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

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ABSTRACT: Microfossils from Cretaceous coal-bearing strata can be used to establish key stratigraphic surfaces that mark marine flooding events with intermediate-frequency (fourth-order) and high-frequency (fifth-order) periodicities. We document several examples of this cyclicity from the transgressive and regressive facies at the land–sea transition of the Greenhorn Marine Cycle on the Colorado Plateau. Estuarine strata from the upper Cenomanian Dakota and middle Turonian Straight Cliffs Formations yield four primary fossil assemblages: Assemblage A, the lagoonal assemblage, comprising a rich agglutinated foraminiferal population of *Trochammina* and *Verneuilinoides* and brackish ostracodes and molluscs in a skeletal shell accumulation; Assemblage B, the proximal estuarine assemblage, comprising the brackish ostracode *Fossocytheridea*, charophytes, and smooth admetopsid gastropods within bituminous coal zones giving rise to distal estuary with the addition of brackish gastropods and sparse agglutinated foraminifera in sandy marlstones; Assemblage C, the open-bay (distal estuarine) assemblage, comprising the ostracodes *Fossocytheridea posterovata*, *Cytheromorpha*, *Looneyella*, and *Cytheropteron*, the foraminifera *Trochammina* and *Ammobaculites*, and ornate brackish molluscs in calcareous shelly mudstones; and Assemblage D, the marsh, comprising an exclusive population of the foraminifera *Trochammina*, *Miliammina*, and *Ammobaculites* in rooted lignites. Intermediate flooding surfaces are marked by normal marine taxa that are superimposed on the background of a primary marginal marine assemblage. In general, intermediate flooding events approximate lithologic and biostratigraphic boundaries and record basin-wide paleoenvironmental changes with the advancing Greenhorn Sea. We correlate coal zones from the coast to maxima in calcium carbonate and planktic foraminifera in the offshore. The intermediate cycles approximate ammonite biostratigraphic zones and therefore maintain periodicities within the 100–400 kyr bandwidth. The onshore–offshore correlations suggest that a regional and perhaps global sea-level mechanism controlled the stratigraphic position of the coal zones. Superimposed on the intermediate cycles are higher-frequency cycles that represent short-lived flooding events. As many as six high-frequency cycles constitute an intermediate cycle, and therefore periodicities fall within an approximate 10–25 kyr range. The general asymmetry of the packages suggests that a combination of oceanographic, climatic, and autogenic processes influenced the high-frequency stratal architecture. Overall, the primary mechanism controlling the stratigraphic position of the coals was tectono-eustasy. Compactional processes and/or climate modulations contributed to the observed internal coal-zone cyclicity that we interpret as a secondary coal-forming process.

INTRODUCTION

Sea-level oscillations range in scale from the daily advance and retreat of the tide to the marine inundation of a continental basin. Superimposed on the spectrum of sea-level rise and fall are multiple transgressive and regressive cycles that occupy differing temporal periods. Oceanographers investigating Pleistocene and Holocene sedimentary deposits enjoy a high-resolution isotopic record of waxing and waning polar ice sheets and rhythmic stratal repetition that can be constrained with remarkable temporal precision. Unfortunately, as we extend further into the geologic record it becomes increasingly difficult to achieve cyclostratigraphic resolutions that can be attributed with confidence to allogenic process, such as orbitally induced climate change. This problem is intensified in marginal marine peat-forming environments where fluvial and oceanic processes are superimposed one upon another. The resultant cyclostratigraphic trends in coal-bearing strata, if preserved, are difficult to assign to any one primary controlling mechanism, whether tectonic, allogenic (e.g., eustatic or climatic), or autogenic (e.g., compaction and/or fluvial drainage diversion).

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Our study interval encompasses the Dakota, Tropic, and Straight Cliffs Formations of the third-order Greenhorn Marine Cycle, deposited in the foredeep of the Western Interior Seaway (WIS). This suite of marginal marine strata was deposited during the Cenomanian–Turonian boundary interval, which is well known for high rates of biotic turnover (Elder, 1991), anoxia of the oceans (Arthur et al., 1987), greenhouse atmospheric conditions (Arthur et al., 1988), enhanced oceanic volcanism (Bralower et al., 1997), and exceptionally high global sea level, which contributed to widespread flooding of continental landmasses (Haq et al., 1988). Given the rapid regional subsidence in the foreland basin of the WIS, many researchers have emphasized tectonic depositional models for the western margin of the seaway (e.g., Eaton, 1991). For example, Gustason (1989) showed a westward thickening of marginal facies across fault blocks, which certainly demonstrates a significant tectonic influence during deposition of the Dakota Formation. However, Gustason (1989) and Elder et al. (1994) drew attention to the basin-wide correlations of marginal marine strata to the central regions of the seaway, which indicates significant depositional influence beyond the confines of the tectonically dominated WIS foredeep.

This paper employs previously unidentified microfossil population data from the coal-bearing units of southwest Utah to demonstrate that peat accumulation during deposition of the Greenhorn Marine Cycle was intimately linked to offshore processes. We use "background" brackish microfossil populations in marginal facies that are punctuated by periodic incursions of normal marine taxa as proxies for basin-wide flooding events recognized across the Western Interior Seaway. Using the well-constrained molluscan biostratigraphic framework of Kauffman et al. (1993), we present evidence for intermediate-scale (100–400 kyr) cyclicity that corresponds to fourth-order carbonate sea-level cycles recognized by Leithold (1994) in the adjacent prodeltaic facies of the Tropic Shale (see Table 1 for definitions of cyclostratigraphic nomenclature). Further, we recognize high-frequency (10–25 kyr) stratal cycles, which suggest that autogenic compactional processes and/or climate exerted significant control on sea-level modulations preserved in the coal zones. Although the westward thickening of the marginal facies indicates subsidence and infilling of a foreland basin, our model presented herein demonstrates the utility of ostracodes and foraminifera to detect and correlate what are likely allogenic events in an otherwise tectonically controlled siliciclastic sequence.

GEOLOGIC SETTING

During Late Cretaceous time, a subsiding foredeep basin developed in southwestern Utah. This basin formed a V-shaped ancient embayment known as the Grand Canyon Bight (Stokes and Heylmun, 1963) (Fig. 1). Brackish-water facies transgressed the perimeter of this embayment during late Cenomanian–middle Turonian time (~ 94.5–90.5 Ma) (Molenaar, 1983; Kauffman, 1984; Ryer, 1984; Eaton and Nations, 1991). Figure 2 shows the generalized stratigraphy of the embayment; we focused exclusively on the coal zones and mudrocks of the uppermost Dakota Formation, the Tropic Shale, and the lower part of the Straight Cliffs Formation (Tibbet Canyon and Smoky Hollow Members). We refer the reader to Gustason (1989), Elder et al. (1994), Uličny (1999), and Eaton et al. (2001) for more detailed accounts of the estuarine and shoreface sandstones that separate the Dakota Formation coal-bearing units on Markagunt Plateau. Likewise, detailed sedimentologic and stratigraphic studies of the Tropic Shale, Straight Cliff Formation, and equivalent units include the work of Peterson (1969a, 1969b), Shanley and McCabe (1991, 1995), Eaton (1991), Kirkland, 1991, Elder and Kirkland (1993),

TABLE 1.—Nomenclatural usage of orders of relative sea level change (Vail et al., 1977) for the North American Western Interior Sea.

Stratigraphic Cycle	Duration Vail et al. (1977)	Stratigraphic Usages Western Interior Sea
1st	200–500 myr	Global Supercontinental cycle (Vail et al., 1977)
2nd	10–100 myr	Eustatic ocean-basin volume changes and regional tectonic variability (Fulthorpe, 1991); flooding of the WIS (Hancock and Kauffman, 1979; Ryer, 1984)
3rd	1–5 myr	Greenhorn and Niobrara Cyclothems (Kauffman, 1985); Ryer (1984); long-term cycle (Gardner 1995a,b); Greenhorn cycle (Kauffman, 1977; Ryer, 1984; this study)
4th	0.3–0.6 myr	"Biozone-scale" tectono-eustasy parasequences – "sawtooth" cycles Ryer (1984); intermediate-term cycles (Gardner, 1995a,b); prodeltaic carbonate cycles (Leithold, 1994); intermediate cycles (this study)
5th	100 kyr	Allogenic parasequences and cycles – production–dilution cycles (Eicher and Diner, 1989; Pratt et al., 1993); short-term cycles (Gardner, 1995a, 1995b); High-frequency carbonate cycles (Leithold, 1994); basin–nearshore cycles Elder et al. (1994); eccentricity cycles (Sageman, 1997); high-frequency cycles (this study)
6th	40 kyr	Allogenic parasequences and cycles – production–dilution cycles (Eicher and Diner, 1989; Pratt et al., 1993); short-term cycles (Gardner, 1995a, 1995b); basin–nearshore cycles (Elder et al., 1994); Bridge Creek Limestone shale couplets – obliquity cycles (Sageman et al., 1997); high-frequency cycles (this study)
7th	20 kyr	Bridge Creek Limestone shale couplets – precession cycles (Sageman et al., 1997); mudstone–coal and marl–shale alternations = high-frequency cycles (this study)

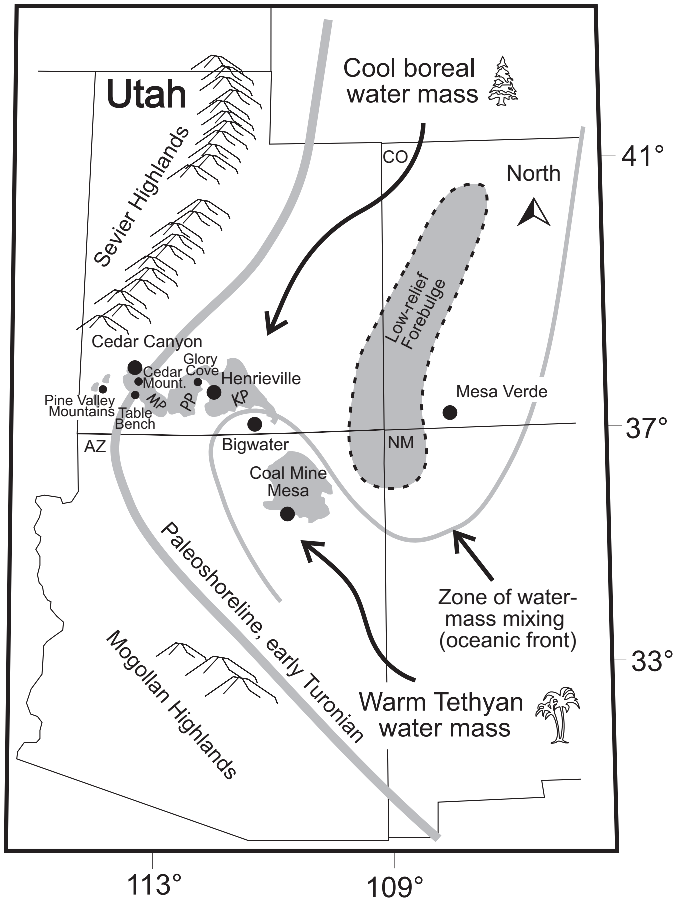


FIG. 1.—Paleogeographic map of the Colorado Plateau and surrounding areas of Utah. Paleogeographic reconstructions indicate the southwestern mid-continent U.S. lay at approximately 40–50º N (Ziegler et al., 1987; McCabe and Parrish, 1992). To the west of the shoreline, the Sevier thrust belt and the Mogollan Highlands provided significant paleo–topographic highs (Parrish, 1993). To the east, the relatively shallow seaway extended from Alaska to Mexico (Kauffman, 1977). Cenomanian–Turonian coals are largely confined to southwestern margins of the seaway (Kirschbaum and McCabe, 1992; Shanley and McCabe, 1991, 1995). The leading edge of the Sevier thrust belt in southwestern Utah and Wyoming was active during Cenomanian and Turonian times (Jordan, 1981; Gustason, 1989; Pang and Nummedal, 1995). Note that data were collected from geographic highs in southwestern Utah that include the following, arranged from west to east: the Pine Valley Mountains; Markagunt Plateau (MP); Paunsaugunt Plateau (PP); and Kaiparowits Plateau (KP). Large solid dots indicate sites where tabulated dated are reported. Small black dots indicate data not tabulated herein (Tibert, 2002).

Leithold (1994), Leckie et al. (1997), Leckie et al. (1998), Leithold and Dean (1998), and West et al. (1998).

On the Colorado Plateau, the Dakota Formation is divided into three informal members (Peterson, 1969a; Gustason, 1989; am Ende, 1991; Kirkland, 1991; Kirschbaum and McCabe, 1992): (1) a basal chert-pebble conglomerate and coarse, trough cross-bedded sandstone unit interpreted as braided fluvial; (2) a carbonaceous middle unit comprising sandstone, siltstone, and coal facies interpreted as an alluvial mire; and (3) an upper sandy unit comprising laterally continuous sandstones, shelly mudstones, and coals interpreted as estuarine and brackish mire deposits. The age of the upper Dakota Formation is diachronous from east to west across the Colorado Plateau, with marine invertebrate faunas attributed to the upper Cenomanian *Calycoceras canitaurinum* zone at Mesa Verde to the *Neocardioceras juddii* and basal Turonian *Watinoceras coloradoense* biostratigraphic zones on Markagunt Plateau. In southern Utah, the Dakota interfingers with the overlying brackish to marine Tropic Shale, the western equivalent to the Mancos Shale (Fig. 3).

At Coal Mine Mesa, in northeastern Arizona (Fig. 1), the Dakota Sandstone comprises three informal members not unlike those described from southwestern Utah (Kirkland, 1991, 1996). On the southwest side of Black Mesa (= Coal Mine Mesa), a meter-thick coal caps the middle carbonaceous member, which is overlain by shelly shales of the upper sandstone member. These uppermost shales are interpreted as brackish-lagoonal facies deposited during *Metoicoceras mosbyense* time (Fürsich and Kirkland, 1986; Kirkland, 1996).

The Straight Cliffs Formation overlies the Tropic Shale across southern Utah (Kaiparowits, Paunsaugunt, and Markagunt Plateaus) (Fig. 2). Peterson (1969b) subdivided the 300-m-thick formation into the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members. We focused on the lower two members. The Tibbet Canyon Member comprises marine shoreface sandstone containing sparse granules and pebbles. Rare fossils include oysters, bivalves, and ammonites. Like the Dakota Formation, the Tibbet Canyon Member of the Straight Cliffs Formation is diachronous, on the basis of the marine invertebrates ranging from the middle Turonian *Collignoniceras woollgari* Zone (or upper *Mammites nodosoides* Zone) on Markagunt Plateau to the upper middle Turonian *Prionocyclus hyatti* Zone on the Paunsaugunt and Kaiparowits Plateaus (Eaton, 1991; Kauffman et al., 1993; Cobban, personal communication 2001). Overlying the Tibbet Canyon Member are sandstone and mudstones that are intercalated with carbonaceous shale and coal of the Smoky Hollow Member, some of which were deposited in a brackish-water environment (Eaton et al., 1997).

SIGNIFICANCE OF MICROFOSSILS

Estuarine environments are among the most productive ecosystems because of a bountiful supply of nutrients and sunlight in shallow waters that are constantly being stimulated by the daily mixing of the tidal flood and ebb. In addition, an abundance of organics-laden river water and widespread coastal vegetation makes this an ideal habitat for select biota that can tolerate the highly variable environment. Two groups of organisms that have migrated and successfully occupied marginal environments include agglutinated foraminifera (unicellular protists) and ostracodes (bivalved crustaceans). To resist the high acidity of coastal marshes, agglutinated foraminifera construct their shells using sedimentary particles (Podobina, 1990). Ostracode adaptive strategies include short life cycles and breeding strategies (such as brood rearing within pouches) that ensure survival of a species in the highly unstable marginal marine ecosystem (Horne, 1983).

Foraminifera

Agglutinated foraminifera are exclusively marine unicellular protists. Most of these microorganisms construct their tests of sediment grains bound with organic cement. Consequently, they are extremely tolerant of acidic conditions of salt marshes and

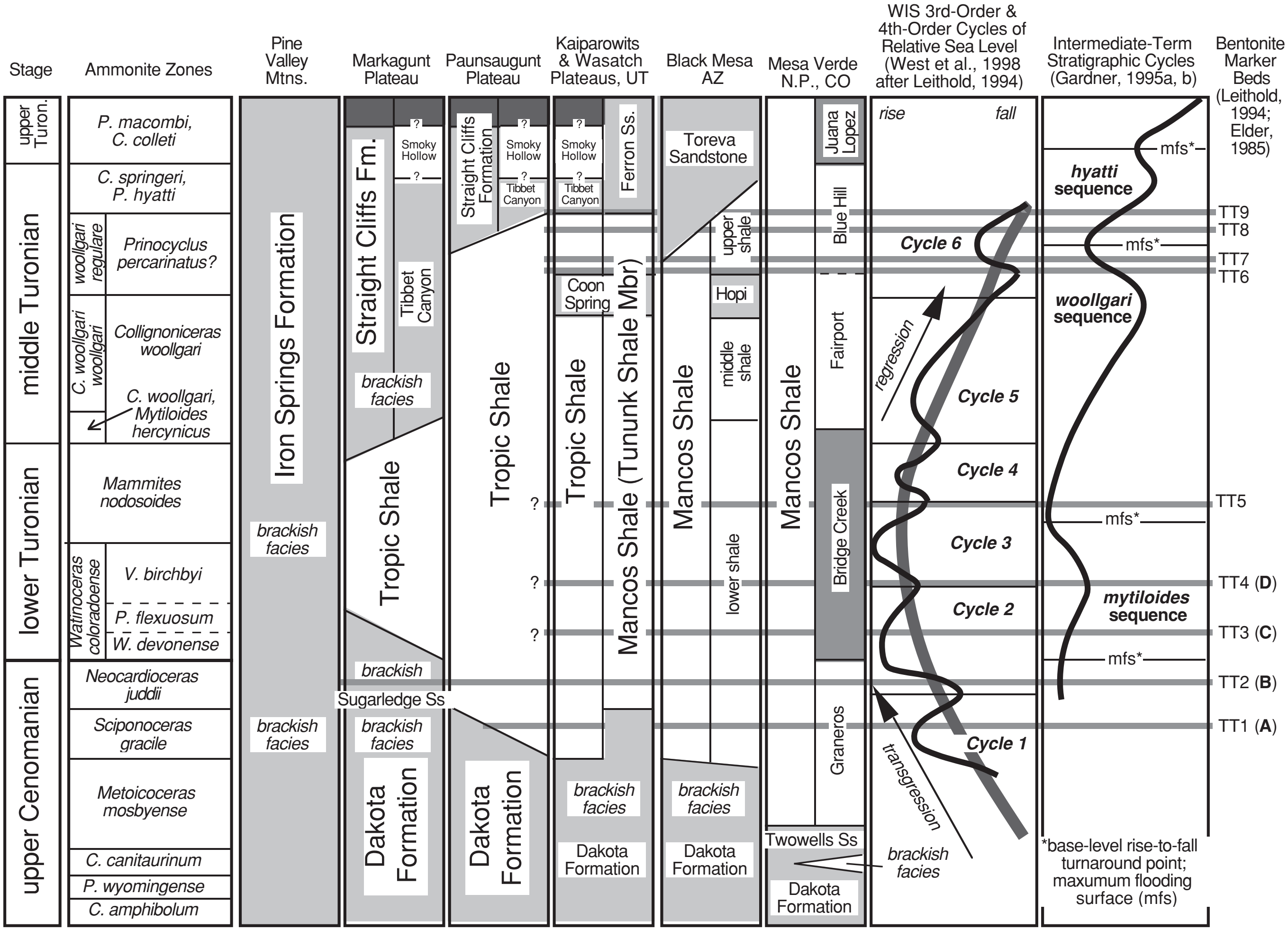


FIG. 2.—Biostratigraphic zones and fourth-order sedimentary cycles recognized across the Colorado Plateau.

organic sediments of estuaries and bays, and therefore have high preservation potential. Most Cretaceous agglutinated foraminiferal genera are extant. In fact, the perseverance of the primary morphotypes with similar taxon associations since the Carboniferous demonstrates that agglutinated foraminifera are a useful paleoecological tool for the differentiation of marsh, estuarine, and lagoonal habitats (Morris, 1971; McNeil and Caldwell, 1981; Scott et al., 1991; Wightman et al., 1994; Leckie and Tibert, 1997; Tibert and Scott, 1999).

Morphological Design of Agglutinated Foraminifera.—

Agglutinated foraminifera belong to the Suborder Textulariina. At present, the most widely accepted criterion for the Textulariina is that the wall constitutes no less than 25% agglutinated material and the optical axes of the mineral grains do not have a preferred orientation (Podobina, 1990). Micropaleontologists classify agglutinated foraminifera using the arrangement of the chambers (coiling design), characteristics of the sutures, and the position and type of the apertural opening(s). Table 2 provides a brief description of the most common agglutinated morphotypes and key genera found in marginal marine environments. Figure 3A shows the most common agglutinated foraminiferal morphotypes observed in modern marginal marine ecosystems.

Composition of Modern Foraminiferal Populations.—

Scott and Medioli (1980) have demonstrated the utility of marsh agglutinated foraminifera for locating past sea-level acmes. This follows that living taxa display a distinct zonation of vertical habitats between mean sea level and the highest high-water position recorded in modern coastal marshes (Scott and Medioli, 1980; Scott et al., 1980; Patterson, 1990; Scott et al., 1990; Scott and Leckie, 1990; Scott et al., 1995; Scott et al., 1996). In this paper we compare Cretaceous agglutinated foraminifera to modern data sets from Nova Scotia (Scott and Medioli, 1980; Scott et al., 1980), Massachusetts (Jones and Cameron, 1987), Japan (Scott et al., 1995), and Argentina (Scott et al., 1990). To minimize taxonomic subjectivity, the modern population data are grouped into their five major morphologic coiling categories, which include trochospiral, planispiral, quinqueloculine, uncoiled, and serial (= uniserial, biserial, and triserial) (Table 2; Fig. 3A). In addition to the agglutinated foraminifera, freshwater thecamoebians (agglutinated protists) and calcareous benthic foraminifera are included in the data set to track nonmarine and normal marine conditions, respectively. Below are the primary characteristics observed for foraminiferal populations from freshwater marshes, high salt marshes, low salt marshes, upper-estuary marshes, lower-estuary marshes, and open marine bays (Fig. 4).

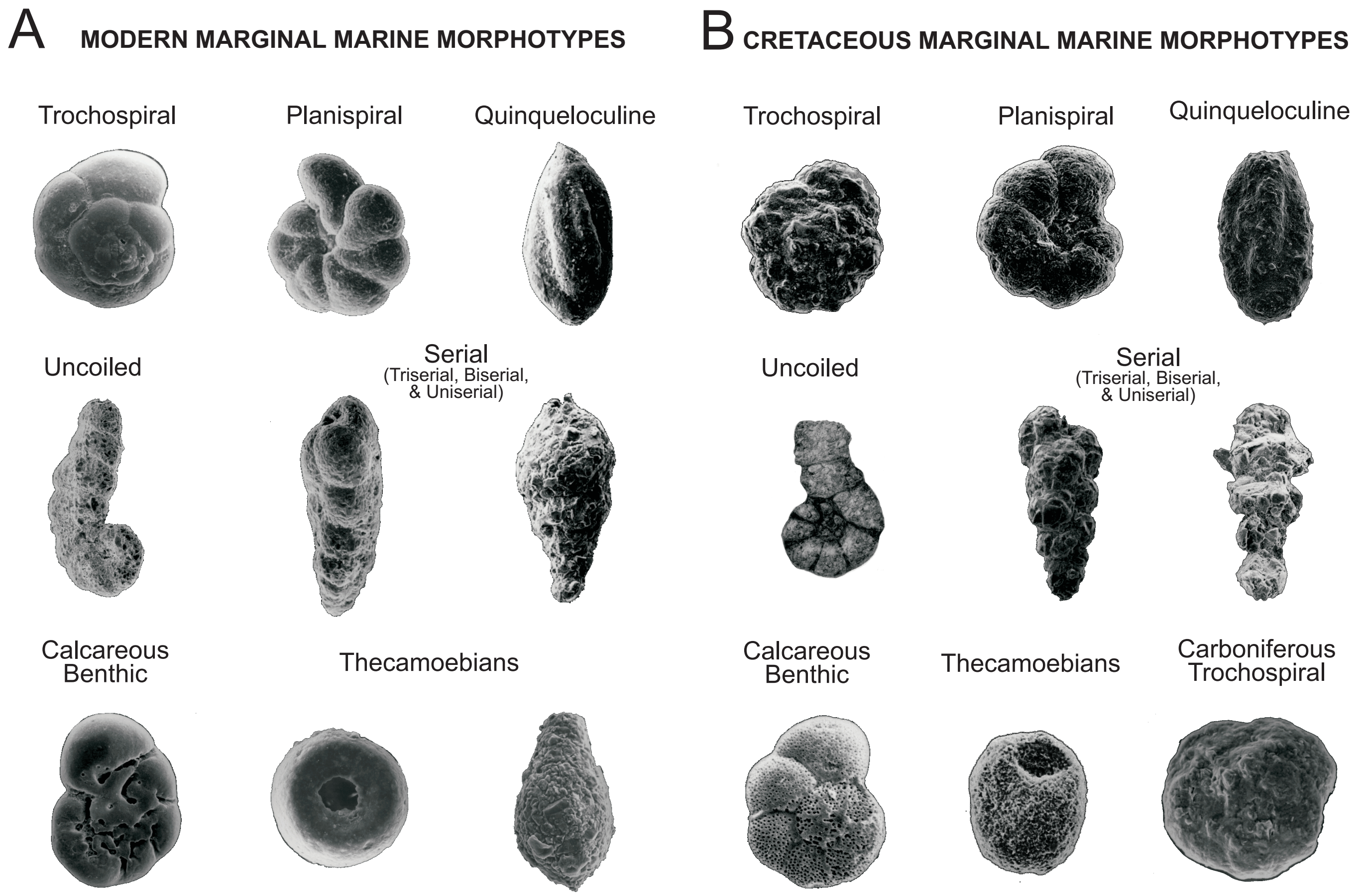


FIG. 3.—Modern and ancient marginal marine foraminiferal morphotypes. **A**) Modern specimens reproduced from Scott and Medioli (1980) and Tibert and Scott (unpublished). **B)** Ancient specimens reproduced from Eicher (1966), Wall (1976), MacNeil and Caldwell (1981), Oleson (1987), and Tibert and Scott (1999).

Freshwater marshes occur at landward localities where marine influence is minimal and an exclusive population of nonmarine thecamoebians includes *Difflugia* and *Centropyxis* (Fig. 4) (Medioli and Scott, 1983; Scott and Medioli, 1983). The empty tests of trochospiral, planispiral, and quinqueloculine foraminiferal morphotypes are commonly transported into freshwater ponds during storm surges (Collins et al., 1999).

Saltwater marshes yield populations dominated by agglutinated foraminifera (Murray, 1991). Although benthic calcareous species of *Elphidium* and *Ammonia* live on the low-marsh surface, they are rarely preserved in fossil assemblages (Scott and Medioli, 1980). Modern populations typically show dominance of either trochospiral and/or quinqueloculine taxa within the upper and lower marsh, respectively (Fig. 4). De Rijk (1995) demonstrated

TABLE 2.—Agglutinated foraminiferal morphotypes characteristic of marginal marine environments.

Morphotype	No. Chambers	Coiling Arrangement	Aperture Position	Primary Genera
Unilocular	one	sac-like	terminal	*Sacammina*
Planispiral	multiple	coiled in one plane	evolute and extra umbilical	*Haplophragmoides*
Trochospiral	multiple	coiled in a trochoid spire	involute umbilical to extra-umbilical	*Trochammina*
Uncoiled	multiple	initially 1-to-2 planar or trochoid whorls that later form a biserial or uniserial array	terminal	*Ammobaculites*, *Ammotium*
Serial	multiple	chambers arranged in a linear array; may be uniserial, biserial, or triserial	terminal or extraumbilical	*Reophax*, *Textularia*, *Eggerella*, *Verneulinoides*
Quinqueloculine	five	five chambers arranged about a central axis	involute	*Miliammina*

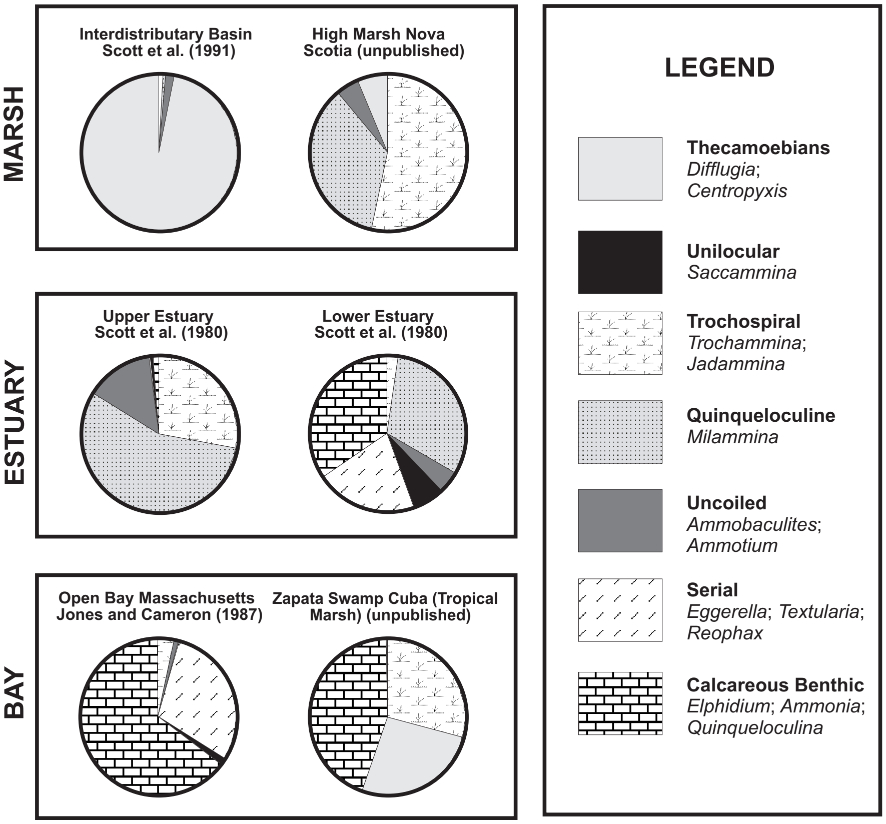


FIG. 4.—Modern marginal marine foraminiferal communities. Marsh foraminiferal populations from Louisiana (Scott et al., 1991) and Chezzetcook, Nova Scotia (Tibert and Scott, unpublished). Estuarine foraminiferal populations are from eastern Canada (Scott et al., 1980). Bay and tropical data include Buzzards Bay, Massachusetts (Jones and Cameron, 1987) and unpublished data from Zapata Swamp, Cuba.

that some agglutinated taxa, such as *Haplophragmoides* (planispiral) could tolerate extremely low salinity, an observation common to many temperate ocean margins (Scott et al., 1996).

Uncoiled morphotypes characterize estuarine channel environments (Fig. 4). In particular, the uncoiled genus *Ammobaculites* is considered the "proprietor of Chesapeake Bay" (Ellison, 1972) a trend observed elsewhere along the North American coast (Buzas, 1974). An important characteristic for central estuarine assemblages is the relative increase of calcareous benthic morphotypes at more seaward localities (Fig. 4).

Serial agglutinated morphotypes, mainly *Eggerella advena* and *Textularia* spp., characterize open bay/lagoonal settings, as exemplified in population data from Nova Scotia (Scott et al., 1980) and Massachusetts (Jones and Cameron, 1987) (Fig. 4). Serial morphotypes associated with quinqueloculine and to a lesser extent trochospiral forms delineate low-energy bays/lagoons landward of sand barriers (Boyd and Honig, 1992). Populations dominated by agglutinated trochospiral and calcareous benthic taxa are common in back-barrier lagoons (Culver et al., 1996).

Ostracodes

Ostracodes are ubiquitous in marginal marine settings. Because of their short life cycles and large populations, they also show great adaptability that favors their migration and occupation of restricted and relict marine basins that are extremely susceptible to changes in salinity and temperature (Neale, 1988). Because ostracodes molt eight or nine times during their life cycle, we can use the ratio of adults to instars (pre-adult stages) to determine whether or not a taxon is likely *in situ* (autochthonous) or reworked (allochthonous). Considering that marginal marine water bodies always have mixed nonmarine and brackish assemblages, it is possible by use of ratios of instar to adult valves to determine which taxa are *in situ* and thus the best paleoenvironmental indicators (e.g., Whatley, 1988; Tibert and Scott, 1999). An abundance of well-preserved juvenile and adult valves indicates an autochthonous assemblage. In contrast, an abundance of one or two instar fractions or an exclusive assemblage of adult valves likely represents post mortem transport. In addition to the taphonomic usefulness of ostracodes, nonmarine and marine species demonstrate taxonomic partitioning (i.e., the ostracode Superfamily Cypridacea are primarily nonmarine and the ostracode Superfamily Cytheracea are primarily marine) easily detectable by the internal arrangement of the adductor muscle scars and the hinge characters. This facet of ostracode taxonomy further enhances our ability to distinguish between fresh waters and brackish waters in estuarine settings (Forester and Brouwers, 1985).

LABORATORY METHODS

Many of the samples obtained for this study were collected during the summers of 1998, 1999, and 2000. This paper reports micropaleontological results collected from vertebrate localities published by Eaton et al. (1997) and from samples graciously provided by Fürsich and Kirkland (1986) from Coal Mine Mesa on the Hopi Reservation of northeastern Arizona. We report microfossil data from the following localities (included are references to previous paleontologic studies):

1) Coal Mine Mesa (Black Mesa), northeastern Arizona (Fürsich and Kirkland, 1986);
2) MacFarlane Mine, Cedar Canyon, Utah (Route 14, mile marker 9);
3) Maple Canyon, Utah, Locality 1226 (Eaton et al., 1997)(Route 14, mile marker 6);
4) Cedar Canyon, Utah, Locality 1258 (Eaton et al., 1997);
5) Cedar Mountain, Utah (Kolob Reservoir)
6) Table Bench, Utah (north fork of the Virgin River)
7) New Harmony (Kelsey Deer Camp), Utah (Pine Valley Mountains)
8) Glory Cove (near Tropic), Utah (Route 12), Museum of Northern Arizona, Flagstaff Locality 996 (Eaton et al., 1997);
9) Henrieville, Utah (Route 12), Locality HV-99-1 (Eaton, 1991);
10) Big Water, Utah, Leithold (1994) and Leithold and Dean (1998); and
11) Mesa Verde, southwestern Colorado (Leckie et al., 1997).

Microfossil Analysis

Mudrocks were processed using standard micropaleontological disaggregation techniques (e.g., Leckie et al., 1991; Wightman et al., 1993). After processing, all foraminiferal and ostracode specimens were picked from split residues using a binocular dissecting microscope. Foraminiferal specimens were sorted into their respective morphological categories (trochospiral, planispiral, uncoiled, serial, and quinqueloculine). In the prodeltaic facies of the Tropic Shale we picked 300 foraminiferal specimens from 32 samples and plotted the relative abundances of agglutinated, calcareous benthic, and planktic taxa. In all samples, ostracodes were identified to the generic level and grouped into the following three superfamilies following the classification scheme of Benson et al. (1961). We recognize the following ostracode groupings: Cypridacea and Darwinulacea (mainly nonmarine taxa), brackish taxa (Cytheracea) belonging to the Family Cytherideidae, and normal marine taxa (Cytheracea) that belong to the Family Cytheruridae.

Carbon and Sulfur Analyses

Carbon and sulfur studies have been applied to organic-rich strata, where sulfur values greater than two percent generally indicate marine influence (Berner, 1984; Berner and Raiswell, 1984). To provide a proxy for brackish conditions in the Dakota Formation uppermost coal zone, 10 samples of mudstone and coal from Maple Canyon were analyzed for carbon and sulfur. Each sample was crushed, weighed, and separated into four replicate subsamples. Two of the replicate subsamples were soaked in weak HCl (1N) overnight to dissolve the calcium carbonate. All subsamples were dried in an oven prior to analysis. Values of total organic carbon (TOC) and total sulfur (TS) were obtained from the Carbon-Sulfur LECO analyzer at the University of Massachusetts.

BIOSTRATIGRAPHY AND CYCLICITY OF THE PRODELTAIC TROPIC SHALE

Offshore–Onshore Correlations and Cycle Analysis

Essential to the interpretations in this paper are the regional correlations provided by the microfossil and stratigraphic trends observed from prodeltaic facies on Kaiparowits Plateau. We analyzed 32 samples that span the Cenomanian–Turonian boundary interval from the Tropic Shale at Big Water that represent proximal, normal marine facies adjacent to the marginal marine strata. Six fourth-order cycles (intermediate cycles of this study) characterize the uppermost Cenomanian and lower to middle Turonian (Fig. 2) (Leithold, 1994; Leithold and Dean, 1998; West et al., 1998). Leithold (1994) argued that peaks in total carbonate content in the mudrocks represent periods of maximum flooding along the western margin of the seaway. Essential to the above cyclic delineations is the chronologic control attained by invertebrate biostratigraphy and the presence of numerous regionally correlative bentonites (altered volcanic ash beds). To test the viability of Leithold's carbonate cycles, we analyzed the same samples used for her studies and plotted total percent agglutinated, calcareous benthic, and planktic taxa against the data on total carbonate (Fig. 5). We recognize planktic maxima in foraminiferal abundance that coincide with the carbonate peaks of Cycles 1 and 2 (Figs. 5, 6, 7). We also observe general distributional patterns of foraminifera and ostracodes where key associations of marine species provide useful points for correlation, as demonstrated by West et al. (1998).

Cycle 1—Sciponoceras gracile Ammonite Zone

The *Sciponoceras gracile* ammonite zone accumulated during transgression of the Greenhorn Marine Cycle, and, according to Obradovich (1993) and Kauffman et al. (1993), represents approximately 250 kyr of the upper Cenomanian (see Table 10). The Tropic Shale at Big Water disconformably overlies the Dakota Formation, which yields a *Metoicoceras mosbyense* invertebrate fauna (Zelt, 1985; Leithold, 1994). Bentonite TT1 (Bentonite A of Elder, 1988, 1991) was observed in the field at 1.5 m above the base of this section. Although the base of the *Sciponoceras gracile* zone is likely truncated, Leithold (1994) recognized a carbonate acme (Cycle 1) 0.5–1.0 m below bentonite TT2 (Fig. 5). The microfossil assemblages are dominated by agglutinated taxa, which include *Trochammina rainwateri*, *Ammobaculites* spp., and *Haplophragmoides arenatum*. Another biotic component for this interval is an abundance of the ostracodes *Cythereis eaglefordensis* and *Cytheropteron eximium*.

Cycle 2—Neocardioceras juddii and lower Watinoceras devonense Ammonite Zones

The *Neocardioceras juddii* ammonite zone represents approximately 350 kyr of calcareous shale at Big Water (Kauffman et al., 1993; Obradovich, 1993). Planktonic foraminifera (primarily *Hedbergella* and *Whiteinella*) show significant population maxima at approximately 17 m, and this corresponds to the second calcium carbonate acme of Leithold (1994) (Fig. 5). At the base of Cycle 2, there is a relative abundance peak of the calcareous benthic foraminifera *Gavelinella dakotensis* immediately overlying bentonite TT2 (see also Leckie et al., 1998; West et al., 1998). The strata immediately overlying the *Gavelinella dakotensis* acme contain an abundance of the ostracode *Clithrocytheridea*?. Localized abundances of *Cytherella* sp. coincide with the maxima in planktic foraminifera and calcium carbonate (Fig. 5). The Cenomanian–Turonian boundary interval is marked by a carbonate minimum where agglutinated taxa show a relative increase. The last occurrence of the ostracode *Cythereis eaglefordensis* and the foraminifera *Haplophragmoidium arenatum* mark the boundary just below TT3 (Fig. 5). We recognize a second *Gavelinella* acme in the lowermost Turonian followed by another planktic foraminiferal maximum immediately overlying bentonite TT3. Agglutinated foraminifera show a significant species-level turnover where *Trochammina*

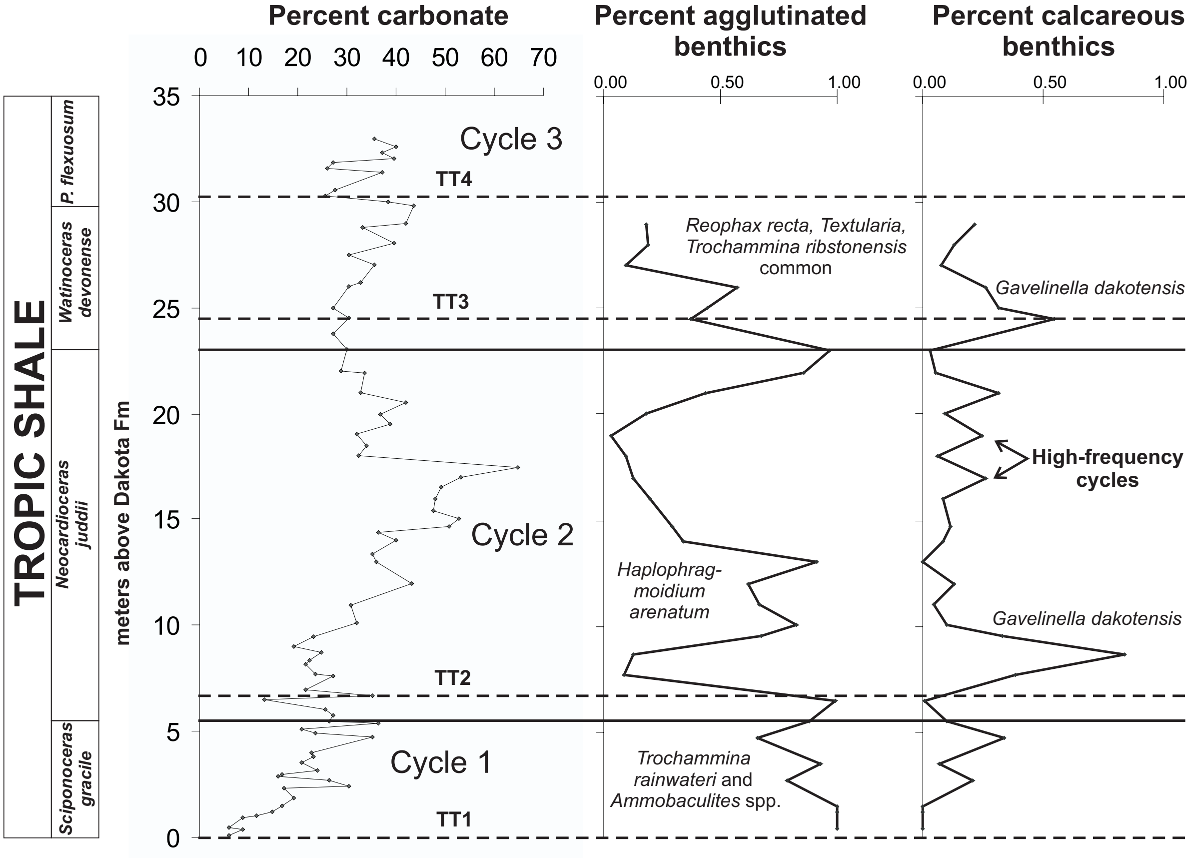


FIG. 5.—Distribution of total percent agglutinated, calcareous benthic, and planktic foraminifera plotted against total percent carbonate across the Cenomanian–Turonian boundary interval. Carbonate and foraminiferal trends for the Bigwater measured section were published in Leithold (1994), Leithold and Dean (1998), and West et al. (1998). Ostracodes are plotted as total numbers. Bentonites TT1, TT2, and TT3 are equivalent to Bentonites A, B, and C, respectively (Elder, 1988, 1991). Key biotic trends include first occurrence (FO) and last occurrence (LO) and the prominent taxa that characterize specific intervals.

ribstonensis and *Reophax recta* are prominent in Turonian strata at most localities.

LITHOLOGIC AND BIOSTRATIGRAPHIC CHARACTER OF THE MARGINAL MARINE DAKOTA AND STRAIGHT CLIFFS FORMATIONS

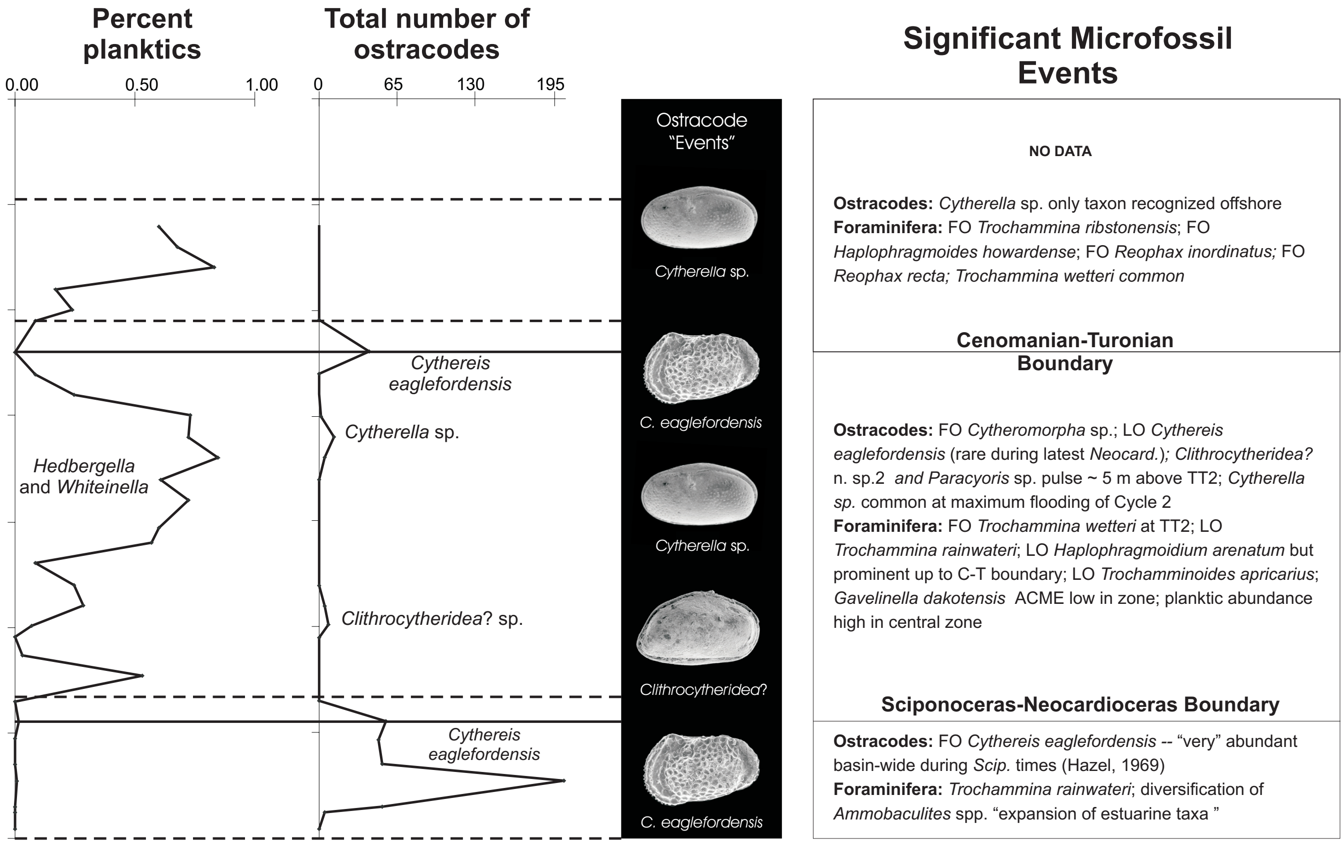
Coal-bearing strata deposited during transgression of the Greenhorn Cycle differ in biotic composition, stratal geometry, and coal quality from those deposited during regression (Table 3). Retrogradational and aggradational coastal-plain strata of the upper Cenomanian Dakota Formation characterize the transgressive systems tract whereas regressive facies and stacked prograding shorelines characterize the Turonian Straight Cliffs Formation (e.g., Peterson, 1969a, 1969b; Gustason, 1989; Shanley and McCabe, 1991, 1995).

Transgressive Facies of the Dakota Formation

Middle Member Coals, Kaiparowits Plateau and Black Mesa.—

Deposition of the middle and upper members of the Dakota Formation corresponds to the early phase of the marine transgression during the late Cenomanian (Fig. 2). Gustason (1989) differentiated the lower and upper coal zones in the middle member. The lower coal zone corresponds to coal beds 1–2 of Peterson (1969a, 1969b), coal seams 2–3 of Kirschbaum and McCabe (1992), and the Bald Knoll coal zone of Doelling and Graham (1972) (Paunsaugunt Plateau). The upper coal zone corresponds to coal beds 3 and 4 of Peterson (1969a, 1969b), coal beds 4 and 5 of Kirschbaum and McCabe (1992), and the Smirl Coal Zone of Doelling and Graham (1972). We observe three pre–*Metoicoceras mosbyense* coal zones (CZ1–3) that are equivalent to the lower coal zone of Gustason (1989), and these will be presented in later publication. Our Coal Zone 4 (CZ4) is the uppermost bounding coal of the middle member and serves as an important regional lithologic marker given its laterally continuity and that it separates the nonmarine fluvial-dominated facies from the overlying brackish deposits (see Fig. 16).

The coals of the middle member of the Dakota Formation are on average 1.5 m in thickness, but a maximum of 5.5 m has been reported from western Paunsaugunt Plateau (Kirschbaum and McCabe, 1992). In general, the coals are dull to bright-banded, high volatile, C bituminous (Doelling and Graham, 1972). Kirschbaum and McCabe (1992) reported 18.2% ash and 0.7% sulfur from the Bald Knoll Coal Zone and values of 9.7% ash and



NO DATA

Ostracodes: *Cytherella* sp. only taxon recognized offshore
Foraminifera: FO *Trochammina ribstonensis*; FO *Haplophragmoides howardense*; FO *Reophax inordinatus;* FO *Reophax recta; Trochammina wetteri common*

Cenomanian-Turonian Boundary

Ostracodes: FO *Cytheromorpha* sp.; LO *Cythereis eaglefordensis* (rare during latest *Neocard.*)*; Clithrocytheridea?* n. sp.2 *and Paracyoris* sp. pulse ~ 5 m above TT2; *Cytherella sp.* common at maximum flooding of Cycle 2
Foraminifera: FO *Trochammina wetteri* at TT2; LO *Trochammina rainwateri*; LO *Haplophragmoidium arenatum* but prominent up to C-T boundary; LO *Trochamminoides apricarius*; *Gavelinella dakotensis* ACME low in zone; planktic abundance high in central zone

Sciponoceras-Neocardioceras Boundary

Ostracodes: FO *Cythereis eaglefordensis* -- "very" abundant basin-wide during *Scip.* times (Hazel, 1969)
Foraminifera: *Trochammina rainwateri*; diversification of *Ammobaculites* spp. "expansion of estuarine taxa "

FIG. 5 (continued).—

0.5% sulfur from the Smirl Coal Zone (Alton coal fields). Kaolinitic and smectite claystone with beta quartz and zircon are intercalated with the coal seams and likely represent altered ash deposits. Sedimentary units associated with the coals are predominantly fluvial, although Uličny (1999) recently reported evidence for estuarine influence at Henrieville.

Upper Member Coals and Marlstones on Markagunt Plateau.—

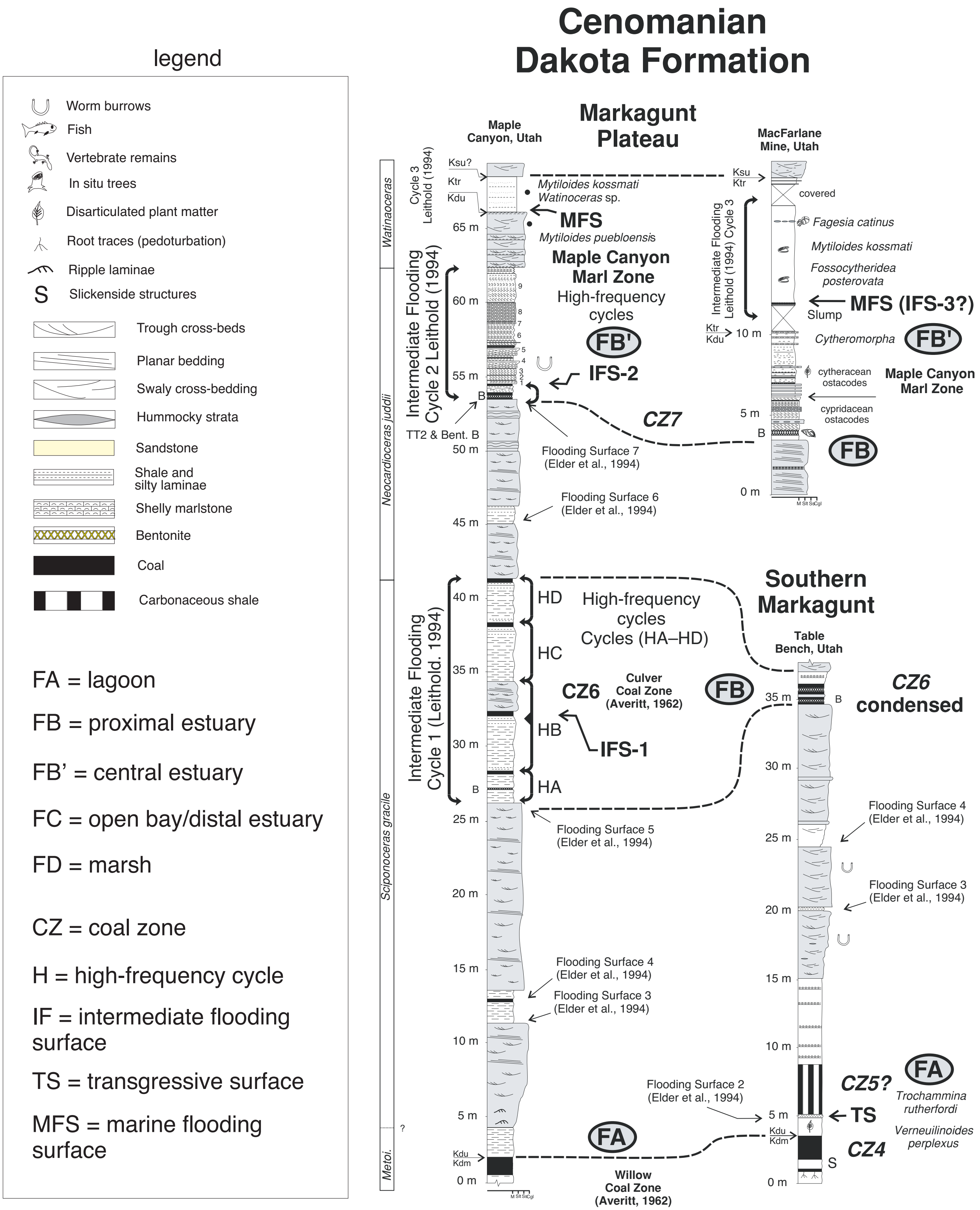
Coal-bearing intervals described from the Dakota Formation on Markagunt Plateau include the Willow and Culver coal zones (Averitt, 1962). Our Coal Zone 5 (CZ5) corresponds to the Willow Coal Zone (Averitt, 1962), recognized at both Table Bench and Maple Canyon (Fig. 6). Doelling and Graham (1972) correlated the Smirl Coal Zone on Paunsaugunt Plateau (CZ4) to Markagunt Plateau. Gustason (1989) proposed that CZ4 and CZ5 merge at the westernmost localities (Fig. 6), but he was unable to trace the Lower and Upper Culver coal zones (the brackish *Sciponoceras – Neocardioceras* coals) outside the confines of Markagunt Plateau.

Higher in the section at Maple Canyon there are two recognizable brackish coal-bearing intervals that include Coal Zones 6 and 7 (CZ6–CZ7, Fig. 6). The uppermost, CZ7, of the Dakota Formation at Maple Canyon (Fig. 7) yielded total sulfur values as high as 4.19% (Table 4). X-ray diffraction of gray claystones from CZ7 confirms a significant abundance of smectite and minor kaolinite (Newton, personal communication). Thin coal underclays are root penetrated. Intervals of trough cross-bedded and oscillation-rippled sandstones intercalate with the Coal Zones 6 and 7 and have been interpreted as estuarine-dominated facies (Eaton et al., 2001).

Approximately 7 m of sandy marlstone and shale overlie CZ7. we place the Cenomanian–Turonian boundary at the contact between the uppermost marlstone bed (Figs. 6, 7) and the sandstone bearing the lower Turonian bivalve *Mytiloides puebloensis*; we consider the basal Turonian sandstone to be part of the Dakota Formation, on the basis of its distinct yellowish-orange color and abundant oysters and inoceramids. Silty shales above the basal Turonian sandstone contain the ammonite *Watinoceras* and the bivalve *Mytiloides kossmati*, which suggests a late early Turonian age (Kennedy et al., 2000) and therefore represents a thin interval of Tropic Shale. Samples from MacFarlane Mine yielded similar lower Turonian faunal elements that include the ammonite *Fagesia catinus*, the bivalve *Mytiloides kossmati,* and the ostracode *Fossocytheridea posterovata* (Fig. 6). The contact between the silty shale and the tabular sandstone marks the boundary between the Tropic Shale and the overlying undifferentiated Straight Cliffs Formation (Figs. 6, 7).

Regressive Facies of the Straight Cliffs Formation

The Straight Cliffs Formation recorded the overall regression of the Greenhorn Marine Cycle during early to middle Turonian time. The most widespread and lignitic coals occur at


Cenomanian
Dakota Formation
legend
Worm burrows
Fish
Vertebrate remains
In situ trees
Disarticulated plant matter
Root traces (pedoturbation)
Ripple laminae
S Slickenside structures
Trough cross-beds
Planar bedding
Swaly cross-bedding
Hummocky strata
Sandstone
Shale and silty laminae
Shelly marlstone
Bentonite
Coal
Carbonaceous shale
FA = lagoon
FB = proximal estuary
FB' = central estuary
FC = open bay/distal estuary
FD = marsh
CZ = coal zone
H = high-frequency cycle
IF = intermediate flooding surface
TS = transgressive surface
MFS = marine flooding surface
Markagunt Plateau
Maple Canyon, Utah
MacFarlane Mine, Utah
Watinaoceras
Neocardioceras juddii
Sciponoceras gracile
Metoi.
?
Cycle 3 Leithold (1994)
Intermediate Flooding Cycle 2 Leithold (1994)
Intermediate Flooding Cycle 1 (Leithold. 1994)
Ksu?
Ktr
Kdu
Kdm
65 m
60 m
55 m
50 m
45 m
40 m
35 m
30 m
25 m
20 m
15 m
10 m
5 m
0 m
Mytiloides kossmati
Watinoceras sp.
MFS
Mytiloides puebloensis
Maple Canyon Marl Zone
High-frequency cycles
FB'
IFS-2
9 8 7 6 5 4 3 2 1
B
TT2 & Bent. B
Flooding Surface 7 (Elder et al., 1994)
CZ7
Flooding Surface 6 (Elder et al., 1994)
HD
HC
HB
HA
High-frequency cycles
Cycles (HA–HD)
CZ6
Culver Coal Zone (Averitt, 1962)
FB
IFS-1
Flooding Surface 5 (Elder et al., 1994)
Flooding Surface 4 (Elder et al., 1994)
Flooding Surface 3 (Elder et al., 1994)
FA
Willow Coal Zone (Averitt, 1962)
M Slt Ss Cgl
Ksu
Ktr
covered
Intermediate Flooding Leithold (1994) Cycle 3
Fagesia catinus
Mytiloides kossmati
Fossocytheridea posterovata
MFS (IFS-3?)
Slump
Ktr
Kdu
10 m
Cytheromorpha
FB'
cytheracean ostacodes
Maple Canyon Marl Zone
cypridacean ostacodes
5 m
B
FB
0 m
M Slt Ss Cgl
Southern Markagunt
Table Bench, Utah
CZ6 condensed
35 m
B
30 m
Flooding Surface 4 (Elder et al., 1994)
25 m
Flooding Surface 3 (Elder et al., 1994)
20 m
15 m
10 m
FA
CZ5?
Trochammina rutherfordi
Flooding Surface 2 (Elder et al., 1994)
5 m
TS
Kdu
Kdm
Verneuilinoides perplexus
CZ4
S
0 m

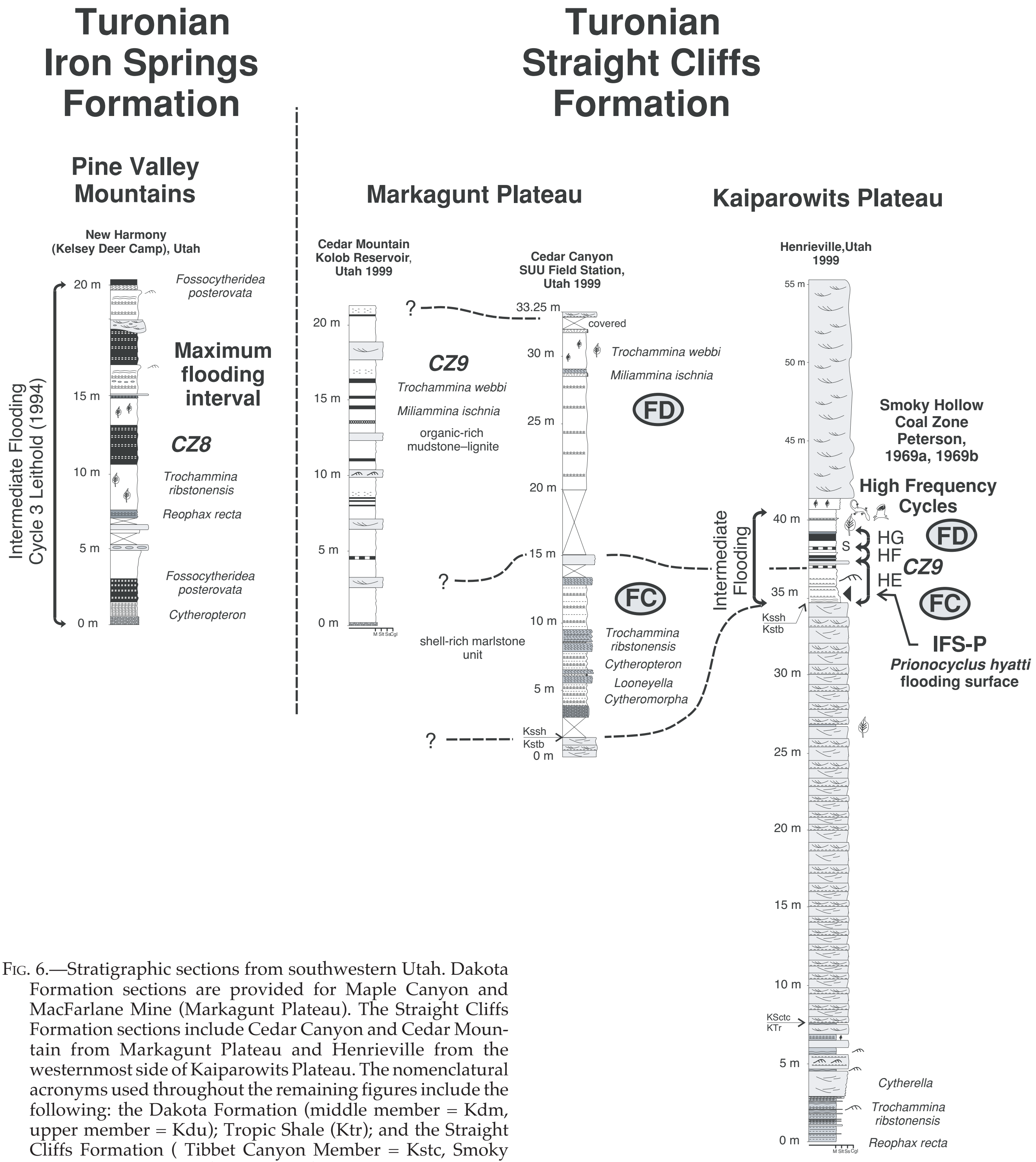


FIG. 6.—Stratigraphic sections from southwestern Utah. Dakota Formation sections are provided for Maple Canyon and MacFarlane Mine (Markagunt Plateau). The Straight Cliffs Formation sections include Cedar Canyon and Cedar Mountain from Markagunt Plateau and Henrieville from the westernmost side of Kaiparowits Plateau. The nomenclatural acronyms used throughout the remaining figures include the following: the Dakota Formation (middle member = Kdm, upper member = Kdu); Tropic Shale (Ktr); and the Straight Cliffs Formation (Tibbet Canyon Member = Kstc, Smoky Hollow Member = Kssh, and Straight Cliffs undifferentiated = Ksu). Coal Zones 4–9 are discussed in the text. Stratigraphic excerpts are provided for Table Bench and New Harmony (Pine Valley Mountains) to demonstrate key surfaces for correlation. The details from these localities will be published as a separate manuscript (Tibert, Ph.D. dissertation, 2002).

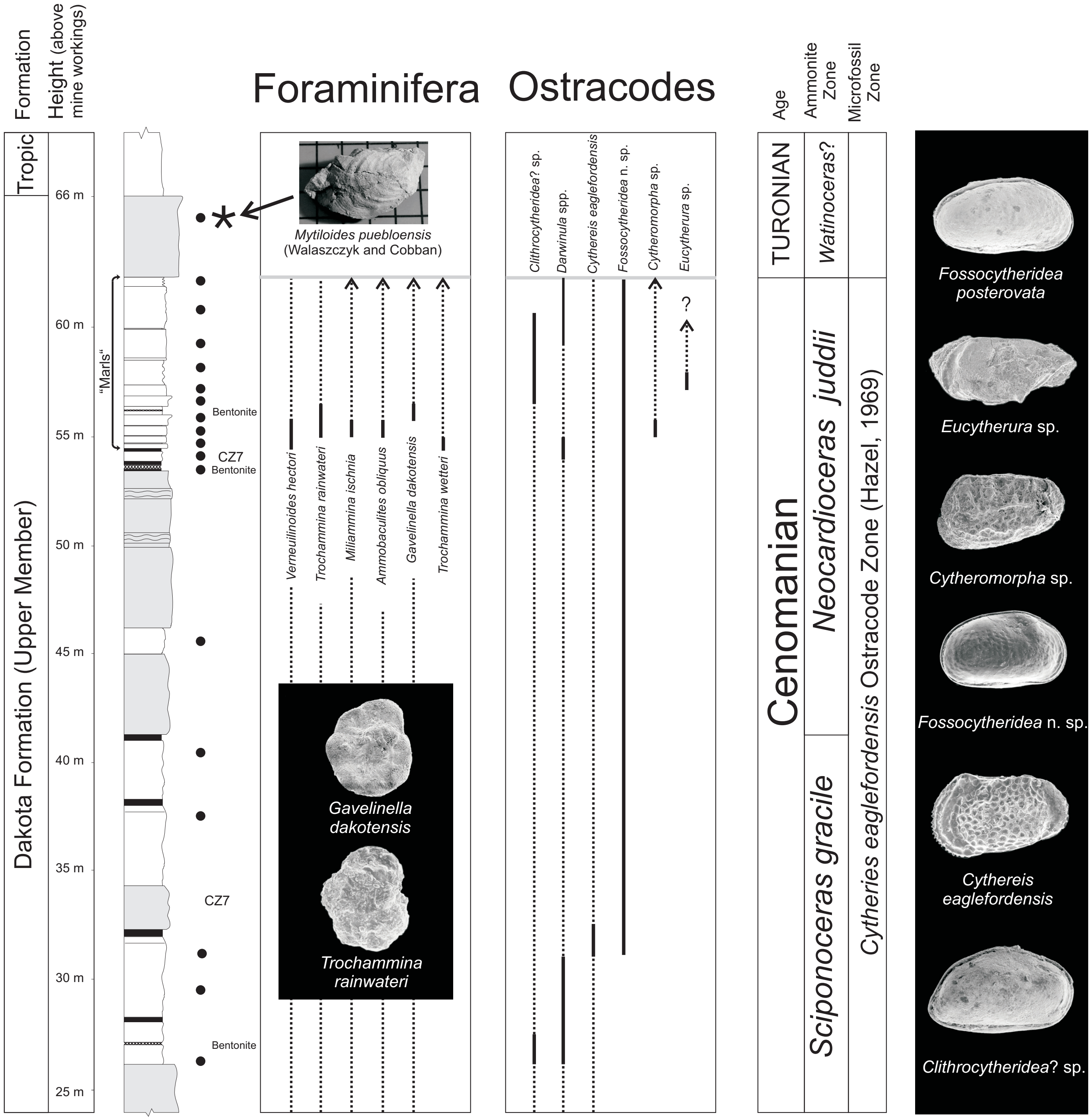


FIG. 7.—A biostratigraphic excerpt from the Maple Canyon Section. Solid lines indicate actual taxon occurrences. Dashed lines indicate that the taxon has been identified in stratigraphic equivalents at nearby localities (Table Bench, MacFarlane Mine, and Bigwater). Solid black circles indicate beds sampled. The first occurrence (FO) of *Cythereis eaglefordensis* and *Clithrocytheridea*? characterize the *Sciponoceras gracile* ammonite zone. An abundance of *Fossocytheridea* n. sp. and the FO of *Cytheromorpha* n. sp. and *Eucytherura* characterize the *Neocardioceras juddii* ammonite zone. In addition, an abundance of *Trochammina rainwateri*, the FO of *Trochammina wetteri*, and the presence of *Gavelinella dakotensis* mark the approximate position of Leithold's (1994) bentonite TT2 (equivalent to Bentonite B of Elder, 1988, 1991) as observed in prodeltaic strata in the Kaiparowits Plateau region. We place the base of the *Sciponoceras gracile–Neocardioceras juddii* boundary below the medial sandstone unit (as indicated by Elder et al., 1994). The bivalve *Mytiloides puebloensis* (Walaszczyk and Cobban) marks the first lower Turonian unit. Finally, *Fossocytheridea posterovata* (Lankford, *in* Peterson et al., 1953) was identified at approximately 5 m above the uppermost *Neocardioceras* marlstone in the Tropic Shale at MacFarlane Mine.

TABLE 3.—Summary of the transgressive and regressive coal-bearing facies from the Western Interior Seaway.

Features	**Dakota Coal (Upper Member)**	**Smoky Hollow Coal**
Geometry	thick and discontinuous (middle member coals are more continuous)	thin and continuous (localized discontinuities)
Quality	high sulfur (~ 2–4%) and low ash (middle member S = 0–2%)	lower sulfur (~ 1–2%) and high ash
Seat earths	Smectite- and kaolinite-rich in gray-brown mudstone	kaolinite-poor in rooted organic rich mudstones
Overlying facies	estuarine and shoreface sandstones and glauconitic mudstones	alluvial sandstones and mudstones
Underlying facies	fluvio–estuarine sandstones and mudstones	beach (upper shoreface) with organic-rich sandstone
Nature of coal–mudstone contacts	unconformable (sharp upper and lower)	gradational
Stratigraphic surfaces	transgressive lags and intermediate marine flooding surfaces	high-frequency marine flooding surfaces
Associated biofacies above and below	FA – lagoon (central estuary) (depauperate assemblage of molluscs, ostracodes, and foraminifera) FB – proximal estuary (euryhaline ostracodes and gastropods within coal zones)	FC – open bay (distal estuary) (rich faunae of molluscs, ostracodes, foraminifera) FD – salt marsh (exclusively agglutinated foraminifera in mudstone and lignite)
Stratigraphic nature	transgressive (retrogradational)	regressive (progradational)
Primary controls	tectono–eustatic with superimposed climate–oceanic cycles	autogenically influenced

Henrieville in the basal 10 meters of the Smoky Hollow Member (Fig. 6). This coal zone (CZ9) is widely recognized across the Kaiparowits, Paunsaugunt, and Markagunt plateaus, extending for tens to hundreds of kilometers (Peterson, 1969a, 1969b). The coal seams are thin (less than 1.0 m in thickness) and are apparently locally discontinuous. As many as five decimeter-scale coal seams (but typically three) intercalate with black–gray mudstone rich in plant detritus and shells of brackish-water molluscs. Root traces penetrate the lower mud–coal contacts. Values of ash and sulfur for the total Straight Cliffs Formation on the Kaiparowits Plateau range from 5.7 to 15.2% ash and from 1.40 to 1.46% sulfur (Peterson, 1969a, 1969b). Gregory (1951) classified the coals of the Smoky Hollow Coal Zone as lignites on the basis of the observation that the Smoky Hollow Member coals have a dull and oily appearance and emit a petroliferous aroma, which is in stark contrast to the C subbituminous coals that occur in the overlying John Henry Member (Peterson, 1969a, 1969b). We recognize two brackish units in the Smoky Hollow Member (Fig. 6): (1) a lower interval of shelly shale and marlstone (much like the marlstones of the Dakota Formation and best preserved in Cedar Canyon), and (2) an upper coal and mudstone unit (the best lignites occur at Cedar Mountain, Glory Cove, and Henrieville). Each facies contains a characteristic biotic assemblage, which we describe below. The sandstones underlying the Smoky Hollow Member are characterized by low-angle cross beds. In contrast, the sandstones above the Smoky Hollow Member lignites are characterized by trough and ripple cross-laminae.

The likely age of CZ9 at Glory Cove (Paunsaugunt Plateau) and Henrieville (Kaiparowits Plateau) is late middle Turonian, on the basis of the presence of the ammonites *Prionocyclus hyatti* and *Inoceramus howelli* in the underlying shoreface sandstones of the Tibbet Canyon Member (Peterson, 1969a, 1969b; Eaton, 1991; Cobban, personal communication). The age of the Straight Cliffs Formation in Cedar Canyon is uncertain and will be discussed below.

MARGINAL MARINE FOSSIL ASSEMBLAGES

Fossil Assemblage A (Middle Member of the Dakota Formation)

At Coal Mine Mesa (northeastern Arizona), a 1-m-thick coal is overlain by 2–3 m of shell-rich marine shale (Fig. 8). The coal seam below this zone is similar in character (coal quality, geometry, and associated facies) to Peterson's (1969a, 1969b) coal bed 4 in the Kaiparowits Plateau region. Assemblages of agglutinated foraminifera include a trochospiral-dominated association (*Trochammina rutherfordi* and *T. wickendeni*) observed in the lower half of the succession (Fig. 9, A–F), which is superseded by a triserial-dominated association (*Verneuilinoides perplexus*) observed in the uppermost shales (Fig. 8; Table 5). Glauconite also increases upward concurrently with *Verneuilinoides*. *Miliammina ischnia* (quinqueloculine) and specimens of *Ammobaculites obliquus* (uncoiled) are relatively sparse. The only ostracode observed is *Clithrocytheridea*? *graysonensis* (Fig.10, A–D), which occurs with relative abundance in a thin red siltstone unit (~ 10 cm thick); this taxon was first described from the middle Cenomanian Grayson Formation of Texas (Alexander, 1929). Associated bivalves include free-living, cemented, and/or byssate epifaunal molluscs (Fürsich and Kirkland, 1986). Finally, the uppermost shell-rich shales are truncated by well-rounded, medium-grained sandstone that contains abundant humic matter.

At Mesa Verde, near Cortez, Colorado, the Twowells Member of the Dakota Formation interfingers with the Mancos Shale. Poorly preserved agglutinated foraminifera occur in fine sandstone and carbonaceous siltstone. The best-preserved specimens occur directly below the base of the Twowells Member in carbonaceous, muddy sandstone. The genera of agglutinated foraminifera include, in decreasing order of abundance, *Verneuilinoides perplexus* (triserial), *Textularia* (biserial), *Ammobaculites* (uncoiled), *Trochammina* (trochospiral), and *Reophax* (uniserial). This associa-

TABLE 4.—Carbon and sulfur results from Coal Zone 7 (Maple Canyon).

Sample	TOC %	Average %	Sulfur %	Average %
DK17	8.374	8.3615	1.033	1.254
	8.349		1.475	
DK19	14.52	14.49	2.869	2.9605
	14.46		3.052	
DK20A		42.07	4.192	4.1735
	42.07		4.155	
DK20B	0.8494	0.8379	1.346	1.269
	0.8264		1.192	
DK21	2.602	2.6575	0.8612	0.895
	2.713		0.9288	
DK22	7.035	6.9995	0.6152	0.6257
	6.964		0.6362	
DK23	1.023	1.0043	0.1068	0.09909
	0.9856		0.09138	
DK24	9.413	9.514	0.7422	0.78865
	9.615		0.8351	
DK25		13.31	2.362	2.5845
	13.31		2.807	
DK26	22.2	20.9	1.626	1.688
	19.6		1.75	

Note that the samples begin at the contact with the underlying Sugarledge Sandstone and end in the second marlstone bed overlying last coal seam.

tion resembles closely the uppermost *Verneuilinoides*-dominated association described from Coal Mine Mesa.

The two primary taxa that define this assemblage (*Trochammina rutherfordi* and *Verneuilinoides perplexus*) occur in Unit 6 of Uličny (1999) at Henrieville and in a thin shell bed (TS2 Elder et al., 1994) at Table Bench in strata overlying CZ4 (Fig. 6).

Fossil Assemblage B (Upper Member of the Dakota Formation)

The upper Dakota Formation contains coal-bearing strata at two localities in Cedar Canyon (Maple Canyon and MacFarlane Mine). These localities comprise the Willow and Culver coal zones (Averitt, 1962) and include our CZ5, CZ6, and CZ7 (Figs. 6, 7). At Maple Canyon, the uppermost coal zones (CZ6 and CZ7) contain an assemblage of the eurytopic ostracode *Fossocytheridea* n. sp., a smooth species of the gastropod *Admetopsis*, and charophytes (Table 6); these taxa define this assemblage, given their prominence throughout most of the upper member of the Dakota Formation on Markagunt Plateau. The uppermost CZ7 is overlain by nine couplets of alternating skeletal shell beds and fossiliferous sandy shales (Maple Canyon Marl Zone: Figs. 6, 7) that contain additional key taxa and are therefore considered a subassemblage (FB’) of the primary assemblage (FB). Numerous *Thalasinoides* burrows mark the contact with the underlying CZ7. Bedding thicknesses of the marlstone range from 0.1 m to as much as 0.7 m. In general, marine ostracodes and oysters characterize the marlstone beds whereas brackish ostracodes and gastropods characterize the shale beds (Table 6). Biota in the marlstone beds include abundant oysters, gastropods, ostracodes, and foraminifera, the last including *Trochammina wetteri* and *Gavelinella dakotensis* (Fig. 7). Ostracodes in the marlstones include the eurytope *Fossocytheridea* and the marine taxa *Cytheromorpha* and *Eucytherura* (Fig. 10, E–H). The lower marlstone beds contain local patches of current-oriented admetopsid gastropods and bivalves (*Flemingostrea*, *Fulpia*, and *Crassostrea*). Overall, the shales in the marl zone show an upward-thickening trend. Biota in the shales includes low-diversity populations of the ostracode *Fossocytheridea*, agglutinated foraminifera, including *Trochammina rainwateri* and *Verneuilinoides hectori* (Fig. 9), and abundant ornate specimens of the gastropod *Admetopsis*. Nonmarine ostracodes, *Candona*?

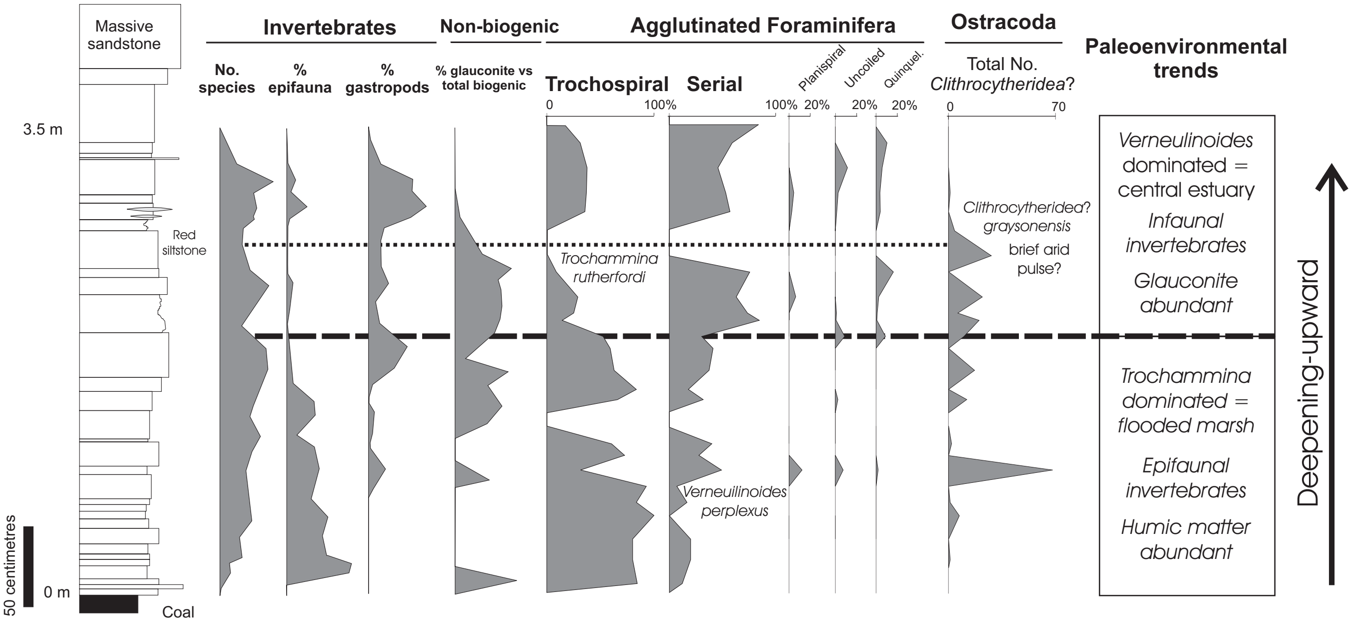


FIG. 8.—Paleoecological trends for Coal Mine Mesa (Black Mesa), northeastern Arizona.

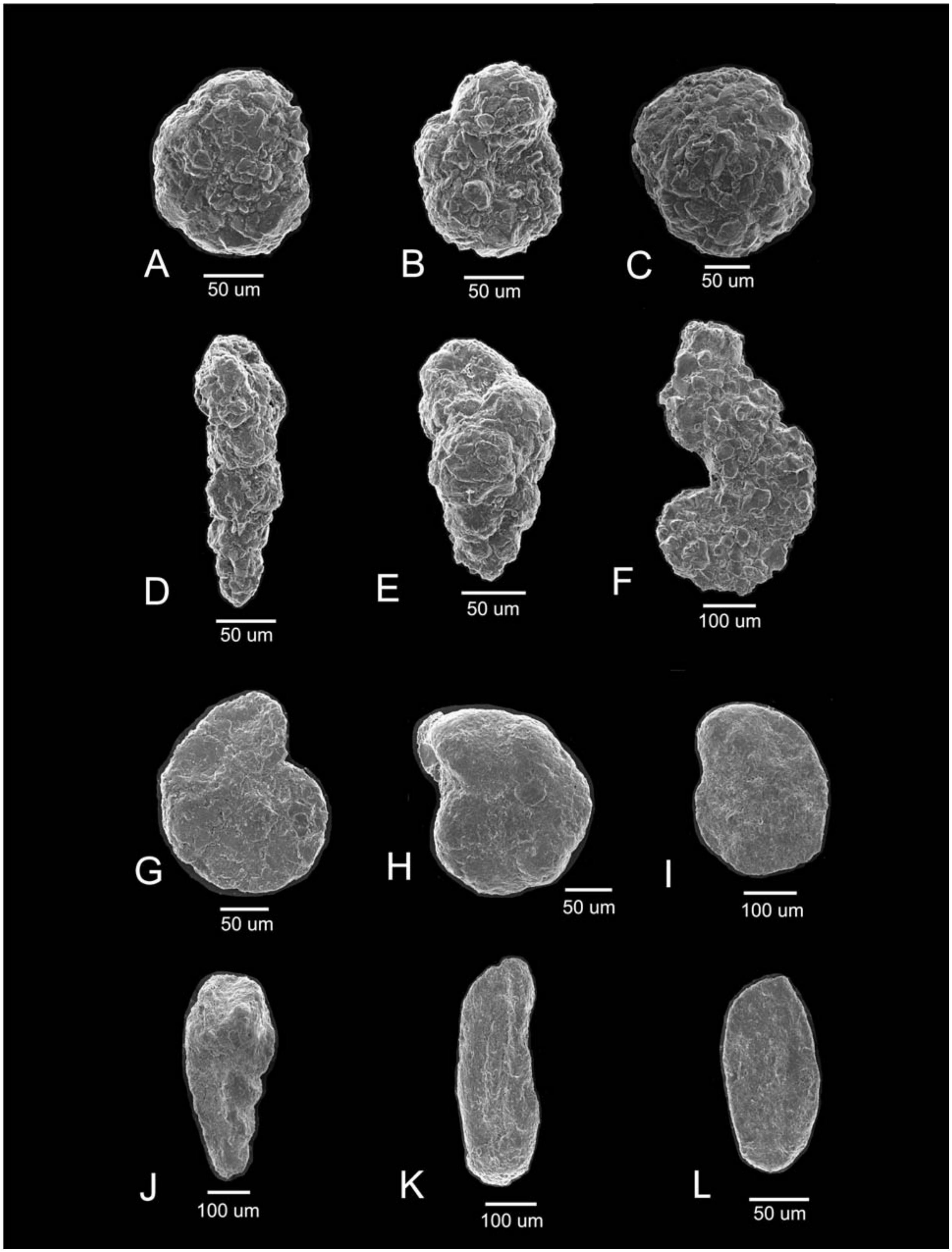


FIG. 9.—Foraminifera from the Colorado Plateau. Cenomanian specimens from the Dakota Formation include: **A, B)** *Trochammina rutherfordi* dorsal and ventral aspects; **C)** *Trochammina wickendeni* 2; **D, E)** *Verneuilinoides perplexus*, 2; **F)** *Ammobaculites obliquus*. Turonian specimens from the Smoky Hollow Member (Straight Cliffs Formation) include: **G)** *Haplophragmoides* sp. 1; **H, I)** *Trochammina webbi*; **J)** *Textularia* sp.; and **K, L)** *Miliammina ischnia*.

and *Darwinula*, co-occur with *Fossocytheridea* in the uppermost shale bed of the Dakota Formation at Maple Canyon (Fig. 6).

Strata at MacFarlane Mine yield ostracode populations that include a mixture of the families Cytherideidae and Cyprididae (cyprids), primarily *Candona*? and *Cypria* (Table 7). In general, nonmarine cyprids characterize the basal coal-bearing strata (CZ7) comprising an assemblage of thin, small, disarticulated adult valves. Charophytes and planispiral gastropods commonly occur with the nonmarine ostracodes. Strata at both MacFarlane and Maple Canyon record a sharp faunal change at 6.5 m and 54 m, respectively (Fig. 6), where the cytherid ostracodes *Fossocytheridea* n. sp. and *Cytheromorpha* occur with numerous, ornate admetopsid gastropods. Charophytes are notably sparse in the more diverse marine ostracode associations. *Darwinula* sp. occurs with both cyprid and cytherid ostracodes throughout the section (Table 7).

Fossil Assemblage C
(Smoky Hollow Member, Straight Cliffs Formation)

Marlstone and shell-rich mudstone beds are a prominent feature of the Smoky Hollow Member on Markagunt Plateau. For

TABLE 5.—Relative percentage of foraminifera from the Dakota Formation at Coal Mine Mesa, northeastern Arizona.

Strat. Height (cm above coal)	Trochospiral		Serial		Uncoiled		Quinquel		Planispiral		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	No.
8	0	0	0	0	0	0	0	0	0	0	0
14	1	0.20	3	0.60	0	0	1	0.20	0	0	5
24	4	0.33	7	0.58	1	0.08	0	0	0	0	12
48	1	0.50	1	0.50	0	0	0	0	0	0	2
64	2	0.50	1	0.25	1	0.25	0	0	0	0	4
79	0	0	0	0	0	0	0	0	0	0	0
85	0	0	8	1.00	0	0	0	0	0	0	8
98	0	0	1	1.00	0	0	0	0	0	0	1
105	0	0	2	0.67	0	0	1	0.33	0	0	3
117	1	0.06	14	0.88	1	0.06	0	0	0	0	16
127	0	0	6	0.60	0	0	4	0.40	0	0	10
140	1	0.09	6	0.55	0	0	4	0.36	0	0	11
155	1	0.13	6	0.75	1	0.13	0	0	0	0	8
167	0	0	0	0	0	0	0	0	0	0	0
176	1	0.50	1	0.50	0	0	0	0	0	0	2
197	0	0	5	1.00	0	0	0	0	0	0	5
207	2	0.17	8	0.67	0	0	2	0.17	0	0	12
216	4	0.14	23	0.82	0	0	1	0.04	0	0	28
226	2	0.07	27	0.90	1	0.03	0	0	0	0	30
236	0	0	4	1.00	0	0	0	0	0	0	4
243	0	0	1	1.00	0	0	0	0	0	0	1
254	0	0	0	0	0	0	0	0	0	0	0
283	0	0	3	0.38	0	0	5	0.63	0	0	8
305	0	0	0	0	0	0	0	0	0	0	0

Strat. Height (cm above coal)	Trochospiral		Serial		Uncoiled		Quinquel.		Planispiral		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	No.
7	98	0.75	15	0.11	0	0	3	0.02	0	0	131
23	12	0.67	3	0.17	0	0	0	0	0	0	18
37	4	0.67	1	0.17	0	0	0	0	0	0	6
53	3	1.00	0	0	0	0	0	0	0	0	3
63	5	0.71	1	0.14	0	0	0	0	0	0	7
73	13	0.87	1	0.07	0	0	0	0	0	0	15
84	51	0.21	81	0.33	12	0.05	1	0.00	20	0.08	246
94	26	0.57	10	0.22	0	0	0	0	0	0	46
102	3	0.43	2	0.29	0	0	0	0	0	0	7
114	0	0	0	0	0	0	0	0	0	0	0
123	0	0	0	0	0	0	0	0	0	0	0
132	136	0.50	66	0.24	5	0.02	0	0	00	0	273
139	145	0.70	31	0.15	0	0	0	0	0	0	208
152	82	0.46	49	0.27	0	0	0	0	0	0	180
167	10	0.42	7	0.29	0	0	0	0	0	0	24
175	12	0.40	7	0.23	2	0.07	2	0.07	0	0	30
186	18	0.07	111	0.46	1	0.00	1	0.00	0	0	242
191	25	0.14	75	0.42	1	0.01	1	0.01	0	0	177
202	23	0.17	51	0.39	0	0	2	0.02	5	0.04	132
219	3	0.05	28	0.43	0	0	6	0.09	0	0	65
230	0	0	0	0	0	0	0	0	0	0	0
247	0	0	0	0	0	0	0	0	0	0	0
260	54	0.22	88	0.36	2	0.01	6	0.02	4	0.02	242
273	42	0.24	61	0.35	3	0.02	4	0.02	5	0.03	176
290	13	0.25	16	0.31	4	0.08	2	0.04	0	0	51
307	15	0.19	29	0.37	0	0	5	0.06	0	0	78
318	1	0.09	5	0.45	0	0	0	0	0	0	11

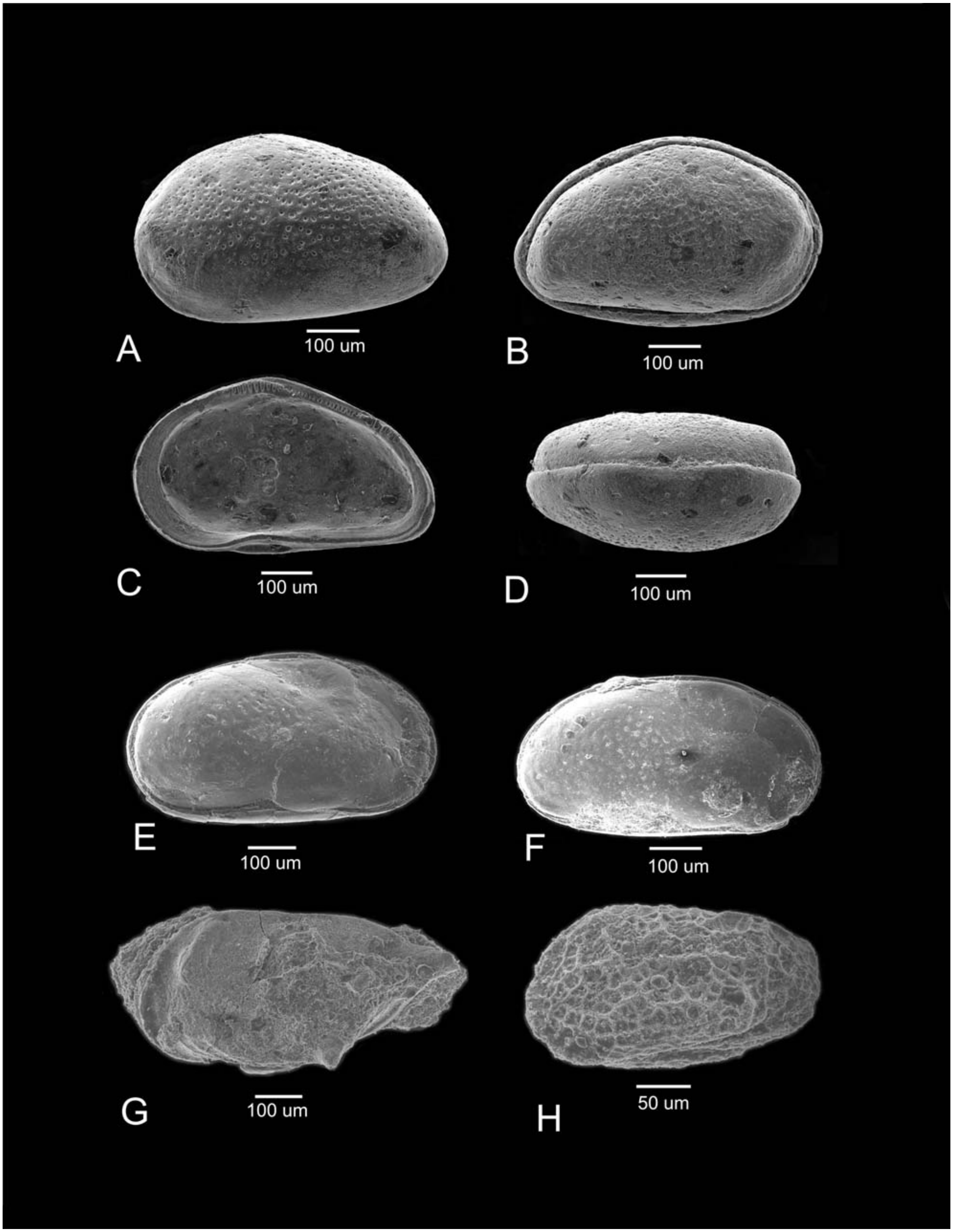


FIG. 10.—Ostracodes from the Cenomanian Dakota Formation. **A–D)** *Clithrocytheridea*? *graysonensis*; **E, F)** *Fossocytheridea* n. sp.; **G)** *Eucytherura* n. sp.; and **H)** *Cytheromorpha*.

TABLE 6.—Biotic characteristics from Coal Zone 7 and the marlstones Maple Canyon, Utah. Acronyms listed as follows: VA = very abundant; A = Abundant; C = common, R = rare; and N = barren.

Sample	Sed. Facies	Forams	Ostracodes	Gastropods	Chara
DK17	sandstone	N	N	N	N
DK19	coaly shale	R Troch./Serial	N	N	N
DK20A	coaly shale	N	N	N	N
DK20B	marlstone	N	VA Cytherideidae	VA ornate	A
DK21	marlstone	N	VA Cytherideidae	VA ornate	N
			R Darwinula		
DK22	shale	N	VA Cytherideidae	VA ornate R plan.	N
DK23	clayey marl	N	VA Cytherideidae	VA ornate	N
DK24	marlstone	N	VA Cytherideidae	VA ornate	C
DK25	coal/marl	N	N	VA smooth	N
DK26	coaly shale	C Troch./Serial	N	R smooth	N
DK27	marlstone	N	N	N	N
DK28	shale	N	VA Cytheromorpha	VA ornate	C
DK29	silty marl	A Troch./Serial Uncoiled	VA Cytherideidae	VA ornate	N

example, at Cedar Canyon, a thick sequence of skeletal marlstone and shale (~ 15 m) underlies the first organic-rich mudstones (Fig. 6). At eastern localities, this equivalent shelly interval is less than 3 m in thickness and the tabular marlstone beds are absent. The unifying characteristic for both the shelly mudstones and the marlstone beds are several ostracode taxa (Fig. 11) listed in decreasing order of abundance (Table 8): *Fossocytheridea posterovata*, *Cytheropteron* n. sp., *Looneyella* n. spp., and rare *Darwinula* and *Cytheromorpha*. Agglutinated foraminifera include *Trochammina ribstonensis* (trochospiral), *Ammobaculites* spp. (uncoiled), and *Textularia* (biserial) (Table 9, Fig. 9). Also enclosed in the shell beds are brackish-water mollusks, including the bivalves *Ostrea*, *Lucina*, and *Corbicula*, as well as numerous ornate, brackish gastropods *Levicerithium* and *Dircella*. This lower shelly unit overlies both low-angle, swaly cross-stratified and planar-bedded sandstones at most localities. A thin sandstone unit separates the marlstone unit from the overlying lignite at Cedar Canyon. In contrast, lignites mark the upper contact of the shelly mudstone at Glory Cove and Henrieville.

Fossil Assemblage D
(Smoky Hollow Member, Straight Cliffs Formation)

The Smoky Hollow Member at Cedar Mountain, Henrieville, and Glory Cove (Fig. 1) comprises mudstone and lignite that overlie the shelly mudstone and marlstone unit. The population composition for the mudstone–lignite association is listed in order of decreasing abundance: *Miliammina ischnia* (quinqueloculine), *Trochammina webbi* (trochospiral), *Haplophragmoides*? (planispiral), *Ammobaculites* (uncoiled), and *Textualaria* (biserial) (Fig. 9). This foraminiferal assemblage characterizes the shales that are in gradational contact with the pedoturbated lignites (Fig. 6). Slickenside structures and root traces are common in the mudstones. At Glory Cove, a thin (< 1 m) mudstone–lignite underlying the shell beds (FC) yielded an exclusive population of foraminifera (FC). At the top of the sequence, the foraminifera–lignite association ends with a trough cross-bedded medium sandstone where all fossil groups are apparently absent.

PALEOECOLOGY

To interpret the paleoecology of our microfossil assemblages, we follow a general estuarine model (see Dalrymple, 1992; Dalrymple et al., 1992; Reinson, 1992). In this framework, there are three primary divisions for an estuary: (1) the proximal zone, where fluvial processes and sandstone deposition are prominent; (2) the central zone, where both fluvial and marine processes balance and shelly muds accumulate; and (3) the distal zone, where marine processes are prominent at the shoreface or in an open bay. We prefer the term estuary because we believe that both the biofacies and the lithofacies record significant interactions between nonmarine (fluvial) and marine processes and

TABLE 7.—Microfossils from Cedar Canyon at McFarlane Mine.

Sample No.	CC-DT-03	CC-DT-04	CC-DT-05	CC-DT-06	CC-DT-07	CC-DT-08	CC-DT-09	CC-DT-11	CC-DT-16	CC-DT-17	CC-DT-18	CC-DT-19	CC-DT-20
Strat. Hgt.	4.38	4.83	5	5.15	5.34	5.43	5.6	5.85	9.45	9.6	9.75	9.95	10.1
Ostracodes													
Fossocytheridea	0	0	0	0	0	0	6	115	4	113	40	26	101
Darwinula sp.	1	0	7	2	5	2	4	2	0	3	0	2	2
Candona? spp.	17	2		6	5	7	4	0	0	0	0	0	0
Gastropods													
Planispiral	15	16	12	16	10	12	3	5	0	7	3	0	4
Trochospiral	4	8	5	9	4	2	4	11	8	28	24	2	38
Charophytes													
Genus unknown	2	2	22	6	31	5	37	1	0	0	0	0	0

Note that the samples begin at the contact with the underlying Sugarledge Sandstone and end in the marlstone unit overlying last coal seam (see Fig. 6).

FIG. 11.Ostracodes from the Smoky Hollow Member (Straight Cliffs Formation) at Cedar Canyon, Utah. **AC**) *Fossocytheridea posterovata;* **D, E**) *Cytheropteron* n. sp. 1; **F, G)** *Looneyella* n. sp. 1; **H)** *Looneyella* n. sp. 2; and **I)** *Cytheromorpha.*

therefore satisfy the geologic definition of an estuary according to Dalrymple et al. (1992). Furthermore, the coal-bearing strata of southwest Utah represent a flooded paleotopographic low where evidence for fluvial deposition was persistent throughout much of the study interval (Gustason, 1989; Shanley and McCabe, 1991; Shanley and McCabe, 1995; Uličny, 1999; Eaton et al., 2002). Our use of the term lagoon refers to those systems that are restricted from open marine circulation and where salinities may range from less than normal to above normal. Figure 12 shows the schematic model to demonstrate our paleoenvironmental interpretations for the four fossil assemblages.

Assemblage A: Lagoon

The dominance of a single taxon in a fossil assemblage is an important paleoecological gauge for wide-ranging physical and chemical conditions (Fürsich, 1994). For example, the modern eurytopic cytherid ostracode *Cyprideis* occupies hypersaline lakes, coastal ponds, and estuaries where most other biota are sparse (De Deckker, 1981; Debenay et al., 1994). Of interest are the depauperate ostracode assemblages recognized in the Dakota coal zones.

At Coal Mine Mesa, shelly mudstones overlie a 1-m-thick coal in the uppermost Dakota Formation and contain a foraminiferal assemblage that bears striking resemblance to modern estuarine–lagoonal associations. In addition, there is an inverse relationship between trochospiral (= epifaunal: Goldstein et al., 1995) and serial (= infaunal: Goldstein et al., 1995) morphotypes that corresponds to increasing glauconite upwards (Fig. 8). Foraminifera occur with brackish-water gastropods and bivalves, including *Admetopsis* spp., *Corbicula*, *Voysa* spp., and *Vascellum*. This association of free-living, cemented, and/or byssate epifaunal molluscs represents a brackish-water community (Fürsich and Kirkland, 1986; Kirkland, 1996). The invertebrates also show an increased infaunal domination upwards that parallels the foraminiferal trends and may reflect a softening substrate. The trochospiral foraminifera and epifaunal invertebrate association represents the landward marsh. The glauconitic mudrock containing serial foraminifera and infaunal invertebrates represents the deeper reaches of the lagoon (central estuary) (Fig. 12). One final observation is that medium-grained sandstone containing abundant humic matter, interpreted as a shoreline/washover depositional unit (Fürsich and Kirkland, 1986; Kirkland, 1996), truncates the shelly shales. We interpret these observations of biota and sediments to reflect a transition from flooded marsh to muddy lagoon during landward retreat of a barrier built shoreline.

The initial flooding of the coal swamp saw an abundance of *Trochammina rutherfordi* and sparse *Verneuilinoides perplexus*. Midway in the sequence this trend is reversed as the system deepened with continued transgression of the Greenhorn Sea. The invertebrate association reveals an upward increase of infaunal taxa. Goldstein et al (1995) demonstrated that trochospiral morphotypes live in the uppermost marsh surface and therefore are thought to

TABLE 8.—Ostracode distribution from shelly marlstones at Cedar Canyon (Fossil Assemblage C) and the mudstones–lignites at Henrieville (Fossil Assemblage D), both from the Turonian Smoky Hollow Member (Straight Cliffs Formation).

OSTRACODES		**Valve Distribution**		
Fossocytheridea posterovata	**Articulate**	**Left**	**Right**	**Total in Fraction**
> 250 micron size fraction	216	25	31	272
> 125	41	19	22	82
> 63	0	33	38	71
Total	**257**	**77**	**91**	**425**
***Cytheropteron* n. sp.**	**Articulate**	**Left**	**Right**	**Total**
> 250	1	0	0	1
> 125	3	1	0	4
> 63	0	0	0	0
Total	**4**	**1**	**0**	**5**
***Looneyella* spp.**	**Articulate**	**Left**	**Right**	**Total**
> 250	0	4	3	7
> 125	2	24	15	41
> 63	0	0	0	0
Total	**2**	**28**	**18**	**48**
***Darwinula* sp.**	**Articulate**	**Left**	**Right**	**Total**
> 250	1	0	0	1
> 125	0	0	0	0
> 63	0	1	2	3
Total	**1**	**1**	**2**	**4**
***Cytheromorpha* sp.**	**Articulate**	**Left**	**Right**	**Total**
> 250	0	0	0	0
> 125	1	0	0	1
> 63	0	0	0	0
Total	**1**	**0**	**0**	**1**
Total Ostracodes				**483**

TABLE 9.—Foraminifera from the Smoky Hollow Member (Straight Cliffs Formation).

Morphotype	Cedar Canyon (FC)	Henrieville (FD)
Planispiral	0	13
Trochospiral	90	19
Uncoiled	30	1
Serial	26	11
Quinqueloculine	4	32
Total	**150**	**76**

be largely epibiotic. In contrast, serial specimens have been observed living at substantially deeper intervals and are thought to be inbiotic. In this context, the foraminiferal trends replicate those observed for the invertebrate fauna.

Of interest in the Coal Mine Mesa bay-fill sequence is the monospecific population of *Clithrocytheridea*? *graysonensis* (Fig. 10, A–D) that comprises a relatively complete growth series enclosed in red siltstones (Fig. 8). We postulate that this ostracode bed indicates a brief period of increased aridity that was intolerable for both nonmarine and marine biota; a short-term climatic perturbation would account for the oxidized siltstone. Furthermore, cytherid ostracodes are known halobionts, and the domination of a single ostracode taxon is not uncommon where high evaporation budgets create hypersaline conditions (Neale, 1988). Both the biotic and lithologic evidence at Coal Mine Mesa indicate a restricted setting that we interpret as lagoonal, in which both freshwater influx and open marine communication was more restricted than for the other fossil assemblages described herein (Fig. 12).

The Dakota Formation contains both *Clithrocytheridea*? and *Fossocytheridea*, and both are well-known eurytopes (Neale, 1988). The dominance of these two Cretaceous genera in red siltstones (Fossil Assemblage A) and the low-diversity coal zones (Fossil Assemblage B) supports the hypothesis that the ecosystems were at times isolated from open marine influence and therefore susceptible to regional climate modulations. An example of modern climate-induced paleoecological change is the estuary of the Casamance River in Africa, which has witnessed increased aridity spanning the last several decades (i.e., precipitation/evaporation ratios are in decline). During this period, the euryhaline ostracode *Cyprideis* has successfully replaced other brackish-

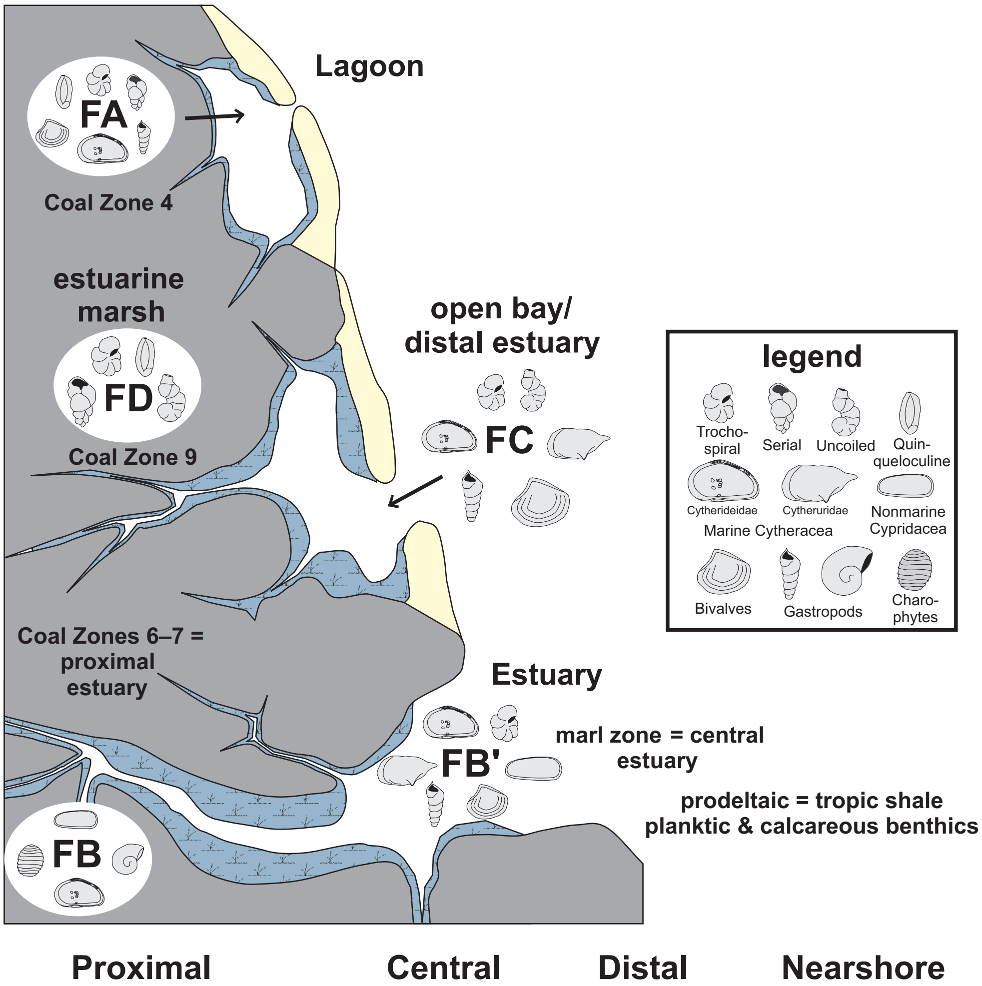


FIG. 12.—Paleoenvironments of the coastal microfossil assemblages, western Greenhorn Sea. Schematic that depicts a model for distribution of the fossil assemblages (modified from Reinson, 1992). An example is provided to demonstrate the paleoecological interpretations for each fossil association. See "Paleoecology" sections in the text for details.

water and freshwater taxa as far inland as 150 km, where salinity fluctuations now range between 5 and 50 parts per thousand on an annual basis (Debenay et al., 1994). The agglutinated foraminifera that once flourished in the central regions of the river are now restricted to within 30 km of the estuary mouth (distal estuary). Nonmarine ostracodes now occupy the uppermost reaches of the river, where ample freshwater still flows. To conclude, the monospecific populations of cytherid ostracodes and the scarcity of foraminifera at Coal Mine Mesa and in Coal Zones 5, 6, and 7 at Cedar Canyon (MacFarlane Mine and Maple Canyon) support the idea that salinity perturbations were significant during deposition of these strata.

Assemblage B: Proximal Estuary to Central Estuary

The prominent ostracode identified from Fossil Assemblage A belongs to the cytherid genus *Fossocytheridea* (Fig. 8, E–F), which has been reported from other U.S. Cretaceous localities (Peterson et al., 1953; Swain and Brown, 1964, 1972; Swain, 1982). The dominance and abundance of *Fossocytheridea* in association with rare specimens of the nonmarine genera *Darwinula* and *Candona* indicates a low-salinity coastal assemblage. The abraded valves of the nonmarine taxa suggest post-mortem transport via adjacent fluvial systems (Fig. 12). Other indicators of low salinity include charophytes and smooth-shelled gastropods (*Planorbis*? sp.). This hyposalinity hypothesis is further supported by the apparent exclusion of foraminifera in CZ6 and CZ7. The relatively high percentage of sulfur (2–4%) in the uppermost coals is a testament for brackish-water conditions during peat accumulation; middle-member coal zones to the east of Markagunt Plateau yield sulfur values less than 1%, suggesting that peat accumulation during *Metoicoceras mosbyense* times was primarily nonmarine (Bustin et al., 1983; Berner, 1984; Berner and Raiswell, 1984; Cohen et al., 1987). Overall, the proximal estuarine assemblage is marked by a dominance of *Fossocytheridea* and the near exclusion of all other taxa and therefore is considered far from direct marine influence (Fig. 14). Estuarine valley fills and ebb-tidal deltas intercalate with the coal zones (Eaton et al., 2001) and further support our estuarine interpretation.

The fossil association in the marlstone beds (FB′) differs from the mudstone intervals in CZ6 and CZ7 because they contain the ostracodes *Clithrocytheridea*? and *Cytheromorpha* and the foraminifera *Trochammina* and *Ammobaculites*, all of which have modern representatives in estuarine settings (Ellison, 1972; Cronin, 1988). The presence of *Eucytherura* and the calcareous benthic foraminiferal taxon *Gavelinella dakotensis* provide additional support for an interpretation of meso-to-normal salinity (Neale, 1962; West et al., 1998). It is important to emphasize that *Fossocytheridea* persists into the marl zone, but the incursion of normal marine ostracodes and foraminifera in the shelly marlstones marks a significant landward-stepping facies shift. The marlstones therefore record a long-term paleoenvironmental change, which we interpret as a transition from proximal to central estuarine conditions during *Neocardioceras juddii* times (Fig. 6).

Assemblage C: Open Bay/Distal Estuary

This foraminifera–ostracode assemblage occurs at the base of the Smoky Hollow Member in shelly mudstones and marlstones. Nicely preserved specimens of *Ammobaculites obliquus* and sparse tests of *Trochammina ribstonensis* and *Textularia* sp. support an interpretation for a large and relatively open estuarine system (Fig. 13) (e.g., Buzas, 1974). There is a noticeable absence of calcareous morphotypes, perhaps because of dissolution. In addition to foraminifera, ostracodes are dominated by the brackish species *Fossocytheridea posterovata*, for which a succession of both juvenile and adult valves likely indicates a low-energy autochthonous assemblage (Whatley, 1988; Tibert and Scott, 1999). Both nonmarine and normal marine ostracode taxa (*Cytheropteron, Looneyella* spp., *Cytheromorpha, Candona*?, *and Darwinula*) (Fig. 11) are relatively common and comprise an assemblage of mostly disarticulated valves (Fig. 14); these taxa were likely reworked

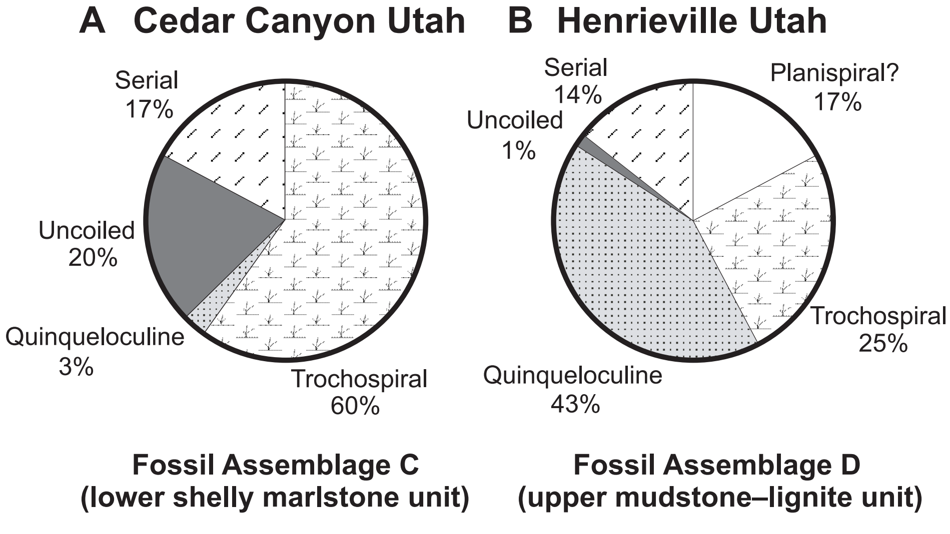


FIG. 13.—Distribution of foraminifera from the Straight Cliffs Formation. **A**) The shelly marlstone unit from Cedar Canyon, representative of Fossil Assemblage C, and **B)** the lignitic unit, representative of Fossil Assemblage D. Fossil Assemblage C is interpreted as open bay/distal estuarine given the abundance of *Ammobaculites* and *Reophax*. *Trochammina ribstonensis* also characterizes the open-bay assemblage and is common to Turonian strata in the Tropic Shale. Fossil Assemblage D is characterized by an abundance of *Trochammina webbi*, which has not been identified outside of the lignites of the Smoky Hollow Member. *Miliammina ischnia* always occurs with *Trochammina webbi,* and this intimate association is remarkably similar at all lignite-bearing localities and suggests that this association represents a true fossil marsh assemblage.

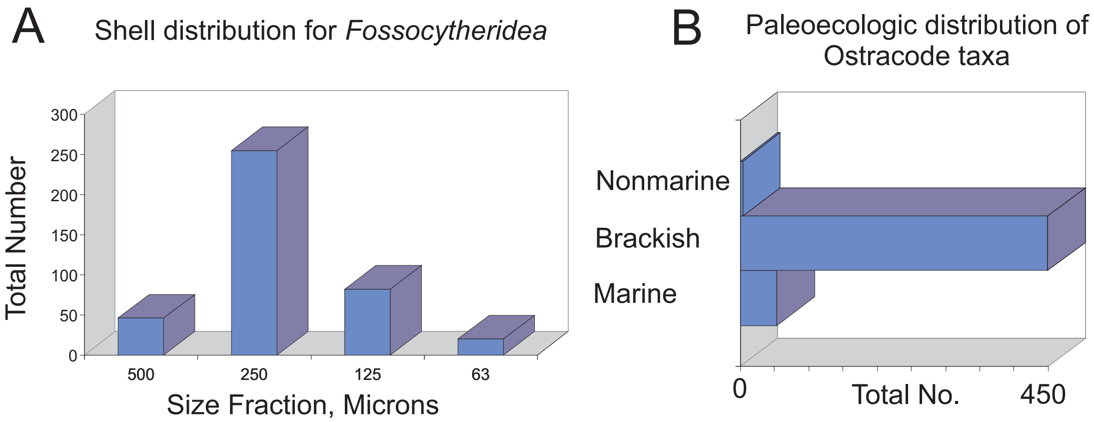


FIG. 14.—Ostracode shell size distribution and relative proportion of brackish taxa (FC) from Turonian strata from southwest Utah. **A)** Histogram that demonstrates a growth series of single valves, whereas the last instars (A-1 and A-2) dominate. **B)** Histogram showing dominance of brackish taxa relative to nonmarine and normal marine taxa.

and/or transported into the system from adjacent nonmarine and marine sources. We interpret the lower part of the Smoky Hollow Member as deposited in an open bay or distal estuary that maintained relatively continuous marine communication (Fig. 12); however, nonmarine influence was considerable and contributed to less than normal marine conditions.

Assemblage D: Estuarine Marsh

In terms of foraminiferal paleoecology, marsh populations in ancient strata have been difficult to confirm where "brackish conditions" are inferred on the basis of a low-diversity agglutinated biota (see Wall, 1976; Scott et al., 1983). Wightman et al. (1994) and Tibert and Scott (1999) have documented agglutinated foraminifera in marginal marine strata indicating that agglutinated foraminifera occupied coastal habitats as early as the Carboniferous. In most of these studies, poor preservation of the tests makes uniformitarian comparisons problematic. Figure 9 (E–J) shows that Cretaceous foraminifera from southwest Utah, although laterally compressed, closely resemble modern taxa (Fig. 3A, B). In particular, the foraminiferal populations from Henrieville and Glory Cove bear a striking resemblance to modern marshes of temperate latitudes (Scott et al., 1996; compare Figs. 4 and 12). The thin, laterally extensive, low-quality lignites of the Smoky Hollow Member support our marsh hypothesis. Furthermore, the gradational contact between the foraminifera-bearing, root-penetrated mudstones and the lignites suggests relatively continuous deposition. The sulfur values of the Smoky Hollow lignites are substantially less (1–2%, Peterson, 1969a, 1969b) than those we analyzed from the uppermost Dakota Formation, which suggests that peats accumulated in a low-salinity envoronment (~ 0-5 ppt) (Berner, 1984; Berner and Raiswell, 1984; Cohen et al., 1987).

Modern marshes can be subdivided with respect to mean sea level (e.g., Scott and Medioli, 1980). *Haplophragmoides* spp. and *Trochammina* spp. characterize the lowest-salinity marshes (De Rijk, 1995; Scott et al., 1996). *Miliammina* and *Trochammina*, however, characterize the marsh adjacent to tidal channels (Scott and Leckie, 1990). We believe that the *Miliammina* (quinqueloculine), *Trochammina* (trochospiral), and sparse *Ammobaculites* (uncoiled) association identified from Cretaceous coal-bearing strata in southwestern Utah are diagnostic of an ancient marsh population (Figs. 12, 13). Given the associated lithologic and sulfur data, our results provide compelling evidence that Mesozoic agglutinated foraminifera occupied low-salinity coastal swamps, as they do today.

RECOGNITION OF MARINE FLOODING SURFACES

Cyclostratigraphy and Marine Flooding Surfaces

Observation of cyclicity in the coal-bearing strata is a topic that has received much attention since the inception of the cyclothem concept in the 1930s (Wanless and Weller, 1932). Many studies of Carboniferous sequences have applied the cyclostratigraphy concept with reasonable success (e.g., Cecil et al., 1993; Gibling and Bird, 1994; Gibling and Wightman, 1994; Gibling et al., 1995). Ryer (1984) discussed stratal repetition in the southwest Utah coalfields and recognized multiple orders of cyclicity. In accordance with Hancock and Kauffman (1979), Ryer (1984) acknowledged that the late Cenomanian–middle Turonian Greenhorn marine cycle represents one third-order cycle of Vail et al. (1977) and that the "saw tooth" stratigraphic patterns, overprinting the southwestern Utah coal fields, represent fourth-order cycles likely spanning hundreds of thousands of years. Since then, cycles of this duration have been recognized in this region (Leithold, 1994; Shanley and McCabe, 1995; Gardner, 1995a, 1995b) (Fig. 3). Our concept of a cycle follows Ryer's in that a transgressive and regressive package of strata represents a pattern of relative sea-level rise and fall where higher-frequency (shorter-duration) cycles overprint and complicate those of longer duration.

We follow the genetic stratigraphic approach in that flooding events serve as the primary correlative surfaces between onshore–offshore sections of the Western Interior Basin (e.g., (Galloway, 1989; Gardner, 1995a, 1995b; Underhill and Partington, 1996). Incursions of marine ostracodes and agglutinated foraminifera that are superimposed on the background biotic community within coal/carbonaceous shale (e.g., Dakota and Straight Cliffs formations) represent marine flooding or significant landward migration of normal marine facies. We do not interpret the intervals between flooding events as parasequences, and consequently we do not analyze our strata in terms of high-frequency stacking patterns (e.g., Mitchum and Van Wagoner, 1991). Instead, inferences about landward-stepping or seaward-stepping facies are made from the observed biostratal succession of the fossil assemblages. Implicit in our definition of cyclicity is that marine flooding surfaces represent distinct events that record environmental changes that may be either long-term or short-term. The former is an abrupt and basin-wide environmental shift (wholesale faunal immigration or community replacement) such as an upward progression from proximal to central estuarine conditions (e.g., Fossil Assemblage B to B′). A short-term change is a sudden and short-lived incursion (incursion epibole after Brett, 1998) of marine taxa that simply overprints the background brackish population; these incursions are often temporary and repetitive (e.g., incursions of Fossil Assemblages B and D in association with cyclic mudstone–coal alternations). The intermediate surface records landward-stepping biostratal successions associated with regional sea-level oscillations, which in some cases mark lithostratigraphic boundaries. In contrast, the shorter-duration cycles record temporary, perhaps autogenic and/or climatic perturbations within the interval. Examples of both "styles" of flooding punctuate the Cenomanian–Turonian coal zones of the Colorado Plateau and occur on two temporal orders of magnitude (Fig. 15).

Intermediate Flooding Surfaces and Events

Elder (1991) demonstrated that regional disconformities and biotic turnover define the molluscan biozones and coincide with significant oceanographic perturbations recorded across Cenomanian–Turonian boundary interval. We consider significant flooding and/or basin-wide environmental shifts within the approximate confines of a single ammonite biozone (and/or equivalents) as an intermediate-frequency "flooding event." The duration between the intermediate flooding surfaces (IFS) records an approximate 100–400 kyr periodicity (Table 10). This agrees reasonably well with Leithold's (1994) approximate durations for her six 400 kyr carbonate cycles from the Tropic Shale.

TS and Cycle 1′—Early Transgression of the Greenhorn Sea (Coal Zones 4 and 5).—

The third-order Greenhorn Cycle has complex stratal architecture in southwest Utah. Gustason (1989) provided a detailed description of the Dakota Formation across the region and described the middle member as entirely nonmarine, in which packages of coal and mudstones punctuate a broad valley fill. Uličny (1999) has since identified estuarine influence in these same strata. The first foraminiferal or marine ostracodes–bearing unit marks the change from nonmarine to marginal marine deposition in the coastal-plain stratigraphic succession. We recognize this surface at Coal Mine Mesa, Arizona, and Mesa Verde, Colorado, as Fossil Assemblage A, overlying CZ4. This same assemblage can be tracked to Henrieville Utah at the boundary of the middle and upper member of the Dakota Formation (Units 4–5 of Uličny, 1999). The age of strata below this surface is *Calycoceras canitaurinum* as reported by Uličny (1999).

At Coal Mine Mesa, the age of the upper sandstone member of the Dakota Formation is assigned to the *Metoicoceras mosbyense* ammonite zone (Fürsich and Kirkland, 1986), and the underlying coal is therefore equivalent to CZ4. Our foraminiferal results support this correlation, based on the occurrence of *Trochammina rutherfordi*, *T. wickendeni,* and *Psamminopelta bowsheri*; these taxa also occur exclusively in the *Metoicoceras mosbyense* biozones, directly overlying CZ4 at Henrieville. This corresponds to Units 4 and 5 of Uličny (1999), and Kirschbaum and McCabe (1992) denote this same interval as a tongue of the Tropic Shale. Given the widespread recognition of Fossil Assemblage A from Mesa Verde, Black Mesa, and Henrieville, we consider those strata that separate CZ4 and CZ5 as a Cycle 1′ in the context of Leithold's (1994) delineations of fourth-order cycles. This association represents the first westward pulse of the Greenhorn sea during *Metoicoceras mosbyense* times (Fig. 16).

At proximal localities on Markagunt Plateau, the first evidence for marine influence in the Dakota Formation occurs at Table Bench, as indicated by brackish microfossils overlying CZ4. More specifically, a unit of shell-rich mudstone separates CZ5 from an overlying carbonaceous shale unit (TS2 of elder et al., 1994) at Table Bench (Tibert, 2002). Recent analysis of this shell bed revealed several abraded specimens of *Trochammina rutherfordi* and *Verneuilinoides perplexus*, the two prominent taxa that constitute Fossil Assemblage A. As presented above, Gustason suggested that CZ4 (= Peterson's Coal Bed 4) and CZ5 (= upper member brackish coal) merged into a single coal zone on Markagunt Plateau (Averitt, 1962, Willow Coal Zone). This indicates that either the *Metoicoceras mosbyense* brackish-water equivalents are restricted to a single bed separating CZ4 and CZ5 or that erosion during the initial *Sciponoceras* transgression cannibalized the *Metoicoceras* strata and the enclosed specimens we incorporated into the transgressive shell pavement. Although further fieldwork will be required to resolve these stratigraphic relationships, the first evidence for significant marginal marine influence overlies the last "substantial" coal seam of the middle member of the Dakota Formation (Coal Bed 4 of Peterson 1969). This laterally extensive surface can be identified by ostracodes and foraminifera (Fossil Assemblage A) and represents the principal flooding of the Greenhorn Cycle on the Colorado Plateau (Fig. 16). This flooding surface is likely

TABLE 10.—Average duration of the molluscan biozones for the Cenomanian–Turonian boundary interval for the North American Western Interior Sea (extrapolated from Kauffman et al., 1993, and Obradovich, 1993).

Ammonite Biozone (Kauffman et al. 1993)	Duration (Myr)	Age, base of zone (Ma)
Prionocyclus hyatti	0.30	90.70
Prionocyclus percarinatus	0.45	91.15
Collignoniceras woollgari	0.95	92.10
Mammites nodosoides	0.40	92.50
Vascoceras birchbyi	0.50	93.00
Pseudospidoceras flexuosum	0.34	93.34
Watinoceras devonense	0.06	93.40
Neocardioceras juddii	0.35	93.75
Sciponoceras gracile	0.25	94.00
Metoicoceras mosbyense	0.54	94.54

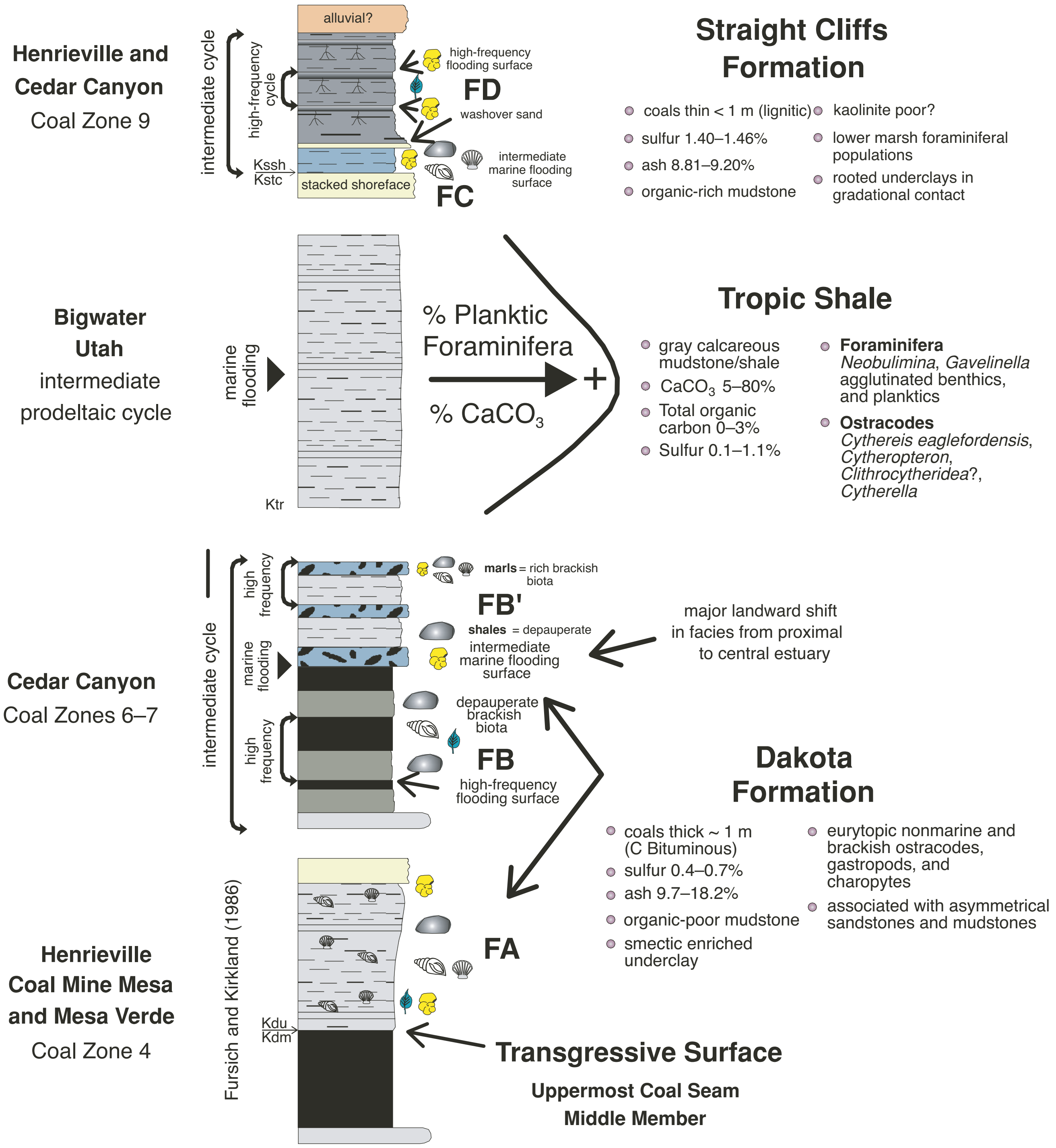


FIG. 15.—Intermediate- and high-frequency flooding, western margin of the Cretaceous WIS. Schematic that demonstrates physical, chemical, and biotic variability between the Dakota, Tropic, and Straight Cliffs formations (see Table 2). Flooding surfaces are described in Table 11. The transgressive surface overlies CZ4 and can be observed at most localities, including Markagunt Plateau, Kaiparowits Plateau, Mesa Verde, and Black Mesa. IFS-2 marks the boundary between CZ7 and the Maple Canyon Marl Zone. The schematic of the Tropic Shale demonstrates the flooding surfaces coincident with maximum carbonate preservation and planktic foraminiferal abundance. The Smoky Hollow Member lignite unit (CZ9) comprises IFS-P where FC (the open-bay assemblage) overlies FD (the marsh assemblage). High-frequency cycles occur in the coal zones of the upper member of the Dakota Formation and the Smoky Hollow Member of the Straight Cliffs Formation. Key to the compactional interpretations of CZ9 are the foraminifera-bearing, rooted, slickenside-rich (indicating dewatering) mudstones, which are gradational with the lignites.

TABLE 11.—A summary of the flooding surfaces recognized from the marginal marine Greenhorn Cycle. See Figure 16 for the stratigraphic position of each surface relative to the molluscan biostratigraphy.

Flooding surface	**Fossil assemblage**	**Associated unit and coal zones**	**Biostratal succession and style of flooding**	**Ammonite biozone**	**Position in sequence**
TS	FA (lagoon) FB (proximal estuary)	CZ4 — Kdm CZ5 — Kdu	diachronous east–west habitat migration (tracking)	*Calycoceras* & *Metoicoceras*	Cycle 1' and early Cycle 1 = early transgression (initial Greenhorn flooding)
IFS-1	FB (proximal estuary)	CZ6 — Kdu	short-term flooding (incursion epibole)	*Sciponoceras gracile*	Cycle 1 = middle–late transgression
IFS-2	FB (proximal estuary) FB' (central estuary)	CZ7 — Kdu MCMZ	FB proximal to FB' central estuary (community replacement)	*Neocardioceras juddii*	Cycle 2 = latest transgression
MFS	FC? (distal estuary) Normal marine Molluscan fauna	CZ8 — Ki Kt (lower)	Ki FC? recognized at farthest western position; Kt westernmost nearshore marine faunas recognized (ammonites and inoceramids)	*Watinoceras coloradoense* to *Mammites nodosoides*	Cycle 3 = peak transgression–early highstand (Maximum flooding surface)
IFS-P	FC (distal estuary) FD (marsh)	CZ9 — Ksu, Kctc and Kssh	FD–FC–FD = marsh and estuarine (symmetrical transgressive–regressive cycle)	*Prionocyclus hyatti*	superimposed intermediate flooding event on third-order regressive facies

diachronous, and we refer to it as the transgressive surface (TS: Figs. 6, 15, 16).

IFS-1 and 2 (Coal Zones 6, 7, and 8).—

We recognize two prominent intermediate flooding intervals (coal zones) that superimpose *Sciponoceras gracile* and *Neocardioceras juddii* strata on Markagunt Plateau. Overall, these coal-bearing intervals are interpreted as proximal estuarine biofacies (Fossil Assemblage B) referring to an environment far removed from direct marine influence and serves as an important beacon for the advancing Greenhorn Sea (see Fig. 12). It is the background domination of *Fossocytheridea* that provides the basis for the paleoecological association. The shell bed at 32 m in Maple Canyon marks the first intermediate flooding surface (IFS-1; Figs. 6, 16), when *Cythereis eaglefordensis* migrated westward during a *Sciponoceras gracile* flooding event and therefore records an abrupt marine inundation of the coastal plain (incursion epibole of Brett, 1998).

Coal Zone 6 at Cedar Canyon correlates to the first carbonate cycle in the adjacent prodeltaic muds of the Tropic Shale (Leithold, 1994) and encompasses flooding surfaces 2 through 6 identified by Elder et al. (1994). The presence of *Cythereis eaglefordensis,* which is observed in both the Tropic Shale (Fig. 8) and the Dakota Formation on Markagunt Plateau (Fig. 6), supports assignment of CZ6 to the *Sciponoceras gracile* biozone (Elder et al., 1994). Overall, this taxon is at peak abundance in *Sciponoceras gracile* strata at many coeval North American localities (Hazel, 1969).

Another prominent intermediate flooding event defines the contact between CZ7 and the Maple Canyon Marl Zone (IFS-2: Figs. 6, 16). The first occurrence of foraminifera (including calcareous benthics) and the ostracodes *Cytheromorpha* and *Eucytherura* mark a pronounced shift from proximal to central estuarine and increased marine influence. This trend is replicated at nearby MacFarlane Mine, where there is a distinct change from nonmarine cypridacean domination (including rare *Fossocytheridea*) to marine cytheracean domination (Fig. 6). Given the common association of *Fossocytheridea*, *Cytheromorpha*, *Trochammina*, and *Ammobaculites,* Fossil Assemblage B' and Fossil Assemblage C are intimately related. This striking similarity in genera between the marl biota and the lowermost marlstone beds of the Straight Cliffs Formation in Cedar Canyon indicates a sustained shift in depositional environment and the onset of long-term community replacement (see Brett, 1998).

Coal Zone 7 correlates to Cycle 2 of the Tropic Shale, on the basis of the following biotic trends observed in the uppermost Cenomanian *Neocardioceras juddii* ammonite zone: (1) the first occurrence of *Gavelinella dakotensis* and *Trochammina wetteri*; (2) a relative abundance of *Clithrocytheridea*?; and (3) a relative increase in carbonate productivity. According to Gustason (personal communication), the underlying sands are equivalent to the Sugarledge Sandstone (Fig. 16) and this unit is capped by transgressive surface 7 of Elder et al. (1994). The smectite-rich mudstone enclosed in CZ7 is equivalent to Bentonite TT2 (Leithold, 1993, 1994) of the Tropic Shale and Bentonite B (Elder, 1988, 1991) observed at Table Bench (Elder et al., 1994).

We recognize another flooding event overlying the Dakota Formation. The uppermost sandy unit is characterized by a high-density association of oysters, inoceramids, and microfossils that we interpret as a transgressive lag (Fig. 16). The thin unit of silty shale overlying this surface (Fig. 6) contains specimens of the ostracode *Fossocytheridea posterovata*, the bivalve *Mytiloides kossmati*, and the ammonite *Fagesia catinus,* indicative of a late *Watinoceras coloradoense* to *Mammites nodosoides* age (early Turonian). On the basis of the age of this faunal association, the shale unit correlates to Cycle 3 of Leithold (1994) at or near peak transgression of the Greenhorn Sea (maximum flooding surface; Figs. 2, 16). We correlate this flooding interval to the westernmost carbonaceous shales and coals of the Iron Springs Formation in the Pine Valley Mountains (New Harmony, Utah) (Figs. 6, 16; Coal Zone 8), where a taxon association bears close resemblance to Fossil Assemblage C given the occurrence of the ostracodes *Fossocytheridea posterovata* and *Cytheromorpha* and the foraminifera *Trochammina ribstonensis* and *Reophax recta*.

IFS-Prionocyclus (Coal Zone 9).—

The basal Smoky Hollow Member of the Straight Cliffs Formation records an intermediate flooding event in an otherwise regressive package of prograding sandstones. Coal Zone 9 (Figs. 6, 16) is a 5-m-thick coal-bearing unit deposited during late middle Turonian (*Prionocyclus hyatti*) times (Eaton, 1991). The open-bay (distal estuary) ostracode assemblage (Fossil Assemblage C) commonly precedes the coal and marks an intermediate flooding surface (Figs. 6, 15). The exception to this trend occurs at Glory Cove, where the marsh biofacies (Fossil Assemblage D) is overlain by the open bay / distal shelly mudstones (Fossil Assem-

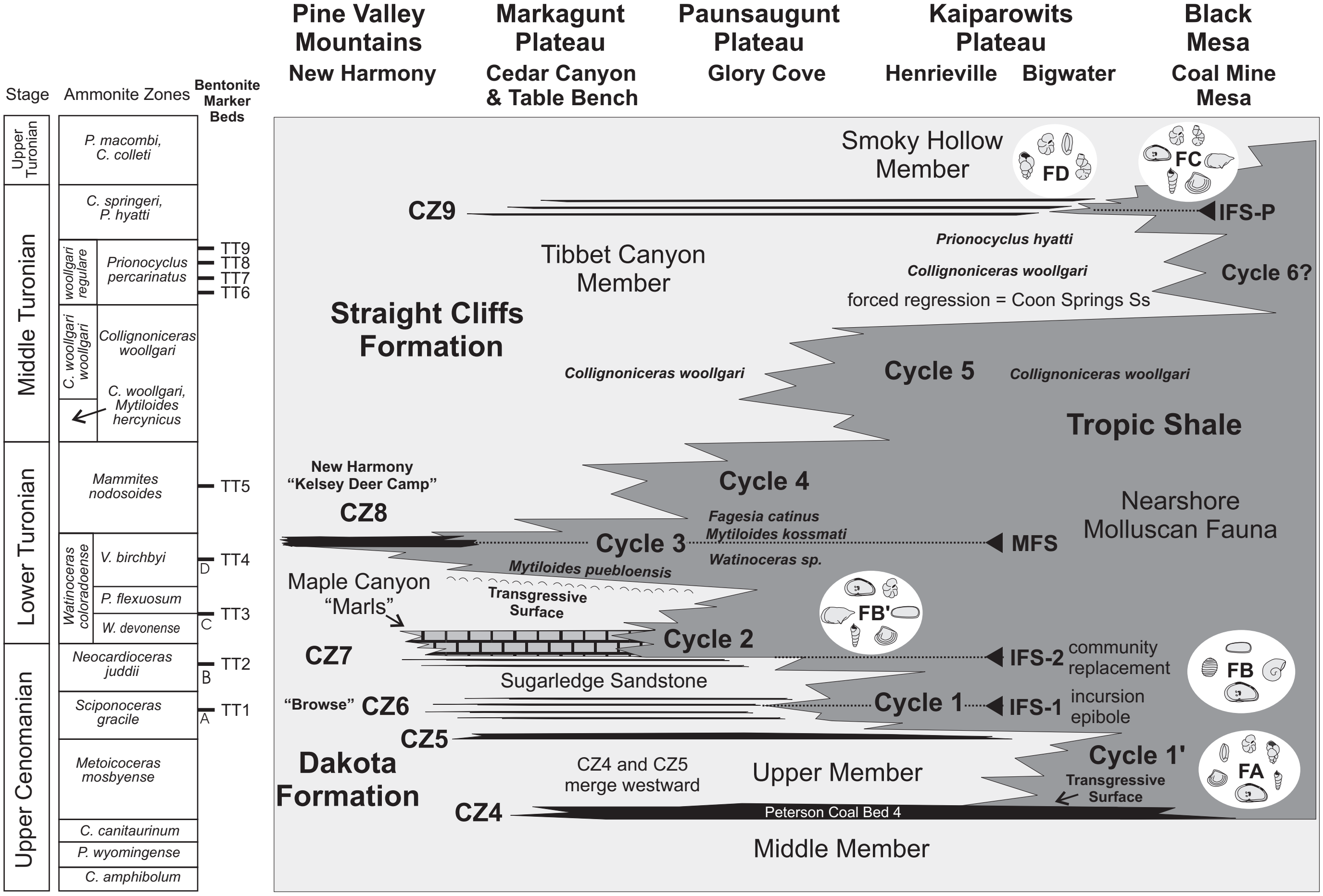


FIG. 16.—Summary figure showing the cycles and flooding surfaces recognized from the Greenhorn Cycle. Table 11 provides a summary for each of the key marine surfaces also described in the text. Note that Cycles 4 and 5 of Leithold (1994) are placed tentatively and will require further study to confirm. See Figure 12 for the symbol legend.

blage C). This biostratal succession confirms the transgressive nature of the flooding. The "*Prionocyclus*" flooding event is characterized by a relative abundance of marine ostracodes and a rich association of agglutinated foraminifera (FC) that overlie the stacked shoreface deposits of the Tibbet Canyon Member (Figs. 6, 15). This FD–FC trend is reversed at the contact between the shelly mudstones and the overlying lignites (FC–FD), thereby indicating a seaward migration of the biofacies.

As presented above, the Smoky Hollow Member was deposited no later than *Prionocyclus hyatti* times and therefore correlates in part to the Blue Hill Member of the Carlile Shale (Peterson, 1969a, 1969b). Shanley and McCabe (1995) document a stratigraphic sequence (Sequence #1 = middle Turonian *Prionocyclus hyatti*) from these same strata. The lower bounding surface of their sequence corresponds to the top of Cycle 5 (Leithold, 1994). This event is interpreted as a forced regression during *Collignoniceras woollgari* times that correlates both with the Hopi Sandy Member of the Mancos Shale in northeast Arizona and with the Coon Spring Sandstone Member of the Tropic Shale in eastern Utah (Figs. 2, 16). The regionally recognized Calico bed at the top of the Smoky Hollow Member bounds Sequence #1 (Shanley and McCabe, 1995). Gardner (1995a, 1995b) also reports a "*Prionocyclus hyatti*" intermediate cycle from the region.

At western localities on Markagunt Plateau, the shoreface sandstones of the Tibbet Canyon Member yielded a specimen of the ammonite *Collignoniceras woollgari* (Cobban, personal communication, 2001) and therefore may correlate in part to Cycle 5 of Leithold (1994); the uppermost sandstone at Cedar Canyon might record the forced regression observed at eastern localities. It is possible that the lower shelly unit of the Smoky Hollow Member records the flooding of Leithold's Cycle 6, deposited during latest *Collignoniceras woollgari* time. However, the striking similarity between the biota at all Smoky Hollow localities, especially between the lignites at Cedar Mountain and Glory Cove, suggests a single chronostratigraphic event. The westward-thickening Tibbet Canyon Member and its highly diachronous contact with the underlying Tropic Shale supports this interpretation. We conclude that the shelly mudstone in the east and the thick marlstone unit in the west (Fossil Assemblage C) represent a *Prionocyclus* intermediate flooding event and that the contact with the underlying regressive sands or with the lignitic-foraminiferal association (FD) marks this surface (IFS-P) (Figs. 6, 16). The recognition of coeval flooding events in Utah (Shanley and McCabe, 1995; Gardner, 1995a, 1995b) and a tentative identification of the Calico bed equivalent in Cedar Canyon (Cobban and Dyman, personal communication, 2000) further supports this idea. Additional field and micropaleontological study will be required to test the validity of this hypothesis of isochronous *Prionocyclus* flooding.

High-Frequency Flooding Surfaces

High-frequency cycles that occur on the order of 10-25 kyr are superimposed on the intermediate cycles presented above. We recognize high-frequency marine flooding surfaces by tracking the decimeter-scale biotic shifts in the populations of ostracodes and agglutinated foraminifera. For example, mudstones that cap thin coal seams in the upper member of the Dakota Formation (CZ6) contain depauperate populations of the eurytopic ostracode *Fossocytheridea* n. sp. associated with nonmarine (?) gastropods and charophytes (Fossil Assemblage A) (Fig. 15) and record repeated flooding of the coastal marsh. Smoky Hollow Coal Zone 9 best exemplifies high-frequency flooding events observed in laterally extensive and impure lignites that are intercalated with gray and black mudstones where *Trochammina* and *Miliammina* (Fossil Assemblage D) mark the mudstone–coal contacts (Figs. 12, 15). During deposition of these high frequency mudstone–coal cycles, sedimentation was nearly continuous, as indicated by gradational, root-penetrated contacts.

To assess the duration of the mudstone–coal cycles, we consider the biostratigraphic framework of the Dakota Formation. As discussed above, Elder et al. (1994) recognized six parasequences at Maple Canyon. Parasequences 3, 4, and 5 occur within the *Sciponoceras gracile* ammonite biozone and therefore represent no more than 250 kyr according to the timescale of Kauffman et al. (1993). The *Neocardioceras juddii* biozone encompasses parasequences 6 and 7 and represents approximately 350 kyr. Our work at Maple Canyon suggests that there may be as many as eight packages of mudstone, sandstone, and coal. For example, in CZ6 we recognize four mudstone–coal cycles (HA, HB, HC, and HD; Fig. 6); a similar relationship occurs in CZ9, where we recognize three high-frequency cycles (HE, HF, HG). Given that Elder et al. (1994) approximated the duration of their parasequences to be 40–100 kyr, our four cycles that overprint their parasequence may record high-frequency flooding events with periodicities between 10 and 25 kyr.

We can also use modern models for peat accumulation (McCabe, 1984) to further constrain this problem. Peat accumulates at an average rate of 1 mm/year; these values may approach 4 mm/year in tropical bogs and 0.1 mm/yr in colder sphagnum bogs (Bustin et al., 1983). Therefore, we estimate that 1.0 m of peat could accumulate in 1000 years. Assuming a peat-to-coal compaction ratio of approximately 10:1, it should take approximately 10,000 years to accumulate enough peat to form 1 m of coal. Ryer and Langer (1980) estimated that compaction ratios for Cretaceous bituminous coals of the Dakota Formation are approximately 8:1. It would seem plausible, therefore, that a coarsening-upward 0.5–1.0 m mudstone capped with a thin decimeter-scale coal seam and overlain by a fossiliferous marine bed should record a cycle of sea-level change on the order of several tens of thousands of years. We suggest that decimeter-meter scale mudstone–coal alternations of the Dakota and Straight Cliffs Formation coal zones record high-frequency cycles of 10–25 kyr periodicity, and certainly no more than 100 kyr, as constrained by the biozone chronological approximations.

Marginal strata on Markagunt Plateau correlate to the limestone–shale couplets of the Bridge Creek Limestone (Elder et al., 1994), where multiple Milankovitch periodicities (10–100 kyr) have been observed (Sageman et al., 1997; Sageman et al., 1998). In this context, the Tropic Shale also contains high-frequency parasequences that are superimposed on the intermediate cycles (Fig. 5), which are attributed to Milankovitch-band climate oscillations (Leithold, 1994; Sethi and Leithold, 1994). We believe that individual coal zones, many of which contain multiple thin coal seams, accumulated contemporaneously with intervals of enhanced carbonate accumulation observed in the Tropic Shale (intermediate cycles). Superimposed on the coal zones are high-frequency events distinguished by cytherid ostracodes (Fossil Assemblage A) and marsh foraminiferal beds (Fossil Assemblage D) that cap mudstone–coal alternations, and those flooding surfaces are the bounding surfaces of the high-frequency cycles. We propose that the coarsening-upward mudstone-to-siltstone beds that separate thin coal seams represent seaward-stepping packages comparable to the parasequences of Elder et al. (1994), Leithold (1994), and Sethi and Leithold (1994), but perhaps with shorter duration than these authors estimated.

DEPOSITIONAL MECHANISMS

Prolonged sea-level rise spanning a period of 10^4–10^5 years satisfies the requirements for optimal peat growth by elevating the water table and slowing down the influx of siliciclastic sediment (McCabe, 1984; Cohen et al., 1987). Substantial peat accumulation also requires a relatively stable platform for peat to aggrade; this has been demonstrated for the Mississippi Delta, where an ancient shoreline provided a stable platform for peat to accumulate at or near highstand (Kosters and Suter, 1993). Climate and local compactional processes can also significantly influence peat accumulation (Cecil, 1990; Cecil et al., 1993). In this section we discuss tectonic subsidence, eustasy, autogenic processes (e.g., compaction), and orbitally forced oceanic and climatic perturbations as the possible mechanisms that controlled the stratigraphic position and internal coal-zone architecture of the Cenomanian–Turonian coals of southwest Utah.

Tectonics and Eustasy

The forcing mechanisms that control fourth-order and fifth-order flooding in marginal marine strata is a topic of much interest. In field-based models from the Upper Cretaceous Book Cliffs of Utah, Van Wagoner (1995) presented a detailed synthesis demonstrating parasequence stacking patterns interpreted as largely allogenic. This model was challenged by Yoshida et al. (1996), who demonstrated that episodic tectonic subsidence could also account for the "nested" high-frequency sequences. In fact, many recent subsidence models developed for the U.S. foreland basin support a primary tectonic control on high-frequency sequence development (Kamola and Huntoon, 1995; Pang and Nummedal, 1995; Houston et al., 2000). Likewise, subsidence histories of Coniacian–Campanian strata of the WIS support a model for significant tectonic control on stratal architecture; however, the recognition of 13 basin-wide foraminiferal events suggests significant allogenic influence (Martinson et al., 1998).

The general asymmetry of the foredeep west of Kaiparowits Plateau suggests rapid subsidence and high sedimentation rates in proximity to the Sevier thrust belt (Gustason, 1989; Eaton and Nations, 1991; Gardner, 1995a, 1995b). The westward-thickening siliciclastic wedge of the Dakota Formation is undoubtedly related to local tectonic subsidence, which may have exerted significant control over deposition of the coarser fluvio-estuarine and shoreface facies. Leithold (1994) also considered episodic thrusting to be a likely mechanism to explain the intermediate carbonate cyclostratigraphy recorded in the Tropic Shale.

The Cenomanian–Turonian Greenhorn Cycle represents a third-order, large-scale sea-level rise and fall that is recognized worldwide (Kauffman, 1977; Haq et al., 1988; Robaszynski et al., 1993; Sahagian et al., 1996; Robaszynski et al., 1998). With respect to sea-level histories in our region, our first three coal cycles (CZ5-7) compare reasonably well to a composite sea-level curve constructed for the Western Interior Basin (see Sageman et al., 1998). The exception is our middle "*Sciponoceras* pulse", which contrasts with the relatively "steady" sea-level rise through *Sciponoceras–Neocardioceras* times (Elder and Kirkland, 1993; Sageman et al., 1998). Regional variations in sea-level histories are not uncommon (see Molenaar, 1983). For example, Elder (1991) recognized relative sea-level oscillations on eastern Markagunt Plateau (Orderville) and at Black Mesa that correspond more or less to the biostratigraphic positions of our Coal Zones 6 and 7 at Maple Canyon. These trends may reflect localized events, yet the similarities signify that there is much potential to use biotic signals to improve and expand regional sea-level histories.

Also in our study area, Shanley and McCabe (1991, 1995) and Hettinger (1995) delineated sequences of relative sea-level rise and fall from Turonian–Campanian marginal marine strata. Shanley and McCabe (1995) used the stratal stacking patterns of their parasequence sets to establish a sea-level curve that compares reasonably well with the Exxon sea-level curve (Haq et al., 1988). Although the results demonstrate significant high-frequency variability on an approximate fifth-order scale, the major sea-level peaks roughly correlate to the Exxon curve, suggesting that eustasy may have exerted significant influence on sequence development (including CZ9 of this study).

It is not the intention of this paper to discriminate between the effects of tectonics and eustasy on these marginal marine strata. However, the correlations between coal zones and intermediate carbonate cycles (fourth-order) in both the Tropic Shale and other recognized stratigraphic sequences (Shanley and McCabe, 1991; Shanley and McCabe, 1995; Gardner, 1995a, 1995b) support the hypothesis that allogenic influences (eustatic and climatic/oceanographic modulations) contributed significantly to the observed stratigraphic position of the coal zones, the geometry and quality of the seams, and the internal stratal cyclicity that is preserved along the westernmost margin of the seaway.

Autogenic Influence

Peat-forming environments respond to autogenic processes where the central reaches of an estuary accumulate fine sedimentary particles and organic matter that compact to as much as one-tenth of the original thickness (McCabe, 1984). In contrast, sandstone-dominated deposits, such as stacked beaches and fluvial channels, compact very little. This facet of coastal geomorphology predicts that increased compaction should occur in topographic lows (bays and infringing swamps). In southwestern Utah, local subsidence and compactional processes related to the paleotopography remain largely unstudied. Complex north–south trending faults are common across the area and mark the boundaries between the plateaus (Eaton and Nations, 1991). In the Kaiparowits region, Peterson (1969a) demonstrated that the thickest coals occur in the paleotopographic lows (synclines), and this indicates that compactional processes and/or local tectonic fault-block movements influenced the coal-basin architecture. Similar conclusions can be inferred from the observed westward-thickening stratal architecture of the Dakota Formation (Gustason, 1989). We acknowledge that the thickest, highest-quality coals rest upon sandstone units of substantial thickness, whether fluvial, estuarine, or shoreface. Given the lateral variability of the coals and associated lithofacies, compactional processes contributed to the mudstone–coal alternations during the Dakota Formation transgression. This is best exemplified in the Smoky Hollow Member, where gradational and symmetrical alternations between coals, rooted mudstones (containing slickensides), and flooding surfaces indicate that compaction exerted fundamental control over the short-term cyclostratigraphic architecture of the regressive coal zones.

Climate

Peat accumulation and preservation are influenced by precipitation–evaporation budgets and sedimentary supply, and many models for peat accumulation invoke climate as an important cyclostratigraphic mechanism (e.g., Cecil et al., 1993). Marginal marine strata on Markagunt Plateau correlate to the Bridge Creek Limestone of Colorado and Kansas, which is thought to record climate seasonality in the region (Barron et al., 1985; Parrish, 1993; Pratt et al., 1993; Parrish et al., 1998). The organic-rich shale beds of the Bridge Creek represent intervals of increased precipitation, enhanced terrigenous influx, and poor benthic ventilation (e.g., Barron et al., 1985; Pratt et al., 1993; Leckie et al., 1998). In contrast, the limestone beds of the Bridge Creek represent intervals of increased aridity, reduced terrigenous influx, and improved benthic ventilation. Gilbert (1895) suggested that the mudstone–limestone alternations record orbitally forced Milankovitch cycles. This poses a problem, given the sparse evidence for orbitally forced ice-sheet growth and decay during the late Cenomanian (Parrish, 1993; Huber et al., 1995; Herman and Spicer, 1996; Parrish et al., 1998). Even so, the Bridge Creek Limestone demonstrates stratal periodicities within the Milankovitch band, which are generally thought to reflect alternations of orbitally driven wet and dry climatic regimes (e.g., Barron et al., 1985; Pratt et al., 1993). More recently, Sageman et al. (1997, 1998) used spectral analysis to test the orbital forcing hypothesis; their results clearly show periodicities that fall within the eccentricity, obliquity, and precessional Milankovitch bandwidths. Similar results have been demonstrated for rhythmic marine strata from the Cenomanian of Western Europe (Schwarzacher, 1994; Gale, 1995).

Paleomagnetic and paleobotanic evidence from the Western Interior Basin suggest late Cretaceous paleolatitudes of approximately 40–50º (Ziegler et al., 1987; McCabe and Parrish, 1992; Parrish, 1993). Parrish (1993) emphasized the potential for arid conditions in the region given that the WIS lay at mid-latitudes and the topographically high Sevier thrust belt to the west likely blocked paleo-Pacific moisture, but she also pointed out that the occurrence of widespread coal in the region suggests a relative abundance of moisture (see also Glancy et al., 1993). According to Hay (1995), the influence of subtropical convergence on oceanic–atmospheric systems is restricted to low latitudes (0–30°). The climate of the southern Colorado Plateau was therefore a cool temperate climate (boreal) as indicated by the floras of the region (Upchurch and Wolfe, 1993). Recently, Leckie et al. (1998) provided micropaleontological and clay-mineral evidence that indicates that cool boreal and warm Tethyan waters mixed just to the east of our study area (Fig. 1). If this holds true, interactions of oceanic water masses may have contributed to short-term and long-term climatic shifts in the region. Evidence for short-term atmospheric–oceanic modulations can be inferred from the work of Slingerland and Keen (1999), who provide a computer model showing a prevailing counterclockwise gyre that transported cool water and sediment southward along the western margin of the seaway and that this circulation pattern was occasionally reversed during extended intervals of cyclonic activity.

In the broadest sense, we observe a relative increase of southern foraminiferal taxa from *Metoicoceras mosbyense* through

Watinoceras coloradoense times (~ 40-80%) that tracks increased Tethyan influence in the region (Tibert, 2002). Additionally, the southern Utah ostracode fauna contains generic elements strikingly similar to Tethyan faunas described from Florida, Portugal, southern France, and northern Africa (Swain, 1964; Hazel, 1969; Babinot and Colin, 1976; Swain, 1982; Mendez and Swain, 1983; Andreu, 1992). The change from a boreal-dominated biota (e.g., Fossil Assemblage A) to a Tethyan-dominated biota (Tropic Shale and Fossil Assemblage B′) occurred steadily during transgression (see also Eicher and Diner, 1985; Caldwell et al., 1993). After the maximum flooding of the Greenhorn, the biota apparently maintained its Tethyan composition until deposition of the noncalcareous Blue Hill facies (Caldwell et al., 1993). Coal quality and thickness also deteriorate upward in concert with increased Tethyan influence. Given the documented oceanic perturbations (e.g., climate, anoxia, and watermass mixing) across the Cenomanian–Turonian boundary interval in the WIS, an intensified seasonality and/or short-term ocean–climate modulation hypothesis to explain the observed internal high-frequency cyclostratigraphic alternations of the coal zones is a reasonable one.

Hierarchical Control

Cyclostratigraphic models for coal-bearing strata are becoming increasingly multifaceted where high-resolution inferences are attributed to the combined influences of tectonic, allogenic, and autogenic processes (e.g., Cross, 1988; Demko and Gastaldo, 1996). We conceive a hierarchical depositional model to explain the origin of the two orders of cyclicity observed in the Cenomanian–Turonian coal zones of the Colorado Plateau.

Hierarchical models have been applied to cyclic coal-bearing packages from the Paleocene Williston Basin, northern U.S. plains (Belt et al., 1992; Tibert et al., 2001), the Paleogene Wilcox Group, Texas (Breyer, 1997), and the Carboniferous of Atlantic Canada (Tibert and Gibling, 1999). In the last two cases, bayfill parasequences (fourth-order) constitute the transgressive systems tracts (third-order). With respect to Carboniferous coal measures, it is widely believed that eustatic sea-level highs correspond to intervals of widespread coal formation (Heckel, 1995). However, regional influences exerted significant control on the geometry and quality of the coals. For example, thin, impure marine-influenced coals of the Upper Carboniferous of the Sydney Basin (Atlantic Canada) prevail in the position of paleotopographic lows (downthrusted structural blocks) (Tibert and Gibling, 1999). In contrast, thick, high-quality coals overlie noncompactable sandstone bodies situated in the position of paleotopographical highs (upthrusted structural blocks). In the Paleocene Williston Basin, U.S.A., a "drainage-diversion model" predicts that tectonic subsidence can significantly divert clastic sediments away from interdistributary basins and ultimately create conditions favorable for the development of thick peat (Belt et al., 1992; Belt, 1993). Marine-influenced beds from these Paleocene strata are coeval with flooding events in the adjacent Cannonball Sea and thereby signify secondary marine influence on the otherwise tectono-autogenic deposit (Tibert et al., 2001). A recent model demonstrates that steady sea-level rise and autogenic delta lobe switching are intimately related (Muto and Steel, 2001). What these studies show is that hierarchical models for depositional control, whether eustatic, tectonic, or autogenic, are the best approach to construct coal-basin histories. Such a multifaceted approach should therefore incorporate the prominent regional signals in addition to widespread global events recorded in the strata. We believe that the widespread microfossil events reported herein and from West et al. (1998) correspond to biotic trends that characterize the WIS (e.g., Eicher and Worstell, 1970; Frush and Eicher, 1975; McNeil and Caldwell, 1981; Eicher and Diner, 1985; Caldwell et al., 1993; Bloch et al., 1999) and exemplify the potential to recognize extrabasinal influence on marginal marine strata.

The highest-quality and thickest coals in our study interval accumulated during initial transgression and deposition of the Dakota Formation. Gustason (1989) and Kirschbaum and McCabe (1992) invoked tectonic subsidence and sediment diversion as a mechanism to explain the coal architecture of the middle member of the Dakota Formation on Kaiparowits Plateau. More recently, Uličny (1999) drew attention to the potential for eustatic influence in these same *Metoicoceras* coal-bearing strata. At western localities, *Sciponoceras–Neocardioceras* coals demonstrate an upward deterioration of quality and thickness with increasing marine influence and climatic cyclicity near the time of the Cenomanian–Turonian boundary. Regressive coals of the Straight Cliffs Formation have a more autogenic gradational character than those of the underlying Dakota Formation.

We conclude that the coal-bearing strata of southwestern Utah record a primary signal of the combined influence of foreland-basin subsidence and rapid global sea-level rise. The allocyclic signal was apparently amplified during latest Cenomanian–early Turonian transgression, given our ability to correlate to the offshore. That the coal-bearing strata of the upper member of the Dakota Formation are coeval with the Bridge Creek Limestone also supports this proposition. During regression, peat accumulation was less prominent, perhaps because of the lower relative rates of sea-level rise on a low-gradient coastal plain. We speculate that the diminished rates of relative sea-level rise during the late middle Turonian reduced the potential for extrabasinal correlations but greatly improved the preservation potential for autogenic mudstone–coal alternations of the Straight Cliffs Formation. Although compactional and climate modulations are hard to differentiate, they both likely contributed to the high-frequency, short-term cycles that are superimposed on the Cenomanian–Turonian coal zones on the Colorado Plateau.

CONCLUSIONS

Transgressive strata of the third-order Greenhorn Cycle (Dakota Formation) contain relatively thick bituminous coals associated with asymmetrical marginal marine facies. Regressive strata of the Greenhorn Cycle (Smoky Hollow Member of the Straight Cliffs Formation) contain thin lignitic coals associated with tabular marginal marine facies. We recognize four paleoenvironmental associations from the Greenhorn coal zones: (A) the back-barrier lagoon, comprising agglutinated foraminifera (*Trochammina rutherfordi* and *Verneuilinoides perplexus*) and brackish invertebrates; (B) the proximal estuary, comprising the eurytopic cytherid ostracode *Fossocytheridea* and brackish-water invertebrates gradational to the distal estuary with the addition of foraminifera (*Trochammina*, *Ammobaculites*, *Gavelinella*, and marine ostracodes); (C) the open bay (distal estuary), comprising a rich assemblage of cytheracean ostracodes (*Fossocytheridea*, *Cytheropteron*, *Looneyella,* and *Cytheromorpha*), agglutinated foraminifera (*Ammobaculites* and *Trochammina ribstonensis*), and brackish-water invertebrates; and (D) the marsh, comprising an exclusive population of foraminifera (*Trochammina webbi* and *Miliammina ischnia*) in mudstones gradational with lignites. Microfossil populations and mudrock–coal associations can be used to identify two temporal orders of marine flooding: intermediate-frequency (100–400 kyr) and high-frequency (10–25 kyr) events. The central estuarine biota (Fossil Assemblage B) and the distal estuarine biota (Fossil Assemblage C) mark major lithostratigraphic boundaries and serve as intermediate flooding surfaces that correlate to biozones-scale fourth-order carbonate cycles recorded in the prodeltaic Tropic Shale. Superimposed on the intermediate-frequency cycles are decimeter-scale mudstone–coal cycles that record high-frequency flooding events (fifth-order) identified on the basis of the proximal-estuary (Fossil Assemblage A) and the marsh (Fossil Assemblage D) biotas.

We hypothesize that the combined effects of tectonic subsidence and global sea-level rise provided the necessary accommodation space for accumulation of thick peats at the westernmost fringe of the seaway and ultimately controlled the stratigraphic position of the coal zones (peak flooding of an intermediate cycle). Autogenic processes (compaction) and ocean–climate influence exerted secondary control over peat accumulation, as indicated by the high–frequency cyclicity. It is our synthesis that global influences such as eustasy and orbitally forced climate change can override a regional basin-forming mechanism (tectonism) and therefore contribute significantly to the cyclostratigraphic trends recorded in coal-bearing strata.

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ABBREVIATED TAXONOMY

This list represents an abbreviated account of the primary taxa used for this study and is by no means extensive. A more detailed taxonomic treatment will be published at a later date (Tibert, Ph.D. dissertation, 2002). Foraminiferal designations follow Loeblich and Tappan (1988). Ostracode systematics follow Benson et al. (1961).

Order Foraminifera
Haplophragmoides? sp.
Fig. 9C

Remarks: This agglutinated foraminifera comprises flattened specimens that may actually be slightly trochospiral. They occur only in marsh facies of the Turonian Straight Cliffs Formation (Fossil Assemblage D).

Ammobaculites obliquus Loeblich and Tappan, 1949
Fig. 9F

Remarks: This species is long ranging and occurs in both Cenomanian and Turonian marginal marine facies.

Trochammina rutherfordi Stelck and Wall, 1955
Fig. 9A, B

Remarks: Stelck and Wall (1955) and Eicher (1965) report this species from Cenomanian arenaceous foraminiferal units including the Graneros Shale. Specimens from this study are restricted to the *Metoicoceras mosbyense* biozone in the Dakota Formation in both Utah and northeast Arizona (Fossil Assemblage A).

Trochammina wickendeni Loeblich, 1946
Fig. 9C

Remarks: This is a relatively tiny and sparse taxon restricted to Coal Mine Mesa from the *Metoicoceras mosbyense* ammonite biozone (Fossil Assemblage A). Other reported occurrences include the Bearpaw of Alberta (McNeil and Caldwell, 1981) and the Woodine Formation/Pepper Shale of Texas (Loeblich, 1946).

Trochammina webbi Stelck and Wall, 1954
Fig. 9F, G

Remarks: This species is easily distinguished by the lateral compression and curved, arcuate sutures. This taxon is restricted to the Turonian Smoky Hollow Coal Zone (Fossil Assemblage D). Stelck and Wall (1954) report this species from marginal facies of the Kaskaupau Formation, Peace River, Canada.

Verneuilinoides perplexus Loeblich, 1946
Fig. 9D

Remarks: This species is easily recognized by the slender and irregular triserial chamber arrangement. This taxon is very abundant in strata assigned to the *Metoicoceras mosbyense* ammonite biozone of the Dakota Formation at all localities (Fossil Assemblage A).

Verneuilinoides hectori Nauss, 1947
Fig. 9E

Remarks : This taxon is distinguished from *V. perplexus* by its inflated chambers and a somewhat short and stubby appearance. It ranges from the *Metoicoceras mosbyense* ammonite zone into the *Neocardioceras juddii* ammonite zone of the Dakota Formation of southwestern Utah (Fossil Assemblages A and B).

Textularia sp.
Fig. 9H

Remarks: A species of *Textularia* most common in the Turonian Smoky Hollow Coal Zone (Fossil Assemblage D).

Miliammina ischnia Tappan, 1957
Fig. 9I, J

Remarks: This species is easily distinguished from *M. manitobensis* by its thin slender test. A common species to the WIS, this taxon ranges from the Albian to the Turonian in both Canada (McNeil and Caldwell, 1981) and the United States (Caldwell et al., 1993). In southwestern Utah, occurrences include the Dakota Formation (Fossil Assemblage A), Tropic Shale, and the Straight Cliffs Formation (Fossil Assemblage D).

Order Ostracoda
Superfamily Cytheracea
Family Cytherideidae

Clithrocytheridea? *graysonensis* Alexander, 1929
Fig. 10A–D

Remarks: This species was described from the Cenomanian Grayson Formation, Texas. *Clithrocytheridea*? resembles species of *Antibythocypris* (Jennings) from the Maastrichtian Atlantic coast (Brouwers and Hazel, 1978) in hingement and muscle scar patterns, but *Antibythocypris* lacks the general angular carapace and maintains larger normal pores. This species is restricted to the *Metoicoceras mosbyense* ammonite biozone at Coal Mine Mesa (Fossil Assemblage A).

Genus *Fossocytheridea* Swain and Brown, 1964

Remarks: This genus was erected to encompass those Cytherideidae ostracodes that yield distinct dimorphism and medial sulcation. Babinot and Colin (1976) erected a genus *Sarlatina* based on similar diagnostic characters that we consider synonymous with *Fossocytheridea*. The new species described herein will remain in open nomenclature until formally published (Tibert, Colin, Leckie, and Babinot, manuscript in prep.).

Fossocytheridea n. sp.
Fig. 10E, F

Remarks: This species of *Fossocytheridea* has a high-amplitude sulcus, and the carapace often displays a distinct pattern of reticulation. This taxon resembles *F. lenoirensis* (Swain and Brown, 1964, 1972) but maintains a generally shorter length and a less angular shape. Specimens in southwest Utah have been recovered only from the *Sciponoceras gracile* and *Neocardioceras juddii* ammonite biozones from the Dakota Formation (Fossil Assemblage B).

Fossocytheridea posterovata Lankford, 1953
Fig. 11A–C

Remarks: This taxon resembles *Sarlatina merlensis* (Babinot and Colin, 1976) in its general shape but is easily recognized by the elongate carapace and swollen posterior observed in dorsal view. Lankford (*in* Peterson et al., 1953) described this species from Turonian coal-bearing strata of the Frontier Formation in northeastern Utah and western Wyoming. In southwestern Utah, this species occurs exclusively in the Straight Cliffs Formation (Fossil Assemblage C).

Family Cytheruridae
Eucytherura n. sp.
Fig. 10G

Remarks: Species assigned to this genus are common to Cretaceous strata (Weaver, 1982), and this new taxon is confined to the capping marlstone unit of the Dakota Formation (Fossil Assemblage B').

Cytheropteron n. sp.
Fig. 11D, E

Remarks: Neale (1962) described morphologically similar taxa from the Cretaceous of Britain that he assigned to the genus *Cytheropterina.* This new species we assign to *Cytheropteron* because of the distinct caudal process, ventral alae, and convex dorsal margin and hingement. In southwestern Utah, this taxon occurs in relative abundance in the Straight Cliffs Formation (Fossil Assemblage C) with *F. posterovata* and a rich assemblage of foraminifera.

Looneyella n. sp. 1
Fig. 11F, G

Remarks: Peck (1951) described species of *Looneyella* from the Albian Bear River Formation in Utah. This new species maintains the same general shape, hingement, and nodation of the genus. In southwest Utah, specimens occur exclusively in the Straight Cliffs Formation (Fossil Assemblage C) associated with *Cytheropteron* and *F. posterovata*.

Looneyella n. sp. 2
Fig. 11H

Remarks: this taxon is similar to and occurs exclusively with *Looneyella* n. sp. 1 but differs in an absence of nodes.

Cytheromorpha spp.
Figs. 10H

Remarks: *Cytheromorpha* is an estuarine genus that is common in Cretaceous strata (Andreu and Ettachfini, 1994). Specimens have been identified from both the uppermost Cenomanian Dakota Formation (Fossil Assemblage A—*Neocardioceras juddii* ammonite biozone) and the westernmost middle Turonian Straight Cliffs Formation (Fossil Assemblage C) at Maple Canyon and as far west as the Pine Valley Mountains (New Harmony).

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