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RELATIVE SEA-LEVEL CHANGES RECORDED ON AN ISOLATED CARBONATE PLATFORM: TITHONIAN TO CENOMANIAN SUCCESSION, SOUTHERN CROATIA

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ABSTRACT: **Superb sections of Tithonian to Cenomanian carbonates of the Adriatic (Dinaric) platform are exposed on the islands of southern Croatia. A succession approximately 1,800 m thick consists exclusively of shallow-water marine carbonates (limestone, dolomitized limestone, dolomite, and intraformational breccia), formed in a protected and tectonically stable part of the platform interior. Several phases of exposure and incipient drowning are recorded in the platform interior. Four are crucial for understanding the Late Jurassic to mid-Cretaceous evolution of the wider peri-Adriatic area: (1) latest Jurassic–earliest Cretaceous sea-level fall, (2) Aptian drowning, followed by (3) Late Aptian platform exposure, and (4) Late Albian–Early Cenomanian sea-level fall. Deciphering these complex events from the vertical and lateral facies distribution has led to an evaluation of facies dynamics and construction of a relative sea-level curve for the study area. This curve shows that long-term transgression during the Early Tithonian, Hauterivian, Early Aptian, and Early Albian, resulted in generally thicker beds deposited in subtidal environments of lagoons or shoals. Regression was characterized by shallowing-upward peritidal parasequences, with well-developed tidal-flat laminites commonly capped by emersion breccia and/or residual clay sheets (Early Berriasian, Barremian, Late Aptian, Late Albian). The southern part of the Dinarides was tectonically quiet during the Tithonian through Aptian; sea-level oscillations appear to have been the primary control on facies stacking. Some correlation exists between local sea-level fluctuations and the published global eustasy charts for the Tithonian through Aptian. A significant departure is recognized at the Albian–Cenomanian transition, suggesting that it was influenced by tectonics associated with the disintegration of the Adriatic (Dinaric) platform.**

INTRODUCTION

Isolated carbonate platforms are shallow-water carbonate accumulations surrounded by deep water (Read 1985). Their best present-day example is the large, isolated, unattached, rimmed platform of the Great Bahama Bank. Mesozoic isolated platforms flourished in the Tethyan region; some of their finest outcrops are in the peri-Adriatic mountain belt (e.g., Bosellini 1984, 2002; Blendinger 1986; Vlahović et al. 2002; Vlahović et al. 2005; Jelaska 2003). The northern part of this belt (Fig. 1A) forms the Southern Alps, where the comparatively gently deformed passive margin of the Adria microplate spectacularly exposes Triassic, particularly Anisian–Ladinian, carbonate-platform successions (Bosellini et al. 2004, and references therein). Unlike this area, which has become almost classic for studying the early Mesozoic Tethyan stratigraphy, the late Mesozoic evolution of this part of the Tethys is much better preserved in western (Apennines) and eastern (Dinarides) limbs of the peri-Adriatic mountain belt (Fig. 1A). In both of these regions with similar depositional histories, the well exposed late Mesozoic platform successions show prevailingly cyclic sedimentary organization with a dominantly aggrading architecture. They consist of predominantly shallowing-upward units as a result of transgressive–regressive events. The Upper Jurassic to Albian successions of the Apenninic and Apulian platforms (Fig. 2B), exhibiting sedimentological evidence of high-frequency sea-level changes, have been studied extensively in terms of genetic mechanisms that controlled their evolution (e.g., Eberli et al. 1993; D'Argenio et al. 1997; D'Argenio et al. 1999; Bosellini et al. 1999). In all of these studies, the eustatic nature of the cyclicity and the hierarchical organization of the cycles appears related. The subsequent exposure during the early Late Cretaceous (generally Early Albian to end-Cenomanian), which is a common feature on both of these platforms, is considered to be the consequence of tectonic uplift, inasmuch as the Adria microplate was already in the collisional stage with Europe (Eberli et al. 1993). In contrast to the southern Italian platforms, until recently no attempt has been made to reveal the genetic mechanisms that controlled cyclicity on the Adriatic (Dinaric) platform. So far only the Upper Jurassic succession has been studied with respect to this, and it appears that Tithonian parasequences were formed by precessionaly driven, small-scale sea-level changes (Husinec and Read 2005, 2006). Moreover, Husinec and Read (unpublished data) conclude that the parasequence stacking patterns suggest strongly that the Tithonian was a time of global greenhouse during the Middle Jurassic to Early Cretaceous "cool" mode.

Carbonate platforms are sensitive recorders of relative sea level through geologic time. A number of coexisting factors control their facies stacking pattern. The purpose of this paper is to test mechanisms of sea-level change within Tithonian-to-Cenomanian isolated carbonate platform successions by (1) describing evidence for relative sea-level change and (2) evaluating how relative sea-level change influenced facies dynamics, i.e., spatial and temporal facies distribution. This paper presents a qualitative overview of the sea-level history. Work is in

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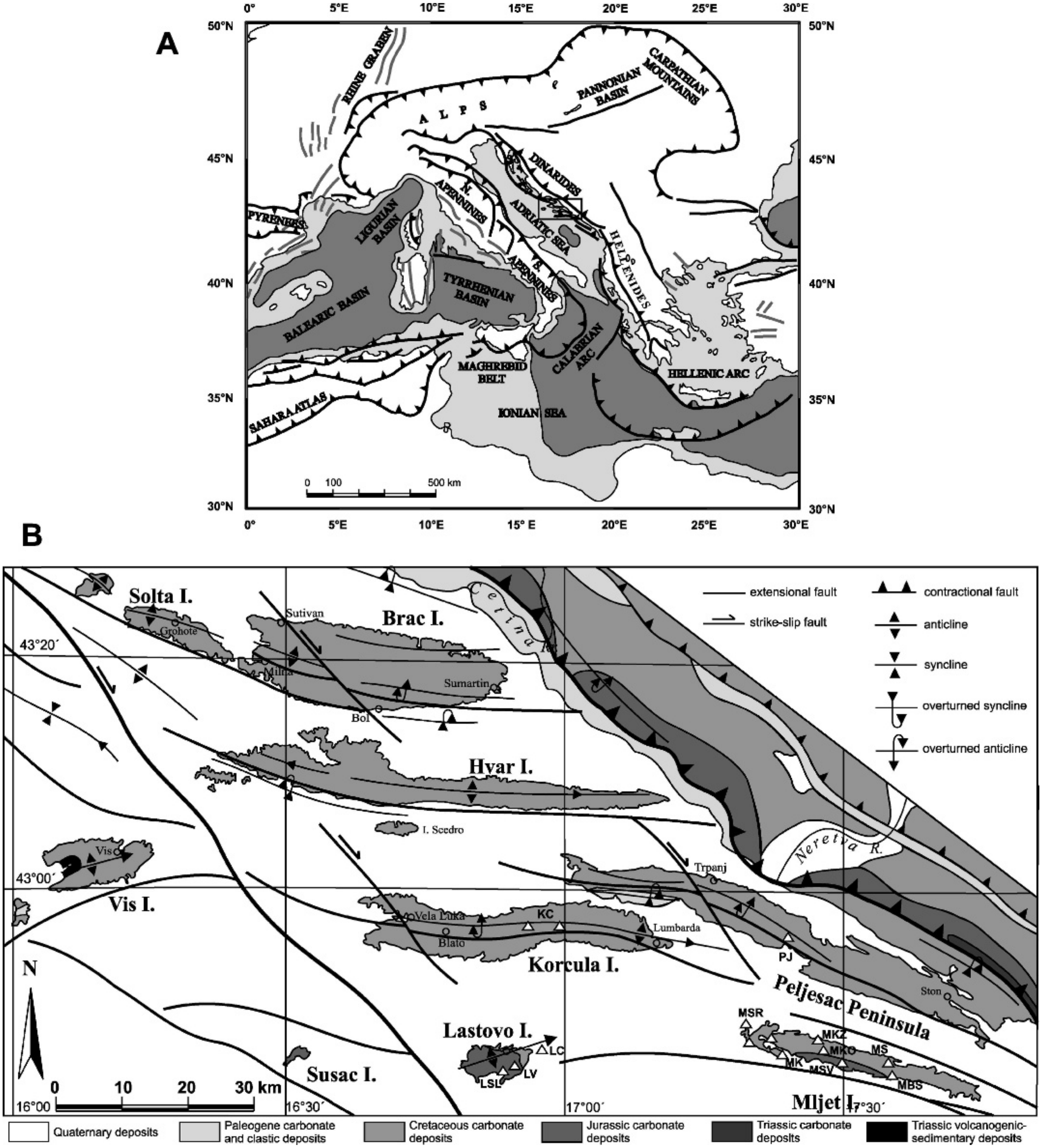

FIG. 1.—**A)** Map showing the tectonic setting of the central Mediterranean region with peri-Adriatic region in the center (after Jolivet and Faccenna 2000; Oldow et al. 2002). Contractional faults indicated by black lines with teeth on upper plate, transcurrent faults by black unadorned lines, and extensional fault systems by gray lines. Gray shaded areas indicate water depths of 0–1000 m (light gray), and below 1000 m (dark gray). Rectangle outlines study area shown enlarged in part B. **B)** General geologic map of the southern part of Adriatic (Dinaric) platform with locations of outcrops and profiles used (white triangles). More detailed locations are available in Husinec (2002). Map modified after Federal Geological Institute (1970). Structural–tectonic features after Prtoljan (2003).

progress on a more quantitative evaluation. The data presented in this paper are based on detailed facies analysis on the island of Mljet, coupled with data from adjacent localities on the islands of Korčula and Lastovo and the Pelješac Peninsula (Fig. 1B). This Upper Jurassic to mid-Cretaceous succession is well exposed, which allows detailed analysis of the spatial and temporal patterns of facies distribution. Detailed analysis of facies distribution, in turn, provides insight into relative sea-level change during that interval. The succession is characterized by exclusively shallow-marine, platform-interior carbonate sediments. Only local interbeds of terrestrial clastic facies and no coarse-grained megabreccias that would indicate resedimentation exist; either would appreciably complicate the relationships between relative sea-level changes and facies dynamics. The succession also encompasses the Late Aptian regressive phase that formed one of the major unconformities on peri-Adriatic platforms.

Despite the fact that the Adriatic (Dinaric) platform is a large Mesozoic mega-platform complex that formed during an important time in Earth history, and contains the apparently nearly continuous record of shallow-water deposition, it is very poorly known outside of Croatia. An understanding of its evolution is important not only in interpreting eustatic versus tectonic controls of Mesozoic shallow-water carbonate facies stacking patterns for this part of the Tethys, but also as an analogue for platforms of similar age in the circum-Adriatic region and globally.

GEOLOGIC BACKGROUND

The Adriatic (Dinaric) platform is one of the peri-Adriatic platforms that in the Mesozoic and early Tertiary occupied much of the European continental margin that faced the Tethyan Ocean. This continental margin can be considered either as a promontory of the African plate (Dercourt et al. 1993) or as an independent microcontinent or microplate called Adria or Apulia (Stampfli and Mosar 1999), separated from Africa by a small oceanic basin (Fig. 2A). The margin deformed diachronously within the framework of the convergent motion between the African and European plates since the Late Cretaceous (e.g., Dewey et al. 1989, and references therein). Today the isolated platforms of the Adria microplate are incorporated into the peri-Adriatic mountain belt. The Adriatic (Dinaric) platform succession evolved as an isolated carbonate platform from the Late Triassic to the middle Eocene (Gušić and Jelaska 1993; Pamić et al. 1998; Jelaska et al. 2000; Jelaska 2003). Recently, Vlahović et al. (2005) suggested that only Lower Jurassic to end-Cretaceous deposits can be attributed to the isolated platform type. The inception of the intra-oceanic (isolated) carbonate depositional system was accompanied by extensive deposition of shallow-water carbonate facies overlying platform siliciclastic and carbonate facies of an epeiric carbonate platform that was attached to Gondwana (Africa). This evolution was punctuated by many periods of subaerial exposure with development of paleokarst and bauxites, as well as by pelagic drowning episodes (Fig. 3). The carbonate platform survived until the Lutetian (middle Eocene), when deeply submerged parts of the platform were covered by flysch sediments. Following the Lutetian transgression, the ultimate demise was caused by an Alpine, Eocene–Oligocene Pyrrenean compressional tectonic phase (Matičec et al. 1996). Today the numerous southwest, foreland-verging thrust sheets and imbricates of the Adriatic (Dinaric) carbonate platform characterize the frontal or external, karst part of the Dinarides.

STRATIGRAPHIC FRAMEWORK

The backbone of the island of Mljet consists of a thick pile (~ 1,800 m) of Upper Jurassic (Tithonian) to mid-Cretaceous (Cenomanian) shallow-water limestone, dolomite, and intraformational breccia. On the basis of their lithological features these carbonate facies can be subdivided into nine units (Fig. 4, Table 1).

New stratigraphic information obtained by section measuring, geological mapping, and reconnaissance permits correlation of coeval carbonate successions in the wider southern Adriatic region (Fig. 5, Table 2). Our aim is not to describe the entire Upper Jurassic to mid-Cretaceous stratigraphic succession of these localities but to focus on particular intervals that document the significant geological events in the history of this succession.

FACIES AND VERTICAL DISTRIBUTION

Depositional Facies

The interpreted depositional facies include subtidal and intertidal–supratidal deposits, and subaerial exposure surfaces (Table 3). These three facies correspond almost precisely to Fischer's (1964) C, B, and A horizons, respectively. They do not correspond to his idealized (para)-sequence ABC (deepening upwards) but are arranged in shallowing-upwards parasequences (Husinec and Read 2005). The intervals lacking supratidal members are simply alternating subtidal and intertidal deposits (cf. Enos and Samankassou 1998), and their intertidal members suggest incomplete shallowing-upwards parasequences.

Subtidal Facies.—Subtidal deposits are characterized by thick-bedded to very thick-bedded lime mudstone, wackestone, and floatstone with variable amounts of lime mud, pellets, peloids, oncoids, intraclasts, and skeletal grains (green algae, benthic foraminifers, ostracodes, gastropods, and hydrozoans). Shallower, higher-energy subtidal environments are represented by packstone and grainstone with intraclasts, peloids, ooids, green algae, benthic foraminifers, and mollusk fragments. Barren lime mudstone is found in the nearshore very shallow, low-energy restricted settings seaward of tidal flats, in the area where tidal currents and waves were extremely weak.

Intertidal–Supratidal Facies.—Intertidal deposits, preserved as microbial laminites, fenestral carbonates, and horizontal laminites, show ample evidence of subaerial exposure (fenestrae and polygonal desiccation cracks). This facies is commonly dolomitized.

Subaerial Exposure Facies.—Exposure surfaces are found at the top of some subtidal and supratidal deposits as indicated by dissolution vugs and subsequent brecciation. These intervals are thin, greenish, clay sheets or intraclastic limestone with greenish clay or micrite matrix. The clasts were eroded from the underlying shallow-subtidal and intertidal–supratidal limestones. The angular shape of clasts and the absence of bauxites suggest that stratigraphic gaps were of limited duration.

Vertical Facies Distribution

During the Early Tithonian, lime mudstone and oncoidal wackestone and floatstone (Unit A; Fig. 6A) formed in low-energy subtidal, lagoonal settings (Table 1). The subsequent Late Tithonian oolitic (Fig. 6B) and Late Tithonian–Berriasian fenestral limestones were deposited in very shallow subtidal and peritidal environments that underwent periodic subaerial exposure (Fig. 7B). Laterally, persistent shallow peritidal structures and textures within thick dolomite facies (Unit B; Fig. 7A) also suggest sea-level oscillations within the subtidal–intertidal–supratidal zone.

The Upper Valanginian and Hauterivian peloid–skeletal lime mudstone, wackestone, and packstone (Unit C) were produced in shallow and productive subtidal environments (Tables 1, 2). Extensive bioturbation probably produced the massive bedding by obliterating any original stratification. Only the Late Hauterivian part of this interval (Fig. 4) shows evidence of sediment cyclicity, i.e., from the shallow and productive subtidal to the supratidal.

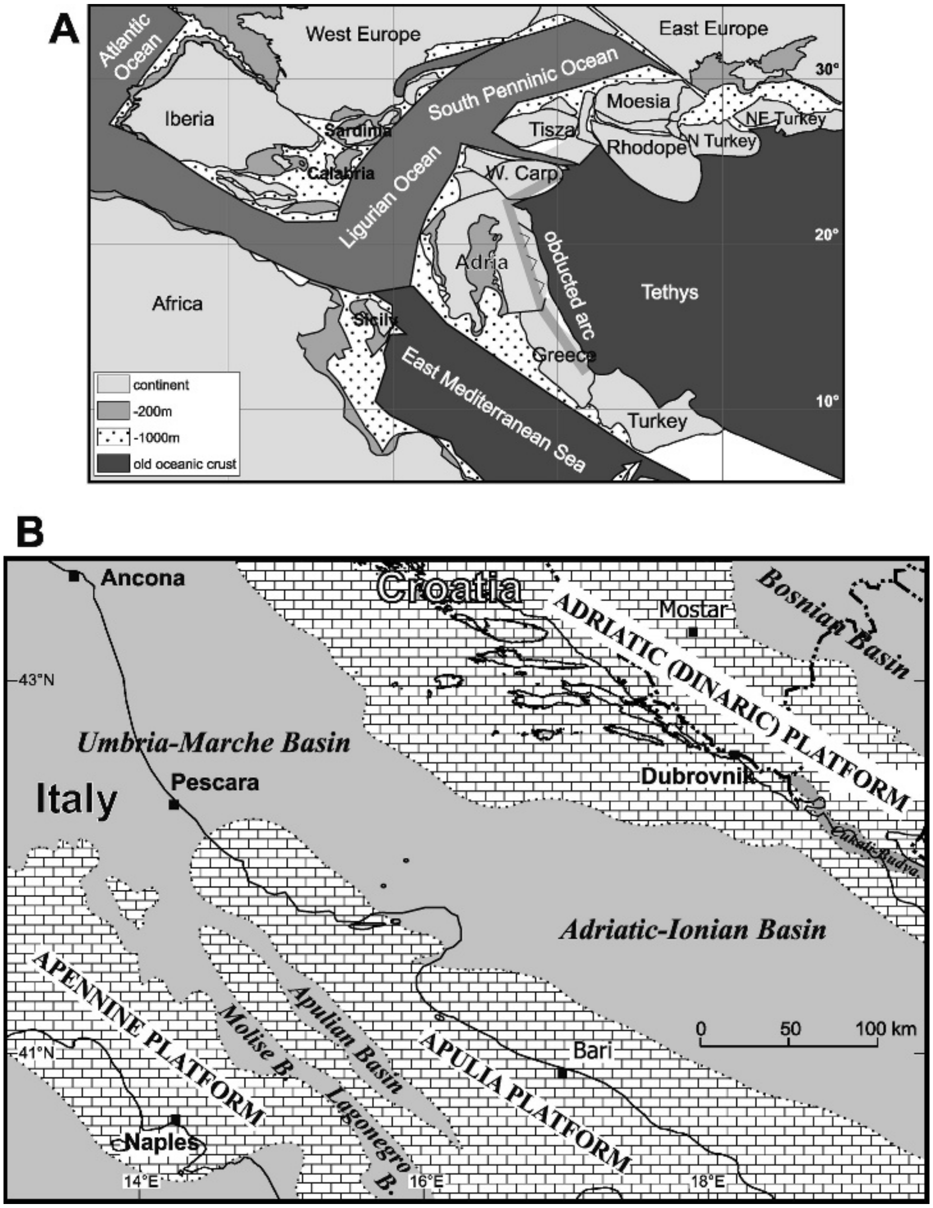

FIG. 2.—**A)** Paleogeographic map of the western margin of the Tethys in the Middle Cretaceous (Early Aptian, 118 Ma), the turning point from the divergence to the convergence between the Adria microplate and Western Europe (after Neugebauer et al. 2001). **B)** Map of the southern Adriatic Sea showing restored distribution of Late Jurassic and Early Cretaceous peri-Adriatic carbonate platforms. Compiled from Grandić et al. (1999), Bosellini et al. (1999), and Velić et al. (2002). See Figure 1 for main present-day structural features.

The Barremian stage was marked by vast tidal flats (Tables 1, 2), where deposition was characterized by shallowing-upwards cycles of shallow subtidal to the intertidal and supratidal facies (Unit D; Fig. 6D). Frequent short-lived exposures formed greenish clay intervals (Fig. 7C) and emersion breccias frequently with black pebbles reworked from cemented and organically darkened underlying or lateral beds. Black pebbles, being valuable indicators of subaerial exposure, are mostly relics because the less consolidated host sediment is washed away (see Strasser 1984).

The subsequent Lower Aptian shallow-subtidal, thick-bedded to very thick-bedded limestone (Unit E; Fig. 6E) indicates slight deepening, as evidenced by the facies shift from tidally dominated to subtidal deposition. These deposits yield *Palorbitolina lenticularis*, one of the biostratigraphically most important foraminifers of the Cretaceous Tethys (Husinec 2001). Open-marine influence is evidenced by local findings of pelagic taxa (Table 2). An apparent regression during the Late Aptian (Unit F; Figs. 6F, 7E) is evidenced by several clayey and/or emersion-breccia intervals consisting of angular limestone intraclasts in a greenish clay matrix (Tables 1, 2). These subaerial exposure intervals are interstratified within irregular alternations of mud- and grain-supported limestone, suggesting deposition within lagoons and high-energy shoals, respectively.

The beginning of the Albian is dominated by subtidal mud-supported limestone (Unit G). The subsequent Upper Albian lime mudstone and peloidal wackestone and packstone with interbeds of peloidal–intraclastic–skeletal packstone and grainstone (Tables 1, 2) were formed in low-energy subtidal settings, interrupted by storm deposits. Rare stromatolites are of peritidal origin. Several emersion-breccia intervals of laterally

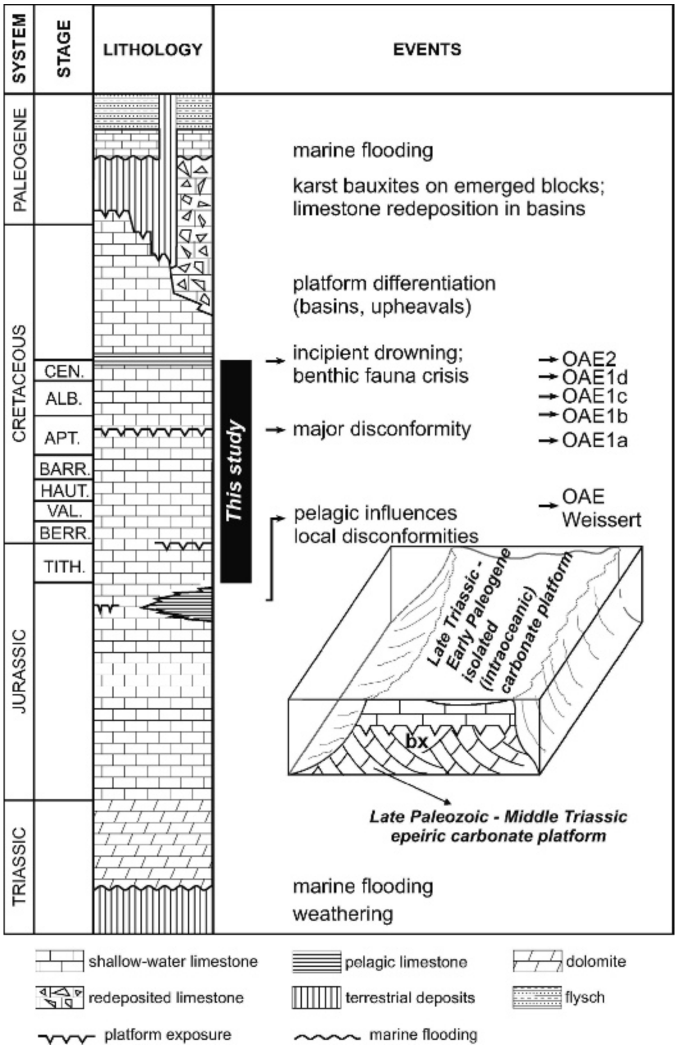

FIG. 3.— Generalized stratigraphic column of the carbonate platform deposits of the external Dinarides. Modified after Jelaska (2003).

variable thickness imply episodic emergence above sea level. Laterally, these shallow peritidal environments might have been associated with lacustrine environments, as suggested by the presence of charophytes (Fig. 6G) in kerogenous limestones (Fig. 7F). Regression at the Albian–Cenomanian transition (Unit H; Figs. 6H, 7G) is indicated throughout the region, either by emersion-breccia intervals or by dolomite with well-preserved structures and textures suggesting shallowing to supratidal conditions (fenestral fabric, desiccation cracks, etc.).

The younger Cenomanian deposits (Unit I) are characterized by an irregular alternation of rudist–*Chondrodonta* floatstone, LLH stromatolites with desiccation-crack occurrences (Fig. 7H), peloidal–skeletal (foraminiferal) wackestone and packstone, and fenestral lime mudstone. These indicate relative sea-level oscillations from the very shallow subtidal to intertidal and episodically supratidal.

RELATIVE SEA-LEVEL CHANGES

The facies distribution indicates repeated oscillations from subtidal to intertidal–supratidal settings with periodic subaerial exposure. Various mechanisms may have caused such oscillations, including tectonics, eustasy, and autocyclicity. Each will be evaluated.

Tectonic Activity

The paleogeographic setting of the Adriatic (Dinaric) platform might be a good indicator of tectonic activity, which was one of the factors controlling its facies distribution. As an isolated (intraoceanic) carbonate platform situated on the Gondwana-detached element (Adria microplate), the platform must have been influenced by tectonic activity that was associated with the post-Middle Triassic to Late Cretaceous drifting of Adria towards Eurasia (Stampfli and Mosar 1999). The Early Jurassic (Toarcian) extensional tectonics resulted in disintegration of the preexisting broad carbonate platform realm on the microplate and led to opening of the deep-marine trough connecting the Adriatic–Ionian and Umbria–Marche basins (Bernoulli and Jenkyns 1974; Bosellini 1989). Late Jurassic–Early Cretaceous tectonics were characterized by the convergence between Adria in the southwest and Tisza to the northeast (Fig. 2A; Neugebauer et al. 2002), marking the end of the sea-floor-spreading phase, which may have lasted in the Dinaridic Tethys (Bosnian basin) over a period of 70–80 My (Pamić et al. 1998). The subsequent subduction initiated the gradual closure of this part of Tethys and generation of a magmatic arc along an active continental margin in the north.

The accumulation rates of the southern part of the Adriatic (Dinaric) platform varied through the Jurassic–Cretaceous from less than 1 cm/ky to approximately 15 cm/ky, with an average of ~ 4 cm/ky (Fig. 8). For the studied stratigraphic interval, maximum rates are about 15 cm/ky for the Tithonian, decreasing in Berriasian through Barremian to 2–4 cm/ky, reaching a minimum value in the Aptian (< 1 cm/ky), and increasing in Albian and Cenomanian to 4 cm/ky. High accumulation rates during Tithonian time favored preservation of a fairly complete, predominantly subtidal stratigraphic succession on the platform. In contrast, low accumulation rates in the Early Cretaceous caused well-developed tidal-flat facies and shallow subtidal facies, as well as periodic emergence and paleosol formation.

The accumulation plot does not show a classic exponential decay of a passive margin, implying that there may have been periodic rifting and collisions. In addition, lateral thickness variations in some of the shallow-water platform facies associations might have been triggered by differential changes in subsidence rates. Although this suggests a tectonic influence, we were not able to isolate actual tectonic events (except for the Cenomanian) from the sedimentary record and describe their possible effect on sedimentation in the study area. Thus, the absence of deep-water marker beds in the shallow-water platform succession, lack of slumps, as well as absence of any earthquake-generated sedimentary features, suggest tectonic quiescence during the Tithonian to Albian, at least in the study area. Conversely, the contemporaneous deposits of the northwestern part of the platform show evidence of tectonic activity. The synsedimentary tectonics has been recorded in the Tithonian of Gorski Kotar (Velić et al. 1994), and, starting in Hauterivian, periodically through the Cretaceous of Istria (Matičec et al. 1996). It resulted in pronounced inner-platform facies differentiation, from deeper subtidal to reefal, peritidal, and terrestrial environments. The Early Cretaceous tectonic quiescence has also been recorded for the adjacent carbonate platforms of southern Italy (D'Argenio et al. 1999), a passive continental margin characterized by constant rates of subsidence (Channel et al. 1979; D'Argenio and Alvarez 1980). Such a regional, Early Cretaceous peri-Adriatic quiescence persisted, because this was a period during which the regional crust on which the shallow-water platform strata deposited was in its last stage of thermal cooling (D'Argenio et al. 1999).

An important tectonic event is evidenced by synsedimentary folding and slumping of the Upper Cenomanian blocks in the study area. These structures have been recognized regionally in Middle and Upper Cenomanian laminated shallow-water carbonates (Tišljar et al. 1998; Prtoljan 2003). Coeval occurrence of these synsedimentary features over such a large area implies an important regional tectonic event,

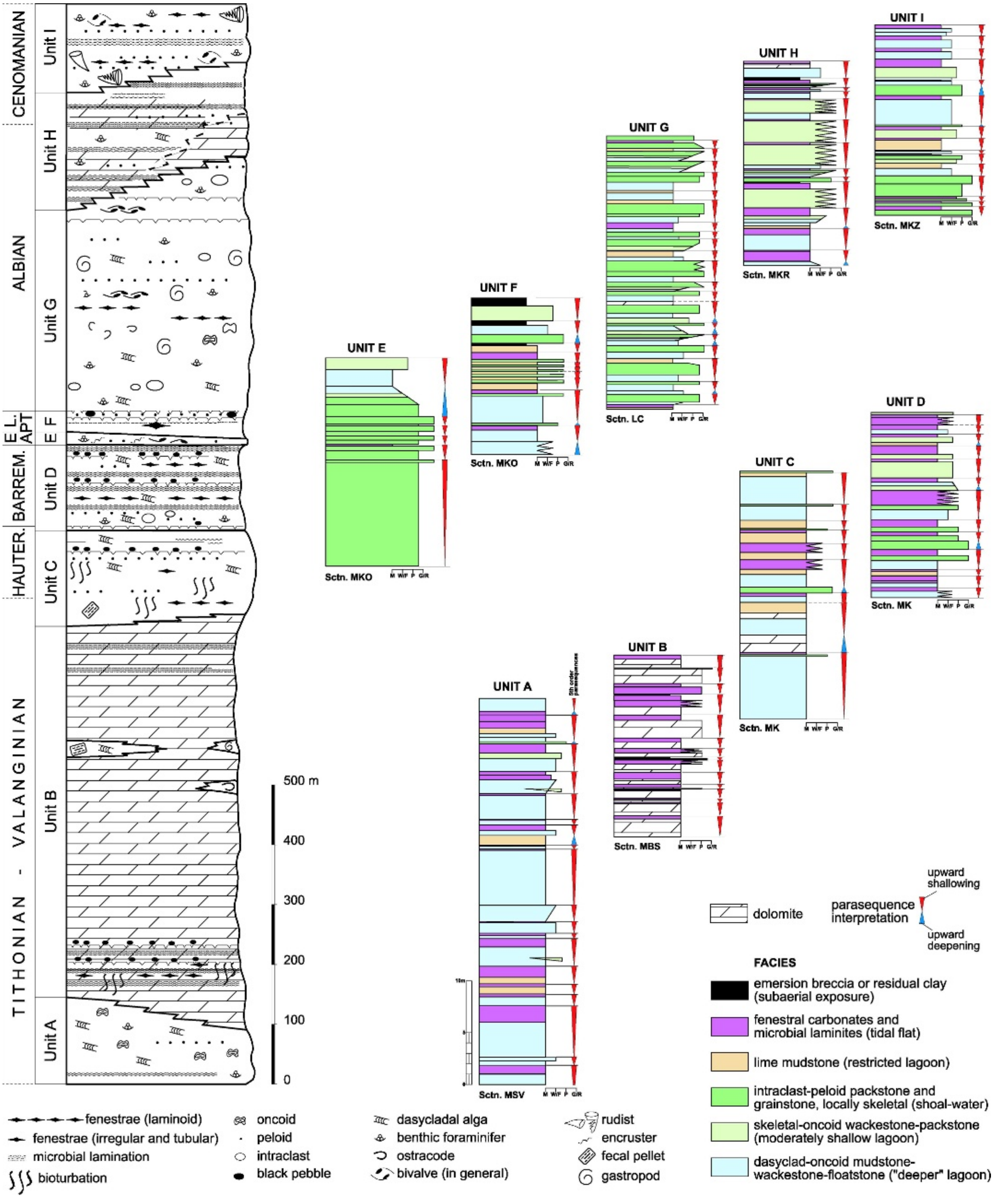

FIG. 4.—Composite stratigraphic column of Mljet Island with detailed partial sections showing characteristic facies stacking and parasequence interpretation for each unit. See Figure 1B for locations.

TABLE 1.—*Lithologic makeup of Tithonian–Cenomanian units, Mljet Island. Detailed sections are found in Husinec (2002). Biostratigraphic features have been described by Husinec and Sokač (2006). Bed-thickness scale after McKee and Weir (1953). Terminology for crystal sizes in dolomites after Folk (1962).*

Unit	Thickness	Lithology and Sedimentary Structures	Dolomitization	Biota	Age
I	> 250 m (the top not exposed)	Molluskan floatstone (dm-thick, locally lenticular) and rudist framestone, and peloidal–skeletal wackestone–packstone alternating with thin stromatolites (some synsedimentary folding and slumping) and fenestral lime mudstone. Polygonal desiccation cracks capped by reworked intraclast sheets 1 to 40 cm thick in lower part of the unit (Fig. 7H).	Stromatolites sporadically dolomitized	Abundant rudists and *Chondrodonta*, common benthic foraminifers, rare gastropods	Late and Middle Cenomanian
H	200 m	Dolomite and limestone alternating vertically and laterally. Dolomite very thick- to thick-bedded (50–100 cm) or massive, common microbial lamination (Figs. 6H, 7G), some bioturbation, laminoid fenestrae, desiccation cracks, and emersion breccia. Limestones are ostracode lime mudstone and wackestone (some fenestral fabric) interlayered with peloidal–intraclastic packstone and grainstone with molluskan bioclasts and rare foraminifers; rare microbial lamination, and exposure breccias.	Intense in the lower part, decreases in the upper part	Rare benthic foraminifers and calcareous algae, ostracodes, small gastropods, and thin-shelled bivalves	Early Cenomanian–Late Albian
G	370–470 m	Mud-supported limestone (pellets, peloids, oncoids, and skeletal grains) alternating with peloidal wackestone and packstone and peloidal–intraclastic–skeletal packstone and grainstone. Dm-thick paleosols (emersion breccias) in upper half of the unit.		Calcareous algae, benthic foraminifers, ostracodes, gastropods, and bivalves (*Chama* sp.)	Albian
F	30 m	Fenestral lime mudstone and wackestone (micritized algae, peloids, intraclasts, foraminifers, and less common ostracodes) alternating with peloidal–intraclastic packstone and grainstone. Three paleosol intervals 10 to 80 cm thick with recrystallized limestone pebbles in a greenish clayey matrix.		Abundant calcareous algae (*Salpingoporella dinarica*, Fig. 6F), common benthic foraminifers, rare ostracodes.	Late Aptian
E	7–22 m	Packstone and grainstone with peloids, foraminifers, algae, intraclasts, bioclasts, and oncoids. Very thick- to thick-bedded oncoidal mudstone and wackestone and floatstone with encrusters, bivalves, foraminifers, and peloids. Rare SH stromatolites.		Abundant encrusting *Bacinella irregularis*, *Palorbitolina*, and other benthic foraminifers, common calcareous algae and bivalves	Early Aptian
D	150 m	Microbial laminites (Fig. 6D) commonly capped by breccia cm to dm thick, alternating with thin beds of mud-supported limestone (commonly bioturbated; contain peloids, intraclasts, rarely oncoids, and ooids), fenestral lime mudstone, and less frequently peloidal–intraclastic–skeletal packstone and grainstone.		Abundant calcareous algae (*Salpingoporella*) and benthic foraminifers, common ostracodes, bivalves, and gastropods	Barremian–latest Hauterivian
C	125–165 m	Thick-bedded bioturbated peloid–skeletal lime mudstone (rare mechanical lamination) and fenestral lime mudstone (burrowing and laminoid fenestrae) and peloidal–skeletal wackestone and packstone (less frequently grainstone) with intraclasts. Rare medium-bedded ooid packstone and grainstone (Fig. 6C) and paleosols (residual clays with limestone fragments) 20–40 cm thick in the upper part of the unit.	Weak dolomitization in the upper part	Common calcareous algae and small benthic foraminifers	Hauterivian–Late Valanginian
B	~ 700 m	Very thick- and thick-bedded coarsely and finely crystalline dolomite with minor relics and lenses of lime mudstone (irregular fenestrae and bioturbation), less frequently skeletal packstone and grainstone with fecal pellets. Rare cryptocrystalline dolomite (Fig. 7A) includes bioturbated muds with laminoid fenestrae capped by stromatolites and desiccation-cracked beds capped by breccia.	Intense throughout	Rare calcareous algae, benthic foraminifers, ostracodes, gastropods	Early Valanginian–Late Tithonian
A	> 150 m (the base not exposed)	Thick- to very thick-bedded lime mudstone with large oncoids, micrite intraclasts, fragments of algae, foraminifers, and ostracodes. Oncoidal (Fig. 6A) wackestone and floatstone–rudstone with algae, foraminifers, peloids, and intraclasts. Microbial and mechanical lamination in the lower and middle part of the unit.	Laminites are commonly dolomitized	Common calcareous algae and hydrozoans, rare benthic foraminifers, and ostracodes	Early Tithonian

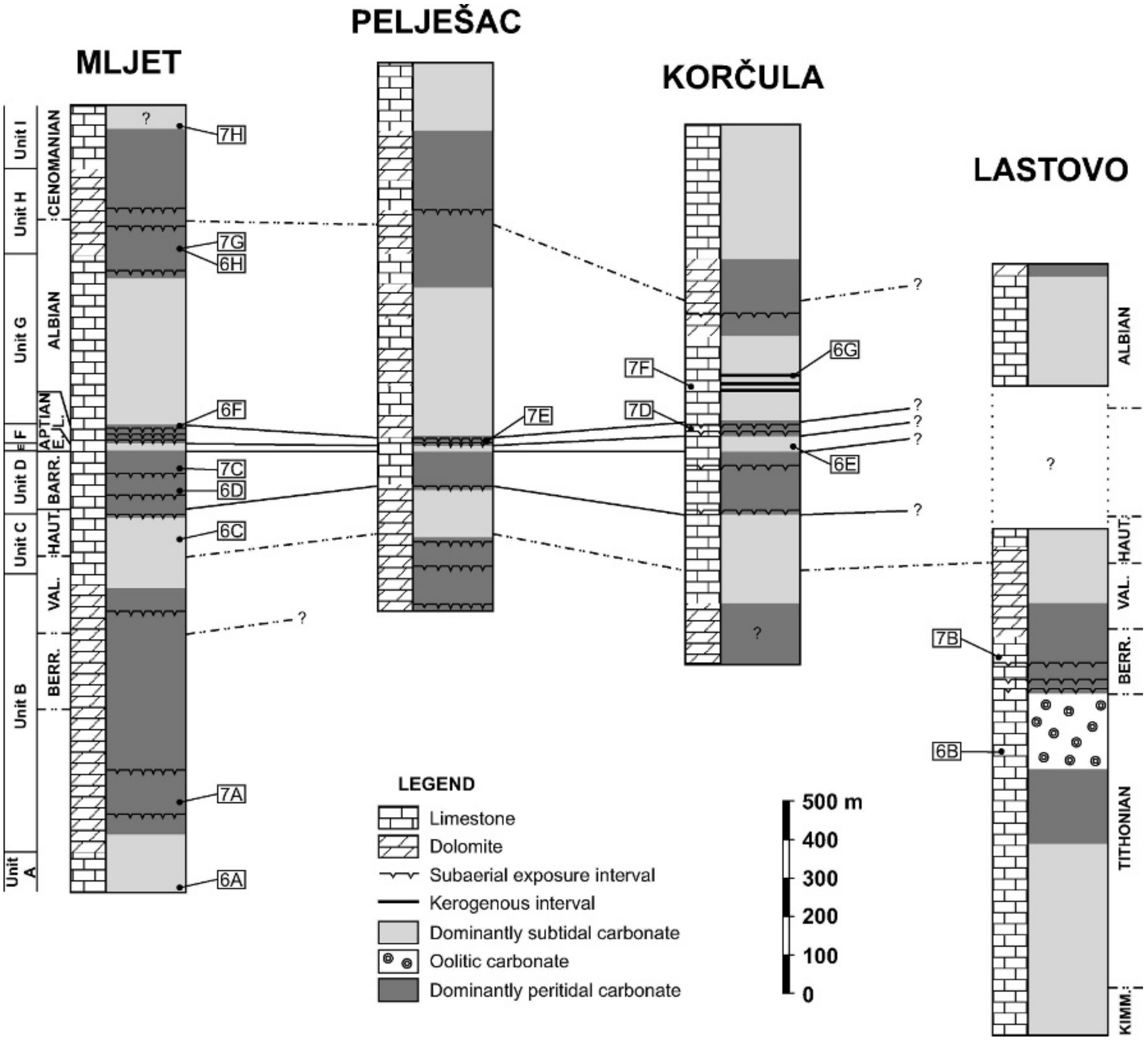

FIG. 5.— Stratigraphic relationships of composite sections for the Tithonian–Cenomanian interval of the southern part of the Adriatic carbonate platform (for locations see Fig. 1); correlations are based on foraminiferal and algal biostratigraphical data, unconformity surfaces, and facies stacking patterns. Sections are schematic, showing the overall facies character of the section. Chronostratigraphic boundaries are indicated by solid lines where biostratigraphic control is good, and dot–dash lines where concealed or inferred. Stratigraphic positions of photographed thin sections and outcrops from Figures 6 and 7 are labeled with figure numbers. The data for Pelješac are modified from Korolija et al. (1977) and Šebečić et al. (1983). The data for Korčula are modified from Sokač et al. (1977) and Korolija (1981).

contemporaneous with a relative sea-level rise and an associated oceanic anoxic event (OAE 2: Schlanger and Jenkyns 1976; Jenkyns 1980; Arthur et al. 1990), and with the onset of platform disintegration (Jelaska et al. 1994). Tectonic instabilities during that time have also been noted by several authors (e.g., Lawrence et al. 1995; Pamić et al. 1998), who attribute this event to the initiation phase of platform disintegration. Shallow peritidal, and periodically even supratidal, features of Cenomanian deposits of the Adriatic (Dinaric) platform, are in sharp contrast to the worldwide drowning and retreat of carbonate platforms during the same time interval (Schlager 1981). The contemporaneous exposure of adjacent platforms of southern Italy points to supraregional tectonics, when, because of conversion from an extensional to compressional regime in this part of the Tethys (Eberli 1991), extensive carbonate platforms of the Adria microplate were not drowned but were either exposed (Apulian and Apennine platforms) or continued with shallow-water carbonate sedimentation with periodic exposure (Adriatic platform).

Eustasy

The reconstruction of vertical facies distribution and variability was used to construct a relative sea-level curve for the study area (Fig. 9). Most facies changes are interpreted as changes in relative water depth, and consequently accommodation space across the area. Transgressive periods favored increased accommodation space, resulting in generally thicker beds of subtidal facies. Because possible depth differences between the various shallow subtidal facies could not be resolved, the curve for Early Tithonian, Hauterivian, Early Aptian, and Early Albian is smooth and lacks smaller-scale deepening and shallowing trends that reflect deposition that essentially kept pace with sea level. Regressions are characterized by tidal-flat progradation and subsequent peritidal shallowing-upward parasequences, commonly ending with emersion-breccia intervals at their tops (Early Berriasian, Barremian, Late Aptian, Late Albian). Consequently, the relative sea-level curve for these intervals is sawtoothed, reflecting smaller-scale fluctuations in an overall falling

TABLE 2.— *Upper Tithonian–Lower Cenomanian lithofacies of Pelješac, Korčula, and Lastovo. See Figure 1B for locations.*

Chronologic Framework	Pelješac[1]	Korčula[2]	Lastovo
Early Cenomanian–Albian	Dolomite and mud- and grain-supported limestone alternating both vertically and laterally. Dolomite sporadically exhibits well preserved horizontal and wavy lamination. Dolomitic breccias and brecciated limestone locally.	Upper Albian deposits contain kerogen-rich, dark, dm-thick dolomitized beds alternating with light-gray lime mudstone containing rare ostracodes and charophytes (Figs. 6G, 7F). Both vertical and lateral alternation of dolomite and limestone around the Albian–Cenomanian boundary. Dolomitic breccias contain fragments of dolomite, stromatolites, and mud-supported limestones.	Thick-beded alternation of lime mudstone and fenestral lime mudstone, and peloid–intraclastic–skeletal wackestone, packstone, and grainstone. Uppermost Albian contains emersion breccia 120–150 cm thick with well-rounded, 2–5 cm fragments of recrystallized lime mudstone and brecciated lime mudstone in a greenish clay.
Late Aptian	*Salpingoporella*-rich, predominantly mud-supported limestone interspersed with several intervals of greenish residual clay sheets and partially dolomitized breccias/conglomerates (Fig. 7D, 7E) with microstilolitized intraclasts or pebbles of fossiliferous limestone, sporadically with vadose pisoids and relict stromatolitic textures.		Presently submerged.
Early Aptian	Lime mudstone and skeletal–intraclastic lime mudstone and wackestone (Fig. 6E) with foraminifers, calcareous algae, and encrusters (*Bacinella*). Subordinate pelagic crinoids (*Saccocoma*) and planktic foraminifers (*Hedbergella*).		Presently submerged.
Barremian–latest Hauterivian	Microbial laminites alternating with thin beds of micritic limestone (commonly bioturbated; contain peloids, intraclasts, rarely oncoids), fenestral lime mudstone, and less frequently peloidal–intraclastic–skeletal packstone and grainstone. Numerous intervals with emersion-breccia/conglomerate with black pebbles and charophytes recorded on Pelješac only.		Presently submerged.
Late Hauterivian–Berriasian	Very thick-bedded or massive predominantly coarsely crystalline (sucrosic) dolomite and fine dolomitized skeletal mudstone and wackestone with ooids, stromatolitic and planar lamination. Relics of dolomitized and recrystallized limestone with ostracodes, rarely foraminifers and small gastropods, and fragments of dasycladaceans (*Salpingoporella annulata*).	Thick-bedded, predominantly mud-supported limestones with calcareous algae (*Clypeina*, *Praturlonella*) and benthic foraminifers (*Montsalevia*). Very thick- to thick-bedded or massive coarsely crystalline dolomites characterize Berriasian (and Lower Valanginian?) part.	Thick-bedded bioturbated peloid–skeletal lime mudstone and fenestral lime mudstone (burrowing and laminoid fenestrae) and peloidal–skeletal wackestone–packstone (less frequently grainstone) with intraclasts. Less common very thick- and thick-bedded coarsely crystalline and finely crystalline dolomite with minor relics and lenses of lime mudstone (irregular fenestrae). Carbonate conglomerate, breccia (Fig. 5B), and residual clay sheets on karstic surfaces above the Tithonian–Berriasian boundary; they contain intraclasts of underlying units.
Late Tithonian	Presently submerged.		Ooid (ooids commonly broken and rehealed) grainstone and packstone and thick micrite/pelmicrite and or biomicrite beds, fenestral lime mudstone, and fenestral peloid–skeletal wackestone–packestone–grainstone.

[1] Modified after Korolija et al. (1977) and Šebečić et al. (1983).
[2] Modified after Sokač et al. (1977) and Korolija (1981).

relative sea level. The actual sea-level history for the Tithonian–Cenomanian interval of the studied southern part of the Adriatic platform could have been much more complex, and work is in progress on a more quantitative evaluation.

The local sea-level signal exhibits some coincidence with second-order (5–20 My) eustatic rises and falls identified by Haq and Al-Qahtani (2005) (Fig. 9) for the Tithonian through the Aptian, suggesting that eustatic variations were probably an important control on the timing of local facies dynamics. It also shows some serious lack of correlation, which may be due to local post-Aptian tectonics and lack of stratigraphic resolution. It should be noted, however, that the global eustatic curve (Haq and Al-Qahtani 2005) is a synthesis of real stratigraphic data from around the world. Many of the events recorded on that curve are a product of regional events that originated from various mechanisms,

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FIG. 6.—Photomicrographs of important rock types. **A)** Tithonian oncoidal ("algal ball") floatstone, Mljet Island (Ogiran Islet). Quiet, low-energy lagoonal setting below the zone of frequent wave reworking. **B)** Upper Tithonian ooid grainstone with meniscus micrite cements, Lastovo Island. Shallow subtidal–intertidal shoal or pond. **C)** Hauterivian ooid grainstone with meniscus micrite cements, Mljet Island. Shallow subtidal–intertidal shoal or pond. **D)** Laminated alternation of Barremian mudstone, fenestral mudstone and cryptalgal laminite, Mljet Island. Intertidal–supratidal setting with thin microbial mat covers. **E)** Lower Aptian skeletal mudstone–wackestone with foraminifer *Palorbitolina lenticularis*, Korčula Island. Quiet, low-energy lagoonal setting below the zone of frequent wave reworking. **F)** Upper Aptian peloidal–skeletal wackestone–packstone with numerous sections of the alga *Salpingoporella dinarica*, Mljet Island. Low-energy setting, shallow lagoon. **G)** Dark, organic-rich, mud-supported dolomitized Upper Albian limestone with charophytes, Korčula Island. Probably lacustrine or brackish environment. **H)** Laminated Upper Albian to Lower Cenomanian early diagenetic dolomite, Mljet Island. Intertidal–supratidal setting.

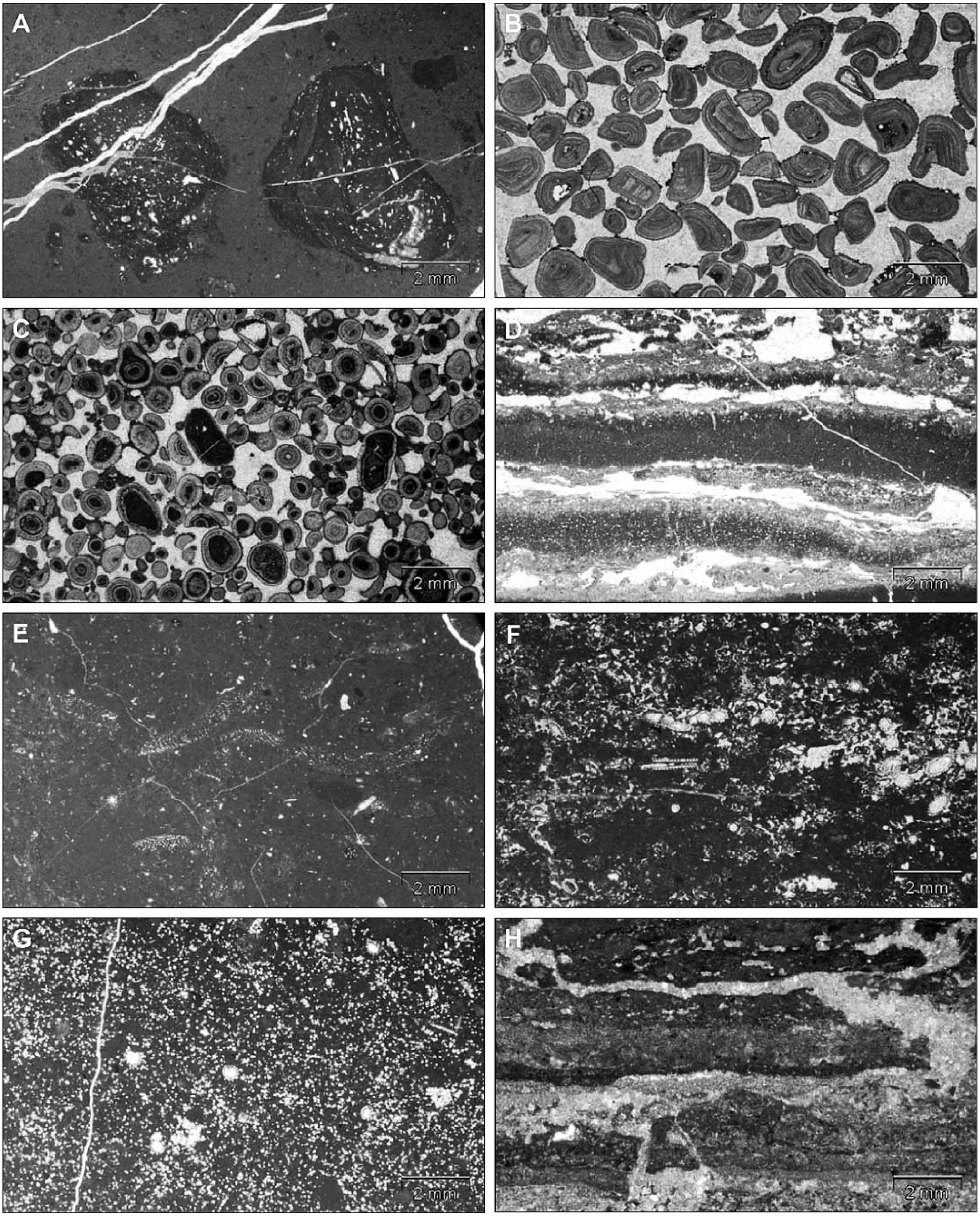
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TABLE 3.—*Summary of Tithonian–Cenomanian platform-interior facies.*

Facies	Lithology	Sedimentary structures	Fossil Content
Subaerial Exposure Facies	Breccia with recrystallized limestone pebbles and intraclasts in micrite or greenish clay matrix	Thin- to thick-bedded, common lateral variation in thickness	None to sparse in recrystallized limestone intraclasts
	Residual clay	Cm- to dm-thick green clay-filled horizons on karstified surfaces	None
Intertidal–Supratidal Facies	Microbial laminite	Wavy lamination, common LLH stromatolites; polygonal dessication cracks	Calcareous algae and benthic foraminifers, rare ostracodes
	Fenestral lime mudstone and wackestone with micritized algae and foraminifers, peloids, and intraclasts	Fenestral lamination	Calcareous algae and benthic foraminifers, rare ostracodes
	Planar laminite (alternation of lime mudstone and peloid–skeletal packstone)	Millimeter lamination	Calcareous algae and small benthic foraminifers
Subtidal Facies	Barren lime mudstone	Unlaminated, homogeneous pure micrite; thin-bedded, rare irregular fenestrae	None to sparse; rarely may have gastropods and ostracods
	Ooid grainstone and packstone (ooids commonly broken and recoated)	Thin- to thick-bedded	Rare algae
	Packstone and grainstone with intraclasts, peloids, foraminifers, algae, bioclasts, and oncoids	Thin- to thick-bedded	Abundant calcareous algae and benthic foraminifers, mollusks
	Peloidal–skeletal wackestone and packstone with oncoids, foraminifers, algae, peloids, intraclasts, fragments of mollusks	Thin- to medium-bedded	Common calcareous algae and benthic foraminifers, bivalves, gastropods
	Wackestone and floatstone with oncoids and/or mollusks, calcareous algae, benthic foraminifers, peloids, and intraclasts	Thick- to very thick-bedded	Common calcareous algae and smaller benthic foraminifers, bivalves, gastropods
	Lime mudstone to wackestone with oncoids, micrite intraclasts, fragments of algae, foraminifers, ostracodes, and encrusters	Thick-bedded, commonly heavily bioturbated	Common calcareous algae and benthic foraminifers, less common ostracodes, bivalves, gastropods

such as plate-margin and intraplate tectonism, including basin loading and relaxation and in-plane stress (Miall 1992). Furthermore, insufficient time resolution complicates the correlation between local and global curves, and synchroneity of most of the sea-level events is hard to demonstrate. Third-order (0.5–5 My) eustatic events are beyond the present resolution for the study area.

The local sea-level curve shows a long-term sea-level fall for Late Tithonian–Early Valanginian, which is also recorded for the Tithonian–Berriasian on the Haq and Al-Qahtani (2005) eustatic curve. There is a long-term local sea-level rise in Late Valanginian–Early Hauterivian, which is also evident on the Haq and Al-Qahtani (2005) curve. Unlike the local curve, which is followed by a fall in the Late Hauterivian and the Barremian, the global curve shows maximum transgression in the Early Barremian. The Early Aptian relative sea-level rise followed by the Late Aptian sea-level fall recorded on the Adriatic (Dinaric) platform does not seem to match well with the second-order global curve which is, despite third-order oscillations of relatively high amplitude and duration, nearly straight throughout the Aptian. Transgression characterizes the Early Albian on both curves. Subsequently, opposite trends characterize the studied interval in comparison to the global curve until the Late Cenomanian, when inflection towards transgression is evident on both curves. Similar post-Aptian discrepancies are seen in other Tethyan sedimentary basins (e.g., Grötsch et al. 1993; Fernández-Mendiola and García-Mondéjar 1997; Immenhauser and Scott 1999; Scott et al. 2000), particularly for the Albian. On the basis of several sea-level curves from various settings, including intracratonic basins (Oman, Paris basin,

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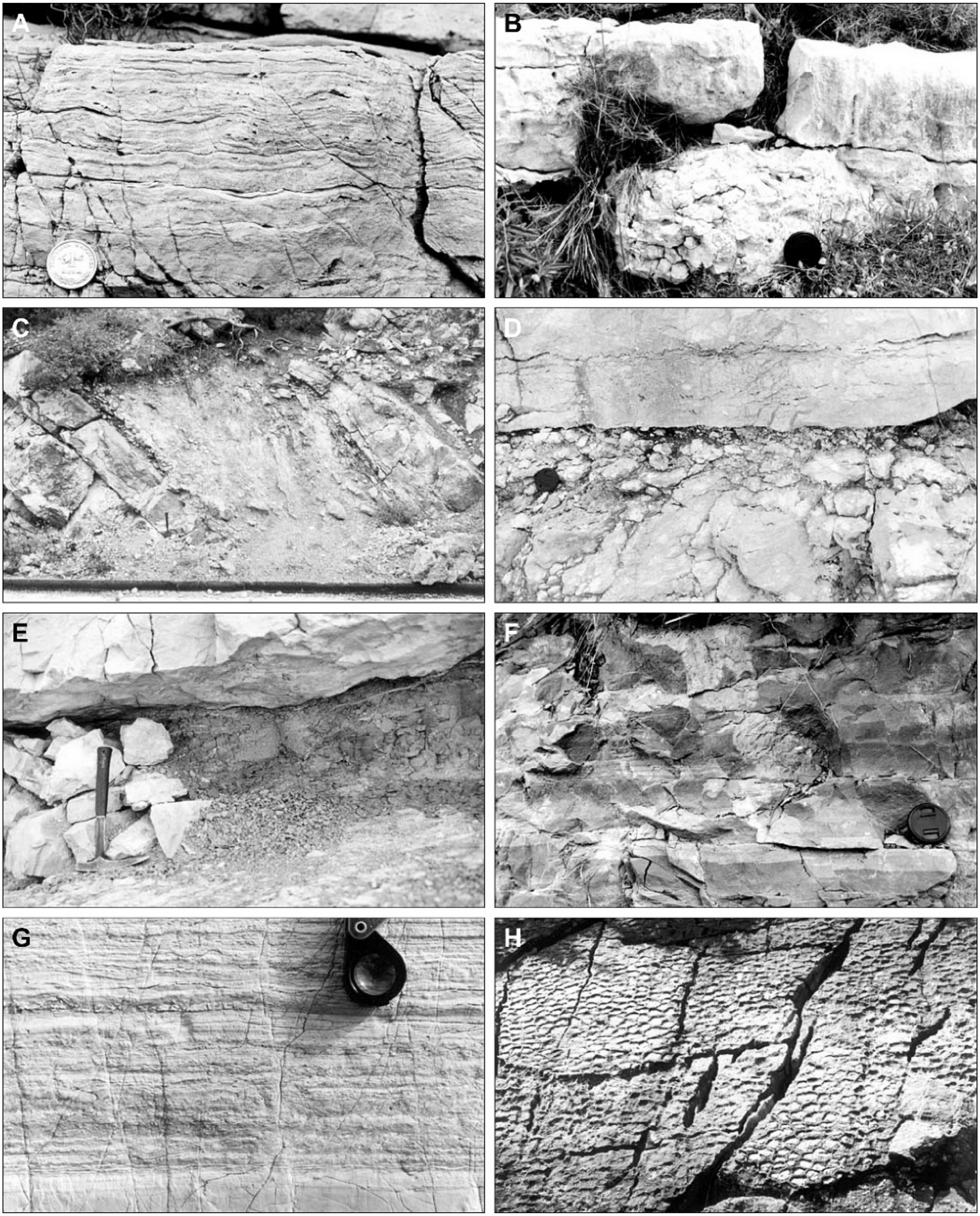
Fig. 7.—Outcrop photographs of lithofacies. **A)** Upper Tithonian early diagenetic dolomite with well-preserved laminated texture of stromatolitic origin, Mljet Island. **B)** Berriasian emersion breccia with clasts of predominantly lime mudstone and fenestral limestone, Lastovo Island. **C)** Approximately 2-m-thick Barremian interval with clasts of brecciated and corroded lime mudstone and peloidal mudstone–wackestone embedded in a greenish-grayish clay matrix, Mljet Island. **D)** Emersion breccia with clasts of Upper Aptian limestones, Korčula Island. **E)** Upper Aptian subaerial exposure interval with grayish-greenish clayey–marly material, Pelješac Peninsula. **F)** Albian alternation of thin beds and laminae of dark, dolomitized limestones containing kerogen and light-gray mudstones, Korčula Island. **G)** Upper Albian–Lower Cenomanian dolomitized stromatolitic laminite, Mljet Island. **H)** Polygonal desiccation cracks in Cenomanian limestone, Mljet Island. Objects for scale: hammer (32.8 cm long), lens cap (52 mm in diameter), magnifier lens (20 mm in diameter), and coin (22 mm in diameter).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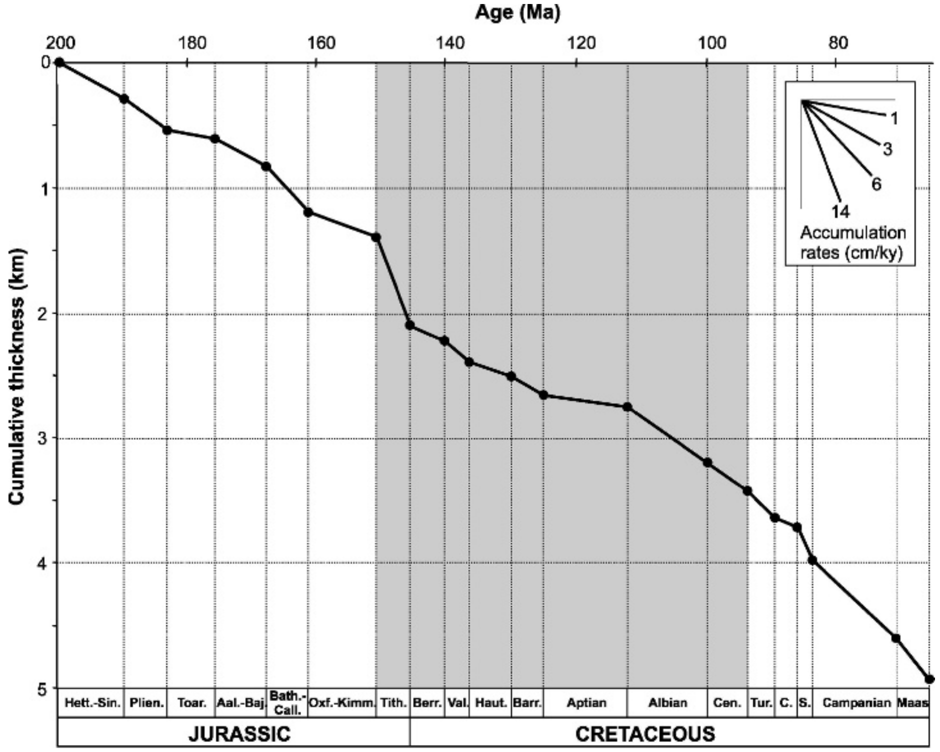

FIG. 8.—Plot of accumulation history for the Jurassic and Cretaceous deposits of the southern Dinarides. Effects of compaction were neglected because much of the dewatering in carbonates is assumed to be early and occurring during deposition of a cycle; subsequent burial compaction is difficult to access given the variable timing of cementation in carbonates. Average thickness is calculated based on the available data in the region, adapted from Tišljar et al. (2002, and references therein), except for Mljet and Lastovo (this study). The following sections were used (stratigraphic span of thickness data in brackets): Dubrovnik/Konavoska brda (Hettangian–Tithonian), Dubrovnik/Slano-Zavala (Pliensbachian–Callovian), Dubrovnik/Osojnik-Grebci (Aalenian–Tithonian), Biokovo Mt. (Aalenian–Cenomanian), Lastovo (Tithonian–Berriasian), Korčula (Berriasian–Cenomanian), Dubrovnik (Berriasian–Cenomanian), Mljet (Berriasian–Cenomanian), and Dinara Mt. (Valanginian–Cenomanian). Post-Cenomanian thickness data for the southern Adriatic are very scarce and stratigraphically less precisely defined, and the only section used here is from Brač. The shaded area indicates study interval. Time scale after Gradstein et al. (2004). See text for discussion.

Moscow depression), continental margin (Texas), and guyots (Western Pacific), Immenhauser and Scott (1999) have shown that Albian sea level was statistically stable from the late Early to the early Late Albian, whereas it fluctuated rapidly in the earliest and latest Albian. This may have been forced by different local, regional, and global factors, primarily tectonic movements associated with major reorganization of lithospheric plates during the latest Albian (see Scotese et al. 1988). In the peri-Adriatic region, these movements marked the beginning phase of disintegration of the carbonate platform. It was probably initiated as early as the Early Aptian, when the South Penninic Ocean reached its maximum width and convergence of Adria and Eurasia started (Neugebauer et al. 2001). Consequently, the Late Cretaceous sea-level changes recorded on the Adriatic (Dinaric) platform were markedly influenced by intense regional (peri-Adriatic) tectonics.

The studied succession appears to have been dominated by low-amplitude eustatic effects. Typical meter-scale shallowing-upwards cycles, the predominance of a very shallow-water facies extending over much of the platform, the aggradational character of the platform, and the lack of interbedded deeper-water facies indicate low-order sea-level fluctuations (Read 1995, 1998). On the basis of the range of stratigraphic distances of facies below the base of laminite cap or the top of restricted lime mudstone, Husinec and Read (2005) estimated that on the studied southern part of the Adriatic platform maximum water depths were less than 10 m during the Tithonian. It should be noted that the existence of a high-frequency global signal during global greenhouse conditions presumed for this interval is disputed (e.g., Miall and Miall 2001, and references therein).

The tidal-flat facies maintain nearly constant thickness throughout the area, suggesting a eustatic origin. The presence of subaerial surfaces capping many subtidal parasequences (e.g., the Barremian) requires a relative drop in sea level. From extensive evidence from the Holocene, Schlager (2005) has argued that a carbonate system is not able to build into a subaerial environment by autocyclic mechanisms. Moreover, it would be difficult to have random, autocyclic flooding of the platform with low subsidence rates (~ 4 cm/ky on average). Those parts of the sedimentary succession which vary laterally in thickness and facies probably result from autocyclic processes operating on timescales significantly shorter than those of eustatic sea-level changes.

Regional Correlation of Events

The Early Tithonian in the wider Dinaric area (external Dinarides) is characterized by an important facies differentiation, ranging from terrestrial (e.g., Velić et al. 1995) to lagoonal to deep water (e.g., Velić et al. 1994). The Late Tithonian–Early Valanginian regression (Fig. 9) with the presence of typical peritidal environments is evident throughout the Karst Dinarides, as well as in the interior of the neighboring Apulia platform (Bosellini et al. 1999). The subsequent Late Valanginian–Early Hauterivian slight deepening corresponds to transgression recorded on numerous Tethyan platforms, from the Caribbean to eastern Arabia (see Bosellini and Morsilli 1997, and references therein). This sea-level rise was associated with an environmental crisis and weakened carbonate production. The regional importance of the Barremian regression is evident in the contemporaneous regressive deposits of the isolated

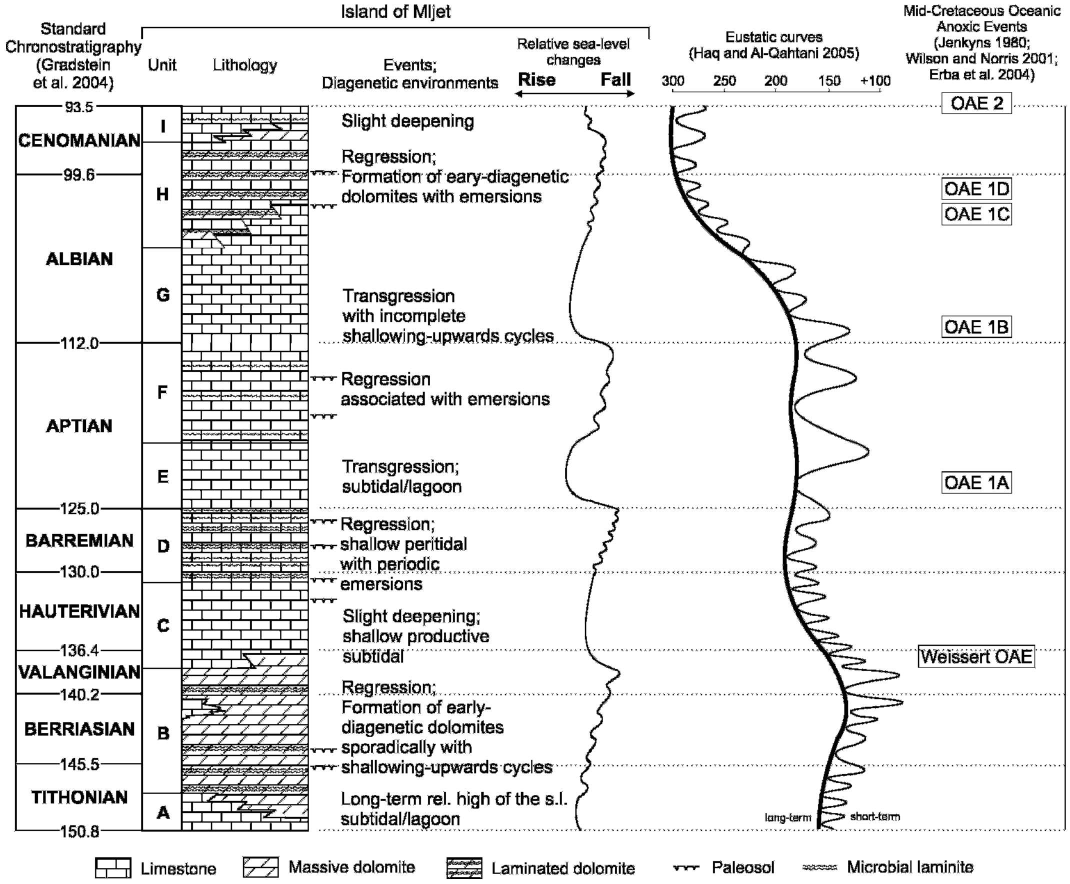

FIG. 9.—Main geological events and relative sea-level oscillations recorded in the Tithonian to Cenomanian shallow-water carbonates of Mljet Island. The third-order sea-level changes are beyond present resolution. Consequently, minor (third-order) wiggles on the local curve are schematic and, unlike the eustatic curve (Haq and Al-Qahtani 2005), do not reflect actual events. Vertical scale is in time, not thickness.

Apennine and Apulia platforms in Italy (Luperto Sinni and Masse 1986; Chiocchini et al. 1994). Examples are greenish clay sheets on micro-karstified surfaces associated with black-pebble microbreccias of the Apulia platform, as well as conglomerate intercalations associated with paleosols and thin marly limestone with charophytes of the Apennine platform.

The depositional system of the present-day Adriatic region was affected by an important environmental change during the Early Aptian. Following the Barremian regression with tidally dominated facies, the Early Aptian transgression is evident throughout the external Dinarides in the presence of very thick-bedded limestones which sporadically contain planktic foraminifers and pelagic crinoids. This event is coeval with the drowning of numerous Tethyan carbonate platforms. It had a major influence on both shallow-water carbonate and pelagic ecosystems and is thus one of the most important global Cretaceous bioevents (Kauffman and Hart 1996). This is evident in many Lower Aptian successions that reflect pronounced environmental changes in ocean waters and several genetically associated geochemical, sedimentary, and biotic events (Masse 1989). Among the most significant deposits of that age in the peri-Adriatic basins are thin-bedded pelagic black shales that record the anoxic event OAE-1A. According to Jenkyns (1991) these shales originated from a particularly thick column of anoxic (euxinic) water in the Umbria–Marche and Adriatic–Ionian basins that lapped onto the peri-Adriatic platforms (Fig. 2B), fostering regional deposition of organic-rich facies.

The pronounced Late Aptian regression documented for the study area corresponds to a significant biological crisis on numerous Mediterranean platforms (Masse 1989). A globally recorded sea-level fall and subsequent sediment exposure is represented by brecciated exposure intervals developed on the three separate peri-Adriatic platforms (e.g., Velić et al. 1979; Sartorio 1992; Gušić and Jelaska 1993; Bravi and De Castro 1995).

In the absence of evidence of significant subaerial exposure (except for, e.g., Istria; Velić et al. 1989), the Early Albian transgression, characterized by simply alternating shallow subtidal and peritidal deposits, is recorded throughout the Karst Dinarides (Tišljar and Velić 1991). The coincidence of these events with the prolonged Albian global sea-level rise and oceanic anoxic event OAE-1B suggests a common cause. However, in contrast to the uniformly developed Upper Aptian facies, the Albian succession of the Adriatic part of the Karst Dinarides includes diverse facies, from deep-water pelagic (e.g., Gušić and Jelaska 1990, 1993; Jelaska et al. 1994), to shallow water and terrestrial (e.g., Vlahović et al. 1994; Husinec et al. 2000). This facies differentiation was triggered by compressive tectonic movements caused by collision of the Adria microplate with Eurasia during the Albian–Cenomanian transition (e.g., Lawrence et al. 1995; Matičec et al. 1996; Pamić et al. 1998). Extensive peritidal facies, commonly dolomitized, and emergent intervals associated with the latest Albian to Middle Cenomanian interval, are similar to those in the adjacent areas of the southern Apennines and Apulia, where contemporaneous deposits are characterized by bauxites and related karst phenomena (e.g., D'Argenio and Mindeszenty 1991, 1995).

End-Cenomanian–Early Turonian transgression in the Dinarides represents the global rise of sea level that reached its peak during the

Early Turonian, accompanied by the prominent mid-Cretaceous oceanic anoxic event, OAE-2 (Jenkyns 1980). Additionally, the strong influence of Cenomanian synsedimentary tectonics throughout the peri-Adriatic region should be emphasized, as indicated by the adjacent Apulia platform succession (Luperto Sinni 1996). This Cenomanian inner-platform development ended with emersion and even the development of sporadic continental facies including bauxites.

CONCLUSIONS

Facies analysis of the Tithonian-to-Cenomanian carbonate succession of the southern Adriatic part of the external Dinarides (Mljet Island; coupled with the data from adjacent Lastovo and Korčula Islands, and the Pelješac Peninsula), documents relative sea-level changes. Tectonic quiescence characterized the study area during the Tithonian through Aptian. Eustatic sea-level change was apparently the primary control on the development of platform cycles, producing phases of pronounced emergence and drowning of the platform interior. Post-Aptian tectonic activity strongly influenced relative sea-level changes.

Facies stacking allows construction of a relative sea-level curve. The Tithonian–Berriasian transition was characterized by a relative sea-level fall. The pronounced regression is evidenced by the establishment of very shallow peritidal facies that were periodically exposed subaerially. An Early Aptian transgression caused a rapid shift from Late Hauterivian and Barremian peritidal deposition to deeper subtidal marine conditions. This sea-level rise corresponds to drowning of many Tethyan platforms and deposition of black shales (OAE-1A) in the basinal areas of the peri-Adriatic region. Rapid sea-level fall in the Late Aptian resulted in several clayey and/or emersion-breccia intervals. This event is recognized throughout the Adriatic part of the Karst Dinarides by a significant hiatus. It corresponds to the biological crisis recorded on many Mediterranean platforms, attributed to the global sea-level fall at the Early–Late Aptian transition. There is some correlation between this curve and global eustasy during the Tithonian through Aptian. A significant post-Aptian departure is a consequence of major tectonic activity in the region caused by the collision of the Adria microplate and Eurasia, which marked the initial disintegration of the platform. Sea-level fall during the Albian–Cenomanian transition was controlled predominantly by regional tectonics. It was characterized regionally by deposition of microbial laminites and subaerial exposure.

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