Microbial laminites versus rooted and burrowed caps on peritidal cycles: Salinity control on parasequence development, Early Cretaceous isolated carbonate platform, Croatia

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ABSTRACT

Some parasequences in the interior of the Early Cretaceous isolated carbonate platform, Croatia, which formed under a greenhouse climate, lack the typical regressive tidal flat laminites. Instead, these bioturbated emergent parasequences have burrowed and rooted upper parts, capped with thin greenish paleosols, and are reminiscent of Triassic “Lofer cycles.” We propose that the bioturbated cycle tops reflect coastal salinities that are normal marine, brackish, or metahaline, whereas the transgressive (rare) and abundant regressive tidal flat laminites formed under hypersaline coastal waters. Thus, these features may be used to track gross salinity changes of coastal waters on the platform through time. In addition, we suggest ways to evaluate whether the salinity changes relate to hypersaline embayments on the platform or changes in the climate at the parasequence scale.

We propose that the bioturbated emergent parasequences could have formed under semiarid conditions, seaward of subtle, shallow embayments on the platform. Contemporaneously, in the bayheads, microbial laminites developed—these would require time-equivalent updip and downdip laminate-capped and bioturbated emergent–capped parasequences. However, the parasequences could also have been controlled by climate changes. The laminate-capped parasequences could have resulted from salinity increase with shallowing of the platform interior under semiarid conditions (stable climate). In contrast, the bioturbated emergence–capped parasequences could have formed during times of more humid climate punctuating the overall semiarid climate. The humid phase would have favored brackish to normal marine salinities in the coastal zone, along with macrophytes, and intense animal and plant bioturbation, which would suppress development of laminitite caps. Thus, these parasequences provide a means of tracking gross salinity of coastal waters, and if climate induced, then they have implications for fluctuating climates in greenhouse worlds.

INTRODUCTION

Most parasequences in the interior of the Early Cretaceous isolated carbonate platform, Croatia, are capped by regressive microbial laminites typical of parasequences that formed under semiarid conditions in a greenhouse world. However, some parasequences lack these regressive laminites and instead have burrowed and rooted carbonates overlain by thin green shaly dolomite (paleosols). We suggest that the microbial laminites formed in hypersaline waters while the bioturbated caps formed under lower, more normal marine or brackish salinities (cf. Wright and Azeredo, 2006). Such changes in coastal salinities may result from platform-wide salinity changes related to climate, or from localized salinity changes due to development of embayed coastlines on the platform top (cf. Davies, 1970a; Gostin et al., 1984). We suggest ways in which these might be differentiated in the geologic record.

Meter-scale carbonate parasequences capped by microbial laminites are common on many ancient peritidal carbonate platforms that were formed during greenhouse times, but they are less common on platforms that developed during icehouse and transitional times (Read, 1998). The greenhouse parasequences typically are asymmetric, shallowing-upward successions of genetically related strata that lack much of a transgressive record, and that have well-developed microbial laminites capped by an emergence surface (regressive laminate-capped parasequences). Symmetrical transgressive-regressive parasequences also may occur, characterized by microbial laminites at the base in a transgressive position and at the top forming a regressive laminitite cap beneath an emergence surface (James, 1977; Demicco, 1985; Koerschner and Read, 1989; Goldhammer et al., 1990; Strasser, 1994; Elrick, 1995; LaMaskin and Elrick, 1997; Anderson, 2004).

However, a third group (bioturbated emergent parasequences), the focus of this paper, may contain a transgressive laminitite record (rare), but it lacks a well-defined regressive laminitite cap. Instead, the caps are highly bioturbated both by plants and animals (cf. Fischer, 1964; Balog et al., 1997; Strasser et al., 2004). Bioturbation of intertidal-supratidal sediments by macrophytes and burrowing organisms (especially crustaceans), which are common for coastlines where the waters are not hypersaline, may be an important limiting factor on development and preservation of laminitite caps, especially in post-Silurian carbonates (Davies, 1970a; Gostin et al., 1984, Wright and Azeredo, 2006).

In this paper, we describe the facies and the stacking patterns within parasequences on the Early Cretaceous Croatian platform, within a sequence stratigraphic framework. It is the restriction of some microbial/fenestral laminitite units to the transgressive phase of parasequences, and their absence from the regressive caps (which instead are bioturbated), that is of interest, and we evaluate this in terms of possible controls influencing coastal salinities versus climate changes at the parasequence scale.

SETTING AND METHODS

This paper is based on sampling of an ~230 m section of Lower Cretaceous carbonates spanning the Hauterivian to early Barremian on the isolated Adriatic platform, Croatia, as part of a...
larger study on the Upper Jurassic to Lower Cre­
taceous carbonates in the region. The Meso­zoic
Adriatic platform was an isolated platform about
the same size as the modern Bahaman platform.

The studied southern platform interior during
this time was tectonically stable (Husinec and
Jelaska, 2006). The measured section is located
near the town of Sobra, Mljet Island, ~45 km
WNN from the city of Dubrovnik, southern
Croatia (Fig. 1). The section was logged bed-by-
bed noting color, sedimentary structures, grain
size, shape, sorting, constituents, and diagenetic
overprints. Samples were taken at 1 m inter­
vals for thin-section analysis and geochemistry
(beyond the scope of this paper).

In this paper, we use sequence stratigraphic
language and hierarchy as summarized by
Vail (1987), Van Wagoner et al. (1988), Mitchum
and Van Wagoner (1991), Posamentier et al. (1992), Handford and Loucks (1993),
and Weber et al. (1995). Parasequences (Van
Wagoner et al., 1988) are shallowing-upward,
conformable successions of genetically related
strata bounded by marine flooding surfaces, also
referred to as fifth-order cycles. Parasequences
may be bundled into parasequence sets (or
fourth-order cycles) of genetically related para­
sequences forming distinctive stacking patterns
(typically becoming shallower and more re­stricted upward in the set) and bounded by sig­nificant flooding surfaces. These fourth-order
parasequence sets commonly are bundled into
third-order sequences (0.5–5 m.y.; Weber et al.,
1995; Matthews and Al-Hussein, 2010); these
sequences are composed of systems tracts con­
taining one or more parasequence sets. In highly
cyclic successions where significant flooding
events may not be evident, systems tracts are
most easily recognized using accommodation
or Fischer plots (not presented here; Read and
Goldhammer, 1988).

The bioturbated, emergent parasequences
in Croatia consist of a basal thin green shaly
dolomite overlain rarely by microbial or fenes­

tral laminate. The bulk of the parasequence is
composed of subtidal carbonate mudstone with
marine biota (algae, microbial lumps, foraminif­
era, mollusks) and pellet-filled burrows, along
with green dolomite-filled root-like structures,
capped by an emergence surface. Such biotur­
bated carbonate caps to parasequences appear
to typify the non-hypersaline Holocene Andros
tidal flats, the metahaline coastal regions in
Shark Bay and Spencer Gulf, Australia (in con­
trast to the hypersaline bays), parts of the Alpine
Middle Triassic, the Late Triassic of Hungary,
and the Late Jurassic of Portugal.

In contrast, laminate-capped parasequences
may contain a thin transgressive lag or micro­
bial laminate overlain by a regressive success­
ion containing two or more subtidal units (lime
mudstone to ooid-skeletal wackestone-float­
stone, skeletal-peloid wackestone-packstone,
peloid-intraclast packstone to grainstone, and
unfossiliferous lime mudstone), capped by a
fenestral and microbial laminite with a sharp
top, indicative of exposure. Such cycle caps are
ypical of parasequences that form under coastal
waters with elevated salinities, as in Shark Bay
and the Arabian Gulf. The parasequences lie
within the Milankovitch precession-obliquity
band and likely formed by a combination of
orbitally driven, high-frequency changes in sea
level along with autocyclic processes and jerky
subsidence.

HAUTERIVIAN–EARLY BARREMNIE
SEQUENCE FRAMEWORK

The 230-m-thick succession of Hauterivian
to Lower Barremian platform-interior carbon­
ates, southern Croatia (Fig. 1), is highly cyclic,
with abundant meter-scale parasequences, bun­
dled into parasequence sets, several of which
make up third-order sequences (Fig. 2). Promi­
nent and common subaerial exposure surfaces
marked by breccia and shale are concentrated
near third-order sequence boundary zones.

The Hauterivian succession is dominated by
limestone and appears to contain three third­
order sequences: Abundant fenestral and laminate
caps in the lower and upper parts of the succes­
sion, and abundant root traces in parasequence
caps occur in the middle of the succession.

Sequence Htr1 is dominated by peritidal para­
sequences with well-developed fenestral and
laminated caps. Up to nine parasequence sets are
developed. Five 0.1- to 1-m-thick breccia layers
occur near the top of the sequence.

Sequence Htr2 has well-developed subtidal
and peritidal parasequences, and thin transgres­
sive oolites near the base and top of the sequence.
Subtidal mudstone caps to parasequences have
numerous root traces. Up to eight parasequences
sets are developed. In the upper part of this se­quence, thin (10–20 cm) breccia beds occur at
the tops of parasequence sets.

Sequence Htr3 extends into the basal Bar­
remian and is characterized by well-developed
fenestral units and less common microbial lamin­
ites, which appear to become more abundant
up-section. Some peritidal parasequences con­
tain root traces penetrating down into subtidal
mudstones of parasequences. The sequence
contains up to 14 parasequence sets. Multiple
emergence layers at the top of the Hauterivian
and base of the Barremian (top of Htr3) are
associated with microkarsting and paleocave
development.

Sequence Brm1 (Barremian) contains
interbedded limestone and dolomite, and a
50-cm-thick oolite near the base. It consists of
muddy parasequences (some of which lack
regressive laminites), with some root traces,
and thin, fenestral laminites and green shaly
dolomite emergence layers. It has up to five
parasequence sets. The top of the sequence is
characterized by multiple short-term exposures
marked by black-pebble emergence layers (cf.
Strasser, 1984).

Barremian sequences Brm2 and Brm3 con­
tain abundant meter-scale parasequences having

Figure 1. (A) Map of south-cen­
tral Europe showing location of Adriatic Platform (modified
from Grandić et al., 1997; Velić
et al., 2002). Rectangle shows
area enlarged in B, southern
Croatia. (B) Location of the
studied section on Mljet Island
(Sobra).
Figure 2 (legend on following page). Hauterivian–Lower Barremian section from Mljet Island of the Adriatic Platform interior showing facies stacking within parasequences, along with parasequence sets and third-order sequences. Upward-deepening units are shown by upward-narrowing triangles; upward-shallowing units are shown by upward-widening triangles.
successive caps that become more stromatolitic and less fenestral up-section. Only the basal part of Brm1 is shown in Figure 2.

Facies, Parasequences, and Stacking Patterns

The facies in the Lower Cretaceous sequences are summarized in Table 1 and Figure 3. These include, from deep to shallow:

Low-Energy Subtidal Lagoon
(Lime Mudstone to Oncoid Wackestone-
Floatstone, Dolomudstone-Wackestone,
Moldic Dolofloatstone)

These muddy carbonates are massive- to thick-bedded units that contain a shallow-marine benthic biota (Table 1). Upper parts of some units have distinctive pellet-filled burrows (5–10 mm diameter) and green dolomite-filled root traces (> 5 mm diameter), some of which bifurcate into millimeter size traces (Figs. 3A, 3C, and 3D).

These muddy carbonates are low-energy facies that formed in water depths perhaps up to a maximum of 10 m (cf. Husinec and Read, 2007), below the zone of frequent wave reworking. The marine biota is predominantly calcareous algae, bivalves, and benthic foraminifera, and indicates relatively open marine conditions compared to the other facies. The highly bioturbated tops of some of the muddy carbonate units beneath emergence surfaces suggest biogenic reworking; some of this burrowing could have occurred in subtidal environments, but with shallowing, there was bioturbation by both plants and animals in the intertidal zone, with perhaps a plant bioturbation continuing into supratidal zone during emergence.

Moderately Shallow Lagoon
(Wackestone-Packstone)

This facies (Table 1) consists of skeletal-peloid wackestone-packstone and microbial lump-pisoid wackestone-packstone. These are platform-interior units that form thin sheets commonly capping "deeper" subtidal facies. The units were likely formed below fair-weather wave base at depths of several meters and were affected by weak winnowing currents. Microbial lump and microbial pisolithic grainy units locally were deposited in very shallow water (<10 m) in which bottom sediments were periodically reworked during higher-energy events.

Shallow Water

The peloid-intraclast packstone-grainstone and less common oncoid packstone to rudstone units range from very thin (1–3 cm) to thick (meter-scale) beds and commonly contain fragments of calcareous algae as well as benthic foraminifera, bivalves, and gastropods (Table 1). Locally, packstones and grainstones are cross-bedded. These units formed on shallow shoals in up-dip, wave- and current- agitated areas of the platform interior.

Shallow Subtidal-Intertidal Oolitic Shoals and Ponds

This facies consists of dark-gray to olive-green oolitic units characterized by oversized ooids with primary radial calcite fabrics. They differ from open-marine, platform-margin ooid grainstones in their dark color, cerebroid outlines (arcuate irregular protuberances rather than smooth coats), commonly broken and recoated grains, highly restricted biota, and lack of cross-stratification (Husinec and Read, 2006). These oolites commonly occur at bases of parasequences (Fig. 3E) and were likely formed during initial inundation of supratidal flats within the hypersaline shallow subtidal to intertidal shoals and ponds of the platform interior. Some of these oolitic units also could be analogous to shallow subtidal platform interior oolites of Caicos Platform, which experienced intermittent movement from wind-waves (Wanless and Tedesco, 1993).

Restricted Lagoon Lime Mudstone

Barren, unfossiliferous lime mudstone is thin bedded, and contains rare irregular fenestrae. This unit is associated with shallow restricted lagoon environments immediately seaward of tidal flats. The restricted fossil content suggests possible hypersalinity.

Tidal Flat Microbial Laminites and Fenestral Carbonates

This facies (Table 1) consists of fenestral lime mudstone-wackestone, microbial laminite, laminated dolomite, and less commonly planar laminite. The laminoid fenestral fabrics (Fig. 3B) occur predominantly in lime mudstones-wackestones, and less commonly in peloid packstones with rare pisoids, and they are characterized by planar to gently curved laminoid fenestrae that are parallel or subparallel to bedding. Unlike microbial laminites, the laminoid fenestral fabrics are not dolomitized and likely indicate slightly more humid climatic conditions from non-hypersaline tidal and groundwaters (cf. Grover and Read, 1978).

In contrast, the microbial laminites consist of couplets of wavy or crinkly laminae of fine peloid packstone draped by lime mudstone (Table 1). They formed in low-energy hypersaline tidal flats, as indicated by decreased diversity of biota, and lack of bioturbation, analogous to the distribution of extensive, stratiform microbial laminites in modern hypersaline prograding tidal flats in the Arabian Gulf and Shark Bay (Kendall and Skipwith, 1969; Davies 1970a, 1970b; Logan et al., 1974). In contrast, microbial laminites in the Bahamas are of limited extent and are restricted to emergent narrow levee crests bordering channels, which undergo relatively infrequent wetting. The relative scarcity of evaporite pseudomorphs in the Croatian examples suggests that the coastal waters never reached gypsum saturation.

Intraclastic Lags

Intraclastic lags were deposited in transgressive, intermittently-high energy coastal settings, which inhibited low-energy laminites from forming. The lags were reworked from the lithified transgressed surface or from lithified hardground layers eroded during transgressive ravinement formation.

Subaerial Exposure Surfaces, Paleosol Breccia, and Green Shaly Dolomite

This facies association (Table 1) is characterized by an irregular microkarstic surface (Figs. 3A and 3F) that is commonly capped by a paleosol breccia and/or green shaly dolomite. The paleosol breccia is typically an intraclast rudstone with granule- to pebble-size clasts in an olive-green, shaly dolomite matrix (Fig. 3A). The intraclasts are tan or less commonly black, and were eroded from the underlying limestones. The green shaly dolomite on the emergence surfaces likely resulted from transgressive reworking of eolian sediment, during which the silicilastic component was mixed with carbonate (cf. Fischer, 1964; Deconinck et al., 1988). Evidence that the fine detrital component is likely windblown dust is indicated by the isolated setting of the Adriatic platform, which would inhibit influx of fluvial silicilastics from the continent.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Subaerial exposure</th>
<th>Intraclast lag</th>
<th>Tidal flat</th>
<th>Restricted nearshore shoals and ponds</th>
<th>Shallow subtidal/intertidal</th>
<th>Shallow-water sandflat</th>
<th>Moderately shallow lagoon</th>
<th>Low-energy subtidal lagoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>Intraclast rudstone</td>
<td>Flat-pebble rudstone</td>
<td>Fenestral lime mudstone-packstone-grainstone (less common)</td>
<td>Barren (unfossiliferous) lime mudstone</td>
<td>Ooid grainstone-packstone</td>
<td>Peloid-intraclast packstone-grainstone, rare oncoid packstone to rudstone</td>
<td>Skeletal-peloid wackestone-packstone Microbial lump-pisoid wackestone-packstone</td>
<td>Lime mudstone to oncoid wackestone-floatstone Dolomudstone/wackestone, molds dolofloatstone</td>
</tr>
<tr>
<td>Color</td>
<td>Interaclasts tan to black (limestone) or olive green (dolomite), matrix olive green Shaly do o limeite dark gray to olive green</td>
<td>Light brown</td>
<td>Light brown (limestone) to dark gray (dolomite)</td>
<td>Cream</td>
<td>Dark gray to gray-green</td>
<td>Light brown</td>
<td>Light brown</td>
<td>Cream to light gray (limestone); dark gray (dolomite)</td>
</tr>
<tr>
<td>Sedimentary structures*</td>
<td>Thin to thick bedded, common lateral variation in thickness, microkastric exposure surface, incipient brecciation (some with fitted fabric)</td>
<td>Thin-bedded, gradational top</td>
<td>Wavy microbial lamination; fenestral lamination; millimeter laminae of lime mudstone and peloid-skeletal packstone</td>
<td>Thin-bedded, homogeneous micrite; rare irregular fenestrae and green shale partings</td>
<td>Thin to thick bedded; rare cross-lamination</td>
<td>Thin to thick bedded; rare cross-lamination</td>
<td>Thin to medium bedded</td>
<td>Highly root disrupted (branching, different sizes, some up to 1 cm in diameter), thick to very thick bedded; random tubular fenestrae with green shale infills beneath karstic erosional surface, gastropod or bivalve molds (floatstone) commonly leached and filled with green shale</td>
</tr>
<tr>
<td>Fabric</td>
<td>Poorly sorted, very coarse sand to pebble size</td>
<td>Several-centimeter-long platy clasts in grainstone matrix</td>
<td>Poorly sorted, mud to granule size</td>
<td>Dominantly mud size</td>
<td>Poor to well sorted, fine sand (peloids) to granule size (ooids)</td>
<td>Range from well sorted to poorly sorted, fine sand to granule size</td>
<td>Poorly sorted, mud matrix with sand- to rare granule-size grains</td>
<td>Poorly sorted muds with sand- to granule-size grains</td>
</tr>
<tr>
<td>Grain types</td>
<td>Intraclasts, some argillaceous dolomite clasts; terrigenous clay and silt</td>
<td>Intraclasts, less common peloids and microbial lumps</td>
<td>Micritized peloids, intraclasts, rare pisoids, microbial lumps, and large ooids</td>
<td>Rare peloids</td>
<td>Ooids (some broken and rehealed), peloids</td>
<td>Peloids, intraclasts, oncocids, rare pisoids and microbial lumps</td>
<td>Peloids, microbial lumps, pisoids, rare intraclasts</td>
<td>Oncoids, microbial lumps, rare micrite intraclasts and ooids</td>
</tr>
<tr>
<td>Biota</td>
<td>None</td>
<td>None</td>
<td>Calcified cyanobacteria (Cayeuxia?), rare calcareous algae</td>
<td>Fossils absent to sparse; rarely may have gastropods and ostracods</td>
<td>None</td>
<td>Calcareous algae, benthic foraminifera and gastropods</td>
<td>Common calcareous algae, less common gastropods and benthic foraminifera</td>
<td>Common calcareous algae, benthic foraminifera, bivalves and gastropods, less common ostracods</td>
</tr>
</tbody>
</table>

*Bed-thickness scale is after McKee and Weir (1953).
Figure 3. Outcrop photographs of platform-interior peritidal limestones from Figure 1. Scale is in centimeters. (A) Marine lime mudstone with abundant dark-green shaly dolomite-filled root traces. The top of the lime mudstone is slightly fenestral and weakly brecciated and has a sharp top (d) beneath a green dolomitic layer with intraclasts. (B) Well-developed laminated fenestral lime mudstone; such fenestral caps can be transgressive (at bases of parasequences) or regressive (capping parasequences). (C) Marine lime mudstone with abundant root traces filled with dark-green shaly dolomite. (D) Close-up photograph of probable branching root traces (outlined in pencil) infilled with greenish dolomitic clay; the host sediment is a light-gray subtidal lime mudstone. (E) Root-disrupted lime mudstone with gastropods (lower half of photo) capped by planar exposure surface. Beneath the contact (d) is a dark, large, wedge-shaped cavity (root trace or bedding plane joint) filled with ooids, peloids, and intraclasts in a green shale matrix. Planar contact (d) is overlain by transgressive marine ooid-peloid grainstone. (F) Erosional irregular surface (d) on light-tan lime mudstone (bottom) with peloidal burrow fills and root traces infilled with green shaly dolomite; the tan color suggests emergence. The contact (d) is overlain by light-gray subtidal lime mudstone with tubular fenestrae and scarce root traces infilled with green shaly dolomite. The mudstone is overlain by paleosol breccia composed of large pale tan mudstone clasts with interstitial green, shaly platy-granule wackestone matrix, marking another exposure surface (above photograph).
Such dust would be a mixture of carbonate and silicilastic silts, analogous to the widespread layers deposited after the frequent wind-generated dust storms in the Middle East (Evans et al., 1969; Kinsman and Park, 1976; Alsharhan and Kendall, 2003). The fine silt and sand (preserved as the green silty dolomite on the emergence surfaces) infiltrated downward, probably under the influence of percolling groundwaters into root traces, and less commonly burrow traces and into cavities formed within leached shells in the underlying typically muddy carbonate unit. This infiltrated dolomitic sediment may have originally been calcium carbonate and clay, the carbonate being dolomitized subsequently. Similar clayey paleosols and reworked paleosols in the Hungarian Late Triassic Dachstein Limestone developed under moderately humid conditions; in contrast, laminated and pisolithic caliche caps typical of the underlying Hungarian Main Dolomite (Hauptdolomit) Formation were formed under more arid, highly dolomitizing settings (Balog et al., 1997). The rarity of such caliche fabrics in the Adriatic platform succession similarly suggests that the climate was not very dry or highly seasonal.

**Parasequence Types**

The parasequences in the Hauterivian–Barremian are commonly limestone, but some are heavily dolomitized, where the dolomitization occurs in zones spanning several parasequences.

**Regressive Fenestral/Laminite-Capped Parasequences**

The regressive parasequences (Figs. 4A and 5) commonly consist of, from base to top, (1) thin lag of microbial lump-pisoid wackestone-packstone (rare) overlain by a regressive succession containing two or more of the following: (2) subtidal unit of lime mudstone to oncoid-skeletal wackestone-packstone, (3) peloid-intraclast packstone to grainstone with calcareous algae, benthic foraminifera, and gastropods; and/or (5) homogeneous, unfossiliferous lime mudstone with rare peloids and irregular fenestrae. The parasequences are capped by (6) fenestral, microbial, and planar laminites (intertidal), and (7) microkarstified tops, locally with incipient breccia of granule- to pebble-size angular clasts in lime mudstone or dolomitic green shale (emergence layers). The regressive laminites lack gypsum or anhydrite pseudomorphs.

**Transgressive-Regressive Laminite-Bounded Parasequences**

The transgressive-regressive parasequences (Figs. 4B and 5) have a well-developed transgressive basal unit composed of one or more of the following: (1) lag of algal lump-pisoid carbonates, (2) microbial laminite, (3) barren lime mudstone (restricted lagoon), (4) intraclast-peloid grainstone-packstone (shoal water), and (5) skeletal-peloid packstone-wackestone (shallow subtidal). This transgressive interval is capped by regressive carbonates, which terminate in fenestral or laminated carbonates by an emergence surface, similar to those in the regressive parasequences described previously.

**Bioturbated Emergent Parasequences**

The bioturbated emergent parasequences are dominated by subtidal facies. They consist, from base to top (Figs. 4C and 5), of one or more of the following: (1) local granule- to pebble-size angular clasts in lime mudstone or dolomitic green shale, overlain by (2) relatively rare transgressive fenestral laminites, locally with green shale stringers, or (3) microbial-lump and pisoid wackestone-packstone to floatstone, or (4) thin dark-colored, coarse ooid rudstone with broken and rehealed ooids (may be capped by erosion or hardground surfaces). These are overlain by (5) subtidal peloid muddy carbonate with gastropods, bivalves, benthic foraminifera, and calcareous algae, with peloid-filled burrows and branching, several-millimeter-wide root traces filled with green shaly dolomite. Capping emergence surfaces (6) may be planar or irregular, and shaly dolomite-filled subhorizontal V-shaped cracks and irregular cavities extend downward from the surface.

**Relative Abundance of Parasequence Types**

The relative abundance of parasequence types (Fig. 6) within the studied succession shows that laminite-capped regressive parasequences make up 50% of parasequences. Bioturbated emergent parasequences are the next most common type, whereas transgressive-regressive parasequences are least common. Bioturbated emergent parasequences and transgressive-regressive parasequences are more common in the transgressive systems tracts of the third-order depositional sequences (cf. Strasser et al., 1999). The laminite-capped regressive parasequences are common in highstands of the sequences (see Fig. 2).

**DISCUSSION**

**Parasequence Durations**

Peritidal parasequences in the geological record can result from Milankovitch- and sub-Milankovitch–driven (e.g., Zühlke et al., 2003) sea-level changes, jerky subsidence, and autogenic processes related to local island shoaling.
The fact that these parasequences formed dominantly under the influence of sea-level changes is indicated by their average duration within the fifth-order Milankovitch band (average 40 k.y.), the emergence tops on many cycles indicating sea-level fall, the asymmetric character of some of the parasequences indicating rapid deepening, and the general lack of seismically induced deformation features (Ginsburg, 1971; Read, 1989, 1995; Goldhammer et al., 1990; Strasser, 1994; Goodwin and Anderson, 1985; Wilkinson et al., 1997; Zühlke et al., 2003; Strasser et al., 2004). The lack of two-dimensional control on the platform prevents regional tracing of cycles.

Based on the total thickness of Hauterivian and Barremian succession (150 m and 160 m, respectively) and the duration of the intervals (Hauterivian ~4 m.y., Barremian ~5 m.y.; Gradstein et al., 2004), subsidence rates (not corrected for compaction) ranged from 4 cm/k.y. in the Hauterivian to 3 cm/k.y. in the Barremian. These subsidence rates are compatible with a mature passive margin and are far less than potential sedimentation rates (Schlager, 1981; Koerschner and Read, 1989). Approximately 100 parasequences developed on the platform during the Hauterivian, and 110 parasequences developed during the Barremian. Given the uncertainty on the boundary ages of stages, these parasequences have rough average durations of ~40 k.y., and thus they are within the orbital (Milankovitch) band. However, this does not imply that obliquity was the dominant control. Given the low long-term subsidence (cf. Koerschner and Read, 1989; Goldhammer et al., 1990) and abundant subaerial breccia exposure layers (~35 in Hauterivian, ~40 in Barremian) in the updip areas of the platform, it is likely that many precessional beats are missing. It seems more likely that precessional climate forcing in a greenhouse world (Schwarzacher, 1975; Koerschner and Read, 1989; Goldhammer et al., 1990; Strasser, 1994; Balog et al., 1997) was an important control, with the numerous missing
beats (associated with breccia layers) resulting in apparently longer average cycle durations (Goldhammer et al., 1990).

Controls on Deposition of Transgressive Phases of Parasequences

Regressive, fenestral/laminite-capped parasequences that lack transgressive units have been widely documented (e.g., Read, 1973; Goodwin and Anderson, 1985; Demicco, 1985; Koerschner and Read, 1989; Goldhammer et al., 1990; Bond et al., 1991; Tišlar and Velič, 1991; Montañez and Osleger, 1993; Elrick, 1995; Strasser, 1994; D'Argenio et al., 1997; Yang and Lehrmann, 2003; Husinec and Read, 2007; Bosence et al., 2009). They result from rapid submergence of the platform to shallow depths, perhaps associated with a short 1–3 k.y. lag time (cf. Schlager, 1981; Kendall and Schlager, 1981; Read et al., 1986; also see Tipper, 1997), which in effect limits deposition of any significant transgressive record. However, lack of a transgressive record could also relate to long lag time, allowing gradual deepening of the platform and/or very slow sedimentation during sea-level rise. As relative sea-level rise slowed and sediment supply exceeded accommodation, initial transgression would have been followed by deposition of a regressive succession of subtidal muddy carbonates grading up into low-energy, intertidal-to-supratidal microbial/fenestral laminates in an overall upward-shallowing mode.

Transgressive deposits (commonly laminites and intraclastic lags) in the transgressive-regressive parasequences and some bioturbated emergent parasequences probably resulted from transgression that was slow, a lag time that was short, and low-energy currents along the shoreline, to allow a transgressive unit to develop prior to full deepening of the platform (cf. Koerschner and Read, 1989). Evidence that laminates low in these parasequences are transgressive includes their position on an underlying emergence surface or green dolomite shale, and the fact that they are overlain by slightly deeper-water facies (cf. Balog et al., 1999). Transgressive laminites developed where microbial mats were able to colonize the sediment surface during transgression, under hypersaline conditions (in which the lack of burrowers prevented layering from being bioturbated). Subsidence also might have promoted preservation of a transgressive record because it brought the surface of the emergent platform down to the fifth-order lowstand position of sea level (characterized by low fall and rise rates). Low rates of sea-level change during a fifth-order lowstand allowed an early transgressive record to be deposited on emergence surfaces/green shale veneers, assuming that the sea-level curves have an asymmetric sinusoidal form.

Transgressive laminites may have only been able to develop on localized subtle topographic highs during transgressive flooding, analogous to the present distribution of (regressive) laminites on tidal channel levees in the Bahamian flats; the bulk of the Bahamian intertidal flats are bioturbated pond and channel facies, with laminated facies making up a relatively small percentage of the overall area (Hardie and Ginsburg, 1977; Rankey, 2002). This topographic control could account for the limited abundance of the Croatian transgressive laminites. However, the humid Bahamian tidal flats are a poor climatic analog; the Croatian laminites lack the humid zone features of the Bahamian laminites, which are characterized by their distinctive Scytonema mats and preserved microbial filaments, algal biscuits, and plant and animal bioturbation.

Significance of Oolitic Units in Parasequences

Oolitic units low in some bioturbated emergent and regressive, fenestral/laminite-capped parasequences are suggestive of oolitic facies deposited in platform-interior hypersaline ponds or oolitic sand flats (cf. Husinec and Read, 2006, 2007), in which case, they may be transgressive if the overlying muds were formed at greater water depths than the oolites. However, some could be analogous to more regional subtidal low-energy oolites, such as those covering much of the Caicos Platform (Wanless and Tedesco, 1993). The Croatian oolites, if analogous to the Caicos Platform oolites (Wanless and Tedesco, 1993), could have formed under a few meters of water depths, with muddy facies being deposited on top as energy levels in the platform interior fell as water depths decreased during muddy shoreline progradation.

Development of Muddy Carbonate Blankets within Parasequences

The subtidal muddy carbonates characterize almost all of the parasequences studied and were deposited as sea level rose on the platform, increasing water depths to a few meters. This caused energy to decrease within the platform interior, and more open-marine biota became established. These muddy carbonates were bioturbated by crustaceans and other burrowers. In Cenozoic succession normal marine to metahaline areas, root disruption also results from bioturbation from sea grasses colonizing the shallow platform areas (Davies, 1970a; Turmel and Swanson, 1976; Wanless, 1981), but sea grasses did not become abundant until the Paleocene (Ivany et al., 1990). In some parasequences, these are overlain by shallowing-upward grainy facies, as energy increased, or by restricted mudstone, where hypersaline conditions were established.

Development of Laminite Caps

Microbial laminites capping the regressive and transgressive-regressive parasequences are regressive in that they are overlain by emergence surfaces and a closely juxtaposed flooding surface. The nonbioturbated laminites, whether transgressive or regressive, likely are indicators of hypersaline, restricted, low-energy tidal flat conditions that inhibited bioturbation by plants and animals (cf. Kendall and Skipwith, 1969; Logan et al., 1974). Today, climate is a major first-order control on formation and preservation of well-developed microbial laminations, as evidenced by the relative abundance of intertidal microbially laminated sediments in arid or semi-arid areas (Kendall and Skipwith, 1969; Logan et al., 1974; Kinsman and Park, 1976). Given that the bulk of the parasequences in the Haiterivian and Barremian, Croatia, are regressive, laminite-capped types, it is likely that salinities generally increased with shallowing of the inner platform, i.e., it did not become more humid with shallowing. This might suggest that the greenhouse sea-level changes were small, as was any forcing climatic signal, as might be expected during global greenhouse climate; with increasing amplitudes of sea-level changes, regionally regressive tidal-flat laminites become rare in the stratigraphy (Read, 1998). Salinites on the broad Croatian platform did not reach the calcium sulfate precipitation field, given the absence of evaporites or vanished evaporites in the outcrops.
Development of Burrowed and Rooted Caps to Bioturbated Emergent Parasequences

The bioturbated emergent parasequences capped by emergence surfaces and incipient paleosols are suggestive of Fischer’s (1964) Triassic Lofer parasequences and are similar to peritidal, so-called “transgressive” parasequences described from the Upper Triassic of Hungary (Balog et al., 1999), and to peritidal successions disrupted by macrophytes described by Wright and Azeredo (2006). The absence of laminates was not due to deposition on a platform margin high (cf. Elrick, 1995), given that the section described here is some 50 km inboard from the platform margin (Fig. 1). There is little evidence that regressive laminates were deposited on these bioturbated emergent parasequences in Croatia; obliteration of such regressive laminates by bioturbation during the subsequent transgression (cf. Tedesco and Wanless, 1991) is unlikely, as ghosts of laminate in the caps of the bioturbated emergent parasequences are very rare.

Laminates were not deposited on the Croatian platform where shallowing occurred under non-hypersaline conditions. The muddy carbonates underwent additional bioturbation by macrophytic plant roots and intertidal burrowers such as crabs as the units became emergent and macrophytes were established along the regressing coastal zone. The coastal zone macrophytes and burrowing and grazing organisms inhibited the development of microbial mats on the intertidal-supratidal surface because coastal waters were normal marine to metahaline. Presence of macrophytes in the coastal zone is also suggested by presence of local, dark-gray, platy, nonfossiliferous, organic-rich mottled mudstone, with scattered black pebbles, limonite, and pyrite implying restricted and oxygen-deficient environments above some parasequence boundaries (Sokač et al., 1977). Such reducing conditions could indicate a peritidal setting with macrophyte vegetation and peaty soils, where root bioturbation may have reworked blackened layers into black pebbles (cf. Strasser, 1984; Wright and Azeredo, 2006).

Such bioturbation that is climate controlled is evident in the relatively humid Bahamian flats, where mangrove roots and pneumatophores and faunal bioturbation commonly destroy laminations, except on the narrow, localized supratidal levees, which are relatively dry and where layering is well preserved (Hardie and Ginsburg, 1977). Under relatively dry climates, intense bioturbation is limited to coastal areas that are non-hypersaline and subject to considerable exchange of marine waters. For example, in Shark Bay, Western Australia, the intertidal zone in metahaline areas (salinities 40–56 ppt) is dominated by mangroves and is highly bioturbated, resulting in un laminated sediments; microbial laminates typically are developed only in the hypersaline zone at the heads of embayments where intense bioturbation and browsing are inhibited (Davies, 1970a, 1970b). Similarly in the Spencer Gulf, South Australia, laminates are well developed around the heads of restricted hypersaline embayments. In the more normal marine coastal zone, which is dominated by salt marsh and mangroves, the intertidal-supratidal sediments are intensely bioturbated, and microbial lamination is not preserved. It should be pointed out that Shark Bay and Spencer Gulf are not fronted by broad, very shallow platforms, such as the Adriatic platform, but instead, open shelves; in the case of the large, shallow Adriatic platform, shallowing of the platform interior to tide levels would likely promote hypersalinity all along the prograding coastline if climate were semiarid.

The previous discussion would imply that burrowed and rooted versus laminate caps to parasequences, if climate controlled, should be relatively regional on the platform interior, except in intrashelf basins and on the platform margin highs (cf. Elrick, 1995). In contrast, if they were formed under semiarid conditions in which a salinity gradient was maintained by bathymetric controls, then burrowed and rooted caps might be expected to pass updip into laminates in heads of hypersaline embayments.

Root disruption in Lower Cretaceous sediments in the Swiss and French Jura was documented by Strasser et al. (2004), especially near sequence boundary zones. Macrophyte vegetated shorelines coupled with intense bioturbation due to burrowers (especially crustaceans) has been invoked for Upper Jurassic parasequences lacking cycle-capping laminates in Portugal (Wright and Azeredo, 2006). Similarly, tubular fenestral (rooted) massive carbonate caps with vadose silts occur in Devonian back reef cycles, Canning Basin, Western Australia, whereas others that presumably formed under hypersaline conditions have well-developed microbial laminate caps (Read, 1973).

If the Croatian burrowed and rooted caps to parasequences were climatically controlled, then warm, humid conditions developed during highstand and falling sea level at various times, interrupting the prevailing semiarid climate. Humid conditions would have prevented the development of hypersalinity along the prograding low-energy coastlines of the shallow platform interior, and thus favored macrophytes and burrowing crustaceans in the coastal zone, precluding laminated sediments from being deposited.

Interestingly, caliches and associated fabrics typical of seasonal wet-dry conditions are absent from tops of parasequences in the Adriatic platform (even from the laminate-capped regressive parasequences). However, melanized haloes, microkarst features, fenestrae, and root traces are present. The lack of caliche may be due to the very short duration of exposure of these peritidal parasequences (given that these are likely precessional cycles), coupled with weak climate seasonality (James, 1977). Longer-term exposure of the Croatian units, especially near third-order sequence boundaries, is marked by breccia with green shale matrix and blackened limestone clasts—again the lack of caliche argues against seasonally wet-dry climates. Also, seasonally wet-dry climates generally would not preserve microbial laminates in the intertidal zone, because any layering would likely be bioturbated during the wet season when salinities of tidal flat groundwaters were lowered.

If the stratigraphic distribution of laminate versus bioturbated caps to parasequences in Croatia was climatically controlled, then the transition from transgressive laminates to regressive burrowed and rooted caps suggests a change from restricted, semiarid conditions and hypersalinity at the base (transgressive laminites) to a more humid climate during highstand and falling sea level, which maintained normal marine to metahaline coastal waters. This transition within a parasequence could have been due in part to subtle platform bathymetry that initially formed shallow hypersaline embayments that were fully flooded by normal marine waters during highstands in sea level. However, given the large extent of the platform and its probably low gradients, it would be difficult to keep the relatively normal marine salinities of the coastal zones in the platform interior without making the platform more humid, and decreasing evaporation.

As pointed out earlier, climatic versus bathymetric control on laminate versus burrowed and rooted caps should be evident in regional distribution of facies. If bathymetrically controlled, the burrowed and rooted caps should pass into the platform interior laminites. Our limited data do not allow this to be documented for the Early Cretaceous.

If the development of laminites (transgressive and regressive) versus burrowed and rooted caps to parasequences was climatically controlled, then it suggests changes in rainfall/humidity/evaporation at the scale of some parasequences, or perhaps longer term. Could such climate swings at the parasequence scale reflect drier, windier climates during lowered sea-level phases, promoting hypersalinity in platform interiors, and wetter and less windy climates during highstand and early fall (reflecting slightly decreased thermal gradient) (Perlmutter and Matthews, 1989)? The wet-dry cyclicity of the Pleistocene is an
extreme case of waxing and waning of immense ice sheets. This resulted from the expansion and contraction of the major global climate zones involving the humid tropics, dry desert belt, and moderately humid temperate belts (Perlmutter and Matthews, 1989). However, the vertical distribution of most of the regressive Croatian laminate-capped parasequences versus burrowed and rooted parasequence caps may reflect longer-term climatic changes (parasequence set scale or longer) independent of sea level. That is, the climate changes at the parasequence scale were relatively small, as might be expected in a relatively ice-free greenhouse world, and it was the longer-term changes in climate that were important.

The bioturbated emergent parasequences, if climate related, would indicate that periods of more humid climates characterized much of the Hauterivian (Hr-t-2, lower part of Hr-t-3), which generally became drier into the Barremian. The late Hauterivian and early Barremian, with abundant stromatolitic caps to parasequences, testify to this drying trend.

In summary, the evidence presented herein suggests that presence or absence of laminites from parasequences, along with evidence of bioturbation by plants and animals in the section, may provide an important coastal salinity indicator, perhaps with implications for climate variability on cyclic carbonate platform interiors. This could perhaps extend back to the Ordovician, when plants began to colonize the land surface (Wellman and Gray, 2000; Wellman et al., 2003); pre-Devonian plants had holocausts that could have caused plant bioturbation.

CONCLUSIONS

The interior of the greenhouse Early Cretaceous isolated carbonate platform, Croatia, has some parasequences that lack the typical regressive tidal flat laminites; instead, they have burrowed and rooted upper parts, capped with thin greenish paleosols (bioturbated emergent parasequences). We propose that this parasequence type reflects coastal salinities that were normal marine, brackish, or metahaline, which allowed macrophytes and burrowers to colonize the shorelines, inhibiting formation of laminites. In contrast, the tidal flat laminates capping other parasequences formed under hypersaline coastal waters. Thus, the presence or absence of the laminates from the parasequences may be used to track gross salinity changes of coastal waters on the platform through time. We suggest means with which to evaluate whether these bioturbated caps versus laminate caps relate to broad embayments in which salinity increased into bayheads, or to climate changes at the parasequence scale.

If related to broad embayments, then they have implications with regard to development of subtle bathymetric relief on the platform within short time spans. If climate-induced, then they have implications for the magnitude of climate changes in greenhouse worlds.

The distribution of most modern microbial laminites in semiarid and arid carbonate settings supports a strong climatic control on these features today. If climate-induced, then the short-term sea-level highstands and falls of bioturbated emergent parasequences were more humid phases. Alternatively, if climate remained semiarid, then the lack of regressive laminites could reflect parasequences that formed in the more open parts of a prograding coastal zone, while time-equivalent laminate-capped parasequences formed in hypersaline embayments in more interior parts of the platform. Thus, if bioturbated caps on parasequences resulted from coastal bathymetry under semiarid climate, then they would be traceable updip into laminate-capped parasequences. However, if the parasequences resulted from a switch from semiarid to humid climate, then the bioturbated caps (more humid phases) would be relatively regional on the platform, as would laminites (semiarid phases).

The absence of such laminites, when associated with bioturbation by plants and animals in upper parts of parasequences, has been documented from rocks of several ages and may provide an important coastal salinity indicator, and perhaps a climatic indicator on cyclic carbonate platforms. This could extend perhaps back to the Ordovician when plants began to colonize the land surface.

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