

CENOMANIAN–TURONIAN COASTAL RECORD IN SW UTAH, U.S.A.: ORBITAL-SCALE TRANSGRESSIVE–REGRESSIVE EVENTS DURING OCEANIC ANOXIC EVENT II

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ABSTRACT: The Cenomanian–Turonian interval of the Sevier foredeep, western U.S.A., is examined in order to (1) establish a high-resolution stratigraphic framework for marginal-marine strata of this interval and (2) test for the existence of high-frequency (tens of kyr-scale) cycles of continental runoff or sea-level change predicted by the hemipelagic record and climate models. High rates of sediment accumulation in marginal-marine environments of southwestern Utah (up to 210 m/Myr, compacted) and a northward translation of the major Sevier thrusting made possible the preservation of a highly detailed record of shoreline movements. The coeval Bridge Creek Limestone, linked with the study interval using biostratigraphic and bentonite-stratigraphic data of previous authors, provides an unprecedented, high-resolution orbital time scale. Three orders of transgressive–regressive cycles defined as genetic sequences are identified in the upper Cenomanian (*S. gracile* and *N. juddii* Zones) through lower Turonian (*W. devonense* through *M. nodosoides* Zones). The longest sequence (*S. gracile* Zone through *V. birchbyi* Zone) spans approximately 800 kyr and is penecontemporaneous with the $\delta^{13}\text{C}_{\text{org}}$ positive excursion that defines Oceanic Anoxic Event II (OAE II). Medium-term and short-term sequences show durations of c. 65–160 kyr and c. 20–40 kyr, respectively. Features suggesting regression due to relative sea-level fall are described from some of the 20–40 kyr cycles in the lowermost *S. gracile* Zone (possibly including the uppermost *M. mosbyense* Zone). The data provide the first physical evidence globally of Cenomanian–Turonian changes in shoreline position and relative sea level, whose recurrence interval was as short as a few tens of kyr. These processes provide a viable depositional link between the rhythmic deposition of the Bridge Creek Limestone and the primary orbital forcing of insolation and climate. Although the possible tectonic influence is difficult to unravel, the study area represents an important reference point for climate and oceanographic modeling of the Cenomanian–Turonian greenhouse and OAE II.

INTRODUCTION

The Cenomanian–Turonian interval is considered part of the middle Cretaceous greenhouse, which experienced elevated atmospheric CO_2 levels (e.g., Barron and Washington 1985), warm climate with a low latitudinal temperature gradient and possible absence of polar ice (e.g., Barron 1983; Herman and Spicer 1997; Frakes 1999; Huber et al. 2002). Hemipelagic records (e.g., the Bridge Creek Limestone; Meyers et al. 2001) and numerical modeling (DeConto and Pollard 2003; Floegel et al. 2005) suggest that, in spite of the equable background climatic conditions, the middle Cretaceous climate responded sensitively to changes in insolation driven by the Milankovitch orbital cycles. The role of these climatic cycles in triggering or modulating Cenomanian–Turonian events such as the global oceanic anoxic event OAE II (e.g., Schlanger et al. 1987) or marine extinctions (Kauffman 1984; Elder 1991) via, for example, changes in nutrient upwelling and/or freshwater fluxes, remains an appealing possibility (e.g., Arthur and Premoli-Silva 1982). Examination of these potential links, however, suffers from the lack of geological data. Continental and marginal-marine records, which bear evidence of changes in weathering, vegetation cover, atmospheric CO_2 levels, continental runoff, and sea level, could provide important clues if placed in a high-resolution temporal framework. The Cenomanian–Turonian deposits of southwestern Utah (Figs. 1, 2) provide an excellent opportunity to fill this

gap in data for two reasons. First, high rates of tectonic subsidence and sediment input (e.g., Pang and Nummedal 1995; Eaton et al. 2001; Laurin 2003) resulted in an expanded, and thus detailed, record of nonmarine through nearshore sedimentation. Second, a high-resolution biostratigraphic and bentonite-stratigraphic framework (Elder 1985, 1991; Elder and Kirkland 1985; Elder et al. 1994) can be used to link the marginal-marine strata with the coeval, Milankovitch-driven hemipelagic rhythmites (Gilbert 1895; Fischer 1980; Sageman et al. 1997; Meyers et al. 2001). Such a linkage makes it possible to apply an orbitally tuned time scale (Meyers et al. 2001; Sageman et al. 2006) to the marginal-marine setting.

This paper tests the limits of temporal resolution of the middle Cretaceous marginal-marine depositional changes by developing a detailed genetic-stratigraphic framework for the Cenomanian–Turonian interval of southwestern Utah and linking this framework with the orbital time scale of the Bridge Creek Limestone. Transgressive–regressive cycles and meter-scale changes in relative sea level are interpreted with the temporal resolution of tens of kyr, thus providing the first opportunity to examine the hypothesis of precession-driven changes in the local continental runoff (Floegel et al. 2005) and sea level. Variations in the volume of high-altitude ice responsible for the hypothesized runoff changes represent an important prediction of high-frequency glacioeustasy during the greenhouse (e.g., Miller et al. 2003).

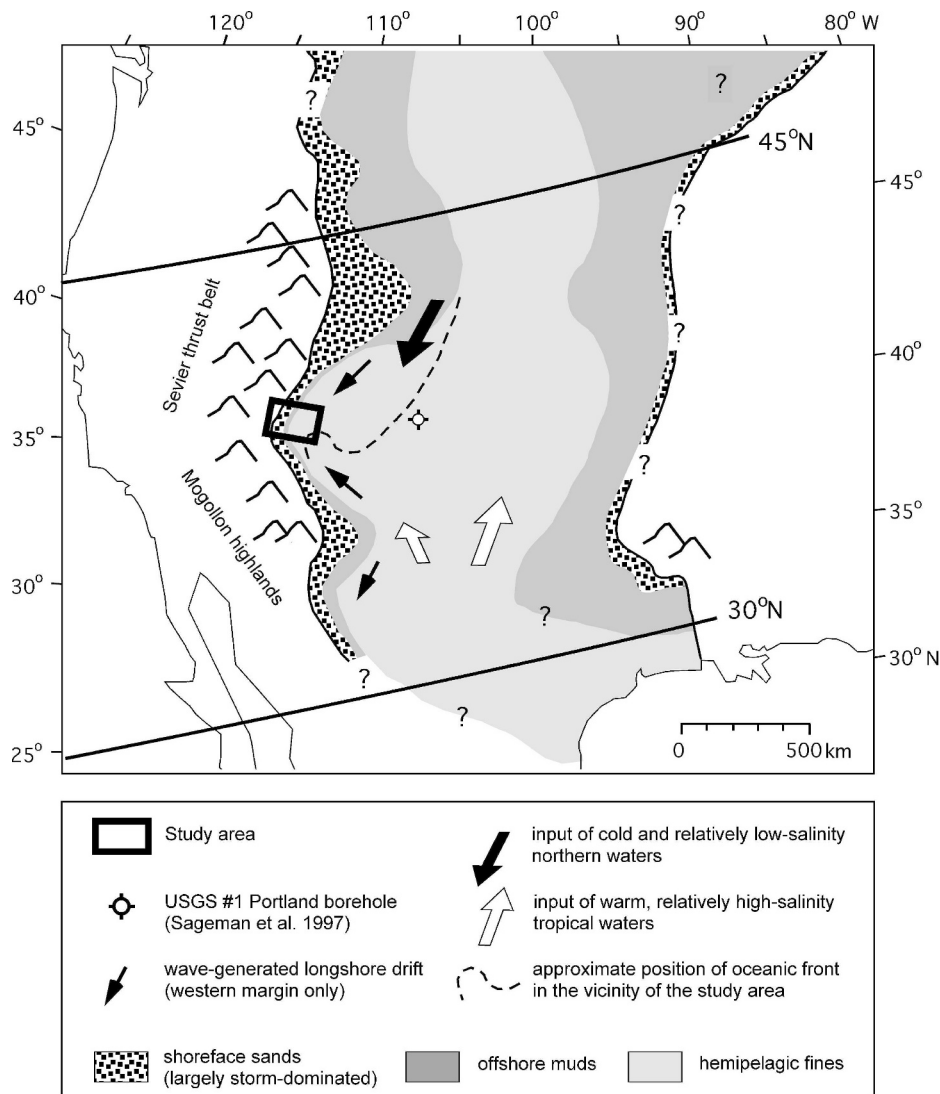


FIG. 1.—Paleogeography of part of the Western Interior Seaway during the latest Cenomanian (after Sageman and Arthur 1994; Roberts and Kirschbaum 1995). Location of the study area, paleolatitude, major circulation patterns (based on Eicher and Diner 1989; Fisher et al. 1994; Slingerland et al. 1996; Leckie et al. 1998; Slingerland and Keen 1999), and probable pathways of sediment redistribution (cf. Johnson 1956; Gustason 1989) indicated.

GEOLOGIC BACKGROUND

The Western Interior basin (Fig. 1) formed as a retro-arc foreland basin on thermally mature lithosphere of the North American craton (e.g., Angevine and Heller 1987; Bally 1989), above the generally eastward-subducting Farallon plate (e.g., Cross 1986). Flexural loading by the Sevier fold-and-thrust belt might have combined with dynamic loading (cf. Mitrovica et al. 1989; Beaumont et al. 1993) and intraplate compression (cf. Peper et al. 1995) to produce a broad basin, whose Aptian through middle Campanian sedimentary record locally exceeds 3 km in thickness (Dyman et al. 1994). The general pattern of westward increase in subsidence was modulated, on a smaller scale, by localized intrabasinal faulting and folding related to intraplate stress variations (e.g., Laferriere and Hattin 1989; Heller et al. 1993), forebulge uplift and local extension due to flexural loading or in-plane compression (cf. Bradley and Kidd 1991; Peper et al. 1995; White et al. 2002), and eastward approach of the thrust belt (e.g., DeCelles and Giles 1996). Pre-existing basement structures (Fig. 2) have probably been involved in the deformation (Picha 1986; Schwans 1995; Gardner 1995a, 1995b).

The study area overlaps with one of the major depocenters of the Cenomanian through Turonian foredeep (Fig. 3; Pang and Nummedal 1995). The westernmost exposures are immediately adjacent to the Hurricane fault, which might have originated as one of the younger Sevier

thrusts (Ersine 2001). The central and eastern parts of the study area are dissected by two major, north-northwest-trending, westward-dipping normal faults (the Sevier and Paunsaugunt faults; Fig. 2), which might have accommodated a significant portion of syndepositional brittle deformation of the proximal foreland (e.g., Gustason 1989; Eaton and Nations 1991). Unlike other proximal-foredeep deposits, the study area has not undergone significant postdepositional deformation and erosion probably because of northward translation of the major Sevier thrusting during the Turonian (cf. Pang and Nummedal 1995).

APPROACH AND TERMINOLOGY

This study is based on outcrop and subsurface (both well log and core) data from the Markagunt, Paunsaugunt, and Kaiparowits plateaus (Fig. 2). Following a discussion of terminology for stratal packages and bounding surfaces (Fig. 4), the presentation of data proceeds in a succession of cross sections with increasing “proximal to distal” scale starting with the most proximal outcrop localities of the foredeep (Cedar Canyon and Kanarra Mountain areas; Figs. 5–8). The next panels of outcrop measured sections and well-log data (Figs. 9, 10) extend from Cedar Canyon to the eastern part of the Markagunt Plateau. A correlation across the Paunsaugunt and Kaiparowits plateaus is stored in the JSR Data Archive (item DA-1, see Acknowledgments section). The

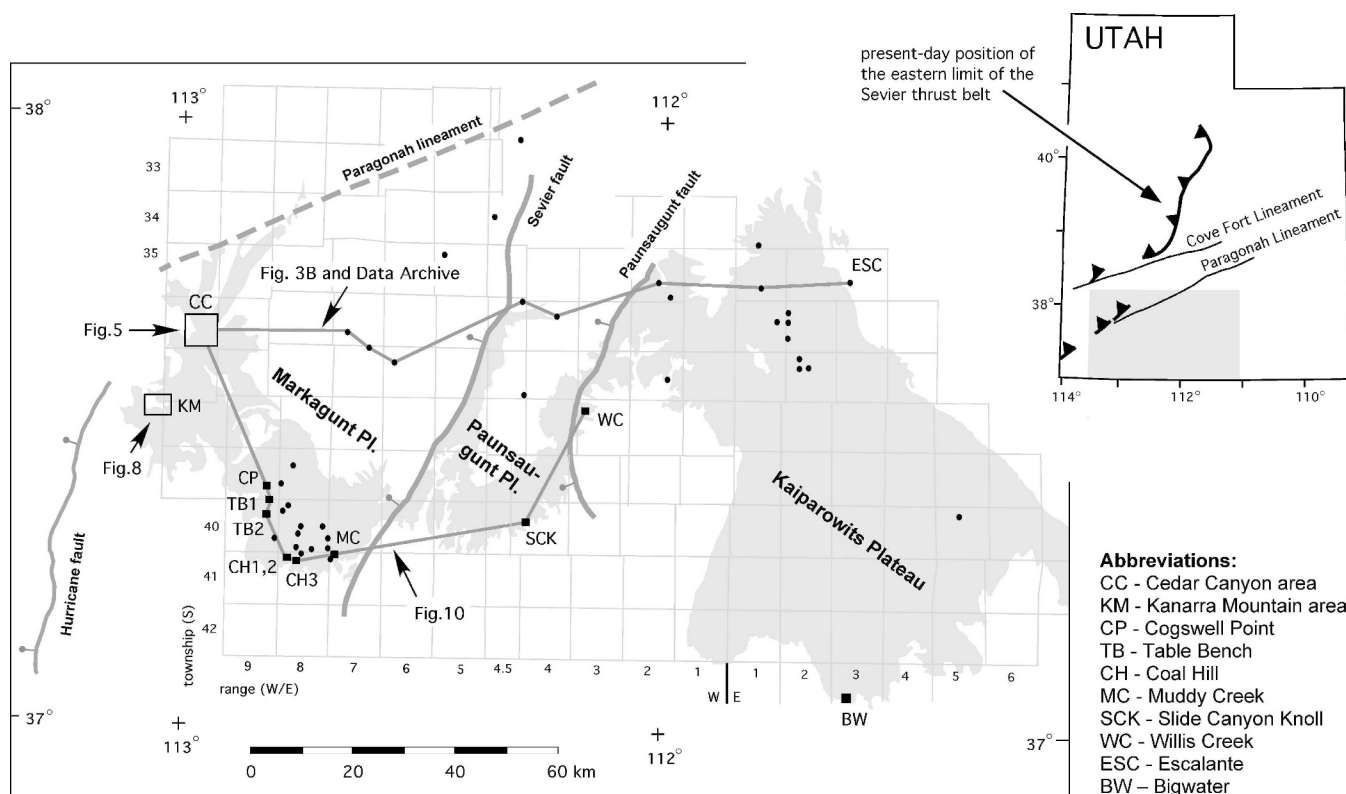


FIG. 2.—Location map of the area of study modified from Geologic map of Utah (Hintze 1980). Position of structural features after Picha (1986). Boreholes are shown as circles, measured sections and field areas as rectangles. Barbs on upthrown hanging wall, and bars with balls on downthrown hanging wall.

final cross section (Fig. 11) traces stratigraphic units from the Kaiparowits Plateau to the Bridge Creek Limestone of central Colorado and links the study interval with the orbital time scale of Meyers et al. (2001).

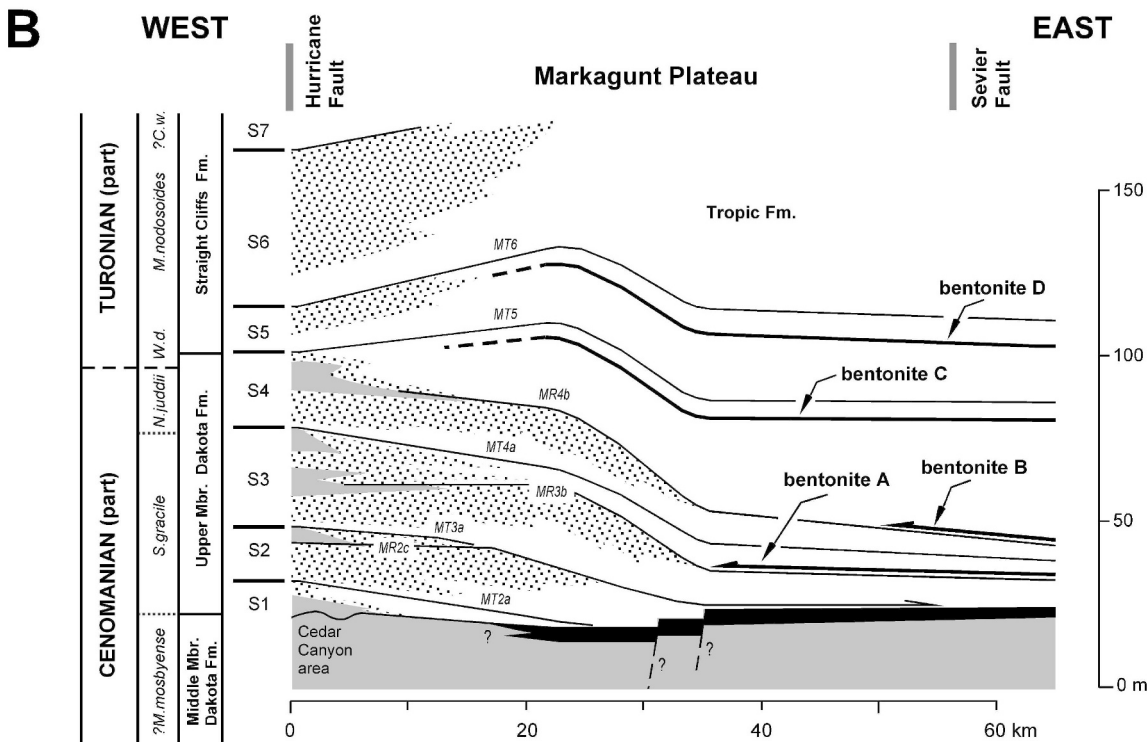
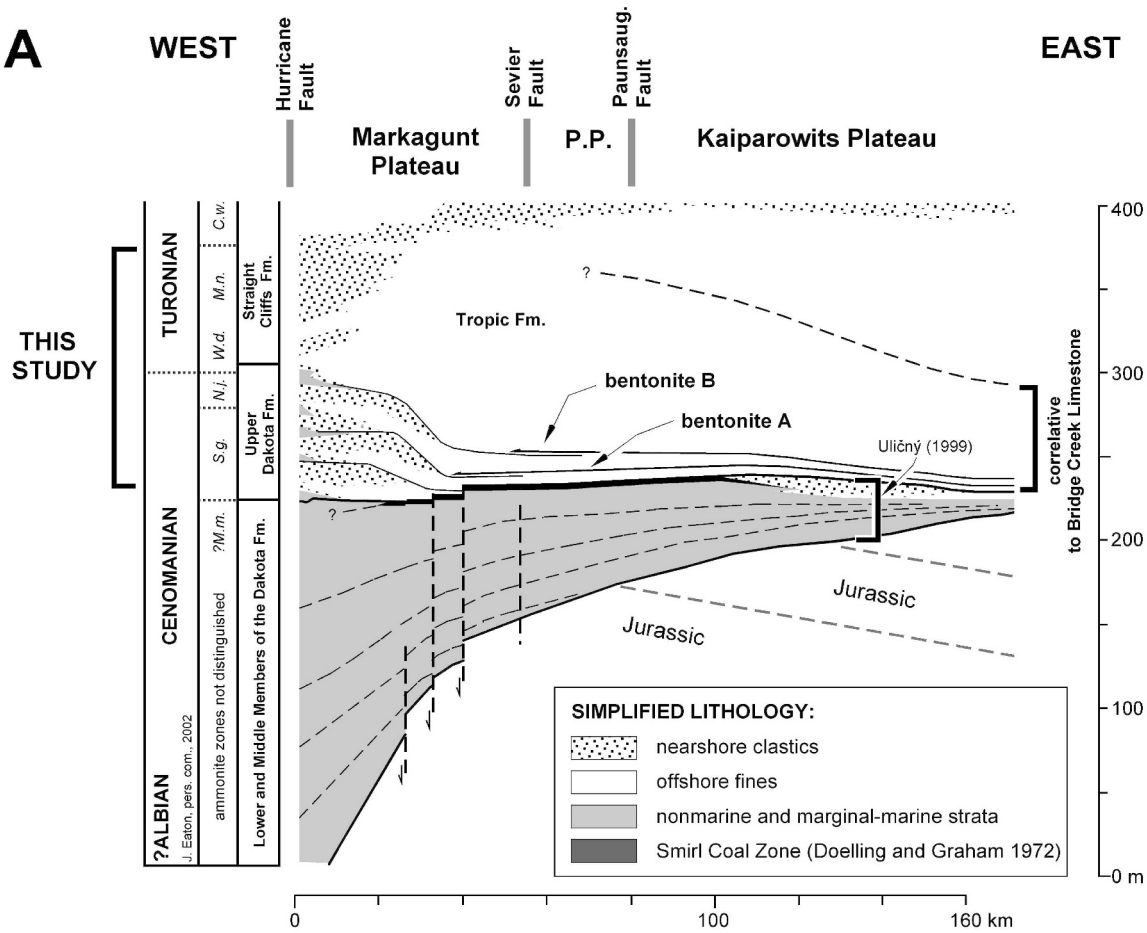
Examination of sedimentary structures and textures, combined with analysis of depositional geometries where possible, were used to interpret depositional environments and to identify the key stratigraphic surfaces. Because the field exposures are typically discontinuous due to extensive plant cover in the area, the individual surfaces and depositional packages could not be traced physically for kilometer-scale distances. The individual measured sections were therefore correlated based on (1) identification of distinct facies associations that appeared to be laterally extensive (e.g., coal zones and lagoonal limestone successions), and (2) analogies in vertical facies stacking. Biostratigraphic data (e.g., Elder et al. 1994; Tibert et al. 2003) were also used to constrain the stratigraphic correlations wherever possible.

The concept of shoreline trajectories of Helland-Hansen and Gjelberg (1994) and Helland-Hansen and Martinsen (1996) appears to be the most efficient tool for description and subdivision of the study interval because of its relatively simple applicability and a lack of connotation with any particular forcing mechanisms. Maximum transgressive surfaces (*sensu* Helland-Hansen and Martinsen 1996) can be correlated with the highest confidence through the nearshore and marginal-marine facies of the study area, and are therefore used to subdivide the stratigraphic succession into packages of genetically linked strata. These packages are termed here genetic sequences (*sensu* Galloway 1989), and each genetic sequence is subdivided into regressive systems tract and transgressive systems tract (*sensu* Helland-Hansen and Martinsen 1996). Three orders of genetic sequences are recognized in the study interval.

The highest-order, or short-term sequences, are delineated most clearly in the proximal localities. They are bounded by maximum transgressive (MT) surfaces that are placed at the bases of beds representing maximum

landward shifts of facies (Fig. 4). These surfaces represent the turnaround from strata deposited during landward shoreline migration (transgressive systems tract) below to strata deposited during basinward shoreline migration (regressive systems tract) above. Packages of marginal-marine strata contained within consecutive maximum transgressive surfaces may contain clearly defined subaerial unconformities (SU; Fig. 4A). These surfaces, conceptually similar to Type 1 sequence boundaries *sensu* Van Wagoner et al. (1988), separate regressive strata deposited during downward shoreline migration (relative sea-level fall) below from regressive strata deposited during upward shoreline migration (relative sea-level rise) above. They are placed at pedogenically leached horizons or subaerial incision surfaces with meters of relief (see Discussion for detailed interpretation). In most cases, however, short-term sequences do not contain well-developed subaerial unconformities because of a lack of downward shoreline migration (no relative sea-level fall; Fig. 4B) or a lack of evidence for such a migration. Herein we use the descriptive term subaerial-exposure (SE) surface to refer to surfaces within regressive systems tracts that bear evidence of subaerial exposure of previously subaqueous strata, but do not contain apparent evidence for relative sea-level fall. The purpose of identifying these surfaces is to highlight the potential records of relative sea-level fall for future research. The boundary between a regressive systems tract below and a transgressive systems tract above is typically impossible to pinpoint in the proximal localities but is assumed to postdate (rarely coincide with) the subaerial unconformity and subaerial-exposure surface and predate or coincide with the onset of marine sedimentation in a particular sequence (Fig. 4; cf. Helland-Hansen and Martinsen 1996).

In the shoreface to offshore facies, the boundary between a regressive systems tract below and a transgressive systems tract above is clearly defined by a maximum regressive (MR) surface that marks the onset of landward shoreline trajectory and typically postdates formation of the



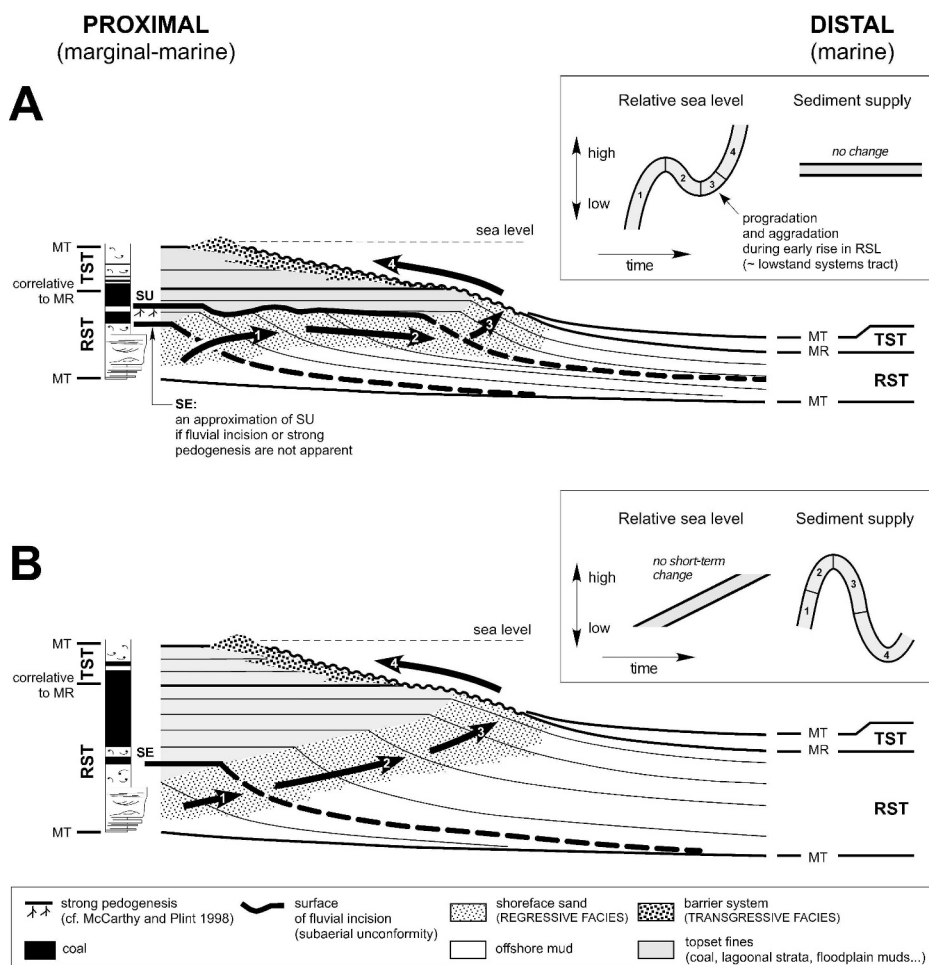


FIG. 4.— Illustration of the internal geometries and facies of genetic-stratigraphic sequences, and along-dip changes in the nature of selected bounding surfaces used in this study: SU = subaerial unconformity, SE = subaerial-exposure surface, MT = maximum transgressive surface, MR = maximum regressive surface; modified after Helland-Hansen and Martinsen (1996). **A**) Sea-level-dominated scenario, **B**) supply-dominated scenario (*sensu* Thorne and Swift 1991). MT surfaces are relatively well distinguishable in both proximal and distal settings, and are therefore used to informally subdivide the study interval and link the marginal-marine and marine successions in the study area. See text for details.

subaerial unconformity and subaerial-exposure surface (Fig. 4). The sedimentary package bounded by the subaerial unconformity below and maximum regressive surface above is equivalent to a lowstand systems tract of Van Wagoner et al. (1988). The basinward expression of a genetic sequence is often that of a single upward-coarsening package bounded above by a surface in which the maximum regressive and maximum transgressive surfaces coalesce due to offshore sediment starvation. These packages conform to parasequences *sensu* Van Wagoner et al. (1988). We avoid use of the term parasequence, however, because in a transect linking coeval nonmarine through marine systems, parasequence appears to represent only a relic expression of a complete genetic sequence (its basinward expression with the transgressive systems tract condensed; Fig. 4). Transgressive and regressive stacks of the short-term sequences define transgressive and regressive systems tracts of medium-term sequences, which in turn stack into a long-term sequence.

The terms “short-term, medium-term, and long-term” have a relative meaning only. Labels S1 through S7 are used for the medium-term sequences. The short-term sequences are referred to as S1a, S1b, S1c, S2a,

S2b, etc. according to their position in the medium-term sequences. The maximum transgressive surfaces are labeled based on the overlying sequence (e.g., MT1b marks the base of sequence S1b). The maximum regressive surfaces (MR1a, etc.), subaerial unconformities (SU1a, etc.) and subaerial-exposure surfaces (SE1b, etc.) adopt their numbers from the short-term sequence they are contained in.

The study area overlaps with the study area of Gustason (1989) and Elder et al. (1994). Our correlations agree with those of Gustason (1989) and Elder et al. (1994) at the scale of ammonite zones, but detailed integration of well-log data with new outcrop information allowed us to refine sub-zone genetic relationships. In addition, our research benefited from recent biostratigraphic data of Tibert et al. (2003). Correlation in the offshore settings was based mainly on bentonite and limestone marker beds (a method used originally by Elder 1985 and Zelt 1985; see also Elder 1991, Elder and Kirkland 1985, Gustason 1989, and Elder et al. 1994).

Shoreface through offshore depositional zones are understood in the sense of McLane (1995). Where possible, storm-dominated coastal environments were subdivided into swash, surf, and breaker zones following Davis (1985).

FIG. 3.—**A**) Transect across the proximal part of the Sevier foreland in southwestern Utah. The intervals of this study and the study of Uličný (1999) indicated (after Kirschbaum and McCabe 1992). Data from Cashion (1961), Averitt (1962), Peterson (1969), Kauffman et al. (1987), Tibert et al. (2003), Elder (1985), and this study. **B**) Simplified stratigraphy of the study interval. Medium-term genetic sequences (S1–7) and selected maximum transgressive (MT) and maximum regressive (MR) surfaces indicated. The top of the Upper Member of the Dakota Formation is placed at the top of sequence S4 following Tibert et al. (2003), although the sandstone facies of sequence S4 correspond to the Straight Cliffs Formation as noted earlier by Averitt (1962). Abbreviations: P.P. = Paunsaugut Plateau. Chronostratigraphic zones: M.m. = *Metoicoceras mosbyense* Zone, S.g. = *Sciponoceras gracile* Zone, N.j. = *Neocardioceras juddii* Zone, W.d. = *Watinoceras devonense* Zone; M.n. = *Mammites nodosoides* Zone, C.w. = *Collignonoceras woollgari* Zone.

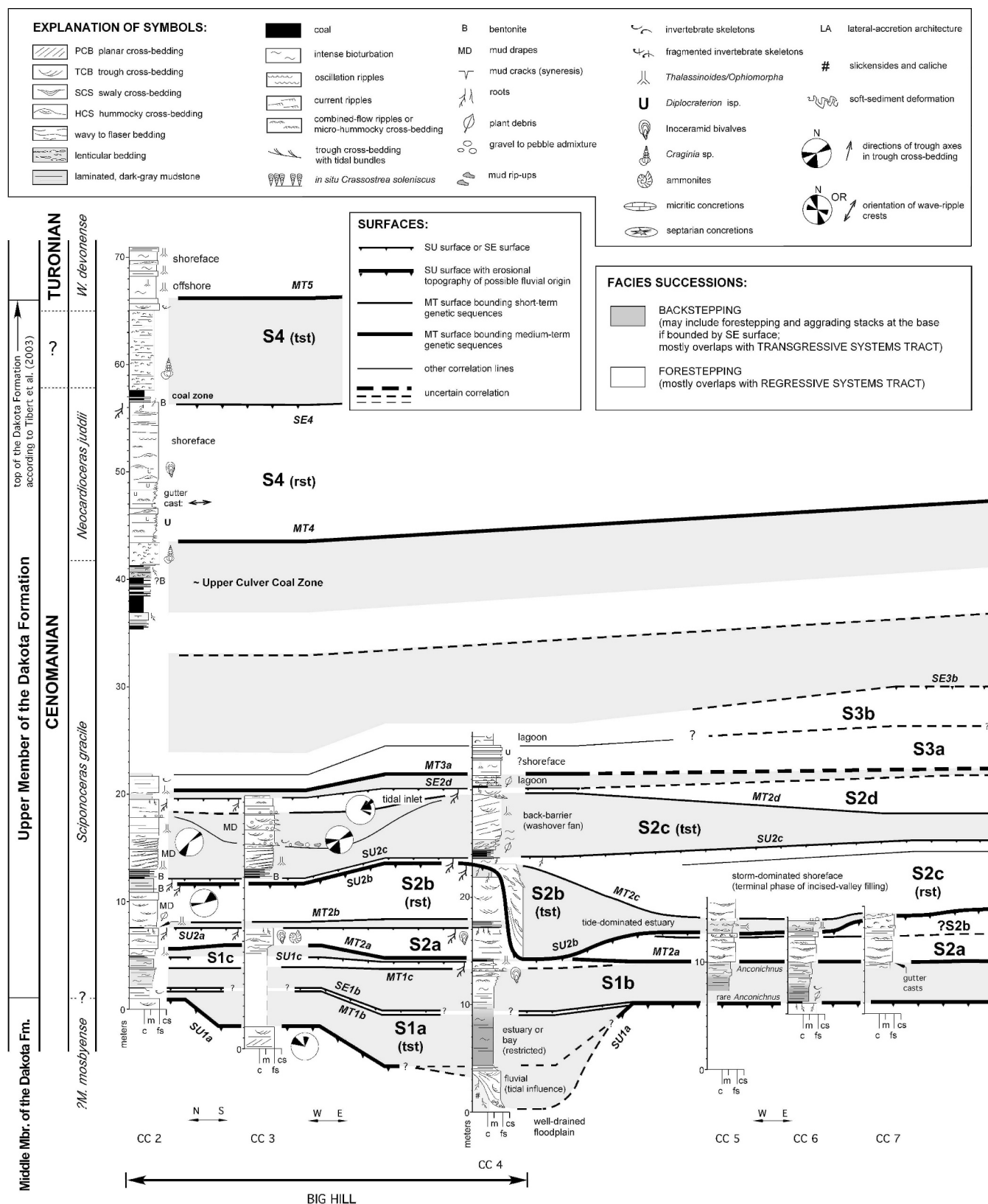


FIG. 5.—Description, interpretation, and correlation of genetic sequences of the Cedar Canyon area. The cross section is not strictly parallel to the local depositional dip (the shoreline trended generally north-northeast; Laurin 2003). Subaerial surfaces (SU and SE) and maximum transgressive surfaces (MT) are labeled after the enclosing and overlying sequences, respectively. Note that the tops of regressive systems tracts (rst) and bases of the transgressive systems tracts (tst) are approximate, because surfaces of maximum regression are not distinguishable in this proximal zone (see text and Fig. 4 for details). Lithology of sequences S6 and S7 is shown in Figure 8. Biostratigraphy is adopted from Tibert et al. 2003 (see Data Archive item DA-5d).

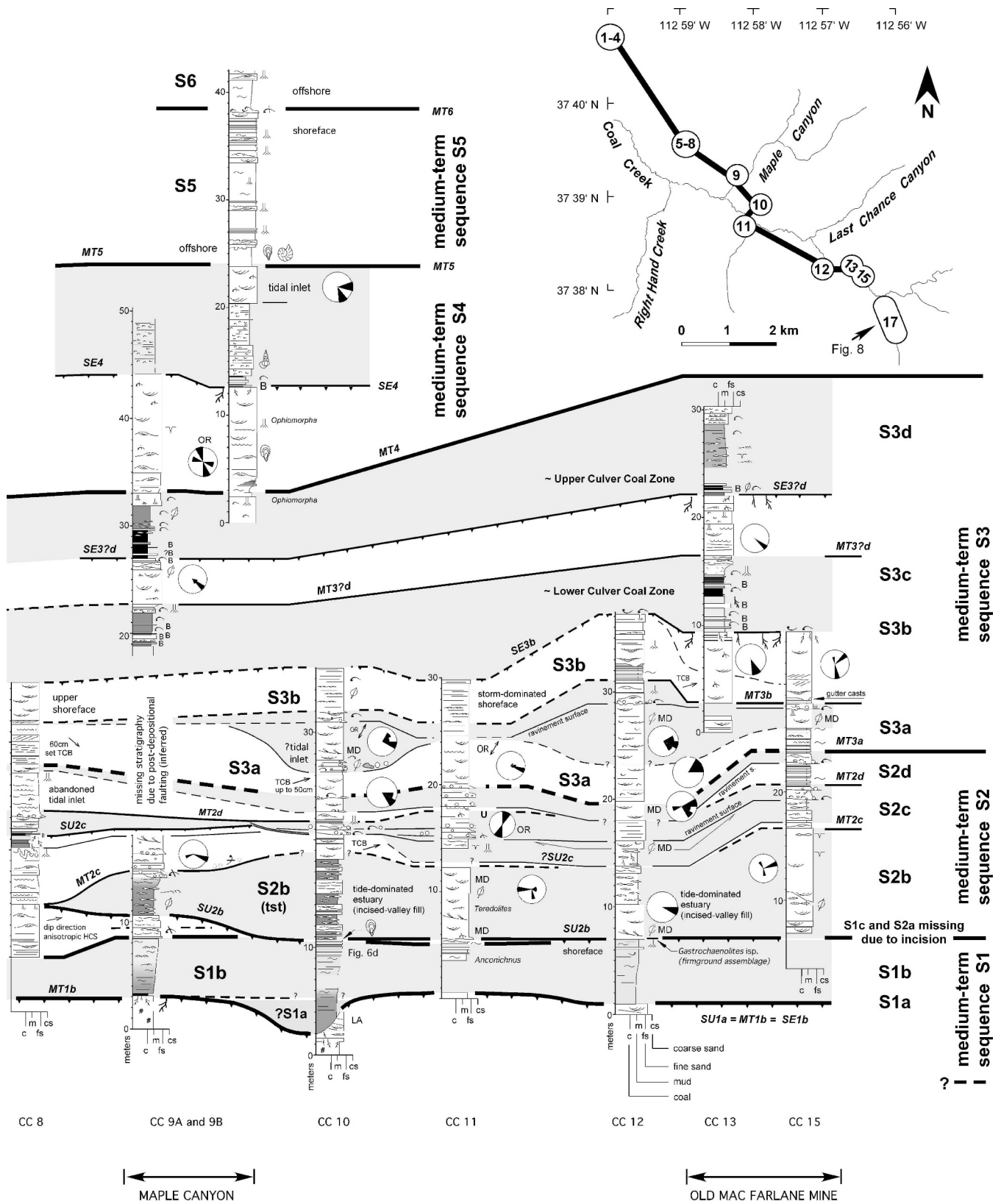
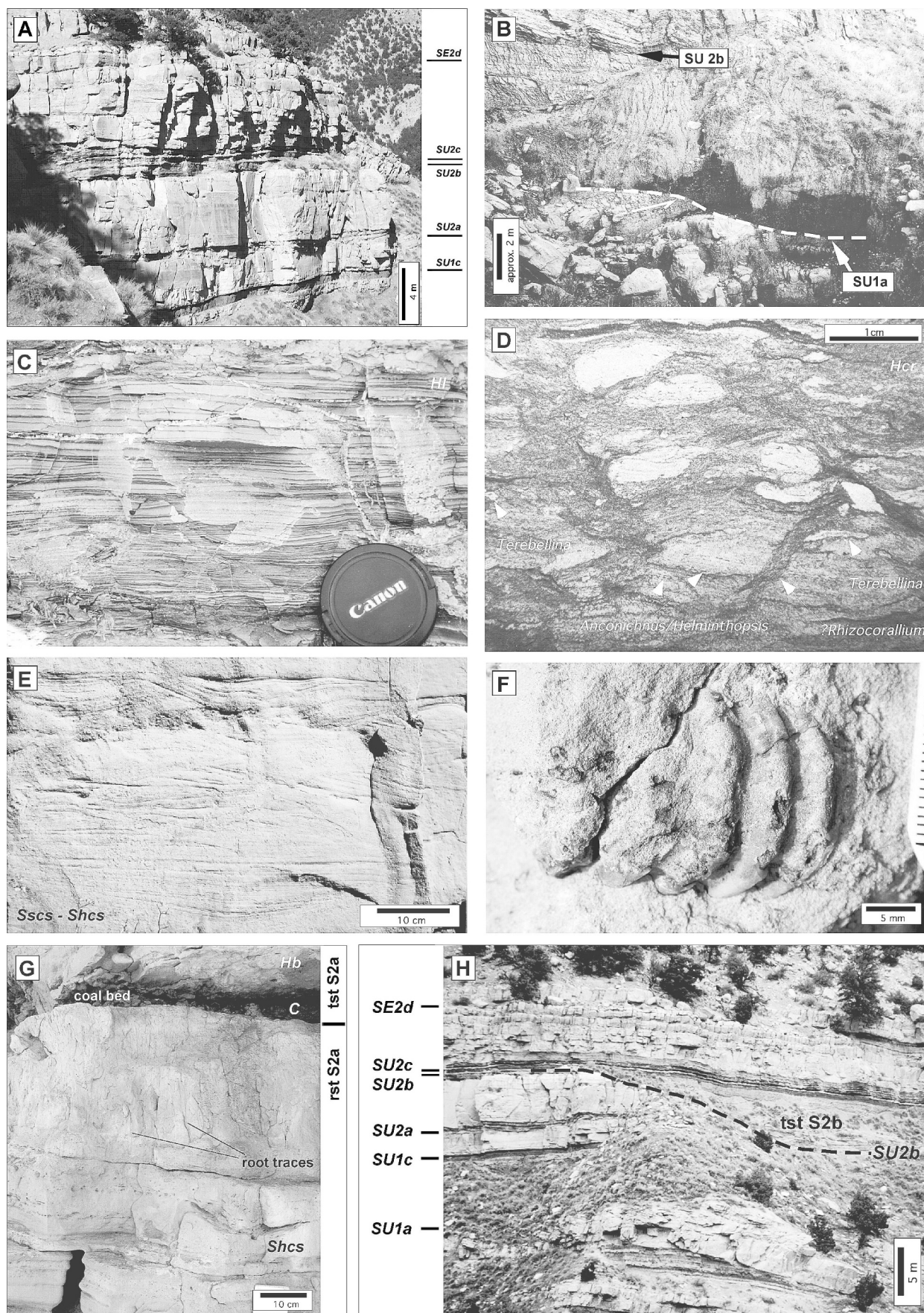


FIG. 5.—Continued.



RESULTS: SEDIMENTOLOGY AND GENETIC STRATIGRAPHY

Facies of the study area are described and interpreted in Table 1. The main focus of the following text is the marginal-marine succession of the proximal foredeep (Figs. 5–8) because these strata provide the most sensitive record of transgressive-regressive and relative sea-level fluctuations. Descriptions and interpretations of each medium-term sequence of the proximal foredeep are given separately, but it should be noted that the “descriptive” part is not free of a primary interpretation of the genetic-stratigraphic context. A strictly descriptive approach would prevent subdivision of the text and make the paper excessively long. Shallow-marine through hemipelagic equivalents of the marginal-marine strata are interpreted for each sequence. Enlarged stratigraphic sections, outcrop and borehole locations, and paleogeographic maps are available from the JSR Data Archive (see Acknowledgments section for URL of Data Archive).

Genetic Sequence S1

Proximal Foredeep—Description.—Paralic strata of the Cedar Canyon and Kanarra Mountain areas rest on rooted and caliche-bearing floodplain deposits and sand-filled fluvial channels of the Middle Member of the Dakota Formation. The paralic strata are separated from the Middle Member of the Dakota Formation by a sharp, locally erosional surface (Figs. 5, 6B). The apparent erosional topography ranges up to 5 m (Big Hill area; Fig. 5) and is filled with dark gray, thinly laminated mudstones (facies Mc and Mf) and micro-burrowed mudstones with silt laminae (facies Hl) that are locally (at well-exposed sites) capped by a coal bed. This package is overlain by a gradational succession of (in ascending order) dark, laminated mudstones (facies Mc), micro-burrowed and weakly fossiliferous (*Corbula* sp.) mudstones with silt laminae (facies Hl; Fig. 6C), and burrowed heteroliths with low-wavelength hummocky cross stratification (facies Hcr; Figs. 5, 6D). The succession is capped locally by an inoceramid-bearing lag that passes upward to a thin interval of bioturbated mudstones, coaly mudstones, and coal. Above the coal is a heterolith bioturbated by a monotypic assemblage of *Thalassinoides* (facies Hb). The top of sequence S1 is placed at the surface separating this heterolith from ammonite-bearing, hummocky cross-stratified (HCS) sandstones (facies Shcs; Fig. 5).

Proximal Foredeep—Interpretation.—The basal surface of paralic strata is a subaerial unconformity (SU1a; see Discussion for details). The alluvial strata immediately beneath this surface include a regressive systems tract of sequence S1, although detailed placement of the basal MT surface must await a comprehensive facies and architectural analysis of the alluvial succession.

The SU1a surface is overlain by a record of punctuated transgression of an increasingly higher-energy coast. The transgression started with the low-salinity and poorly oxygenated environment of a semi-enclosed bay and low-energy shoreface, and culminated in a storm-dominated shoreface. The lowermost bay deposits correspond to a transgressive systems tract of short-term sequence S1a. Two short-term sequences (S1b and S1c) including coal-draped surfaces SE1b and SU1c are distinguished above this interval based on repeated facies stacking (Fig. 5; discussion on the origin of SU1c is given below).

Basinward Correlation.—The alluvial Middle Member of the Dakota Formation is capped by a coal zone c. 3 m thick—the Smirl Coal Zone (Doelling and Graham 1972)—in the central and eastern Markagunt Plateau. This coal and a thin package of tidal-flat deposits underlying the base of *Sciponoceras gracile*-age marine mudstones in this area are correlative with the *Metoicoceras mosbyense*-age unit 4 and transgressive systems tract of unit 5 of Uličný 1999 (Fig. 9). They form the medium-term transgressive systems tract of an older, pre-S1 sequence.

Strata attributable to the regressive systems tract of sequence S1 are not present in the central and eastern Markagunt Plateau, but a correlative offshore-shoreface succession offlaps in the westernmost part of the Kaiparowits Plateau (Figs. 10, 11). It is the *mosbyense*-age regressive systems tract of Uličný's (1999) unit 5. The erosional SU1a surface of the proximal foredeep (Figs. 5, 10) is at least partly equivalent to the major sequence boundary identified by Uličný (1999) at the top of his unit 5. Uličný's unit 6A fills the lower parts of the erosional topography in the Kaiparowits Plateau and could be amalgamated in the SU1a surface in the proximal foredeep. Unit 6A can be considered the upper part of the regressive systems tract of sequence S1. Uličný's unit 6B (uppermost *Metoicoceras mosbyense* Zone) backsteps relative to the underlying units and is therefore attributed to the lowermost part of the transgressive systems tract of sequence S1. The unit either precedes or is partly equivalent to sequence S1a of the proximal foredeep.

The onset of marginal-marine strata in the proximal foredeep (sequence S1a) represents a major landward shift in facies and is therefore correlated with another prominent shift in facies—the base of marine mudstones—in the central Markagunt Plateau (the lowermost *Sciponoceras gracile* Zone; Elder et al. 1994). The transgressive stack of sequences S1a through S1c is probably condensed in a thin (< 1 m), upward-fining interval of bioturbated sandy mudstone in the central Markagunt Plateau, and this interval is downlapped in a shell- and bone-bearing lag in the rest of the study area (Figs. 9, 10). This condensation hampers a detailed interpretation of the boundary between the *Metoicoceras mosbyense* Zone and the *Sciponoceras gracile* Zone in the area. Marine sandstones immediately above sequence S1c yielded the ammonite *Metoicoceras defordi* (identification by Bill Cobban, personal communication, 2004),

FIG. 6.—Facies and bounding surfaces of sequences S1a through S3b (upper Cenomanian *S. gracile* Zone) in the westernmost part of the study area (Cedar Canyon). See Figure 5 for lithological descriptions and correlation. **A)** Section CC 4. The westernmost exposures of the Upper Member of the Dakota Formation consist of stacked barrier, back-barrier, and shoreface deposits, which are punctuated by subaerial surfaces (SU and SE) and maximum transgressive surfaces (not apparent on this photograph). **B)** Section CC 10. The contact of floodplain and crevasse-splay deposits of the Middle Member of the Dakota Formation (probably *Metoicoceras mosbyense* Zone) with paralic deposits of the Upper Member of the Dakota Formation (probably lower part of *Sciponoceras gracile* Zone). The surface is overlain by an upward-coarsening succession (facies Mc–Hl–Hcr; Table 1) that is truncated by an incised-valley fill (transgressive systems tract of sequence S2b). **C)** Section CC 6. The bulk of sequence S1b is formed by parallel-laminated, weakly burrowed heteroliths (facies Hl of Table 1) in the western part of the Cedar Canyon area. Small *Anconichnus/Helminthopsis* burrows, which are preferentially associated with silty laminae, represent the only common ichnotaxa; the strata are interpreted as interdistributary-bay deposits. Upper part of sequence S1b. **D)** Section CC 10. Both intensity and diversity of bioturbation of the S1b heteroliths generally increase upwards and towards the east (compare with Part C), suggesting transition towards normal-marine conditions. **E)** Section CC 7. Well-sorted, hummocky and swaly cross-stratified, ammonite-bearing sandstones form the bulk of the regressive systems tract of sequence S2a in the Cedar Canyon area. **F)** Section CC 3. *Metoicoceras defordi* (identification by Bill Cobban, personal communication, 2004) in sequence S2a in Cedar Canyon. **G)** Section CC 3. Storm-dominated-shoreface deposits of the uppermost part of the regressive systems tract of sequence S2a are strongly rooted at the top and overlain by a thin coal bed. The rooted surface is a subaerial unconformity labeled SU2a. **H)** Section CC 4. Surface SU2b displays more than 9 m of erosional relief, in the Big Hill area. The erosional surface, interpreted as a surface of fluvial incision due to relative sea-level fall (see text), is highlighted. The SU1a surface is underlain by fluvial deposits of the Middle Member of the Dakota Formation.

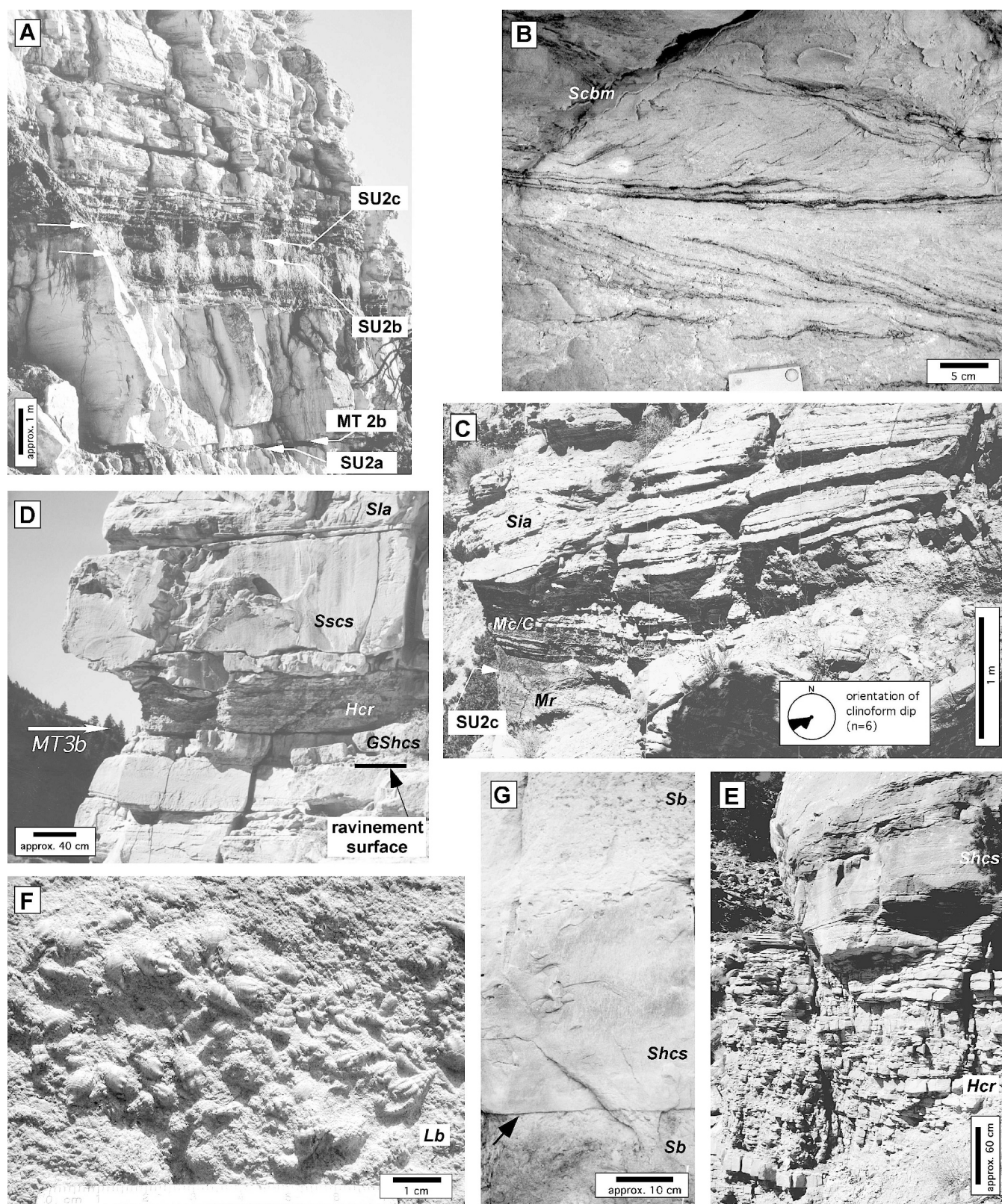


FIG. 7.—Facies and bounding surfaces of sequences S2b through S6 (the uppermost Cenomanian through lower Turonian) in the Cedar Canyon area (Fig. 5). **A)** Section CC 2. Interfluvial representation of surfaces SU2b and SU2c. Transgressive systems tract of sequence S2b and regressive systems tract of sequence S3b are only a few decimeters thick in the interfluvial areas. The surfaces SU2b and SU2c are defined by pedogenically modified, leached mudstones at this site. **B)** Section CC 11. The lower part of the incision topography of surface SU2b is filled with mud-draped trough cross-stratified sandstones (facies Scbm) and sand-mud heteroliths (facies Hle and Hf) that are interpreted as inner-estuary deposits (cf. Allen and Posamentier 1993). **C)** Section CC 2. The transgressive systems tract of sequence S2c is formed by a thick

which is considered a variety of the microconch of *Metoiceras mosbyense* (Cobban et al. 1989). The range of this ammonite in southern Utah is, however, uncertain. It might extend as high as the lowest occurrences of *Vascoceras diartianum*, i.e., the lower part of *Sciponoceras gracile* Zone (Alan Titus, personal communication, 2004). In this study we place the base of the *Sciponoceras gracile* Zone at the base of the transgressive systems tract of sequence S1a for two reasons. First, the facies change across the SU1a surface in Cedar Canyon suggests a major landward shift in facies, which might be analogous to the major drop in siliciclastic sediment accumulation at the base of the Bridge Creek Limestone (Meyers et al. 2001). Second, the transgressive systems tract of sequence S1 exhibits a marked increase in the $\delta^{13}\text{C}_{\text{org}}$ of terrestrial organic matter in the central Markagunt Plateau (Fortwengler et al. 2003). This change corresponds to the onset of more enriched $\delta^{13}\text{C}$ values marking the base of OAE II in the latest *Metoiceras mosbyense* Zone of the central basin (cf. Pratt and Threlkeld 1984; Pratt et al. 1993; Sageman et al. 2006). Such an interpretation implies that the transgressive systems tract of sequence S1a, and sequences S1b and S1c, were coeval with the lower part of limestone LS1 of the Bridge Creek Limestone. However, more biostratigraphic data from the Cedar Canyon area will be necessary to precisely resolve the chronostratigraphic position of sequences S1a through S1c.

Genetic Sequence S2

Proximal Foredeep—Description.—The base of sequence S2 is formed by a 2–3 m thick interval of HCS and swaly cross-stratified sandstones that are interbedded in places with trough cross-stratified, upper-fine to medium-grained sandstones. A fragment of ammonite *Metoiceras defordi* (Fig. 6F) was found in the HCS sandstones. A laterally discontinuous layer of articulated inoceramids (locally shell-supported texture) occurs c. 20 cm beneath the upper surface, which is densely rooted and overlain by a coal bed in the western part of the Cedar Canyon area (Fig. 6G). On top of the coal rest coaly and fossiliferous mudstones and sandstones with a monotypic assemblage of *Thalassinoides* (Fig. 5). This interval is overlain by a 3–4 m thick package of trough cross-stratified sandstones with bimodal paleocurrent directions and reactivation surfaces. Rooted mudstones that cap these strata are punctuated by two distinct leached horizons (Fig. 7A) the lower of which passes laterally to an incision surface that truncates up to 9 m of the underlying strata (including the uppermost part of sequence S1; Figs. 5, 6H). The valley fill is dominated at most study sites by lenticular- through flaser-bedded heterolithic facies and trough cross-stratified sandstones with mud-draped foresets and bimodal to trimodal paleocurrent directions (Figs. 5, 7B). The heterolithic strata are overlain in the Cedar Canyon area by sharp-based, swaly and hummocky cross-stratified sandstones. The upper parts of the valley fill are rooted in places and overlain by leached mudstones of the second leached horizon mentioned above (Fig. 7A). In the western part of the Cedar Canyon area, the leached mudstones are overlain by coals, coaly mudstones, wavy- to flaser-bedded heterolithic facies, and burrowed heterolithic facies (facies C, Mc, Hf and Hb) that grade upward to bioturbated, parallel-laminated

and trough cross-stratified, heterolithic sandstones with distinct, west-southwest-dipping accretion surfaces (facies Sia; Fig. 7C). The sandstones are truncated in places by gravel-based, trough cross-bedded sandstones with bimodal to trimodal paleocurrent directions (e.g., section CC 3; Fig. 5). Bimodal, southwest–northeast-oriented paleocurrents characterize the lower part of this sandstone succession, whereas purely northeastward paleocurrents were found in the upper, less gravelly portion of this unit. The top is rooted. The entire upward-coarsening succession is interpreted to pass eastward (basinward) to a gravel-paved succession of HCS sandstones through heterolithics (Fig. 5). Another package of HCS sandstones locally overlies these heterolithics (e.g., section CC 10; Fig. 5).

The uppermost part of sequence S2 is formed by a succession of coal and fossiliferous mudstone in the western part of the Cedar Canyon area. The upper boundary of sequence S2 is placed at the surface separating this succession from bioturbated, *Diplocraterion*-bearing sandstones (sections CC 2 and 4; Fig. 5). Continuation of these strata to the eastern part of the Cedar Canyon area is uncertain. Similarly to the underlying succession, the coal and fossiliferous mudstones are tentatively interpreted as penecontemporaneous with an interval of gravel-paved HCS sandstones and heterolithics found in the more basinward (eastward) sites of the Cedar Canyon area (e.g., sections CC 11 and 15; Fig. 5).

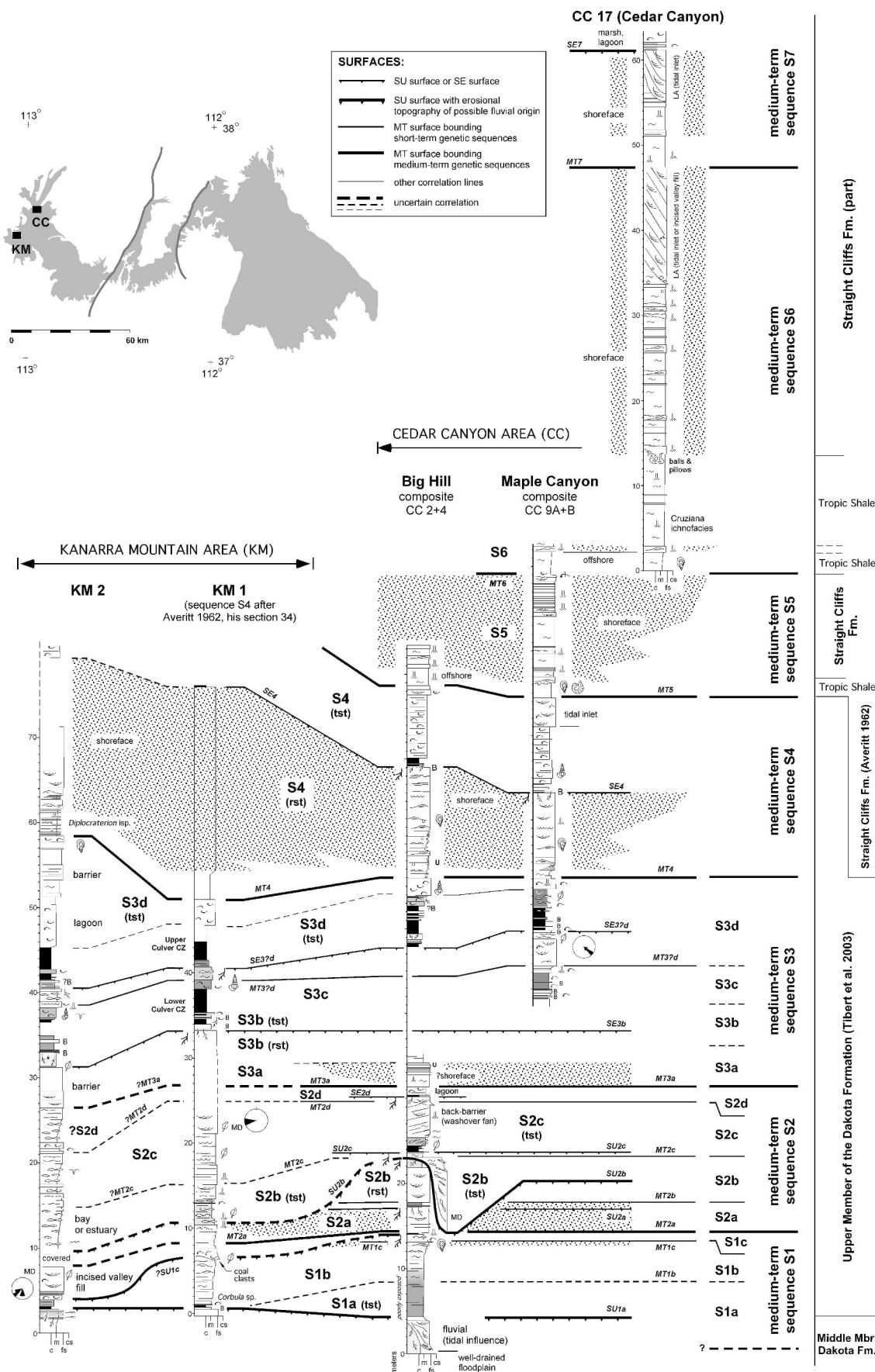
Proximal Foredeep—Interpretation.—Four short-term sequences, S2a through S2d, are recognized based on forestepping and backstepping facies arrangements (Fig. 5). Sequences S2a, S2c, and S2d include coal-capped surfaces SU2a, SU2c, and SE2d. The prominent erosional surface punctuating sequence S2b is labeled SU2b (see Discussion for details on the origin of SU2a, SU2b, and SU2c).

The ammonite-bearing HCS sandstones at the base of sequence S2a are interpreted as storm-dominated shoreface deposits. They mark the turnaround from medium-term transgression to regression. The regressive trend continues with tidal inlet and delta deposits of sequence S2b and culminates in filling of the SU2b incision topography. The valley fill is interpreted as tide-dominated deposits of inner estuary (cf. Allen and Posamentier 1993) that are partly truncated by a ravinement surface and overlain by storm-dominated shoreface deposits (a similar succession was documented by Lessa et al. 1998 from an underfilled, microtidal estuary of the Paranaguá Bay).

The medium-term transgressive trend starts with development of a thick back-barrier succession after a short-term regression of sequence S2c (surface SU2c; Fig. 7A). The inclined, westward-dipping heterolithic strata of sequence S2c (Fig. 7C) are interpreted as transgressive washover fan deposits. They are locally (e.g., section CC 3; Fig. 5) truncated by a tidal inlet. The upward transition from a bimodal, southwest–northeast to a strongly northeast- (i.e., basinward-) dominated paleocurrent regime is interpreted as a shift towards an ebb-tidal-delta setting. The maximum transgression separating sequences S2c and S2d (surface MT2d; Fig. 5) is placed at the base of the ebb-dominated interval. The back-barrier through tidal-inlet succession, capped by a rooted SE2d surface, passes eastward to a transgressive–regressive succession of a storm-dominated shoreface (transgressive systems tract of sequence S2c and regressive

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back-barrier succession in the westernmost part of the Cedar Canyon area. The clinoform package (approx. southwest-dipping accretion surfaces) is interpreted as a washover fan. **D)** Section CC 15. Shoreface succession of the transgressive systems tract of sequence S3a and regressive systems tract of sequence S3b. Hummocky cross-stratified heteroliths mark the maximum transgression between sequences S3a and S3b. They are overlain (sharply, in places) by hummocky and swaly cross-stratified sandstones. Low-angle-stratified sandstones, possibly of swash-platform origin, occur at the top. **E)** Section CC 2. Shallowing-upward shoreface succession of the regressive systems tract of sequence S4. The shoreface deposits of sequences S3b (Part D) and S4 are only scarcely burrowed. In addition, the *Skolithos* and *Diplocraterion* burrows present are apparently dwarfed suggesting stressed conditions possibly due to freshwater input from a proximal fluvial source. **F)** Section CC 9. Strongly fossiliferous lagoonal limestones and mudstones, typically with bioclast-supported fabrics, form the bulk of the transgressive systems tract of sequence S4 in the Cedar Canyon area. **G)** Section CC 17 (Fig. 8). Bioturbated, ammonite-bearing muddy sandstones of the lower part of the regressive systems tract of sequence S6 are punctuated by sharp-based (arrow), parallel-laminated to low-amplitude hummocky cross-stratified sandstone beds.



systems tract of sequence S2d; Fig. 5). Sequence S2d is capped by a transgressive interval of swamp through lagoonal deposits in the western part of the Cedar Canyon area. These back-barrier strata are interpreted to pass eastward (basinward) to ravinement-surface-based shoreface through proximal offshore deposits.

Basinward Correlation.—The foresteping stack of sequences S2a and S2b is correlated with the lower part of the first prominent regressive package of *Sciponoceras gracile*-age offshore through storm-dominated coastal deposits of the central Markagunt Plateau (Figs. 9, 10). The regressive systems tract of sequence S2c is restricted to filling of the SU2b incision topography, suggesting that it predated the medium-term, regional shoreline retreat. It is therefore correlated with the upper part of the offshore through coastal succession of the central Markagunt Plateau (Fig. 10). Sequence S2d represents a marked increase in accommodation in the Cedar Canyon area and is therefore correlated with offshore sandy mudstones that overlie the coastal deposits in the central Markagunt Plateau (Fig. 10).

Well-log data from the Markagunt Plateau (Fig. 9) suggest that the lowermost bentonite of the “A swarm” (labeled bentonite “sub PBC-3” in this paper) overlies the transgressive systems tract of sequence S2. This suggests that the maximum transgression between sequences S2 and S3 (surface MT3a; Fig. 11) slightly precedes Bridge Creek marker bed PBC-3 or LS2.

Genetic Sequence S3

Proximal Foredeep—Description.—The lowermost part of sequence S3 is formed by burrowed (*Diplocraterion* and *Thalassinoides* isp.) sandstones with low-angle-laminated (?HCS) sandstone intercalations in the western part of the Cedar Canyon area (sections CC 2 and 4; Fig. 5). These strata probably pass eastward to trough cross-stratified sandstones with bedsets up to 60 cm thick and occasional reactivation surfaces (mud drapes are typically absent; facies Scb; Fig. 5). The cross bedding indicates mostly southeastward paleocurrent direction. Hummocky cross-stratified heterolithics are found in the most eastward locations (section CC 15; Fig. 5).

The overlying interval is well exposed only in the central and eastern parts of the Cedar Canyon area. Its base, locally erosional (sections CC 10 and 15; Fig. 5), is overlain by mud-draped, trough cross-stratified sandstones. The paleocurrent directions are mostly towards the east. The cross-stratified sandstones are terminated above by a fining-upward succession of gravel- and shell-paved swaly and hummocky cross-stratified sandstones and heterolithics (Fig. 5, 7D). This succession is, in turn, overlain by mud-free, hummocky and swaley cross-stratified sandstones the base of which is marked by gutter casts (section CC 15; Figs. 5, 7D). Low-angle-stratified sandstones (facies Sla) are found locally atop the HCS and swaly cross-stratified sandstones (Fig. 7D). This thick sandstone succession is either amalgamated at the top of the *Diplocraterion*-bearing sandstones in the western part of the Cedar Canyon area (between sections CC 8 and 4; Fig. 5), or it passes to laminated and fossiliferous mudstones that are poorly exposed at the top of section CC 4 (Fig. 5).

The upper surface of the sandstone succession is rooted throughout the eastern part of the Cedar Canyon area and overlain by an up to 3-m-thick

succession of dark gray to black, highly fossiliferous mudstones (facies Mf; Tab 1). These mudstones pass southwestward (Fig. 8) and upward (Fig. 5) to a 1–4 m thick interval of coal and coaly mudstone (Lower Culver Coal Zone of Averitt 1962), which is overlain by dark gray, fossiliferous, sandy mudstones that are lenticular-bedded in places (Fig. 5). The abundance of brackish fossils, density of bioturbation, and sand contents generally increase upward above these mudstones (up to Sf facies). This succession is capped by a sharp-based, fossiliferous, mostly trough-cross-stratified sandstone in the eastern parts of the Cedar Canyon and Kanarra Mountain areas (cf. Averitt 1962, p. 48). The westward correlation of the sandstone is uncertain. In the Kanarra Mountain area it passes laterally to weakly burrowed, current-rippled heterolithic sandstones and mudstones (Fig. 8). The top of this succession is rooted and overlain by a c. 5-m-thick succession including fossiliferous mudstone (lenticular bedded in places), coaly mudstone and coal in both Cedar Canyon and Kanarra Mountain areas. The fossiliferous mudstone is most common in the upper part of this succession, and is overlain by a 1–2 m thick, sharp-based, intensely burrowed, fossiliferous sandstone (facies Sf) in most places (Fig. 8).

Proximal Foredeep—Interpretation.—The lowermost part of this interval is dominated by an ebb-tidal delta, which together with storm-reworked shoreface sandstones and heterolithics forms the regressive systems tract of a short-term sequence S3a in Cedar Canyon. The overlying, erosionally based, mud-draped sandstones are attributable to the active fill of a tidal inlet or creek of the early transgressive systems tract of sequence S3a. No subaerial discontinuity was identified at the base of this transgressive systems tract. The short-term transgression of sequence S3a culminated in deposition of HCS sandstones and heterolithics of a storm-dominated shoreface. The overlying, coarsening-upward succession of hummocky and swaly cross-stratified sandstones preserved in the eastern part of the Cedar Canyon area is interpreted as a regressive, storm-dominated shoreface, and it represents the regressive systems tract of short-term sequence S3b. The shoreface strata are capped by swash-zone deposits (facies Sla). The rooted top of the shoreface through swash-zone deposits is labeled surface SE3b in the eastern part of the Cedar Canyon area. The westward and southward correlation of the SE3b surface is uncertain. The top of the regressive systems tract of sequence S3b either coincides with the SE3b surface or is located in the lagoonal and peat-swamp deposits of the Lower Culver Coal Zone. Short-term genetic sequences were not distinguished in the Lower Culver Coal Zone, but correlation to the central Markagunt Plateau (Figs. 9, 10; see below) suggests that this marginal-marine interval might include one short-term sequence, S3c. The overlying trough-cross stratified sandstones of the eastern part of Cedar Canyon are interpreted as mostly ebb-tidal-delta deposits on the basis of southeastward directed paleocurrents. The base of these sandstones is a short-term MT surface, which is tentatively considered the base of the short-term sequence S3d (best developed in the central Markagunt Plateau; Fig. 10). The overlying lagoonal and peat-swamp deposits of the Upper Culver Coal Zone overlap partly or entirely with the transgressive systems tract of sequence S3d. The terminal transgression of the S3d sequence is best preserved in the southern part of the Kanarra Mountain area (Fig. 8). In more basinward locations, such as the Cedar Canyon area, the marginal-marine record of the retreating shoreline is condensed

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FIG. 8.—Correlation of measured sections of the Cedar Canyon (CC) and Kanarra Mountain (KM) areas. Section KM 1 corresponds approximately to Averitt's (1962) site no. 33. Section KM 2 is located approximately 0.5 km southeastward of Averitt's (1962) site no. 34. Regressive shoreface sands are stippled. Subaerial surfaces (SU and SE) and maximum transgressive surfaces (MT) are indicated. Lithological symbols and detailed stratigraphy of the Cedar Canyon area are shown in Figure 5. Abbreviations: tst = transgressive systems tract; rst = regressive systems tract.

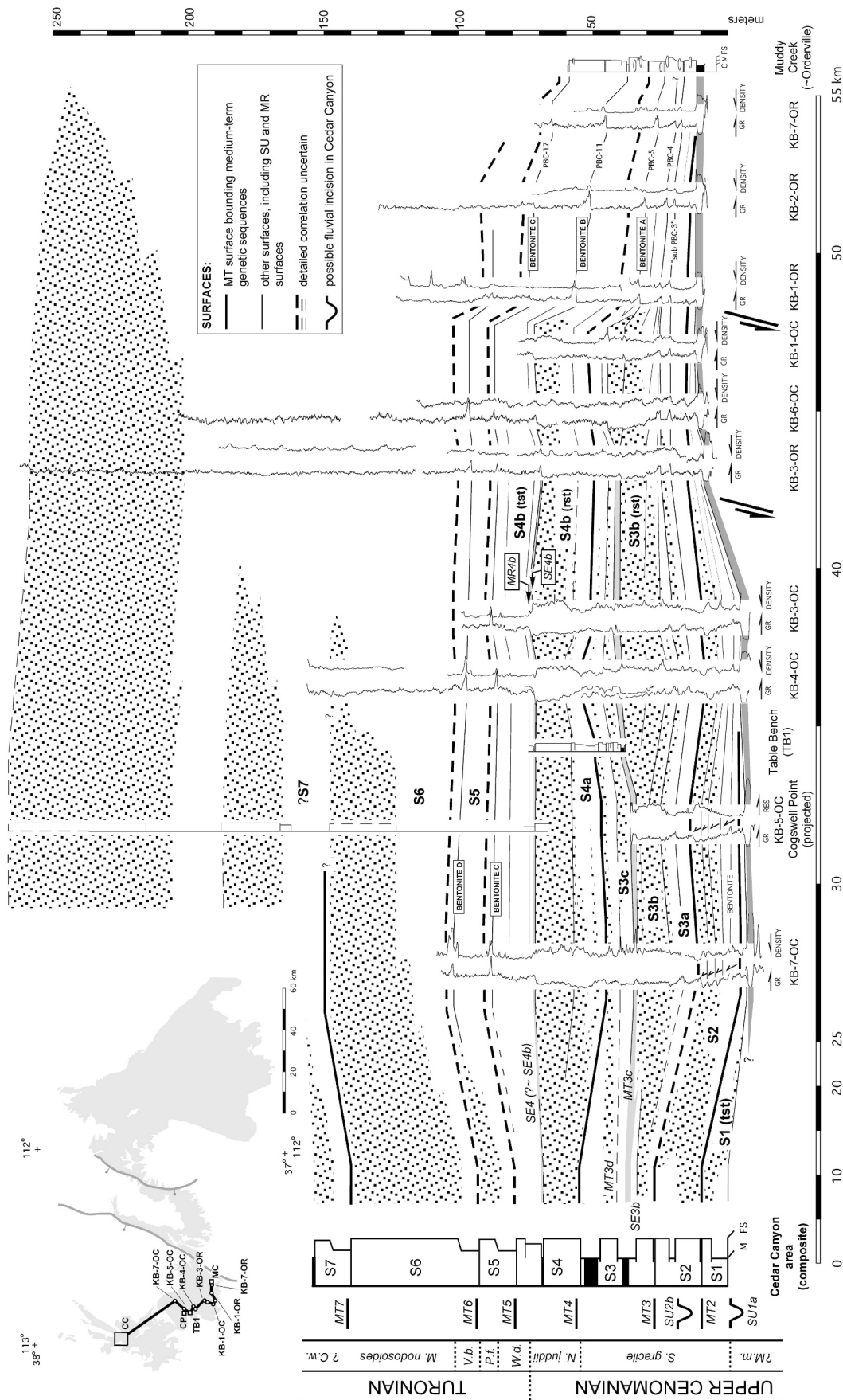
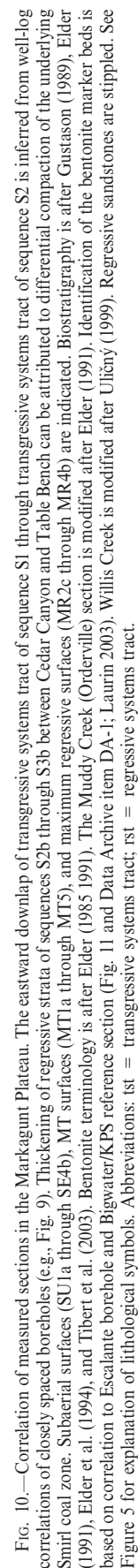


FIG. 9.—Well-log- and outcrop-based section across the Markagunt Plateau (selected data only). The lithological logs are simplified (see Figs. 5 and 10 for details). The Muddy Creek (Orderville) section is modified after Elder (1991). Position of the bentonite A in this section was reinterpreted based on well log-, core-, and outcrop-based correlation to Escalante borehole and Bigwater/KPS reference section (Fig. 11 and Data Archive item DA-1; Laurin 2003). Shoreface sandstones are stippled, coal zones are shown in black. Minor transgressive-regressive cycles in the medium-term sequence S2 are indicated by arrows along the KB-7-OC and KB-5-OC boreholes. Biostratigraphy is after Gustafson (1989), Elder (1991), Elder et al. (1994), and Tibert et al. (2003). Well logs are from Bowers and Strickland (1978). Note that the horizontal scale varies. Abbreviations: SU = subaerial unconformity; SE = surface of subaerial exposure; MT = maximum transgressive surface; rst = transgressive systems tract; rst = regressive systems tract; PBC-3...17 = Bridge Creek marker beds *sensu* Elder and Kirkland (1985); GR = gamma-ray log; RES = resistivity log; C = coal; M = mudstone; FS = fine sandstone; CC = Cedar Canyon; CP = Cogswell Point; TB = Table Bench; MC = Muddy Creek (= Orderville of Elder 1991); M.m. = *Metaceras moshynense* Zone, W.d. = *Watinoceras devonense* Zone; P.f. = *Pseudospidoceras flexuosum* Zone, V.b. = *Vasoceras birchbyi* Zone, C.w. = *Collignoniceras woolgari* Zone. Bentonite "sub-PBC-3" corresponds to the lowermost bentonite layer of the "A swarm." The name refers to its position beneath the Bridge Creek marker bed PBC-3 (*sensu* Elder and Kirkland 1985; see also Hattin 1985).



and poorly preserved due to marine reworking upon continuing shoreline retreat.

Basinward Correlation.—In accordance with biostratigraphic data of Tibert et al. (2003), the regressive interval of sequence S3 (i.e., sequence S3a and regressive systems tract of sequence S3b) is correlated with a major, offshore through storm-dominated coastal succession that forms the middle part of the *Sciponoceras gracile* Zone in the central and eastern parts of Markagunt Plateau (Figs. 9, 10).

The uppermost part of the upward-coarsening sandstone succession in the eastern Markagunt Plateau (Coal Hill; Fig. 10) is formed by over 6 m of surf-zone to breaker-zone deposits (facies Sbs; Tab. 1), suggesting a change from progradational to aggradational stacking. The top of these strata was subsequently modified by tidal ravinement. Nonmarine equivalents of this aggrading system are probably included in the easternmost tip of the Lower Culver Coal Zone.

The stack of marginal-marine deposits of the Lower and Upper Culver Coal Zones of the Cedar Canyon and Kanarra Mountain areas is probably the landward equivalent of a backstepping succession of two short-term sequences found in the shoreface-offshore interval of the uppermost *Sciponoceras gracile* Zone in the central and eastern Markagunt Plateau (labeled S3c and S3d; Fig. 10). This interpretation is in agreement with published biostratigraphic data: (1) Tibert et al. (2003) place the base of *Neocardioceras juddii* Zone in Cedar Canyon right beneath the top of our sequence S3, and (2) Elder et al. (1994) report the first occurrence of *Neocardioceras juddii* from the offshore mudstones immediately above the backstepping shoreface-offshore interval of the central Markagunt Plateau (Fig. 10).

Eastward correlation to Kaiparowits Plateau is aided by the occurrence of several thin (millimeter-scale) bentonites of the “A swarm.” As mentioned above, the lowermost of these bentonites (“sub-PBC-3”) immediately overlies the top of sequence S2 (Figs. 9, 10). This correlation together with the occurrence of bentonite PBC-4 in the lowermost part of the upward-coarsening succession (regressive systems tract) of sequence S3b (Fig. 11) suggest that the Bridge Creek marker bed PBC-3 or LS2 was coeval with sequence S3a or the lowermost part of sequence S3b. The prominent, 20 to 50 cm thick bentonite A (PBC-5) onlaps onto the regressive sandstones of sequence S3b in the eastern Markagunt Plateau and possibly reappears in the low-energy back-barrier deposits of the Table Bench and Cedar Canyon areas (Fig. 10). Textural trends in the Escalante borehole suggest that the limestone marker bed LS3 or PBC-6 correlates with surface MT3c or the lower part of the regressive systems tract of sequence S3c (Fig. 11). Biostratigraphic data of Elder et al. (1994) that place the base of *Neocardioceras juddii* Zone close to the MT4a surface at Table Bench (Fig. 9) suggest that the maximum transgression separating sequences S3 and S4 was penecontemporaneous with the boundary between the *Sciponoceras gracile* Zone and the *Neocardioceras juddii* Zone. It could overlap with the Bridge Creek limestones LS4 or LS5 (Fig. 11).

Genetic Sequence S4

Proximal Foredeep—Description.—The marginal-marine deposits of sequence S3 are overlain in the Cedar Canyon area by a c. 10-m-thick, upward-coarsening succession of weakly burrowed, inoceramid-bearing, hummocky cross-stratified muddy sandstones through trough cross-stratified sandstones (Fig. 7E). The top of this package is rooted and capped by a coal zone (Straight Cliffs Coal Zone of Averitt 1962) in most of the Cedar Canyon and Kanarra Mountain areas. The upper part of sequence S4 is formed by a 7–9 m thick succession of mostly shell-supported mudstones to limestones (“marls” of Gustason 1989 and Tibert et al. 2003; see facies Lb in Table 1). A diverse assemblage of brackish-water bivalves and gastropods (Fig. 7F) was described from this

unit by Kirkland (2001). A similar facies is found in the Kanarra Mountain area, although it is poorly exposed. The sequence is capped by a sharp-based, 0.5 to 3.5 m thick, trough cross-stratified sandstone (sections CC 2 and 9; Fig. 5) with a lower Turonian inoceramid index fossil *Mytiloides puebloensis* (Tibert et al. 2003).

Proximal Foredeep—Interpretation.—The lower part of sequence S4 is interpreted as a prograding, proximal offshore through upper-shoreface system. The fossiliferous mudstones and limestones dominating the upper half of the sequence formed in an aggrading lagoonal setting. The capping sandstones, up to 3.5 m thick, are mostly of upper-shoreface origin.

As with sequence S3, no short-term sequences were recognized in the medium-term sequence S4 in the Cedar Canyon and Kanarra Mountain areas. However, correlation to the central Markagunt Plateau suggests that the sequence consists of at least two short-term sequences (S4a and S4b; see below).

Basinward correlation.—The regressive systems tract of sequence S4 can be traced eastward to an offshore-shoreface regressive succession, up to 20 m thick (Figs. 9, 10), whose upper part is known as the Sugarledge Sandstone (Cashion 1961). This correlation is in accordance with published biostratigraphic data (Elder et al. 1994; Tibert et al. 2003) that place these regressive units in the lower part of the *Neocardioceras juddii* Zone. A thin transgressive interval divides the regressive package in the central Markagunt Plateau into two short-term sequences, S4a and S4b (Fig. 9). Since no short-term transgressive interval is distinguishable in the Cedar Canyon shoreface succession, it is assumed that the transgressive surface MT4b separating sequences S4a and S4b either postdates surface SE4 as defined in the Cedar Canyon or is amalgamated with it (Fig. 10). It follows that the short-term sequence S4b either correlates with the lower part of the lagoonal and back-barrier succession of sequence S4 of Cedar Canyon or offlaps from the SE4 surface between Cedar Canyon and the central Markagunt Plateau (Fig. 10). Thin coal draping the shoreface sandstones of sequence S4b in the Cogswell Point and Table Bench areas can be considered part of the regressive systems tract or the initial transgressive systems tract of sequence S4b (Fig. 9). In either case, the bulk of the transgressive systems tract of sequence S4b consists of offshore mudstones in the central Markagunt Plateau.

Biostratigraphic data of Elder (1987, 1991) and Elder et al. (1994), together with textural trends in the Escalante borehole, suggest that the peak progradation of the medium-term sequence S4 (surface MR4b; Fig. 9) postdates formation of limestone LS5 but predated formation of limestone LS6 (Fig. 11). Bentonite B or PBC-11 drapes the regressive systems tract of sequence S4b (Figs. 9–11).

Genetic Sequences S5 through S7

Proximal Foredeep—Description.—Three prominent, coarsening-upward packages overlie sequence S4 in the Cedar Canyon area. Each package consists of (in ascending order): (1) bioturbated, ammonite- and inoceramid-bearing mudstone, (2) bioturbated, muddy sandstone punctuated by distinct, decimeter-scale sandstone layers with low-amplitude HCS (Fig. 7G), and (3) trough cross-stratified sandstones (sections CC 9 and 17; Fig. 8). The cross-stratified sandstones of the upper two coarsening-upward packages exhibit inclined accretion surfaces whose dip direction is oblique to perpendicular to the dip direction of the trough cross bedding. The cross-stratified sandstones fill an up to 13 m deep erosional topography (Fig. 8). The uppermost sandstones are capped by highly fossiliferous (oyster-bearing) mudstones to limestones and coaly mudstones.

Proximal Foredeep—Interpretation.—The three upward-coarsening units are interpreted as regressive, offshore through upper-shoreface

TABLE 1.—Description and interpretation of facies and facies associations; Upper Member of the Dakota Formation, Tropic Shale, and Straight Cliffs Formation, Markagunt Plateau, southwestern Utah. A more detailed version of this table is stored in JSR's Data Archive.

TRANSGRESSIVE TO EARLY HIGHSTAND FACIES			
FACIES	DESCRIPTION	RELATIONSHIPS TO OTHER FACIES	INFERRED DEPOSITIONAL ENVIRONMENT
Hle	mud-dominated heterolith with lenticular bedding (wave and wave-modified current ripples); laminae of upper fine to lower medium arkosic sand occur; syneresis cracks common; mm-scale layers of fragmented shells of brackish-water bivalves common, in places; <i>in situ</i> roots occur locally; low-abundance, low diversity ichnoassemblage	intergradational with Hf	intertidal to shallow subtidal, tide-dominated, wave-influenced, restricted setting (estuarine and/or back-barrier tidal flat)
Hf	sand-dominated heterolith with wavy to flaser bedding (wave and wave-modified, sinusoidal current ripples); lower fine sand dominates, but laminae of upper fine to lower medium, arkosic sand occur; syneresis cracks common; <i>in situ</i> roots locally occur; low-abundance, low diversity ichnoassemblage	intergradational with Hle	shallow subtidal to intertidal, tide-dominated, wave-influenced, restricted setting (estuarine and/or back-barrier tidal flat)
Hb	fine sand-mud heterolith (mostly sand-dominated), strongly to entirely burrowed by a low-diversity or monotypic ichnoassemblage (<i>Teichichnus</i> and/or <i>Thalassinoides</i>)	intergradational with Hf, Hle, and Sia; locally overlies Scbm (transgressive systems tract of sequence S2b, section CC 4)	shallow subtidal, partly restricted setting (largely back-barrier as suggested by the association with Sia); located marginal to the major paths of sediment redistribution; superposition of Hb over Scbm probably corresponds to abandonment of a tidal inlet or creek (cf. Moslow and Tye 1985; Imperato et al. 1988)
Sf	moderately to poorly sorted, fine- to lower medium-grained sandstones , strongly fossiliferous (oysters dominate); shell-supported texture common; <i>in situ</i> assemblages of <i>Crassostrea soleniscus</i> found in places; strongly burrowed (? <i>Ophiomorpha</i>), in places; sharp, often erosional base; laterally variable thickness (typically due to underlying erosional topography); trough cross-bedding and lateral accretion surfaces preserved locally (e.g., upper part of S3b at Coal Hill; Fig. 10); sub-horizontal stratification dominates in places (e.g., sequence S1c, section KM 1)	caps shoreface or back-barrier facies; typically underlies marine shoreface to offshore facies (Hcr, Hhcs, Sb, or Mb); in most instances a landward shift in facies takes place across these fossiliferous sandstones; lateral transitions to Scb observed	swash-zone through shallow-subtidal settings of clastics-starved coasts; the clastic starvation most likely attributable to a transgressive situation, when most of the clastic sediment is stored landward of the shoreline (cf. Nummedal and Swift 1987); both active tidal inlets and tidal inlets reworked by subsequent wave ravinement are probably included in this facies
GShcs	hummocky cross-stratified sandstone , gravelly at the base; the gravel consists of subrounded to subangular clasts of chert, quartzite and limestone; overlies a strongly burrowed surface in places (e.g., upper part of transgressive systems tract of sequence S3a, section CC 15; Figs. 5 and 7D)	typically at the base of Hcr, Shcs or Sscs	storm-dominated shoreface; lateral correlations and the extensive burrowing beneath these strata suggest that some of the gravelly layers represent a condensed surface of wave ravinement (e.g., transgressive systems tracts of sequences S2c, S2d and S3a in the eastern part of the Cedar Canyon area; Fig. 5)
GStcb	gravelly sandstone (fine to lower medium-grained, arkosic), trough cross-stratified ; sigmoidal cross-sets and reactivation surfaces occur frequently; unimodal to bimodal paleocurrent directions; the gravel consists of subrounded to subangular clasts of chert, quartzite, and limestone; abundant shell hash; typically fills erosional topography	associated with Scb and Scbm	an active tidal inlet of storm-dominated coast (cf. Moslow and Tye 1985); the upward transition from flood-dominated to ebb-dominated conditions, found in the upper part of section CC 3 (Fig. 5), is consistent with a transgressive situation (cf. Moslow and Tye 1985)
Scbm	moderately to poorly sorted, fine- to lower medium-grained sandstone , often arkosic; trough cross-stratified (10 to 30 cm sets); unimodal to trimodal paleocurrent directions; well-developed mud drapes, which locally bundle; wave reworked and mud-draped bottomsets; abundant plant debris, including <i>Teredolites</i> -bored wood; fragmented shells (oysters) occur; typically sharp based (erosional topography documented in places)	associated with Hf and Hle	a wide range of tide-dominated, shallow-subtidal environments, attributable to back-barrier and/or estuarine settings; for example, the upward gradation to Hf and Hle, found locally in the transgressive systems tract of sequence S2b (sections CC 5–7; Fig. 5), would be consistent with filling of an abandoned tidal creek of inner estuary
Spm	fine-grained, well- to moderately sorted sandstone ; planar-laminated ; often with wave-rippled, mud-draped , and burrowed (<i>Thalassinoides</i>) tops; forms low-angle, landward-dipping clinoform units, in places; shell hash occurs locally	associated with Scbm, Hb, and Hf; see also Sia (below)	intertidal to shallow subtidal, relatively high-accumulation portions of washover-fan and flood-tidal-delta settings of wave/storm-dominated coasts (cf. e.g. Hennessy and Zarillo 1987)
Sia~Spm/Hb	fine-grained sandstone with variable mud admixture; alternating layers of strongly bioturbated muddy sand (<i>Thalassinoides</i> and/or <i>Teichichnus</i> ; ~ Hb) and parallel-laminated sand with cm- to dm-scale scours; wave reworking and burrowing of the sand-layer tops; inclined accretion surfaces oriented southwestward (~ landward); dip decreases upward (section CC 2; Fig. 5 and Fig. 7C)	grades laterally and downward to Mf, C, and Hb; can be erosionaly overlain by GStcb and Scb (e.g., transgressive systems tract of sequence S2c, sections CC 2, 3, 4, and 8; Fig. 5)	back-barrier washover fan

TABLE 1.—*Continued.*

TRANSGRESSIVE TO EARLY HIGHSTAND FACIES			
FACIES	DESCRIPTION	RELATIONSHIPS TO OTHER FACIES	INFERRED DEPOSITIONAL ENVIRONMENT
Lb	limestone to mudstone, largely bioclast-supported (brackish-water mollusks, foraminifera, and ostracods dominate; oyster beds present; see Tibert et al. (2003) for details); minor sand admixture in mudstone layers; subhorizontal bedding planes; no apparent bedforms; complete specimens of thin-shelled bivalves common; gastropods locally aligned, but no consistent pattern in superposed beds; see Fig. 7F	no lateral transitions observed; restricted to transgressive systems tract of sequence S4 of Cedar Canyon and Kanarra Mountain areas	semi-enclosed brackish-water lagoon; isolated from the major Sevier and Mogollon drainages; this distinct facies spans probably over 200 kyr and represents a rare confluence of eustatic rise and tectonic uplift in distal wedge-top depocenter (cf. Laurin and Sageman 2001)
TRANSGRESSIVE OR REGRESSIVE FACIES			
FACIES	DESCRIPTION	RELATIONSHIPS TO OTHER FACIES	INFERRED DEPOSITIONAL ENVIRONMENT
C	coal	intergradational with Mf, Mc and ?Lb	coastal (supratidal) peat swamp; mostly low-lying, as suggested by interfingering with lagoonal mudstones
Mc	carbonaceous mudstone ; abundant plant debris; horizontal lamination; no shells	intergradational with C and Mf	supratidal marsh
Mf	mudstone ; black, dark gray, or light gray; horizontal laminae typically well preserved; weakly to strongly fossiliferous (fragile brackish mollusks; cf. Fürsich and Kirkland 1986)	intergradational with C, Mc, Sia and Lb	largely subtidal, isolated, brackish lagoon
Mb	mudstone ; strongly to entirely bioturbated by medium- to high-diversity ichnoassemblage (<i>Planolites</i> , <i>Helminthopsis</i> , <i>Chondrites</i> , <i>Thalassinoides</i> , <i>Palaeophycus</i> , and <i>Zoophycos</i>); physical sedimentary structures rarely preserved	grades laterally and upward to Hcr and Shcs ~ Tropic Shale	offshore marine setting
HI	mud-dominated heterolith with mm- to sub-mm-scale, sharp-based and upward-fining silt laminae ; small <i>Anconichnus/Helminthopsis</i> burrows often rework the silty layers; other burrows absent; fossils rare	passes upward and laterally to poorly bioturbated Hcr; locally (e.g., section CC 2; Fig. 5) grades upward to Mc or Mf, which in turn grades upward to C; found only in S1 of Cedar Canyon and Kanarra Mt. areas	storm-influenced setting, which was out of the reach of fair-weather waves; lowered salinity and/or oxygen levels (cf. Ekdale et al. 1984); gradation to both Hcr and Mc suggests a low-energy bay environment associated with storm-dominated delta and/or sand spit (cf. Dominguez and Wanless 1991)
Hcr	mud-silt heterolith with mm- to cm-scale beds of combined-flow ripple-laminated to parallel-laminated silt to very fine sand (the internal laminae defined by fine plant debris); low to medium intensity of bioturbation; relatively high-diversity ichnoassemblages (<i>Planolites</i> , <i>Helminthopsis</i> , <i>Terebellina</i> , <i>Teichichnus</i> , <i>Thalassinoides</i> , and <i>Diplocraterion</i> ; Fig. 6D); fossils rare	passes laterally to Shcs, in places; typically grades upward to Shcs (e.g., sequence S4, sections CC 2 and 9) or Sscs (e.g., S3b, section CC 15); underlain by GShcs (e.g., S3a, section CC 15) or HI (S1b, section CC 4; Fig. 5)	storm-dominated, lower shoreface to proximal offshore setting (<i>sensu</i> McLane 1995); the poorly bioturbated mode of this facies may correspond to lower delta front setting (cf. MacEachern and Pemberton 1992)
Sb	fine-grained sandstone , variable mud admixture, strongly to entirely bioturbated by medium- to high-diversity ichnoassemblage	intergradational with Shcs and Mb (typically grades upward from the Tropic Fm.); gradation to Hcr observed as well	storm-dominated lower shoreface to proximal offshore (<i>sensu</i> McLane 1995); relatively low-accumulation site (cf. Shcs and Sscs), i.e. not proximal and down-drift relative to a river mouth
Sla	fine-grained, well to moderately sorted sandstone ; no mud; low-angle stratification ; rare trough cross-stratification (cm-scale sets); laminae enriched in heavy minerals are found at the top of regressive systems tract of S2 at Table Bench; large, thick-walled <i>Ophiomorpha</i> burrows locally abundant	overlies Sscs, Scb, or GStcb	swash zone (beach) <i>sensu</i> , e.g., Davis (1985) (cf. Dominguez and Wanless 1991; Walker and Plint 1992); with transition to surf zone
REGRESSIVE FACIES			
FACIES	DESCRIPTION	RELATIONSHIPS TO OTHER FACIES	INFERRED DEPOSITIONAL ENVIRONMENT
Mr	light gray, locally purplish, rooted mudstone with floating sand grains to sand admixture	no gradation to other facies observed; overlies Sla in sequence S2c, section CC 8	interfluvial, subaerial setting

TABLE 1.—Continued.

REGRESSIVE FACIES			
FACIES	DESCRIPTION	RELATIONSHIPS TO OTHER FACIES	INFERRED DEPOSITIONAL ENVIRONMENT
Shcs	very well-sorted fine-grained sandstone with cm- to dm-scale hummocky cross-stratification (<i>sensu</i> Harms et al. 1975); apart from HCS the individual beds may include parallel lamination at the base, and symmetrical to slightly asymmetrical ripples (often climbing) at the top; gutter casts can be developed along basal contacts of these beds with cohesive substrates; rare <i>Diplocraterion</i> and <i>Thalassinoides</i> occur along the upper bedding contacts	intergradational with Hcr, Sb, and Sscs; overlain by Sbs in places (e.g., regressive systems tract of sequence S3b at Table Bench)	storm-dominated lower shoreface (<i>sensu</i> McLane 1995); successions dominated by this largely unburrowed facies represent relatively high-accumulation sites (cf. facies Sb)
Sscs	very well-sorted fine-grained sandstone with swaly cross-stratification (<i>sensu</i> Leckie and Walker 1982); burrowing rare (<i>Diplocraterion</i> occurs); decimeter-scale gutter casts developed locally (e.g., regressive systems tract of sequence S3b, section CC 15; Fig. 7D)	intergradational with Hcr, Sb, and Shcs, can be overlain by Sbs or Sla	storm-dominated shoreface (<i>sensu</i> McLane 1995); generally landward of HCS sandstones of facies Shcs (cf. Walker and Plint 1992)
Scb	moderately to well-sorted, fine-grained sandstone ; trough or (less frequently) planar cross-stratified (10 to 60 cm sets); unidirectional (southeast oriented) paleocurrents are typical, for example, for sequence S2d (Fig. 5); bimodal to trimodal paleocurrent directions occur in the upper part of S2c at Big Hill (Fig. 5); sigmoidal cross-sets and reactivation surfaces; no mud drapes; lamination only locally accentuated by dispersed plant debris; fragmented shells (oysters)	associated with GStcb, in places	shallow-subtidal dunes; mostly ebb-tidal delta setting; weakly storm-affected coast (cf. Hayes 1980)
Sbs	alternating, cm- to dm-scale layers of relatively coarse-grained (up to upper medium) and relatively fine-grained (very fine to fine) sandstone ; the overall texture is often bimodal ; the relatively coarse-grained layers are trough cross-stratified or horizontally stratified (sets 5 to 25 cm thick), with scoured bases ; the finer-grained layers are typically trough cross-stratified, and often display wave-reworked tops, which are locally draped by mm-scale mud layers; largely bimodal paleocurrent directions; no burrowing or fossils found	overlies Sscs and Shcs facies (regressive systems tract of sequence S3b at Table Bench)	surf zone to breaker zone of a storm-dominated coast (cf. Dominguez and Wanless 1991; Walker and Plint 1992)

successions separated from each other by transgressive surfaces (largely “non-accretionary transgression” *sensu* Helland-Hansen and Martinsen 1996). The sharp-based, cross-stratified sandstones with lateral accretion surfaces are probably fills of active tidal inlets, although it is possible that the underlying erosional topography formed initially due to fluvial incision (cf. Oertel et al. 1991). The uppermost unit is capped by transgressive lagoonal deposits.

The three upward-coarsening packages are considered medium-term sequences S5 through S7 because they are comparable in their thickness to the medium-term sequences S1 through S4. Short-term genetic sequences have not been identified.

The offshore mudstones at the base of sequence S6 represent the long-term (second order) maximum transgression in southern Utah (Fig. 9). They are attributed to the *Vascoceras birchbyi* Zone on the basis of an overlap of *Fagesia catinus* (Mantell) and *Mytiloides kossmati* (Kirkland and Cobban in Eaton et al. 2001; J. Kirkland, personal communication, 2001; Tibert et al. 2003). It is emphasized that these new biostratigraphic data change the previous interpretation of the transgressive-regressive history in the area (Leithold 1994) by placing the long-term maximum transgression slightly lower in the chronostratigraphic scale.

Basinward Correlation.—Sequences S5 through S7 are poorly exposed in the central Markagunt Plateau, but biostratigraphic data of Tibert et al. (2003) and the location of bentonites C and D (Elder 1985), which are readily distinguishable in well logs, provide clues to the correlation. Since the offshore mudstones of sequence S5 do not include any bentonite attributable to the marker bed C in the Cedar Canyon area, it is assumed that bentonite C was coeval with high-energy depositional conditions

accompanying either the transgressive systems tract of sequence S4 or the upper part of the regressive systems tract of sequence S5 in Cedar Canyon. The former possibility results in a more realistic geometric solution (Fig. 9). Bentonite D, which should occur near the base of the *Vascoceras birchbyi* Zone (Kennedy and Cobban 1991) but has not been identified in the Cedar Canyon area, can be correlated with the high-energy shoreface deposits at the top of sequence S5 (Fig. 9; cf. Tibert et al. 2003). The regressive systems tract of sequence S6 and sequence S7 are tentatively correlated with the *Mammites nodosoides* Zone through the lower part of the *Collignoniceras woolgari* Zone (late early Turonian through early middle Turonian).

Stacking of the Medium-Term Sequences S1 through S7

Forestepping and backstepping arrangements of the medium-term sequences S1 through S7 define the long-term transgressive-regressive history of the study interval. The transgressive systems tract of sequence S1 marks a major (> 100 km) landward shift of the shoreline. Sequence S2 and the regressive systems tract of sequence S3 represent a forestepping (regressive) trend. The regressive systems tract of sequence S4 aggrades relative to the regressive systems tract of sequence S3. The transgressive systems tract of sequence S4 marks the onset of a long-term transgressive trend that encompasses the Cenomanian–Turonian boundary and culminates at the top of sequence S5 (*Vascoceras birchbyi* Zone). The succession of medium-term sequences S2 through S5 can be considered a long-term genetic sequence comparable in scale to the sequences defined by Gardner and Cross (1994). Sequences S6 and S7 are stacked in a forestepping pattern and represent a renewed long-term regression in the area.

medium-term genetic sequences	systems tracts	biostratigraphy and correlation to Bridge Creek marker beds	estimated duration	uncertainty due to uncertain correlation	number of short-term genetic sequences	average duration of short-term sequences	average uncertainty due to correlation
S7	tst+rst	?	?				
S6	tst+rst	?	?				
S5	tst+rst	postdates bentonite D and predates FAD <i>M. nodosoides</i>	160 kyr	±60 kyr	-	-	-
S4	tst	immediately postdates bentonite C	395 kyr	±45 kyr	-	-	-
	rst	postdates LS5 and predates LS6	65 kyr	±55 kyr	1 + 1/2 (rst)	43 kyr + 22 kyr (rst)	±37 kyr (±19 kyr rst)
S3	tst	penescontemporaneous with <i>S. gracile</i> / <i>N. juddii</i> boundary	100 kyr	±40 kyr	2 + 1/2 (tst)	40 kyr + 20 kyr (tst)	±16 kyr (±8 kyr tst)
	rst	immediately predates bentonite A	40 kyr	±20 kyr	1 + 1/2 (rst)	27 kyr + 14 kyr (rst)	±13 kyr (±7 kyr rst)
S2	tst	coeval or immediately predates "sub-PBC-3"	25 kyr	±20 kyr	1 + 1/2 (tst)	17 kyr + 9 kyr (tst)	±13 kyr (±7 kyr tst)
	rst	predates "sub-PBC-3"	40 kyr	±35 kyr	2 + 1/2 (rst)	16 kyr + 8 kyr (rst)	±14 kyr (±7 kyr rst)
S1	tst	probably postdates FAD <i>S. gracile</i>	100 kyr	±80 kyr	2 + 1/2 (tst)	40 kyr + 20 kyr (tst)	±32 kyr (±16 kyr tst)
	rst	predates FAD <i>S. gracile</i>	200 kyr (Uličný 1999)	?	2 (Uličný 1999)	100 kyr	?
		postdates FAD <i>M. mosbyense</i>					

FIG. 12.—Estimated durations of the medium- and short-term genetic sequences defined in this study. The estimates were based on correlation of the genetic sequences with the Bridge Creek Limestone for which orbitally tuned time scale was developed by Meyers et al. (2001). The orbital time scale does not extend beneath the top of the limestone bed LS1. Therefore, durations of the transgressive systems tract (tst) of sequence S1 and regressive systems tract (rst) of sequence S2, which were probably coeval with the LS1 limestone, were estimated using a linear extrapolation of the orbital time scale to the base of the LS1 limestone. Note that one sequence in the transgressive systems tract of S1, one sequence in the transgressive systems tract of S2, and one sequence in the regressive systems tract of S3 are possibly of autocyclic origin.

DISCUSSION

Duration of the Genetic Sequences

Biostratigraphic and marker-bed correlation of the study area with the Bridge Creek Limestone and its orbital time scale (Meyers et al. 2001) makes it possible to estimate durations of the individual genetic sequences (Figs. 12, 13). The medium-term sequence S1 is poorly constrained, but its duration clearly exceeded 100 kyr (over 300 kyr according to Uličný 1999). The short-term sequences of the transgressive systems tract of sequence S1 represent 40 kyr (± 32 kyr) in average (error margins correspond to uncertainties of the proximal-distal correlation as indicated in Figure 12). The sequences S2 and S3 represent 65 kyr (± 55 kyr) and 140 kyr (± 60 kyr), respectively. Average duration of the short-term sequences that constitute the medium-term sequences S2 and S3 ranges from 16 kyr (± 14 kyr) to 40 kyr (± 16 kyr). The regressive systems tract of sequence S4 lasted 65 kyr (± 55 kyr), which is comparable to the durations of regressive systems tracts of sequences S2 and S3 (Fig. 12). In contrast, the transgressive systems tract of sequence S4 spans 395 kyr (± 45 kyr), which is at least a four-fold increase compared to the durations of transgressive systems tracts of sequences S1, S2, and S3. Sequence S5 is estimated at 160 kyr (± 60 kyr) in duration. Sequences S6 and S7 are poorly constrained, but their durations probably greatly exceeded 100 kyr.

Based on the above data, average accumulation rates of compacted sediment in the proximal foredeep (Cedar Canyon area) are estimated at c. 210 m/Myr for the upper Cenomanian *Sciponoceras gracile* Zone, c. 80 m/Myr for the upper Cenomanian *Neocardioceras juddii* Zone, and c. 70 m/Myr for the lower Turonian. Because the Cedar Canyon site was repeatedly overfilled with sediment and the average sediment composition does not vary significantly, the above decline in compacted sediment

accumulation indicates a decline in the rate of long-term relative sea-level rise (accommodation).

Alloccyclic vs. Autocyclic Forcing of the Transgressive-Regressive Changes

The repeated regressions and transgressions documented in this study could represent (1) autocyclic changes in the rate of local sediment input and/or (2) relative sea-level changes or sediment-input changes forced by tectonics or climate (Fig. 4). Compaction of mud or coal is not considered important in controlling formation of the genetic sequences examined because the characteristics of the bounding surfaces do not show a systematic relationship to the underlying lithology. The potential autocyclic processes in the study area include a change in the shoreline geometry due to tidal-inlet migration in tide-dominated transgressive settings or downdrift deltaic sub-environments (e.g., Moslow and Tye 1985; Bhattacharya and Giosan 2003), sand-ridge accretion in the downdrift part of wave-dominated delta (e.g., Dominguez and Wanless 1991), or river avulsion (e.g., Gürbüz 1999). These autocyclic processes take place on relatively short time scales, typically hundreds to thousands of years, and should be considered the potential control on the short-term sequences.

Sequences S1a, S1c, S2a, S2b, and S2c include features suggesting relative sea-level control (see below) and are therefore attributed to alloccyclic mechanisms (note also that distinct upward-coarsening cycles coeval with sequences S2a–c are found in boreholes KB-7-OC and KB-5-OC, suggesting areally extensive variations in sediment input; Fig. 9). Sequence S1b is poorly exposed (Fig. 5) and should be considered possibly autocyclic. Inherent cycles of river mouth-bar progradation and abandonment in a mixed, river- and storm-influenced setting could account for sequences S2d and S3a, although relative sea-level changes or

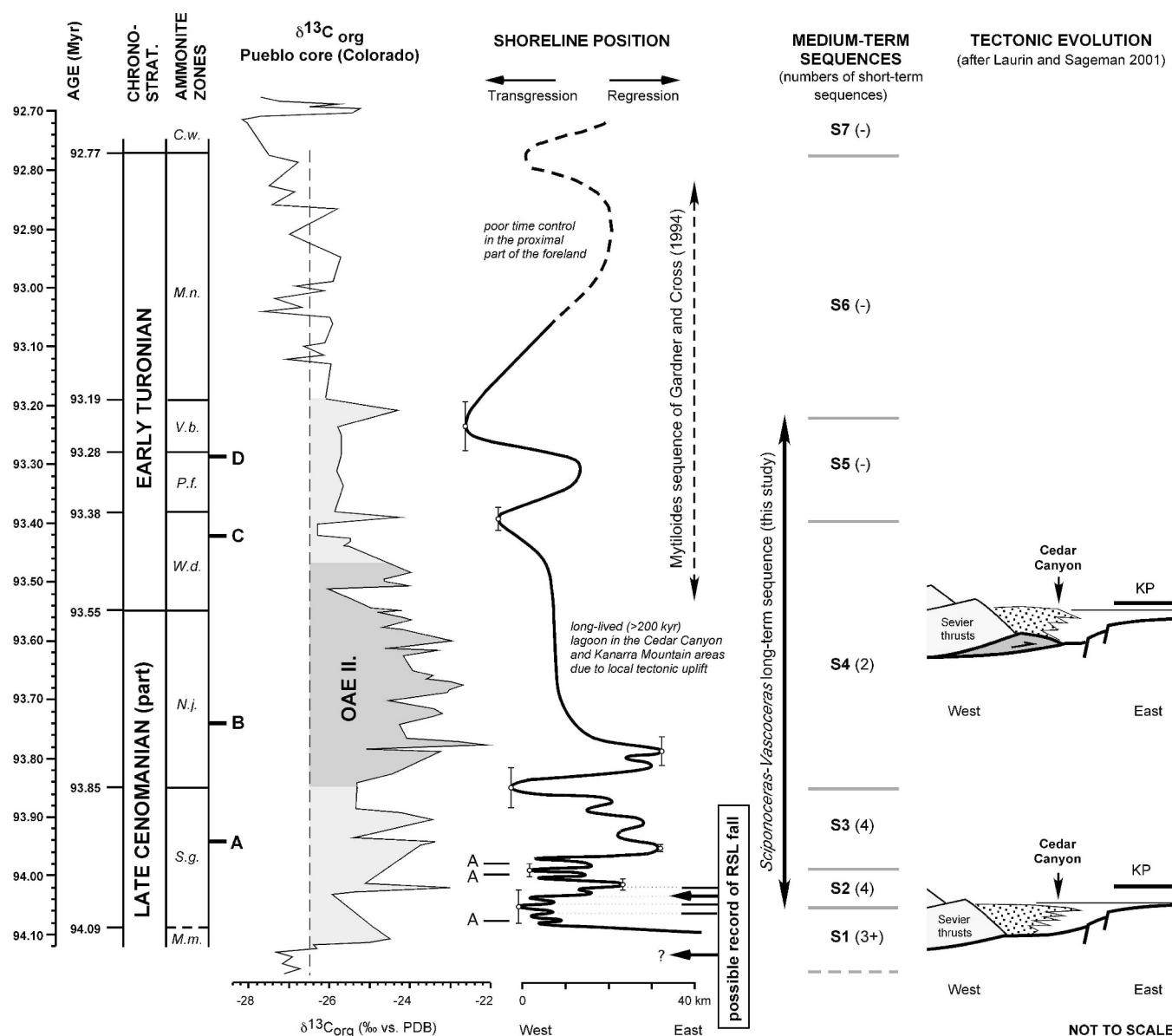


FIG. 13.—Interpreted transgressive-regressive history of the Markagunt Plateau (southwestern Utah) plotted against chronostratigraphic scale (Sageman et al. 2006) and $\delta^{13}\text{C}_{\text{org}}$ values from the Bridge Creek Limestone (Sageman et al. 2006; OAE II. = Oceanic Anoxic Event II). Error bars on the transgressive-regressive curve refer to the uncertainty of the correlation of maximum transgressive and maximum regressive surfaces with the Bridge Creek Limestone marker beds: each error bar is defined below by the lowermost possible correlative level and above by the uppermost possible correlative level (Fig. 12). Possible records of relative sea-level (RSL) falls are indicated (arrows point to intervals of fluvial incision). Possible autocyclic sequences are marked by "A". Approximate timing of incorporation of the Cedar Canyon area into the wedge-top depocenter is illustrated in the right column (after Laurin and Sageman 2001; KP = Kaiparowits Plateau). Western part of the Cedar Canyon area (Big Hill) serves as a "0 km" reference point for the T-R curve. Bentonite marker beds (Elder 1985) are shown for reference. Ammonite zones are after Kennedy and Cobban (1991) and Kennedy et al. (2000). Abbreviated ammonite zones: M.m. = *Metoicoceras mosbyense* Zone, S.g. = *Sciponoceras gracile* Zone, N.j. = *Neocardioceras juddii* Zone, W.d. = *Watinoceras devonense* Zone; P.f. = *Pseudospidoceras flexuosum* Zone, V.b. = *Vascoceras birchbyi* Zone, M.n. = *Mammites nodosoides* Zone, C.w. = *Collignoniceras woollgari* Zone.

allocyclic changes in river runoff would also provide viable explanations. Sequence S3b marks a major regression, which is traceable all over the Markagunt Plateau and farther basinward. This sequence must be attributed to allocyclic mechanisms. Similarly, sequences S3c and S3d are recognizable in normal-marine, storm-dominated shoreface through offshore deposits throughout the central Markagunt Plateau (at least 20 km; Figs. 9–11), and are therefore difficult to explain in terms of autocyclic processes. The absence of lagoonal interbeds together with

a high-diversity fauna and strong burrowing of lower shoreface through offshore strata of sequences S4a and S4b in the central Markagunt Plateau (Fig. 10) suggest that these sequences were distal or updrift from a river mouth. Sediment-input changes to the central Markagunt Plateau are therefore expected to be an integrated response to sediment-input changes over a larger area updrift (southeast) from the site. Allocyclic processes provide the simplest and most powerful mechanism for such changes.

Evidence for Relative Sea-Level Falls at Subaerial Unconformities

The SU surfaces of the Cedar Canyon area represent a distinct type of subaerial surface that is interpreted here to be a possible record of relative sea-level fall on the basis of the following arguments.

Surface SU1a truncates pedogenically modified floodplain mudstones and sandstones and is overlain by low-energy marsh and bay deposits. Correlation in the Cedar Canyon area (Fig. 5) suggests that the incision exceeded 5 m (compacted thickness). The relatively large depth of the incision, mostly microtidal regime (cf. Ericksen and Slingerland 1990) and the absence of tidal-flat deposits beneath the surface collectively suggest that the SU1a surface formed due to fluvial incision rather than due to tidal-creek incision. The absence of fluvial deposits above the incision topography can be explained in terms of net fluvial erosion upon relative sea-level fall (cf. Zaitlin et al. 1994) and subsequent diversion of the drainage system (cf. Clevis et al. 2004, Jones 2004) or sediment bypassing due to a decline of sediment yield relative to stream power (e.g., Blum et al. 2000). In any case, the absence of fluvial deposits suggests that the surface SU1a is most likely allocyclic in its origin.

Surface SU2b represents a major basinward shift in facies and truncates more than 9 m of the underlying marginal-marine and (importantly) shoreface deposits. These features together with strong pedogenic modification of elevated parts of the topography (leaching of the top of the regressive systems tract of sequence S2b in the Big Hill area; Fig. 7A) make this surface attributable to fluvial incision due to relative sea-level fall (cf. Van Wagoner et al. 1990; Zaitlin et al. 1994).

Surface SU2a lies less than 2 meters above the base of ammonite-bearing HCS sandstones of the regressive systems tract of sequence S2a (Figs. 5, 6G), and only 30 cm above a layer which is locally packed with articulated inoceramids. Over the entire stretch of the outcrop (> 100 m) the regressive systems tract of sequence S2a lacks any evidence for intermittent subaerial exposure. Although HCS has been reported from the intertidal zone (e.g., Greenwood and Sherman 1986; Yang et al. 2005) the preservation of ammonite-bearing HCS sandstones and weakly reworked inoceramid shell material together with the lack of evidence for intermittent exposure suggest that the regressive systems tract of sequence S2a formed in a relatively deep subtidal setting. Hence, it is assumed here that the SU2a surface did not form solely by normal progradation upon longer-term relative sea-level rise. A short-term relative sea-level fall would best explain the facies superposition.

An upward gradation from shoreface to marsh, associated with plant colonization of the top of the succession, might represent normal progradation due to, for example, beach-ridge accretion (cf. Dominguez and Wanless 1991). However, this scenario is probably not applicable to the environmental shift across the SU1c surface, because of (i) an overall retrogradational arrangement of the sequences S1a through S1c, and (ii) the fact that only one meter of nonmarine strata separates the inoceramid-bearing shoreface sandstones of the early regressive systems tract of sequence S1c from inoceramid- and ammonite-bearing shoreface sandstones of sequence S2a. Such a high amplitude oscillation in depositional conditions is difficult to explain by unforced progradation superimposed upon long-term relative sea-level rise. A relative sea-level fall or deceleration of relative sea-level rise was likely involved in the formation of SU1c.

Relative sea-level fall or stagnation of the long-term relative sea-level rise is also needed to explain the development of a distinct, pedogenically leached surface at the top of the regressive systems tract of sequence S2c (Fig. 7A; note that both tidal-flat deposits of the transgressive systems tract of sequence S2b and back-barrier mudstones and coals of the transgressive systems tract of sequence S2c, which must have closely followed the base level, exhibit excellent preservation of organic matter and only a weak pedogenic reworking).

Tectonic vs. Climatic Forcing of the Transgressive-Regressive and Relative Sea-Level Changes

Ten out of thirteen short-term genetic sequences described here represent an arguable record of allocyclic changes, i.e., changes in sediment input, marine sediment dispersion, or relative sea-level change driven by tectonics or climate. The study area was part of the Sevier foredeep and might have undergone tectonic deformation due to a basinward approach of in-sequence thrusts. The documented three-fold decline in long-term relative sea-level rise in the *Neocardioceras juddii* Zone could represent the initial stage of incorporation of the Cedar Canyon area into the wedge-top depocenter (Laurin and Sageman 2001). However, deposition of the sea-level-forced sequences predated this uplift by more than 200 kyr. In spite of some theoretical considerations (e.g., Kamola and Huntoon 1995; Gutscher et al. 1996), hierarchically organized changes in foreland subsidence at the scale of tens of kyr have not been documented in the study area, nor elsewhere. The possible climatic explanation suffers from a similar lack of data and is difficult to reconcile with the prevailing greenhouse climate. However, the coeval hemipelagic stratigraphy and recent numerical modeling (see below) suggest that potential climatic scenarios should be examined carefully.

The hemipelagic Bridge Creek Limestone bears strong evidence of orbital-scale climate change (e.g., Sageman et al. 1997; Meyers et al. 2001) and, although the exact mechanism that translates climatic changes into the hemipelagic record is difficult to resolve, it is reasonable to test for their signature in coeval depositional environments. Recent simulations (Floegel et al. 2005) suggest that cycles of Earth's axial precession (c. 20 kyr) controlled seasonal snow accumulation in the Sevier highlands, and thus affected surface runoff and sediment yield into the Western Interior Basin. The model predicts distinct changes in sediment input, which would affect the transgressive-regressive history of the basin. Although no account of the possible eustatic effects of the simulated cycles is made by the authors, the snow-accumulation changes in the Sevier highlands imply a certain glacioeustatic capacity of the greenhouse interval (snow-accumulation changes in the Antarctic mountains could amplify this capacity; cf. DeConto and Pollard 2003; see also Stoll and Schrag 2000; Gale et al. 2002; Miller et al. 2003; Plint and Kreitner in press). In other words, the model inherently predicts coupled changes in sediment input to the Sevier foreland and glacioeustatic oscillations in the 20 kyr rhythm. The short-term genetic sequences preserved in southwestern Utah provide a possible record of such changes (the medium-term sequences could then represent cycles of orbital eccentricity—c. 100 kyr and 400 kyr—which modulate the climatic effect of the precessional cycle). The upward loss of short-term sequences could be attributed to a reduced stratigraphic resolution in the upper parts of the succession (due to deceleration of the long-term relative sea-level rise; see above) or a long-term climate change (e.g., an increase in the minimum polar temperatures). The latter possibility would be consistent with the hypothesized relationship between carbon burial and temperature during OAE II (Arthur et al. 1988; Freeman and Hayes 1992), because the loss of short-term sequences roughly coincides with the termination of the $\delta^{13}\text{C}_{\text{org}}$ excursion (Fig. 13). This scenario is speculative, but it deserves further attention, as do the potential tectonic mechanisms.

Stratigraphic Context of OAE II

Multiple medium-term regressions in the study area appear to correlate with enrichments in the $\delta^{13}\text{C}$ of organic matter from the basin center (Fig. 13). Since organic matter in the Bridge Creek Limestone has been interpreted as predominantly marine (Pratt 1984), these high-frequency oscillations should not reflect changes in the supply of terrestrial organic carbon. Alternatively, they might represent variations in terrigenous nutrient supply that briefly increased levels of primary production and

thus organic-carbon burial rates during OAE II. Although a full analysis of the links between Cenomanian–Turonian climate cycles, carbon burial, and the isotopic record is beyond the scope of this paper, the stratigraphic framework presented here provides a basis for detailed comparative studies of the geochemical and biotic responses of marine and nonmarine systems to OAE II.

CONCLUSIONS

Three orders of transgressive–regressive changes defined by “short-term,” “medium-term,” and “long-term” genetic sequences were recognized in the upper Cenomanian *Sciponoceras gracile* Zone through lower Turonian *Mammites nodosoides* Zone in southwestern Utah. The “short-term” sequences are restricted to the *Sciponoceras gracile* Zone and the lowermost *Neocardioceras juddii* Zone and range from 16 kyr ($\pm$ 14 kyr) to 43 kyr ($\pm$ 37 kyr) in their average duration. Well-constrained medium-term sequences S2, S3 (*Sciponoceras gracile* Zone), and S5 (*Watinoceras devonense*–*Vascoceras birchbyi* Zones) lasted 65 ± 55 kyr, 140 ± 60 kyr, and 160 ± 60 kyr, respectively. The medium-term sequence S4 (*Neocardioceras juddii* Zone) approximates 400–500 kyr and coincides with an accelerated tectonic deformation of the study area. Sequences S2 through S5 form a long-term sequence, which spans approximately 800 kyr and is penecontemporaneous with the $\delta^{13}\text{C}$ excursion of OAE II.

Most (10 out of 13) of the short-term sequences are arguably due to allocyclic mechanisms. Features suggesting relative sea-level control are documented from five sequences in the *Sciponoceras gracile* Zone (possibly including the uppermost *Metoicoceras mosbyense* Zone). Evidence for either tectonic or climatic forcing of the allocyclic sequences is missing, but the stratigraphic record is consistent with orbitally driven changes in continental runoff and sea level (due to high-altitude and high-latitude snow accumulation) predicted by recent numerical models. The stratigraphic framework established here will make it possible to compare the marine and nonmarine geochemical records of OAE II and thus help to define the leads and lags in the atmosphere–ocean interaction of this important interval.

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