *Ammobaculoides*
OPEN BAY	Ten-meter-scale & higher (10–>10 m)	Serial (tri-, bi-, uniserial) Uncoiled		*Eggerella* *Reophax* *Textularia* *Ammobaculites*	*Verneuilinoides* *Reophax* *Textularia*

(*Trochammina, Tipotrocha,* and *Arenoparella*), uncoiled (*Ammobaculites, Ammotium,* and *Ammoastuta*), quinqueloculine (*Miliammina*), serial (*Eggerella, Reophax,* and *Textularia*), and calcareous benthic (e.g., *Ammonia* and *Elphidium*). Marsh environments typically comprise an association of *Trochammina* and *Miliammina* (trochospiral and quinqueloculine: Figs. 3, 4) (Scott and Medioli, 1980; Scott and others, 1980, 1991, 1995, 1996; Scott and Leckie, 1990; Goldstein and Watkins, 1998). Estuarine environments demonstrate a relative abundance of *Ammobaculites* and *Trochammina* (uncoiled and trochospiral: Figs. 3, 4) (Ellison, 1972; Buzas, 1974; Culver and others, 1996). Open bay environments yield abundant calcareous taxa and a relative abundance of serial morphotypes that include *Eggerella, Textularia,* and/or *Reophax* (Figs. 3, 4) (Scott and others, 1991; Culver and others, 1996; Sen Gupta, 1999).

Marginal marine foraminifera can be used to establish the amplitude of relative sea level fluctuations. To demonstrate modern bathymetric partitioning, we present data from Nova Scotia using the above morphologic categorical system (Fig. 5) (Scott and others, 1980). The Chezzetcook Marsh occurs at approximately 45°N and the environment is estuarine dominated where water depths range from 0–10 meters. Figure 5 illustrates a distinct shift in the total foraminiferal population from largely agglutinated to calcareous (approximately greater than 60% of the total population). This corresponds to the approximate position of 10 meters water depth.

Estuary depths range from zero-to-tens of meters given the potential for deep channels. The average depth for most estuaries, however, is approximately 8–10 meters and this also corresponds to the approximate base of the shoreface and fair-weather wave base (Howard and Frey, 1985; Nichols and Biggs, 1985) (see Table 2 for examples). We use the three foraminiferal associations to provide estimates for water depths based on modern foraminiferal studies (e.g., Scott and others, 1980; Boyd and Honig, 1992; Culver and others, 1996). Populations dominated by trochospiral (*Trochammina*) and quinqueloculine (*Miliammina*) agglutinated morphotypes can be used to identify the approximate position of the marsh surface or Mean Sea Level (MSL: ~0 m). If this marsh association prevails in deposits that yield alternations of coal/peat and mudstone, this observed trend can be used as a proxy for minor amplitude changes (0–1 m) (Table 3). Uncoiled morphotypes are considered the ''proprietors'' of estuaries (Ellison, 1972) and the primary genera include *Ammobaculites, Ammoastuta,* and *Ammotium* (Tables 1, 3). Sample intervals that yield increased percentages of estuarine morphotypes (30–40% uncoiled) indicate an approximate depth of 5–8 meters. The distal end of the estuary, open bays and/or lagoons are dominated by serial morphotypes that include *Reophax, Textularia,* and *Eggerella* (Tables 1, 3). Assuming the high potential for dissolution of calcareous taxa in coastal facies, a population composition of predominantly serial morphotypes (e.g., *Eggerella* and *Reophax*) indicates a water depth of approximately ten meters.

RESULTS

Sedimentary Facies

Our work closely examines the upper middle Turonian lignite-bearing zone from the Smoky Hollow Member of the Straight Cliffs Formation. (Coal Zone 9: Tibert and others, 2003b, 2004). We recognize eight lithofacies that are grouped into three paleoenvironmental facies that are categorized based on a tripartite estuarine classification scheme (proximal-central-distal) modified after Dalrymple and others (1992) and Nichols and others (1991); they recognize an upper fluvial or meander zone, a central muddy or funnel zone, and a lower beach or bay/mouth zone.

Proximal Estuary

Lignite (L): Impure coals of sub-bituminous grade occupy 3 to 5 beds (Peterson, 1969; Tibert and others, 2003b). The coal seams range in thickness from 10 to 30 centimeters. The coals, although thin, are laterally continuous spanning tens of kilometers. We interpret these beds as peat swamps that surrounded the perimeter of the central estuarine or lagoonal system.

Carbonaceous Shale (Oxidized) (Cs): Red-to-purple carbonaceous shale that is rich in plant and woody material is intercalated with the lignite and gray mudstones. The beds are gradational with the lignite and root traces are common. Invertebrate fossils are absent and there is an exclusive population of agglutinated foraminifera dominated by *Trochammina* and *Miliammina*. We interpret these units as coastal salt marsh deposits that were poorly drained and susceptible to oxidation.

Fluvial Sandstone (Fs): Medium to coarse sandstone units occupy the uppermost strata at Glory Cove. The units are poorly sorted and they typically comprise fining-upward successions (Fig. 6). Meter-scale cross stratification and ripple cross-stratification are common. The base of the units contain intraclasts of mudstone. We interpret this facies as fluvial channel.

Red-Green Mudstone (Om): This facies comprises mudstone that is mottled red or green locally. The unit is confined to the uppermost 2 to 3 m at Glory Cove and it is in gradational contact with the underlying medium-to-fine fining-upward sandstones. Plant fragments are common. We interpret this facies as a well-drained floodplain. Using the classification system of Mack et al (1991), we regard this unit a vertisol.

Central Estuary

Shelly Mudstone (Sm): This facies comprises mud-rich, calcareous skeletal shell beds that include the bivalves *Corbicula, Lucina,* and *Crassostrea*. This is a single unit that ranges in thickness from 1 to 3 meters. There are no visible sedimentary structures given the intense bioturbation of the unit. Worm burrows, gastropods, bivalves, ostracodes, and foraminifera (*Ammobaculites*) are abundant. These beds were deposited in the central, muddy estuarine zone.

Distal Estuary

Gray Mudstone (Gm): This facies comprises gray, silty mudstone rich in smectite clay. The beds are moderately pedoturbated where slickensides and micro cross-laminae are the only observed sedimentary structures. Root traces and plant matter are common. The beds range from 1 to 3 m in thickness and they typically coarsen up from ''soapy''

TABLE 4. Foraminiferal data from the Turonian Straight Cliffs Formation, southwest Utah. Both number counts and percentages are provided.

		Agglutinated Foraminifera										
Sample No.	Strat. hgt. (m from base)	*Trochammina* sp. indet.	*Trochammina webbi*	*Trochammina ribstonensis*	Total Trochospiral	Percent Trochospiral	*Miliammina ischnia*	Percent Quinqueloculine	*Ammobaculites obliquus*	*Ammobaculites* sp. indet.	Uncoiled	Percent uncoiled
SH-GC-02	1.4		2	3	5	1.00		0.00			0	0.00
SH-GC-03	1.6	4			4	0.44	4	0.44			0	0.00
SH-GC-04	2.3			40	40	0.91		0.00	4		4	0.09
SH-GC-05	3.0			4	4	0.57		0.00		3	3	0.43
SH-GC-06	3.1				0	0.00		0.00			0	0.00
SH-GC-07	3.8	1			1	0.50	0	0.00		1	1	0.50
SH-GC-08	4.0	11			11	0.58	1	0.05		2	2	0.11
SH-GC-10	5.0		17		17	0.77	3	0.14		2	2	0.09
SH-GC-11	5.1		27		27	0.90	1	0.03			0	0.00
SH-GC-12	6.0			1	1	0.50		0.00		1	1	0.50
SH-GC-13	6.1		2	14	16	0.89	1	0.06			0	0.00
SH-GC-15	7.0	2			2	0.50		0.00			0	0.00
SH-GC-19	8.8	8			8	0.89	1	0.11			0	0.00
SH-GC-21	10		1	2	3	0.43	1	0.14			0	0.00

mudstone into gritty muddy-siltstones. Foraminifera include *Reophax, Verneuilinoides,* and *Trochammina*. We interpret these units as hydromorphosed muds and silts that accumulated as bayfills in the distal reaches of the estuarine lagoon.

Swaley Cross-Stratified Sandstone (Ss): This facies comprises fine to medium, moderately sorted, quartz sandstone. Sedimentary structures include decimeter to meter-scale, low angle, swaley cross-beds, less abundant cross-beds, and centimeter-scale ripple cross-beds. Swaley cross-bed sets are stacked and range in thickness from 10 to 30 cm to as much as 100 cm (Fig. 6). The oysters (e.g., *Crassostrea*) are sparsely distributed, but they do occur in localized abundance. We interpret this facies as stacked shoreface.

Well-sorted Sandstone (Sw): This facies comprises well-sorted medium sandstone where the grains are well rounded and pitted on the surface. Glauconite grains are relatively common. Sedimentary structures are rare with the exception of ripple cross-laminae, which are not uncommon. The beds are generally massive not exceeding 30 cm in thickness. Plant matter is common. We interpret these units as storm washovers.

FORAMINIFERAL TRENDS

We recognize Late Cretaceous microfossil populations that bear strong resemblance to the modern. Figure 2 demonstrates the similarity between three primary Late Cretaceous taxa to the modern marginal marine taxa collected from Piermont New York on the Hudson River. These include *Trochammina ribstonensis, Miliammina ischnia,* and *Ammobaculites obliquus* from the Cretaceous and *Trochammina inflata, Miliammina fusca,* and *Ammobaculites* sp. from the Hudson River. In addition, *Verneulinoides* and *Reophax* (serial morphotypes) (Plate 1) are also common in the Upper Cretaceous coal-bearing strata.

Figure 7 shows the foraminiferal population trends for the Glory Cove section of the Smoky Hollow Member. Trochospiral morphotypes dominate throughout the sequence. In the proximal marsh facies (L and Cs), the trochospiral and quinqueloculine association dominates at approximately the 1–2 m, 4–5 m, 6 m, and 8–9 m stratigraphic intervals. This foraminiferal population in association with the lignite and carbonaceous shale facies provides our datum for mean sea level (~0 m) as indicated on the corresponding sea level amplitude curve.

Peak abundance of the uncoiled morphotype (*Ammobaculites obliquus*) occurs between the 2.5–3.5 m and at the 6 m position in association with the central estuarine shelly mudstone (Sm) facies and distal estuarine well-sorted sandstone (Sw). There is also an increase in the relative abundance of the ostracodes *Fossocytheridea* and *Cytheromorpha* (Fig. 7) that are considered exclusively marginal marine (Tibert and others, 2003a, b). We use the combination of *Ammobaculites, Fossocytheridea,* and *Cytheromorpha* in association with the central estuarine facies (Sm) as an indicator of 5–8 m water depth as indicated on the sea level amplitude curve for Glory Cove (Fig. 7).

Intervals with relative abundances of serial foraminiferal taxa (*Verneuilinoides, Reophax,* and *Textularia*) are diagnostic for open bay environments. For example, *Verneuilinoides* dominates at the 7 and 10 m positions in association with the gray mudstone (Gm) bayfill facies. Several specimens of *Cytheropteron* were also recovered from these units (Tibert and others, 2003a, b) and we consider them diagnostic of meso-to-normal salinity shelf environments (Benson and others, 1961). We use the association of the serial foraminiferal taxa, gray mudstones, and swaley sandstones as indication for increasing water depth to as much as ten meters as indicated on the corresponding sea level amplitude curve (Fig. 7).

Preservation in the Henrieville section mudrocks was limited to less than 25 specimens per sample and therefore provides poor statistical representation. Qualitative observations of the foraminifera indicate an abundance of *Trochammina, Ammobaculites,* and *Verneuilinoides* in the shelly mudstone facies low in the section. We interpret this as a relative deepening of 5–8 m at this locality (Fig. 8). High frequency alternations between lignite and *Trochammina-Miliammina*-bearing carbonaceous shale facies are interpreted as small-scale sea level amplitude changes on the proximal estuarine marsh (Fig. 8).

DISCUSSION

We chose this study site because of the exceptional preservation of the marsh biofacies. The method presented here-

TABLE 4. Extended.

Agglutinated Foraminifera					Ostracodes								Total
Reophax recta	*Verneuili-noides* sp. indet.	Total serial	Percent serial	*Total Foramini-fera*	Nonmarine Cyprida-cean	Percent nonmarine Cyprid.	*Fosso-cytheridea posterovata*	Percent *Fosso-cytheridea*	*Cythero-morpha* spp.	Percent *Cythero-morpha*	Total Ostracodes	Percent Ostracodes	Total micro-fossils
		0	0.00	5	1	1.00		0.00		0.00	1	0.17	6
	1	1	0.11	9	1	1.00		0.00		0.00	1	0.10	10
		0	0.00	44		0.00	258	0.99	2	0.01	260	0.86	304
		0	0.00	7		0.00		0.00		0.00	0	0.00	7
		0	0.00	0		0.00	116	1.00		0.00	116	1.00	116
		0	0.00	2		0.00		0.00		0.00	0	0.00	2
	1	1	0.05	19		0.00		0.00		0.00	0	0.00	19
		0	0.00	22		0.00		0.00		0.00	0	0.00	22
1	1	2	0.07	30		0.00		0.00		0.00	0	0.00	30
		0	0.00	2		0.00		0.00		0.00	0	0.00	2
1		1	0.06	18		0.00		0.00		0.00	0	0.00	18
2		2	0.50	4		0.00		0.00		0.00	0	0.00	4
		0	0.00	9		0.00		0.00		0.00	0	0.00	9
3		3	0.43	7		0.00		0.00		0.00	0	0.00	7

in assumes minimal taphonomic disruption to the fossil assemblages. However, recent research has demonstrated that marsh foraminiferal populations are susceptible to reworking and mixing to as much as 30 cm below the marsh surface where as much as 90% of the original population may be destroyed after burial (Goldstein and Harben, 1993; Goldstein and others, 1995; Goldstein and Watkins, 1998, 1999). Furthermore, the effects of time averaging can greatly reduce the potential to recognize centimeter scale sea level changes (Martin, 1999). We take these taphonomic effects into consideration. First, we assume that all calcareous specimens were dissolved soon after burial given the low pH of peat deposits. Second, we draw attention to the fact that the marsh facies contains an exclusive population of the *Tro-*

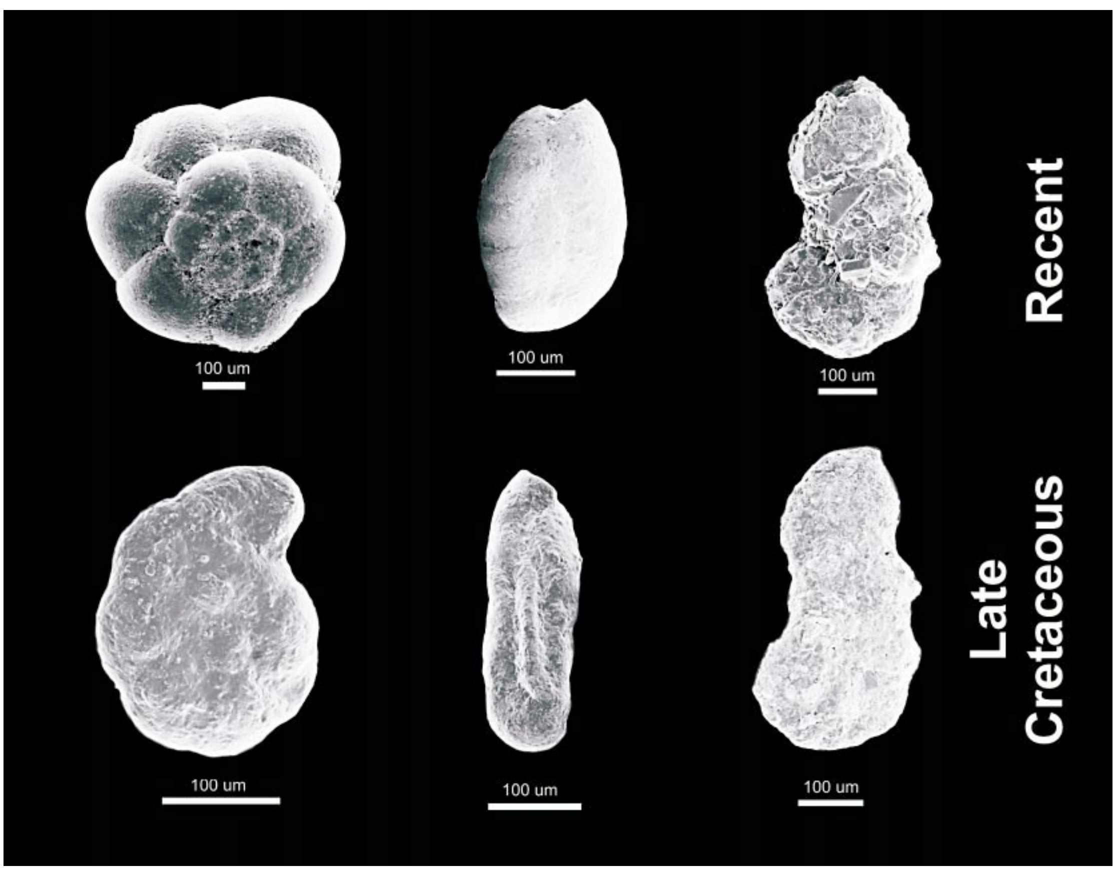


FIGURE 2. A comparison of modern to ancient marginal marine agglutinated foraminifera. Recent taxa include *Trochammina inflata, Miliammina fusca,* and *Ammobaculites* sp. obtained from Piermont, New York on the Hudson River. Cretaceous taxa include *Trochammina ribstonensis, Miliammina ischnia,* and *Ammobaculites obliquus*. In both recent and ancient samples, the *Trochammina-Miliammina* association represents the marsh and the *Trochammina-Ammobaculites* association represents the estuary.

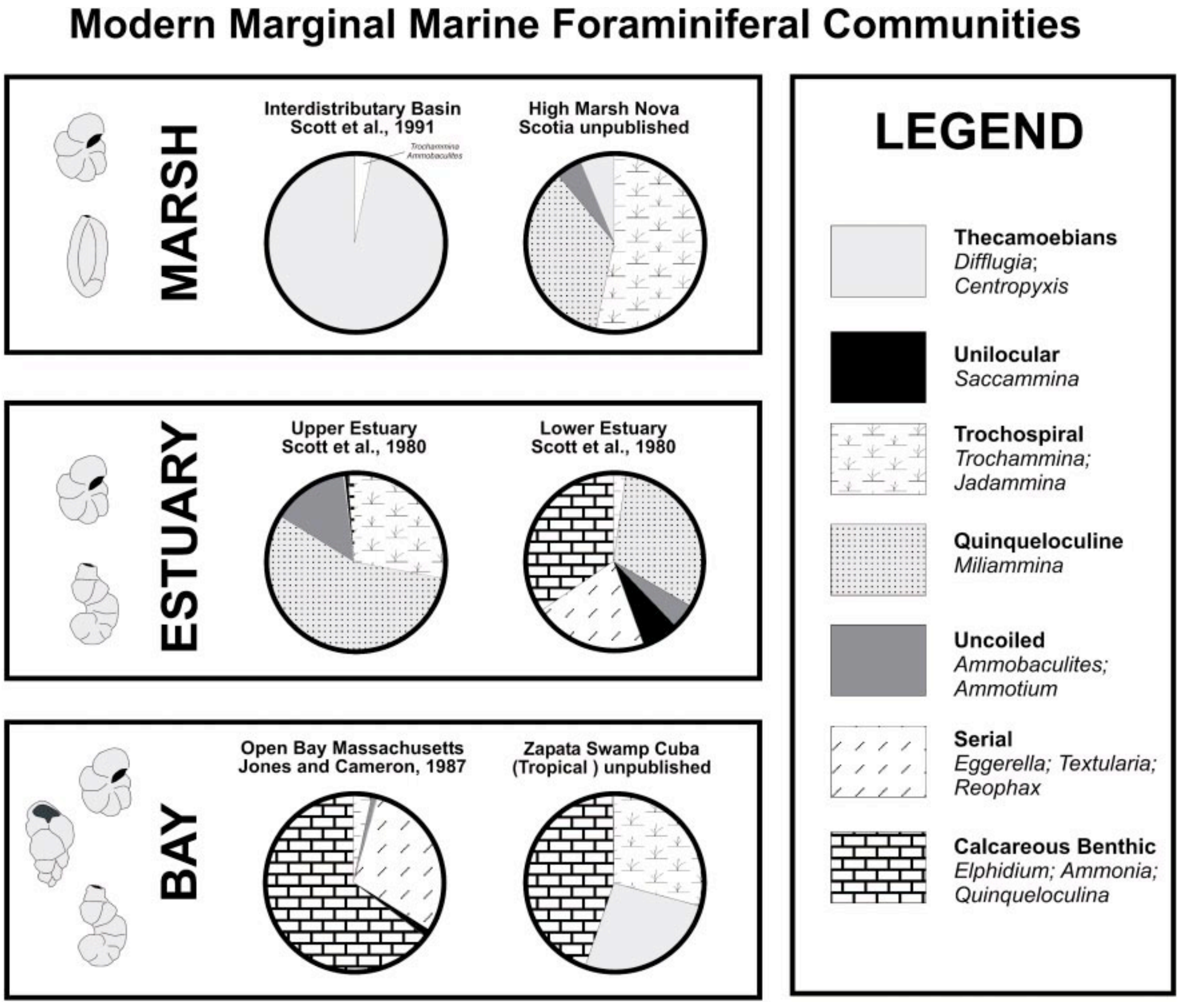


FIGURE 3. Modern population compositions of marginal marine foraminifera.

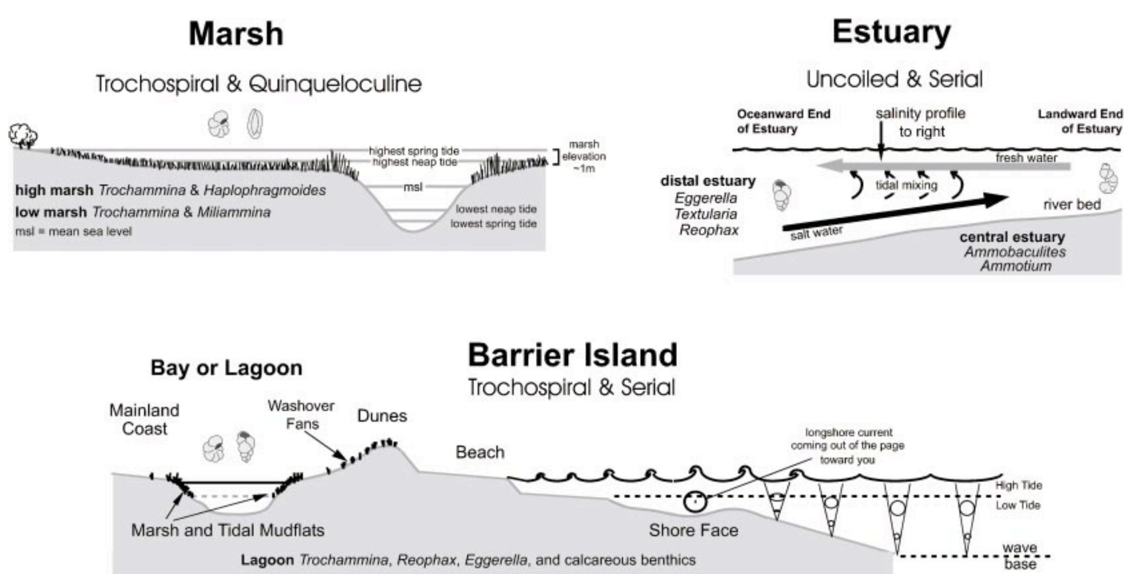


FIGURE 4. Schematic demonstrating the distribution of the foraminifera of the marginal marine environments. Marsh deposits are characterized by abundances of trochospiral and quinqueloculine agglutinated morphotpyes associated with peat. Estuarine deposits are characterized by uncoiled agglutinated morphotypes (*Ammobaculites*) associated with mud. Barrier islands and lagoons are characterized by trochospiral and serial agglutinated morphotypes associated with peat and sand washover beds.

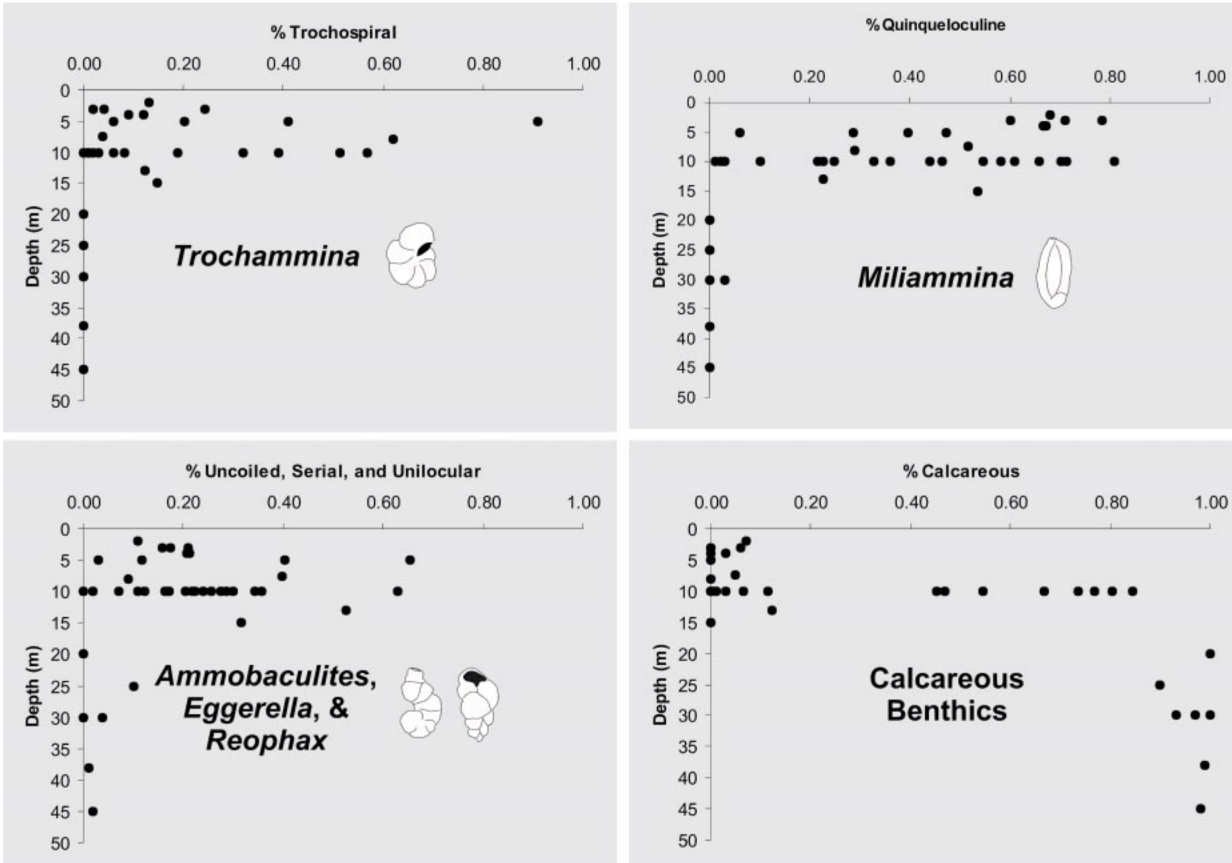


FIGURE 5. Population versus depth plots for modern marginal marine agglutinated morphotypes from Chezzetcook Marsh, Nova Scotia (data from Scott and others, 1980).

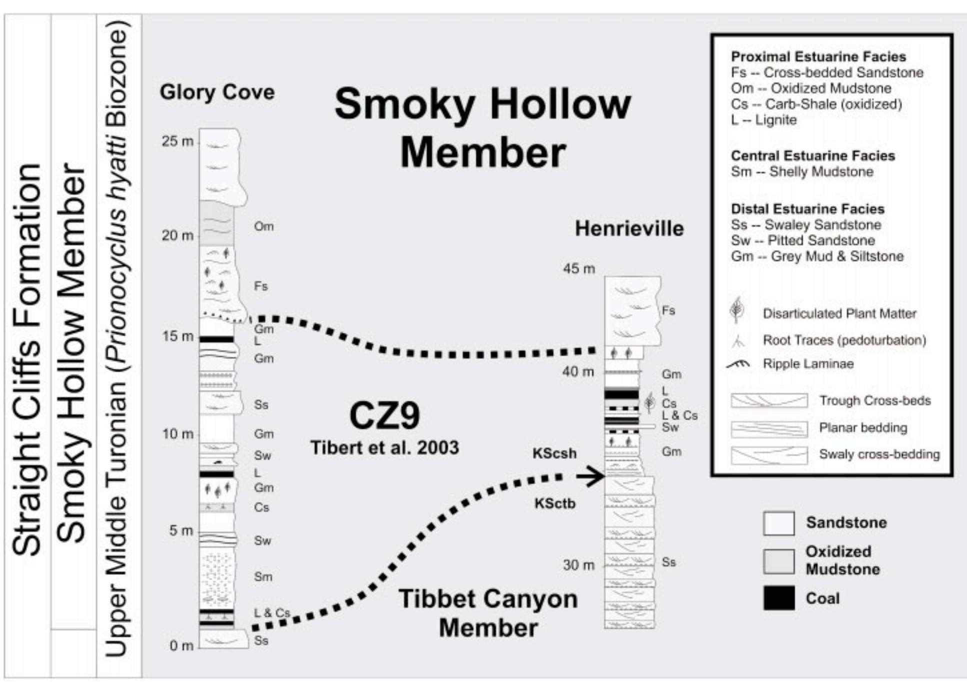


FIGURE 6. Stratigraphic sections of the Smoky Hollow Member of the Straight Cliffs Formation, southwest Utah.

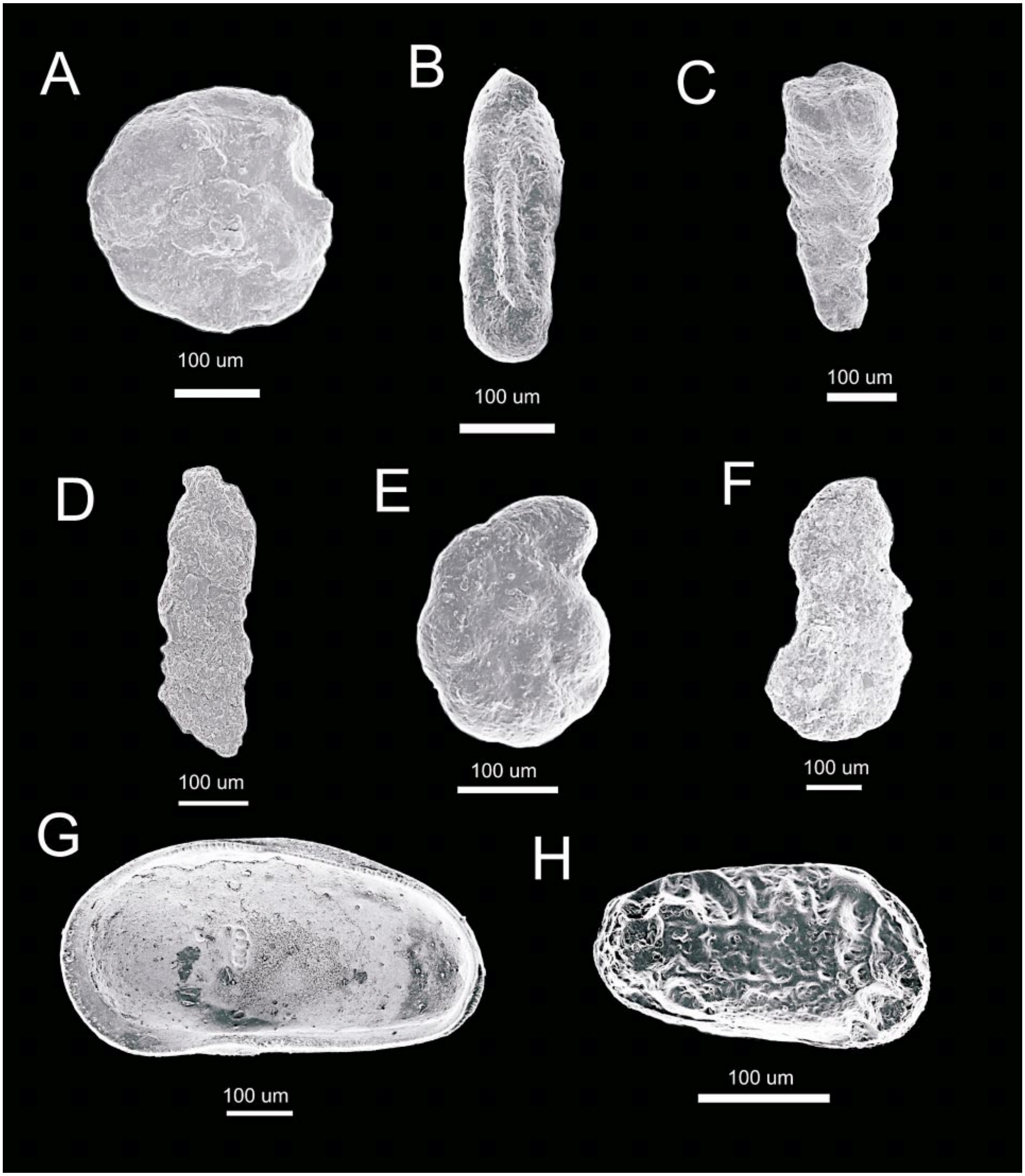


PLATE 1

Foraminifera and ostracodes from the Upper Cretaceous Smoky Hollow Member of the Straight Cliffs Formation, southwest Utah. A. *Trochammina webbi* STELCK and WALL 1954, B. *Miliammina ischnia* (TAPPAN 1957), C. *Textularia* sp., D. *Reophax* sp., E. *Trochammina ribstonensis* WICKENDON 1932, F. *Ammobaculites obliquus* LOEBLICH and TAPPAN 1949, G. *Fossocytheridea posterovata* (LANKFORD *in* Peterson and others 1953), and H. *Cytheromorpha* sp. TIBERT and others 2003b.

chammina and *Miliammina* in rooted lignite and mudstones. We find this biotic and lithologic combination a compelling indicator for true ancient ''salt marsh'' conditions. Centimeter scale sea level histories using marsh foraminifera have been criticized given the potential for taphonomic bias (Martin, 1999; Sen Gupta, 1999). Our model does not distinguish between the high and low marsh and our resolution is far below that possible for Holocene applications. We

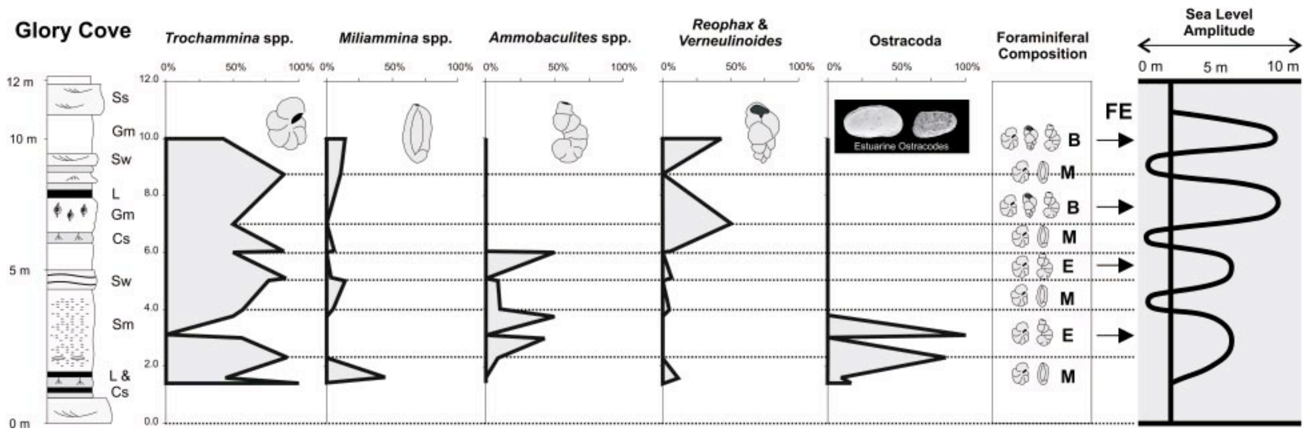


FIGURE 7. Foraminiferal data and sea level curve from Glory Cove. M = marsh, E = central estuary, and B = open bay. Relative position of Flooding Events (FE) indicated by the solid black arrow.

believe that a sustained period of peat accumulation reduced the potential for ''multi-environment'' contamination in this particular deposit. This is especially the case for the Henrieville locality where the coal-mudstone alternations are most prominent.

The duration for deposition of the coal/mudstone stratal alternations presented herein is difficult to constrain. The molluscan invertebrates recovered from the underlying Tibbet Canyon Member indicate a *Prionocyclus hyatti* age for the Straight Cliffs Formation (Eaton, 1991), and according to time scales of Kauffman and others (1993) and Obradovich (1993), suggests a maximum of 300 kyr duration. Smoky Hollow Member coal-bearing strata comprise only a small portion of the Straight Cliffs Formation (<25%) and therefore this sequence represents only a fraction of the time allotted to the *Prionocyclus hyatti* biozone. Coal thickness and compaction models predict that peat (coal-precursor) accumulates on average 1 mm per year and peat compacts at a 10:1 ratio (Ryer and Langer, 1980; McCabe, 1984). The thin coal beds range in thickness from approximately 10 to 30 cm and therefore represent originally deposited 100–300 cm thick peats. We can estimate 1000 to 3000 years for deposition of the lignite beds. The sedimentation rates for the siliciclastic facies are higher perhaps as much as several

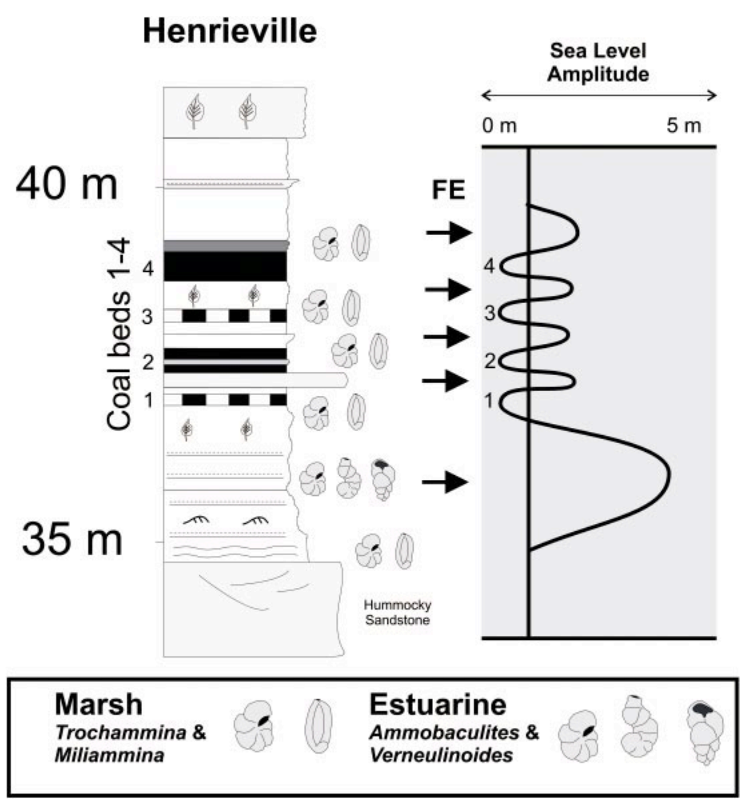


FIGURE 8. Foraminiferal data and sea level curve from Henrieville. Relative position of Flooding Events (FE) indicated by the solid black arrow. Coal beds 1–4 are numerated next to the curves and on the corresponding stratigraphic log.

centimeters per year. The relative sea level cycles from southwest Utah therefore likely represent periodicities ranging from thousands to tens of thousands of years.

An important association with the carbonaceous shale facies (Cs) is the exclusive population of *Trochammina* and *Miliammina* contained in oxidized mudstone. This is potentially an important indicator that evaporation periodically exceeded precipitation. Oxidized sediments associated with coal deposits are not uncommon and they are generally thought to be reasonable proxies for arid climatic conditions (Cecil, 1990; Mack and others, 1991; Cecil and others, 1993). Alternatively, relative sea level fall may have improved drainage of the marsh and contributed to the increase oxidation of the sediments during low stands. Compaction and regional subsidence could have also contributed to a lower water table that ultimately created oxidizing conditions of the peat. That the low amplitude sea level curves do not correlate between Glory Cove and Henrieville (separated by a few tens of kilometers) suggests that local subsidence was an important component for lowered sea level and subsequent sediment oxidation. It may simply be, however, that the preservation potential of these assemblages fall short of the required resolution to correlate between outcrops.

The Smoky Hollow Member coal zone comprises a sea level cycle that can be tracked several hundred kilometers to the westward edge of the Colorado Plateau (Pine Valley Mountains: Fig. 1) where the biotic assemblage is strikingly similar. This cycle corresponds to a fourth-order flooding event of Tibert and others (2003b). The duration of this and similar Mesozoic fourth-order sea level cycles approximate Cenozoic glacio-eustatic successions and their widespread global correlations during the Cenomanian-Turonian certainly suggest global control (Stoll and Schrag, 2000; Gale and others, 2002; Leckie and others, 2002; Miller et al., 2003). Given a presumed greenhouse world for Late Cretaceous time, glacioeustatic models are hard to justify. Tectonic models have also been invoked to explain the fourth and even fifth-order cycles of the WIB (Cross, 1988; Fillmore, 1991; Jordan and Flemings, 1991; Leithold, 1994; Pang and Nummedal, 1995; Gardner, 1995; Yoshida and others, 1996; Martinson and others, 1998; Houston and others, 2000). Regardless of the ''primary'' mechanism, our results presented here demonstrate small-scale sea level variability superimposed on a single coal zone that suggests a complex interaction between tectonics, eustasy, climatic, and autogenic compaction on the southwest margin of the WIB during middle Turonian times.

CONCLUSION

Agglutinated foraminifera provide high-resolution proxies for relative sea level change in Late Cretaceous age coal-bearing strata. We draw the following conclusions resulting from the observed lithologic and biotic character of the coal-bearing upper middle Turonian Smoky Hollow Member of the Straight Cliffs Formation:

1. There is a tripartite estuarine zonation that includes a proximal facies association comprising fluvial sandstone, a vertisol, carbonaceous shale, and lignite. A central estuarine facies association comprising shelly mudstone. A distal estuarine (open bay) facies association comprising gray mudstones and massive, swaley, cross-stratified sandstone.
2. *Trochammina* (trochospiral) is the prominent genus of foraminifera that occurs associated with either *Miliammina* (quinqueloculine) interpreted as the proximal marsh, *Ammobaculites* (uncoiled) interpreted as the central, muddy estuary, or *Verneulinoides, Reophax,* and *Textularia* (serial) interpreted as distal estuary or open bay.
3. We recognize a marsh association that can be used to identify 0–1 m water depth, a central estuarine association that represents 5–8 m water depth, and an open bay association that represents water depths of 10 m or greater.
4. Sea level curves constructed for the Smoky Hollow Member indicate amplitudes that range from one to ten meters.

Although much uncertainty surrounds the origins of these sea level cycles, it appears that compactional effects may have contributed to the development of the small amplitude cycles (0–1 m) and that the 5–10 m amplitude changes likely reflect allogenic control such as climate and/or glacio-eustatic fluctuations.

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REFERENCES

Abbot, S. T., 1997, Foraminiferal paleobathymetry and mid-cycle architecture of mid-Pleistocene depositional sequences, Wanganui Basin New Zealand: Palaios, v. 12, p. 267–281.

Arnold, A. J., 1983, Foraminiferal thanatocoenosis on the continental slope off Georgia and South Carolina: Journal of Foraminiferal Research, v. 13, no. 2, p. 79–90.

Arthur, M. A., Schlanger, S. O., and Jenkyns, H. C., 1987, The Cenomanian-Turonian oceanic anoxic event; II, Palaeoceanographic controls on organic-matter production and preservation, *in* Brooks, J., and Fleet, A., eds., Marine Petroleum Source Rocks: Geological Society Special Publications, 26, p. 401–420.

Benson, R. H., Berdan, J. M., van den Bold, W. A., and others, 1961, Treatise on Invertebrate Paleontology, *in* Moore, R. C., ed., Part Q, Arthropoda 3, Crustacea, Ostracoda: Lawrence Kansas, University of Kansas Press, 442 p.

Bloch, J. D., Schroeder-Adams, C. J., Leckie, D. A., Craig, J., and McIntyre, D. J., 1999, Sedimentology, micropaleontology, geochemistry, and hydrocarbon potential of shale from the Cretaceous Lower Colorado Group in Western Canada: Geological Survey of Canada Bulletin 531, 185 p.

Boyd, R., and Honig, C., 1992, Estuarine sedimentation on the eastern shore of Nova Scotia: Journal of Sedimentary Petrology, v. 62, no. 4, p. 569–583.

Bralower, T. J., Fullagar, P. D., Paull, C. K., Dwyer, G. S., and Leckie, R. M., 1997, Mid-Cretaceous strontium-isotope stratig-

raphy of deep-sea sections: Geological Society of America Bulletin, v. 109, no. 11, p. 1421–1442.
BUZAS, M. A., 1974, Vertical distribution of *Ammobaculites* in the Rhode River, Maryland: Journal of Foraminiferal Research, v. 4, p. 144–147.
CALDWELL, W. G. E., DINER, R., EICHER, D. L., FOWLER, S. P., NORTH, B. R., STELCK, C. R., and VON HOLDT WILHELM, L., 1993, Foraminiferal biostratigraphy of Cretaceous marine cyclothems, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., Evolution of the Western Interior Basin, Geological Association of Canada Special Paper 39, p. 477–520.
CECIL, C. B., 1990, Paleoclimatic controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18, p. 253–536.
———, DULONG, F. T., COBB, J. C., and SUPARDI, 1993, Allogenic and autogenic controls on sedimentation in the central Sumatra basin as an analogue for Pennsylvanian coal bearing strata in the Appalachian basin: *in* Cobb, J. C.; and Cecil, C. B., Modern and ancient coal-forming environments: Geological Society of America Special Paper 286, p. 3–22.
COLLIER, R. E., LEEDER, M. R., and MAYNARD, J. R., 1990, Transgression and regressions: a model for the influence of tectonic subsidence, deposition, and eustasy, with application to Quaternary and Carboniferous examples: Geologic Magazine, v. 127, no. 2, p. 117–128.
CONKIN, J. E., and CONKIN, B. M., 1982, North America Paleozoic Agglutinate Foraminifera, *in* Broadhead, T. W., ed., Foraminifera: Notes for a Short Course: University of TennesseeDepartment of Geological Sciences, Studies in Geology 6, New Orleans, p. 177–192.
CROSS, T. A., 1988, Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, Western Interior, U.S.A., *in* Wigus, A., K., C., Hastings, B. S., Ross, C. A., Posamentier, H., Van Wagoner, J., and Kendall, C. G. S. C., eds., Sea-level changes; an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 371–380.
CULVER, S., WOO, H. J., OERTEL, G. F., and BUZAS, M. A., 1996, Foraminifera of coastal depositional environments, Virginia, U.S.A.: Distribution and taphonomy: Palaios, v. 11, p. 459–486.
———, 1988, New foraminiferal depth zonation of the northwestern Gulf of Mexico: Palaios, v. 3, no. 1, p. 69–85.
DALRYMPLE, R. W., 1992, Tidal depositional systems, *in* Walker, R. G., and James, N. P., eds., Facies Models; Response to Sea Level Change: Geological Association of Canada, p. 195–218.
———, ZAITLIN, B. A., and BOYD, R., 1992, Estuarine facies models; conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, no. 6, p. 1130–1146.
DE RIJK, S., 1995, Salinity control on the distribution of salt marsh foraminifera (Great Marshes, Massachusetts): Journal of Foraminiferal Research, no. 25, p. 156–166.
EATON, J. G., 1991, Biostratigraphic framework for Upper Cretaceous rocks of the Kaiparowits Plateau, southern Utah, *in* Nations, J. D., and Eaton, J. G., eds., Stratigraphy, Depositional Environments, and Sedimentary Tectonics of the Western Margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper 260, p. 47–63.
———, DIEM, S., ARCHIBALD, J. D., SCHIERUP, C., and MUNK, H., 1999, Vertebrate paleontology of the Upper Cretaceous rocks of the Markagunt Plateau, southwestern Utah: Miscellaneous Publication—Utah Geological Survey, v. 99–1, p. 323–334.
———, KIRKLAND, J. I., HUTCHISON, J. H., DENTON, R., O'NEILL, R. C., and PARRISH, J. M., 1997, Nonmarine extinction across the Cenomanian-Turonian (C-T) boundary, southwestern Utah, with a comparison to the Cretaceous-Tertiary (K-T) extinction event: Geological Society of America Bulletin, v. 109, p. 560–567.
———, LAURIN, J., KIRKLAND, J. I., TIBERT, N. E., LECKIE, R. M., SAGEMAN, B. B., GOLDSTRAND, P. M., MOORE, D. W., STRAUB, A. W., COBBAN, W. A., and DALEBOUT, J. D., 2001, Cretaceous and Early Tertiary geology of Cedar and Parowan Canyons, western Markagunt Plateau, Utah: Utah Geological Association Field Trip Road Log September, 2001, *in* Erskine, M. C., Faulds, J. E., Bartley, J. M., and Rowley, P. D., eds., The Geologic Transition, High Plateaus to Great Basin: A Symposium and Field Guide: Utah Geological Association and Pacific Section AAPG, U.G.A., Publication no. 30, p. 337–363.
EICHER, D. L., 1965, Foraminifera and biostratigraphy of the Graneros Shale: Journal of Paleontology, v. 39, no. 5, p. 875–909.
———, 1966, Foraminifera from the Cretaceous Carlile Shale of Colorado: Contributions from the Cushman Foundation for Foraminiferal Research, v. 17, Part 1, p. 16–31.
———, 1967, Foraminifera from Belle Fourche Shale and equivalents, Wyoming and Montana: Journal of Paleontology, v. 41, no. 1, p. 167–188.
ELDER, W. P., GUSTASON, E. R., and SAGEMAN, B. B., 1994, Correlation of basinal carbonate cycles to nearshore parasequences in the Late Cretaceous Greenhorn Seaway, Western Interior U.S.A.: Geological Society of America Bulletin, v. 106, no. 7, p. 892–902.
ELLISON, R. L., 1972, *Ammobaculite*s, foraminiferal proprietor of Chesapeake Bay estuaries: Geological Society America Memoirs, v. 133, p. 247–262.
FILLMORE, R. P., 1991, Tectonic influence on sedimentation in the southern Sevier foreland, Iron Springs Formation (Upper Cretaceous), southwestern Utah, *in* Nations, J. D., and Eaton, J. G., eds., Stratigraphy, Depositional Environments, and Sedimentary Tectonics of the Western Margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper 260, p. 9–25.
GALE, A. S., 1995, Cyclostratigraphy and correlation of the Cenomanian stage in Western Europe, *in* House, M. R., and Gale, A. S., eds., Orbital forcing timescales and cyclostratigraphy, Geological Society Special Publications 85, p. 177–197.
———, HARDENBOL, J., HATHWAY, B., KENNEDY, W. J., YOUNG, J. A., and PHANSALKAR, 2002, Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level: Geology, v. 30, no. 4, p. 291–294.
———, SMITH, A. B., MONKS, N. E. A., YOUNG, J. A., HOWARD, A., WRAY, D. S., and HUGGETT, J. M., 2000, Marine biodiversity through the late Cenomanian-early Turonian; palaeoceanographic controls and sequence stratigraphic biases: Journal of the Geological Society of London, v. 157, p. 745–757.
GARDNER, M. H., 1995, Tectonic and eustatic controls on the spatial architecture of mid-Cretaceous stratigraphic sequences, central western interior foreland basin of North America, *in* Dorobek, S. L., and Ross, G. M., eds., Stratigraphic Evolution of Foreland Basins: Society for Sedimentary Geology (SEPM) Special Publication 52, p. 243–282.
GOLDSTEIN, S. T., and HARBEN, E. B., 1993, Taphofacies implications of infaunal foraminiferal assemblages in a Georgia salt marsh, Sapelo Island: Micropaleontology, v. 39, no. 1, p. 53–62.
———, and WATKINS, G. T., 1998, Elevation and the distribution of salt-marsh Foraminifera, St. Catherines Island, Georgia; a taphonomic approach: Palaios, v. 13, no. 6, p. 570–580.
———, 1999, Taphonomy of salt marsh Foraminifera; an example from coastal Georgia, *in* Martin, R. E., Patterson, R. T., Goldstein, S. T., and Kumar, A., eds., Taphonomy as a Tool in Paleoenvironmental Reconstruction and Environmental Assessment: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 103–114.
———, WATKINS, G. T., and KUHN, R. M., 1995, Microhabitats of salt marsh foraminifera: St. Catherines Island, Georgia, USA: Marine Micropaleontology, v. 26, p. 17–29.
HANCOCK, J. M., and KAUFFMAN, E. G., 1979, The great transgressions of the Late Cretaceous: Journal of the Geological Society, v. 136, p. 175–186.
HAQ, B. U., HARDENBOL, J., and VAIL, P. R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change: Society for Sedimentary Geology (SEPM) Special Publication 42, p. 71–108.
HAYWARD, B. W., GRENFELL, H., CAIRNS, G., and SMITH, A., 1996, Environmental controls on benthic foraminiferal and thecamoebian associations in a New Zealand tidal inlet: Journal of Foraminiferal Research, v. 26, p. 50–171.
HOUSTON, W. S., HUNTOON, J. E., and KAMOLA, D. L., 2000, Modeling of Cretaceous foreland-basin parasequences, Utah, with implications for timing of Sevier thrusting: Geology, v. 28, no. 3, p. 267–270.
HOWARD, J. D., and FREY, R. W., 1985, Physical and biogenic aspects of backbarrier sedimentary sequences, Georgia coast, USA: Marine Geology, v. 63, p. 77–127.
HUBER, B. T., HODELL, D. A., and HAMILTON, C. P., 1995, Middle-

Late Cretaceous climate of the southern high latitudes: Stable isotopic evidence for minimal equator-to-pole thermal gradients: Geological Society of America Bulletin, v. 107, p. 1164–1191.
———, Leckie, R. M., Norris, R. D., Bralower, T. J., and Cobabe, E., 1999, Foraminiferal assemblage and stable isotopic change across the Cenomanian-Turonian boundary in the subtropical North Atlantic: Journal of Foraminiferal Research, v. 29, no. 4, p. 392–417.
Jordan, T. E., and Flemings, P. B., 1991, Large-scale stratigraphic architecture, eustatic variation, and unsteady tectonism: A theoretical evaluation: Journal of Geophysical Research, v. 96, no. B4, p. 6681–6699.
Jones, R. W., and Charnock, M. A., 1985, Morphogroups of agglutinating foraminifera: Their life positions and feeding habits and potential applicability in (paleo) ecological studies: Revue de Paléobiologié, v. 4, p. 311–320.
Kauffman, E. G., 1969, Cretaceous marine cycles of the Western Interior: The Mountain Geologist, v. 6, no. 4, p. 227–245.
———, 1977, Geological and biological overview: western interior Cretaceous basin: The Mountain Geologist, v. 14, p. 75–100.
———, and Caldwell, W. G. E., 1993, The western interior basin in space and time, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39, p. 1–30.
———, Sageman, B. B., Kirkland, J. I., Elder, W. P., Harries, P. J., and Villamil, T., 1993, Molluscan biostratigraphy of the Cretaceous Western Interior Basin, North America, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39, p. 397–434.
Leckie, R. M., Leithold, E. L., Tibert, N. E., McCormick, M., and Polyak, D., 2002, A possible record of glacioeustatic sea level changes from the Cenomanian-Turonian Western Interior Basin, *in* Workshop On Cretaceous Climate And Ocean Dynamics: Florissant, Colorado, USA July 14–1, 2002.
———, and Olson, H. C., 2003, Foraminifera as proxies of sea-level change on siliciclastic margins, *in* Olson, H. C., and Leckie, R. M., eds., Micropaleontologic Proxies of Sea-Level Change and Stratigraphic Discontinuities: SEPM (Society for Sedimentary Geology), Special Publication 75, p. 5–19.
———, Yuretich, R. F., West, O. L. O., Finkelstein, D., and Schmidt, M., 1998, Palaeoceanography of the southwestern Western Interior Sea during the time of the Cenomanian-Turonian boundary (Late Cretaceous), *in* Dean, W., and Arthur, M. A., eds., Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, U.S.A.: Society for Sedimentary Geology (SEPM) Concepts in Sedimentology and Paleontology no. 6, p. 101–126.
Leithold, E. L., 1994, Stratigraphical architecture at the muddy margin of the Cretaceous Western Interior Seaway, southern Utah: Sedimentology, v. 41, p. 521–542.
———, and Dean, W. E., 1998, Depositional processes and carbon burial on a Turonian prodelta at the margin of the Western Interior Seaway, *in* Dean, W. E., and Arthur, M. A., eds., Stratigraphy and Paleoenvironments of the Western Interior Seaway, SEPM (Society for Sedimentary Geology) Concepts in Sedimentology and Paleontology no. 6, p. 189–200.
Mack, G. H., James, W. C., and Monger, H. C., 1991, Classification of paleosols: Geological Society of America Bulletin, v. 105, p. 129–136.
Martin, R. E., 1999, Taphonomy and temporal resolution of foraminiferal assemblages, *in* Sen Gupta, B. K., ed., Modern Foraminifera: Boston, Kluwer Academic Publishers, p. 281–298.
Martinson, V. S., Heller, P. L., and Frerichs, W. E., 1998, Distinguishing middle Late Cretaceous tectonic events from regional sea-level change using foraminiferal data from the U.S. Western Interior: Geological Society of America Bulletin, v. 110, no. 2, p. 259–268.
McCabe, P. J., 1984, Depositional environments of coal and coal-bearing strata, *in* Rahmani, R. M., and Flores, R. M., eds., Sedimentology of Coal and Coal-Bearing Sequences: Oxford, Special Publication of the International Association of Sedimentologists 7, Blackwell Scientific Publications, p. 12–42.
———, and Parrish, J. T., 1992, Tectonic and climatic controls on the distribution and quality of Cretaceous coals, *in* McCabe, P. J., and Parrish, J. T., eds., Controls on the Distribution and Quality of Cretaceous Coals, Geological Society of America Special Paper 267, p. 1–16.
———, and Shanley, K. W., 1992, Organic control on shoreface stacking patterns; bogged down in the mire: Geology (Boulder), v. 20, no. 8, p. 741–744.
McNeil, D. H., and Caldwell, W. G. E., 1981, Cretaceous Rocks and Their Foraminifera in the Manitoba Escarpment: Geological Association of Canada Special Paper 21, 439 p.
Medioli, F. S., Scott, D. B., Collins, E. S., and Wall, J. H., 1990, Thecamoebians from the Early Cretaceous deposits of Ruby Creek, Alberta (Canada), *in* Hemleben, C., Kaminski, M. A., and Scott, D. B., eds., Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera: NATO ASI Series C: Mathematical and Physical Sciences: Tübingen, Federal Republic of Germany, p. 793–812.
Miller, K. G., Sugarman, P. J., Browning, J. V., Kominz, M. A., Hernandez, J. C., Olsson, R. K., Wright, J. D., Feigenson, M. D., and Van Sickel, W., 2003, Late Cretaceous chronology of large, rapid sea-level changes; glacioeustasy during the greenhouse world: Geology (Boulder), v. 31, no. 7, p. 585–588.
Morales, J. A., 1997, Evolution and facies architecture of the mesotidal Guadiana River delta (SW Spain-Portugal): Marine Geology, v. 138, p. 127–148.
Morris, R. W., 1971, Upper Cretaceous foraminifera from the upper Mancos Formation, the Mesa Verde Group, and the basal Lewis Formation, northwestern Colorado: Micropaleontology, v. 17, p. 257–296.
Nichols, M. N., and Biggs, R. B., 1985, Estuaries, *in* Davis, R. A., ed., Coastal Sedimentary Environments: New York, Springer Verlag, p. 77–186.
Nichols, M. N., Johnson, G. H., and Peeble, P. C., 1991, Modern sediments and facies model for a macrotidal coastal plain estuary, the James Estuary, Virginia: Journal of Sedimentary Petrology, v. 61, no. 6, p. 883–899.
Obradovich, J. D., 1993, A Cretaceous time scale, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., Evolution of the Western Interior Basin, Geological Association of Canada, Special Paper 39, p. 379–398.
Pang, M., and Nummedal, D., 1995, Flexural subsidence and basement tectonics of the Cretaceous Western Interior Basin, United States: Geology, v. 23, p. 173–176.
Penland, S., Boyd, R., and Suter, J. R., 1988, Transgressive depositional systems of the Mississippi Delta Plain: A model for barrier shoreline and shelf sand development: Journal of Sedimentary Petrology, v. 58, no. 6, p. 932–949.
Peterson, F., 1969, Cretaceous sedimentation and tectonism in the southeastern Kaiparowits region, Utah: U.S. Geological Survey Open File Report 69–202, 259 p.
Peterson, R. H., Gauger, D. J., and Lankford, R. R., 1953, Microfossils of the Upper Cretaceous of northeastern Utah and southwestern Wyoming: Utah Geological and Mineralogical Survey Bulletin 47, 158 p.
Phleger, F. B., 1960, Sedimentary patterns of microfaunas in northern Gulf of Mexico, *in* Shepard, F. P., ed.: Recent Sediments, Northwest Gulf of Mexico, American Association of Petroleum Geologists, Tulsa, p. 267–301.
———, 1965, Depth patterns of benthonic Foraminifera in the eastern Pacific: Progress in Oceanography, v. 3, New York, Pergamon Press, p. 273–287.
Robaszynski, F., Gale, A., Juignet, P., Amedro, F., and Hardenbol, J., 1998, Sequence stratigraphy in the Upper Cretaceous series of the Anglo-Paris Basin; exemplified by the Cenomanian Stage, *in* Vail, P. R., de Graciansky, P.-C., Hardenbol, J., and Jacquin, T., eds., Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: Society for Sedimentary Geology (SEPM) Special Publication 60, p. 363–386.
Ryer, T. A., 1984, Transgressive-regressive cycles and the occurrence of coal in some Upper Cretaceous strata of Utah, U.S.A., *in* Rahmani, R. A., and Flores, R. M., eds., Sedimentology of Coal and Coal-bearing Sequences: Special Publication of the International Association of Sedimentologists 7, p. 217–227.
———, and Langer, A. W., 1980, Thickness change involved in the peat-to-coal transformation for a bituminous coal of Cretaceous

age in central Utah: Journal of Sedimentary Petrology, v. 50, p. 987–992.

SAGEMAN, B. B., RICH, J., ARTHUR, M. A., BIRCHFIELD, G. E., and DEAN, W. E., 1997, Evidence for Milankovitch periodicities in Cenomanian-Turonian lithological and geochemical cycles, Western Interior U.S.A.: Journal of Sedimentary Research, v. 67, p. 286–302.

———, RICH, J., ARTHUR, M. A., DEAN, W. E., SAVRDA, C., and BRALOWER, T. J., 1998, Multiple Milankovitch cycles in the Bridge Creek Limestone (Cenomanian-Turonian), Western Interior Basin, *in* Dean, W., and Arthur, M. A., eds., Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA, SEPM Concepts in Sedimentology and Paleontology No. 6, p. 153–171.

SAHAGIAN, D., PINOUS, O., OLFERIEV, A., and ZAKHAROV, V., 1996, Eustatic curve for the Middle Jurassic-Cretaceous based on Russian platform and Siberian stratigraphy: Zonal resolution: American Association of Petroleum Geologists Bulletin, v. 80, p. 1433–1458.

SCHLANGER, S. O., ARTHUR, M. A., JENKYNS, H. C., and SCHOLLE, P. A., 1987, The Cenomanian-Turonian oceanic anoxic event; I, Stratigraphy and distribution of organic carbon-rich beds and the marine $\delta^{13}C$ excursion, *in* Brooks, J., and Fleet, A. J., eds., Marine Petroleum Source Rocks: London, United Kingdom, Geological Society of London, p. 371–399.

SCHWARZACHER, W., 1994, Cyclostratigraphy of the Cenomanian in the Gubbio District, Italy; a field study, *in* de Boer, P. L., and Smith, D. G., eds., Orbital Forcing and Cyclic Sequences: Special Publication of the International Association of Sedimentologists 19, p. 87–97.

SCOTT, D. B., COLLINS, E., DUGGAN, J., ASIOLI, A., SAITO, T., and HASEWAGA, S., 1996, Pacific Rim marsh foraminiferal distributions: Implications for sea level studies: Journal of Coastal Research, v. 12, p. 850–861.

———, HASEGAWA, S., SAITO, T., ITO, K., and COLLINS, E. S., 1995, Marsh foraminiferal and vegetation distributions in Nemuro Bay wetland areas, eastern Hokkaido: Transactions and Proceedings of the Palaeontological Society of Japan, v. 180, p. 282–295.

———, and MEDIOLI, F. S., 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: Implications for sea level studies: Cushman Foundation For Foraminiferal Research, Special Publication No. 17, 58 p.

———, SCHAFER, C. T., and MEDIOLI, F. S., 1980, Eastern Canadian estuarine foraminifera; a framework for comparison: Journal of Foraminiferal Research, v. 10, no. 3, p. 205–234.

———, SUTER, J. R., and KOSTERS, E. C., 1991, Marsh foraminifera and arcellaceans of the lower Mississippi Delta: controls on spatial distributions: Micropaleontology, v. 37, no. 4, p. 373–392.

SCOTT, D. K., and LECKIE, R. M., 1990, Foraminiferal zonation of Great Sippewissett salt marsh (Falmouth, Massachusetts): Journal of Foraminiferal Research, v. 20, no. 3, p. 248–266.

SEN GUPTA, B. K., 1999, Foraminifera in Marginal Marine Environments, *in* Sen Gupta, B. K., ed., Modern Foraminifera: Boston, Kluwer Academic Publishers, p. 141–159.

SHANLEY, K. W., and MCCABE, P. J., 1995, Sequence stratigraphy of Turonian-Santonian strata, Kaiparowits Plateau, southern Utah, U.S.A.: Implications for regional correlation and foreland basin evolution, *in* Van Wagoner, J. C., and Bertram, G. T., eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists Memoir 64, p. 103–136.

STELCK, C. R., and WALL, J. H., 1954, Kaskapau Foraminifera from Peace River area of Western Canada [Alberta-British Columbia]: Report—Alberta Research Council, v. 68, 38 p.

STOLL, H. M., and SCHRAG, D. P., 2000, High-resolution stable isotope records from the Upper Cretaceous rocks of Italy and Spain: Glacial episodes in a greenhouse planet: Geological Society of America Bulletin, v. 112, no. 2, p. 308–319.

STRITCH, R. A., and SCHROEDER-ADAMS, C. J., 1999, Foraminiferal response to Albian relative sea-level changes in northwestern and central Alberta, Canada: Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre, v. 36, no. 10, p. 1617–1643.

TAPPAN, H. N., 1957, New Cretaceous index Foraminifera from northern Alaska: Bulletin—U.S. National Museum, p. 201–222.

TIBERT, N. E., and GIBLING, M. R., 1999, Peat accumulation on a drowned coastal braidplain; the Mullins Coal (Upper Carboniferous), Sydney Basin, Nova Scotia: Sedimentary Geology, v. 128, no. 1–2, p. 23–38.

———, COLIN, J. P., LECKIE, R. M., and BABINOT, J. F., 2003a, Revision of the ostracode genus *Fossocytheridea* Swain and Brown 1964: Mesozoic ancestral root for the modern eurytopic *Cyprideis* Jones: Micropaleontology, v. 49, no. 3, p. xx–xx.

———, LECKIE, R. M., EATON, J. G., KIRKLAND, J. I., COLIN, J.-P., LEITHOLD, E. L., and MCCORMIC, M., 2003b, Recognition of relative sea level change in Upper Cretaceous coal-bearing strata: A paleoecological approach using agglutinated foraminifera and ostracodes to detect key stratigraphic surfaces, *in* Olson, H., and Leckie, R. M. (eds.), Microfossils As Proxies For Sea Level Change and Stratigraphic Discontinuities, Society for Sedimentary Geology (SEPM) Special Publication 75, p. 263–299.

———, and SCOTT, D. B., 1999, Ostracodes and agglutinated Foraminifera as indicators of paleoenvironmental change in an Early Carboniferous brackish bay, Atlantic Canada: Palaios, v. 14, no. 3, p. 246–260.

VAN WAGONER, J. C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, USA, *in* Van Wagoner, J. C., and Bertram, G. T., eds., Sequence Stratigraphy of Foreland Basin Deposits, American Association of Petroleum Geologists Memoir 64, p. 137–223.

WALL, J. H., 1976, Marginal marine foraminifera from the Late Cretaceous Bearpaw-Horseshoe canyon transition, southern Alberta, Canada: Journal of Foraminiferal Research, v. 6, p. 193–201.

WEST, O. L. O., LECKIE, R. M., and SCHMIDT, M., 1998, Foraminiferal paleoecology and paleoceanography of the Greenhorn Cycle along the southwestern margin of the Western Interior Sea, *in* Dean, W., and Arthur, M. A., eds., Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, U.S.A.: Tulsa, SEPM (Society for Sedimentary Geology) Concepts in Sedimentology and Paleontology no. 6, p. 79–99.

WICKENDEN, R. T. D., 1932, New species of foraminifera from the upper Cretaceous prairie provinces: Royal Society of Canada, Transactions, v. 26, p. 90.

WIGHTMAN, W. G., 1990, Estuarine and marsh foraminifera from the Lower Cretaceous of the Lusitanian Basin, West Portugal, *in* Paleoecology, biostratigraphy, paleoceanography and taxonomy of agglutinated foraminifera, Tubingen, Federal Republic of Germany, p. 739–764.

———, SCOTT, D. B., MEDIOLI, F. S., and GIBLING, M. R., 1993, Carboniferous marsh foraminifera from coal-bearing strata at the Sydney Basin, Nova Scotia; a new tool for identifying paralic coal-forming environments: Geology (Boulder), v. 21, no. 7, p. 631–634.

———, 1994, Agglutinated foraminifera and thecamoebians from the Late Carboniferous Sydney Coalfield, Nova Scotia: palaeoecology, palaeoenvironments and palaeogeographical implications: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 106, p. 187–202.

YOSHIDA, S., WILLIS, A., and MIALL, A. D., 1996, Tectonic control of nested sequence architecture in the Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah: Journal of Sedimentary Research, v. 66, no. 4, p. 737–748.

ZWAAN, V. D., G. J., JORISSEN, F. J., and STIGTER, D., H. C., 1990, The depth dependency of planktonic/benthic foraminfieral ratios: Constraints and applications: Marine Geology, v. 95, p. 1–16.

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