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Comparison of the Late Triassic carbonate platform evolution and Lofer cyclicity in the Transdanubian Range, Hungary and Pelagonian Zone, Greece

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For comparative studies of Upper Triassic cyclic platform carbonates, the Transdanubian Range (Hungary) and the Pelagonian Zone (Greece) were chosen. Paleogeographically they represent two distant segments of the passive margin of the Neotethys Ocean. During the Late Triassic, on this wide margin a very extensive tropical carbonate platform domain was developed, referred to as the Dachstein-type carbonate platform system. The Transdanubian Range (TR) represents a segment of a continent-encroaching platform system, whereas the Pelagonian-Subpelagonian Zone (PG) may have been a large isolated platform, surrounded by deep-water basins. The discussed Upper Triassic thick platform carbonates (Fődolomit/Hauptdolomit Formation and Dachstein Limestone in the TR, and Pantokrator Formation in the PG) are made up of cyclically arranged facies deposited under similar environmental conditions in the interior zones of carbonate platforms. Three characteristic major facies types can be distinguished: shallow subtidal-lagoonal, intertidal and supratidal-pedogenic, which correspond to the three typical lithofacies (members C, B and A) of Fischer's (1964) Lofer-cycle. The cycles are usually bounded by discontinuity surfaces related to subaerial exposure and pedogenic alteration. The meter-scale (Lofer) cyclicity is predominant throughout the successions. However, various stacking patterns including symmetric complete, truncated, incomplete, and condensed cycles or even alternating peritidal and subtidal facies without any disconformity are recognized in both areas studied. Pervasive or partial early diagenetic dolomitization affected some parts of the cyclic successions in both areas. However, age-dependence of the early dolomitization was clearly demonstrated only in the TR, where the older part of the platform carbonate succession was subject to pervasive dolomitization, whereas the younger part is non-dolomitized and there is a transitional unit between them. This trend is attributed to the climate changing from semiarid to more humid. The Upper Triassic platform carbonates of the TR and PG show strikingly similar features concerning the litho- and biofacies, the stacking pattern and the thickness of the elementary cycles, despite their distant and different paleogeographic setting within the western Neotethys realm. This suggests a

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eustatic signal, i.e. the cyclic deposition was essentially controlled by orbitally-forced eustatic sea-level changes, although the contribution of autocyclic mechanisms cannot be excluded either. Definite signatures of subaerial exposure (karstic features and vadose meteoric diagenesis) at and below the cycle boundaries also support allocyclic control. In the northeastern part of the TR the carbonate platform was drowned at the Triassic-Jurassic boundary, whereas platform conditions persisted until the end of the Hettangian in the southwestern part. However, the Hettangian part of the succession is characterized by non-cyclic subtidal limestone, implying an upward-deepening trend. In contrast, in the PG the platform conditions continued until early to middle Liassic, and the Liassic succession is typified by well-developed pedogenic features, suggesting long-lasting subaerial exposure intervals, i.e. an upward-shallowing trend.

Key words: Dachstein Formation, Pantokrator Formation, carbonate platform, peritidal facies, sedimentary cycles, carbonate diagenesis

Introduction

In the Late Triassic an extremely large carbonate platform system developed along the margins of the western Neotethys Ocean, leading to the accumulation of kilometer-thick platform carbonates. In the Northern Calcareous Alps the thick-bedded or massive platform limestone were named by Simony (1847) as Dachstein Limestone while the dolomite was referred to as Dachstein Dolomite and/or Hauptdolomit. Thick Upper Triassic (Upper Tuvalian to Rhaetian) and locally also lowermost Jurassic platform carbonate sequences showing features akin to those in the type locality of the Dachstein Limestone and Dachstein Dolomite in the Dachstein Group (Austria) occur outside of the Upper Austroalpine units, in the Central and Inner Western Carpathians, Southern Alps, Transdanubian Range, Dinarides, and Hellenides (Zankl 1967; Bosellini and Hardie 1985; Pomoni-Papaionnou et al. 1986; Dimitrieвić and Dimitrijević 1991; Ogorelec and Rothe 1992; Ogorelec and Buser 1996; Michalik 1980, 1993; Haas et al. 1995; Haas and Budai 1995; Gawlick et al. 1999; Mandl 2000; Haas 2004; Haas et al. 2007; Pomoni-Papaioannou 2008; Pomoni-Papaioannou and Kostopoulou 2008). Although the formal lithostratigraphic names of these formations are different, one can refer to them collectively as Dachstein-type platform carbonates (Haas 2004).

There are some important sedimentological characteristics of the Dachstein-type platform carbonates which are amazingly similar all over the very large area of occurrence. From among them the most spectacular is the meter-scale cyclicity of the inner platform deposits. The cyclic nature of the Dachstein Limestone was already recognized by Sander (1936) and Schwarzacher (1948). Fischer (1964) defined the typical lithofacies that make up these cycles that he called Lofer cycles, and he was first to propose a peritidal origin for those peculiar layers that regularly punctuate the shallow subtidal carbonate succession. According to a number of detailed studies on various sequences not only the cyclicity itself but the basic features of the cycle members are also very similar, even in very distant sections. However, these studies also revealed differences in the sedimentological and early diagenetic characteristics of the successions.

The Dachstein-type platforms were developed on rapidly subsiding passive ocean margins, indicating regional geodynamic control. The basic pattern of the cyclicity can be best explained by orbitally-forced sea-level oscillation, which controlled sediment deposition and early diagenesis of the inner platform – tidal flat system. The differences in the cycle stacking pattern, thickness proportion, and facies characteristics of the cycle members reflect local paleogeographic differences.

The aim of this paper is to present and compare the Dachstein-type platform evolution with special regard to the cyclic platform interior deposits of two distant segments of the western Neotethys realm exposed in the Transdanubian Range Unit (Hungary) and the Pelagonian Zone (s.l.) (Greece), respectively (Fig. 1). Evaluation of similarities and differences in the characteristics of the lithofacies and cyclicity may indicate differences in paleogeographic setting and paleoclimate of the compared areas.

Paleogeographic setting of the study areas

In the Late Triassic the study areas were located on the Neotethys passive margin. Reconstructed positions of the areas are presented in Fig. 2.

The Middle-Late Permian continental rifting can be considered as the onset of the Alpine evolutionary cycle in the region of the later western Neotethys. Transgressions in the Late Permian to Early Triassic led to the formation of a large, relatively shallow embayment of the Paleotethys Ocean that is typified by a mixed siliciclastic-carbonate sediment deposition in the Early Triassic and mostly carbonate deposition in the Early Anisian. Neotethys oceanic rifting began in the late Early Triassic in the Hellenides and in the Middle Anisian in the Dinaridic-Alpine realm and also in the area of the Transdanubian Range. Coeval with the development of the oceanic basin, large extensional basins (troughs) began to be formed in the wide marginal zones. This process led to the formation of the Slovenian Trough, which separated the Julian Carbonate Platform (Buser 1989) from the Adriatic Carbonate Platform, and of the Bosnian Trough that separated the Sana-Una and Jadar Blocks (Pamić et al. 1998).

The large area that corresponds paleogeographically to the Apulia-Preapulia-Ionian-Gavrovo-Tripolitza shallow-marine carbonate domain can be considered as the continuation of the Adriatic Carbonate Platform. From this unit the shallow marine Pelagonian-Subpelagonian domain may have also been separated by rift-related extensional tectonic processes that began here somewhat earlier.

During the Late Triassic the spreading of the Neotethys Ocean continued. In the Carnian the smaller interplatform and intraplatform basins were filled up by terrestrial siliciclastic sediments, whereas platform evolution continued in the core of the platforms. By the latest Carnian a flat topography came into existence over large areas that permitted the onset of the Dachstein-type platform evolution. However, in the large troughs pelagic basin conditions persisted. In

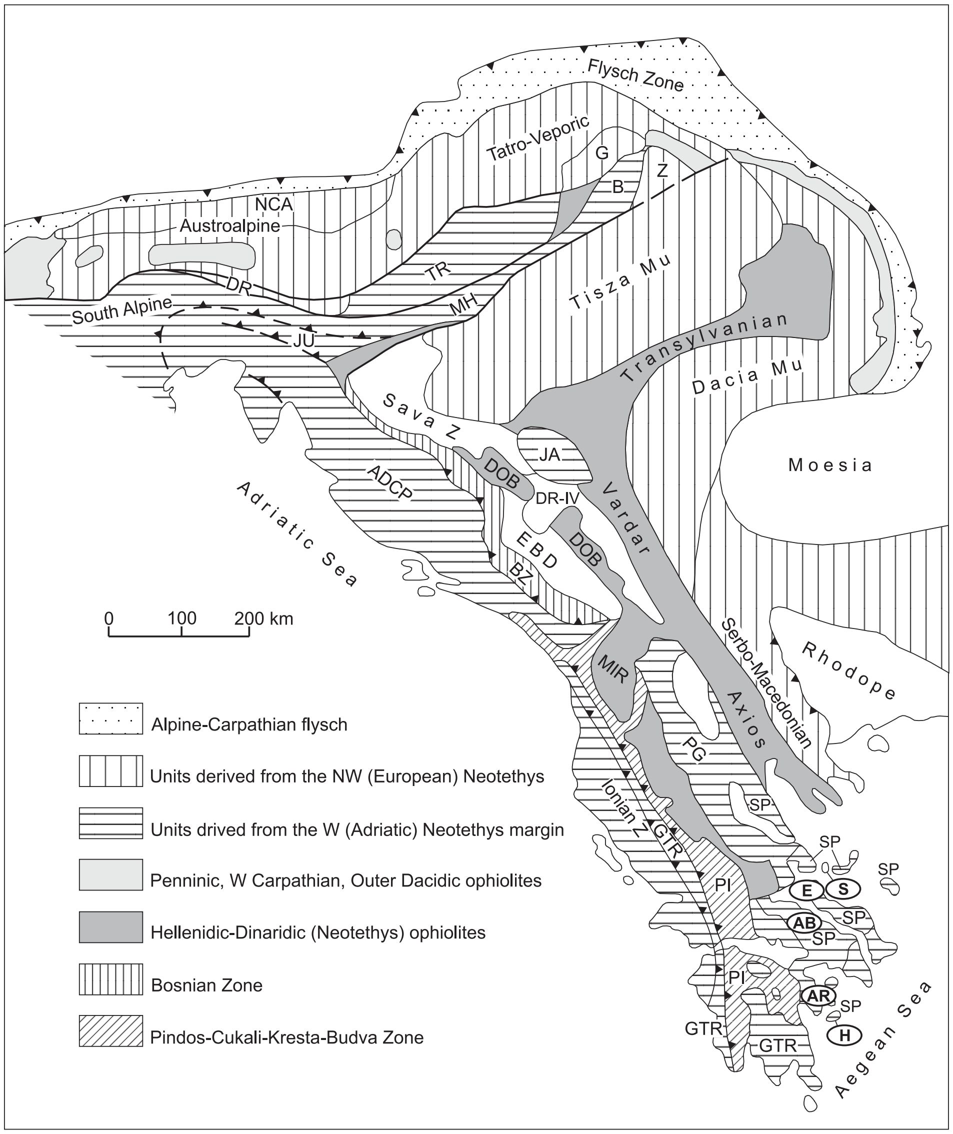


Fig. 1
Geologic setting of the study areas (compiled after Fülöp 1989, Dimitrijević 1997; Papanikolau 1984, 1986; Sandulescu 1980, 1984; Haas et al. 2001; Bernoulli, 2001). Abbreviations: NCA – Northern Calcareous Alps; DR – Drava Range; TR – Transdanubian Range; JU – Julian Alps; MH – Mid-Hungarian Zone; B – Bükk Unit; G – Gemer Unit; Z – Zemplén Unit; ADCP – Adriatic-Dinaridic Carbonate Platform; BZ – Bosnian Zone; DOB – Dinaridic Ophiolite Belt; DR-IV – Drina-Ivanica Unit; JA – Jadar Block; EBD – East Bosnian-Durmitor Unit; MIR – Mirdita Unit; PG – Pelagonian Unit; SP – Subpelagonian Unit; PI – Pindos Zone; GTR – Gavrovo-Tripolitza Zone; H – Hydra Island, AR – Argolis Peninsula, AB – Attica-Beotia, E – Evia, S – Skopelos Island and adjacent areas

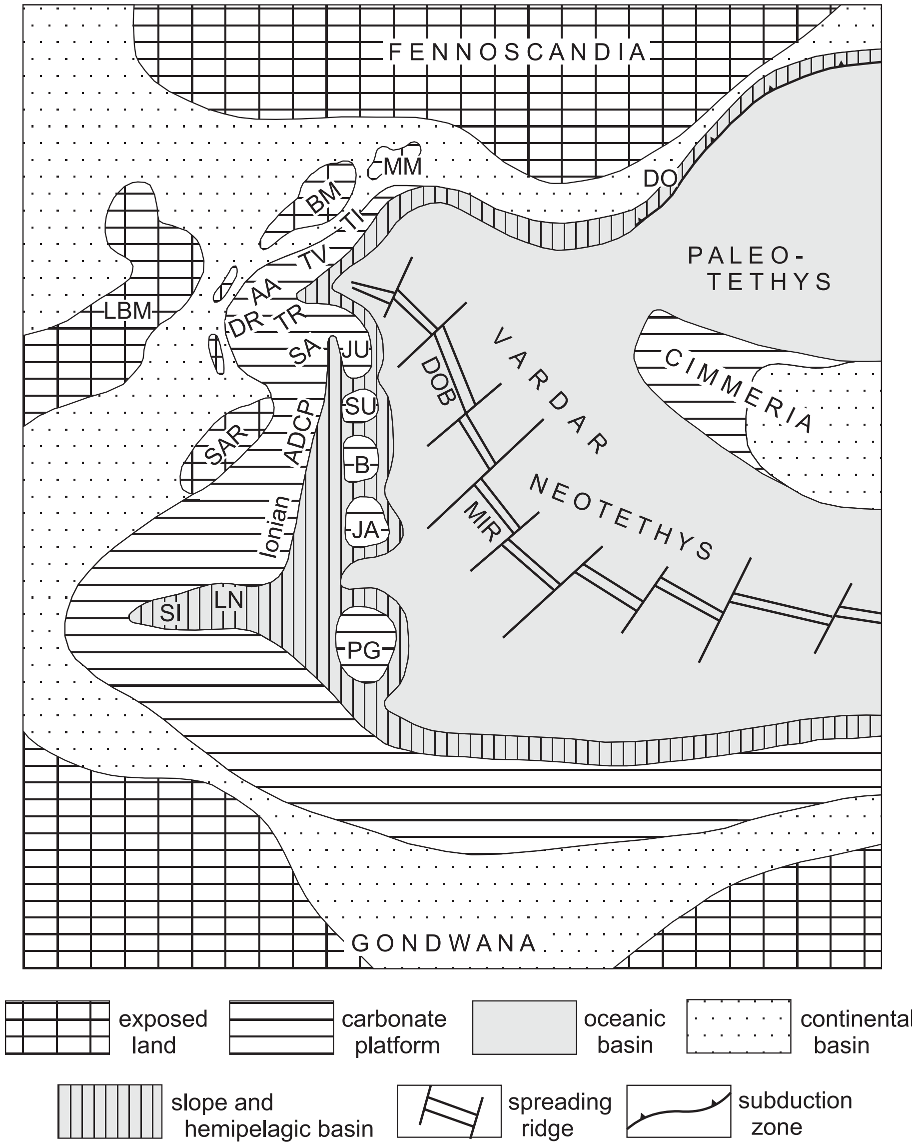


Fig. 2
Paleogeographic setting of the study areas (compiled after Haas et al. 1995; Dercourt et al. 1993; Szulz 2000; Bernoulli 2001; Kovács, in press) Abbreviations: LBM – London-Brabant Massif; BM – Bohemian Massif, MM – Malopolska Massif; SAR – Sardinia DR – Drau Range; AA – Austroalpine Units; TV – Tatra-Veporic Units; TI – Tisza Unit; DO – Dobrogea; DR – Drava Range; TR – Transdanubian Range; SL – Slovenian basin, JU – Julian Alps; B – Bükk Unit; ADCP – Adriatic-Dinaridic Carbonate Platform; BZ – Bosnian Zone; DOB – Dinaridic Ophiolite Belt; MIR – Mirdita Unit; JA – Jadar Block; SI – Sicani Basin; LN – Lagonegro Basin; PG – Pelagonian-Subpelagonian Units

this paleogeographic setting the Transdanubian Range was a segment of the wide marginal carbonate platform developed around the western Neotethys margin, whereas the Pelagonian Unit may have been a large isolated platform, surrounded by deep pelagic basins.

Transdanubian Range Unit

Geologic setting

The Transdanubian Range Unit (TR) is located in the central part of western Hungary (Fig. 3). It is bounded by major structural lineaments. It was one of those exotic terranes which were squeezed out from their earlier position during the early Tertiary as a result of the northward motion of the Adria Microplate. The Alpine evolutionary cycle began in the Middle to Late Permian by deposition of fluvial siliciclastics in the southwestern part, and coastal sabkha and shallow marine carbonate sedimentation in the northeastern part of the TR. Transgression

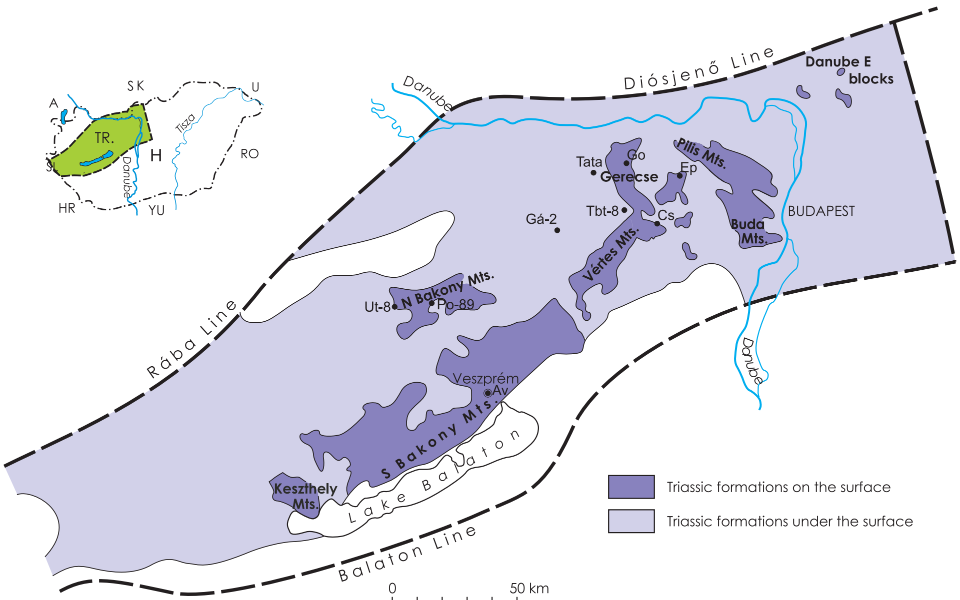


Fig. 3
Pre-Tertiary geologic map of the Transdanubian Range showing extension of the Triassic formations (after Haas and Budai 1995, modified). Av – Aranyosvölgy Quarry; Cs – Csákánykő Quarry; Go – Gorba Quarry; Ep – Epöl Quarry

at the Permian-Triassic boundary led to the establishment of marine conditions over the TR area (Haas and Budai 1995). Mixed carbonate and fine siliciclastic deposition on a large ramp typified the Early Triassic. It was followed by deposition of ramp carbonates in the early Middle Triassic. Extensional tectonics in the mid-Anisian resulted in facies differentiation (Budai and Vörös 1992); isolated carbonate platforms and between them deeper basins developed, and in the Late Anisian significant amounts of volcanic tuff were accumulated in the basins. In the Ladinian a large carbonate platform developed in the northeastern part of the TR, producing approximately 1 km-thick dolomite, whereas in the central part the basin former conditions persisted and pelagic limestone was formed. In the Carnian the active rifting processes came to the end and due to the more humid climatic conditions terrigenous siliciclastic transport intensified, leading to upfilling of the previous basins. By the latest Carnian a flat topography developed, giving rise to the evolution of the large Dachstein-type platforms. Drowning of the Dachstein platform took place at the Triassic-Jurassic boundary in the northeastern TR, and somewhat later at the end of the Hettangian in the southwestern part. Intensive extensional tectonics during the Early Jurassic resulted in disintegration of the former platform and created an articulated basin topography (Vörös and Galácz 1998). By the late Early Jurassic deep-sea conditions were established, followed by pelagic conditions that prevailed until the mid-Cretaceous tectonic events.

Stages of the platform evolution in the Late Triassic

The Dachstein-type platform carbonates can be followed in the Transdanubian Range (TR) over a distance of 250 km, parallel to the NE–SW strike of the mountain range that is roughly perpendicular to the direction of isopic facies belts (Fig. 4). The thickness of the platform carbonates is 1.5–2 km. The platform carbonate complex can be subdivided into several lithofacies (lithostratigraphic) units which reflect differences in the sedimentological and early diagenetic conditions that were controlled by the paleogeographic setting of the depositional area and tectonic, sea-level and climatic factors. All of these controlling factors underwent change during the approximately 16 Ma history of platform evolution. During the early stage of this evolution, in the Late Tuvalian to Late Norian interval, the northeastern part of the TR represented the seaward margin of the continent-encroaching platform, where intraplatform basins were developed roughly parallel to the platform margin as a result of Neotethys rifting. Deposition of oncoidal limestone with patch reefs (oncoidal Dachstein Limestone) characterized the outer platform belt (Haas and Budai 1995). In the inner platform, accretion of a cyclic peritidal-lagoonal carbonate succession took place coevally, which was affected by early diagenetic pervasive dolomitization (Fődolomit Formation = Main Dolomite, Hauptdolomit – Dachstein Dolomit – Dolomia Principale) under the prevailing semi-arid climate. More humid climatic conditions in the mid-Norian resulted in less intense and discontinuous dolomitization (Fenyőfő Member – a transitional unit between the Fődolomit and the Dachstein Limestone Formation). In the Late Norian significant changes took place in the paleogeographic setting. As a consequence of the incipient rifting of the Ligurian-Penninic Ocean branch ("Alpine Tethys") extensional basins were

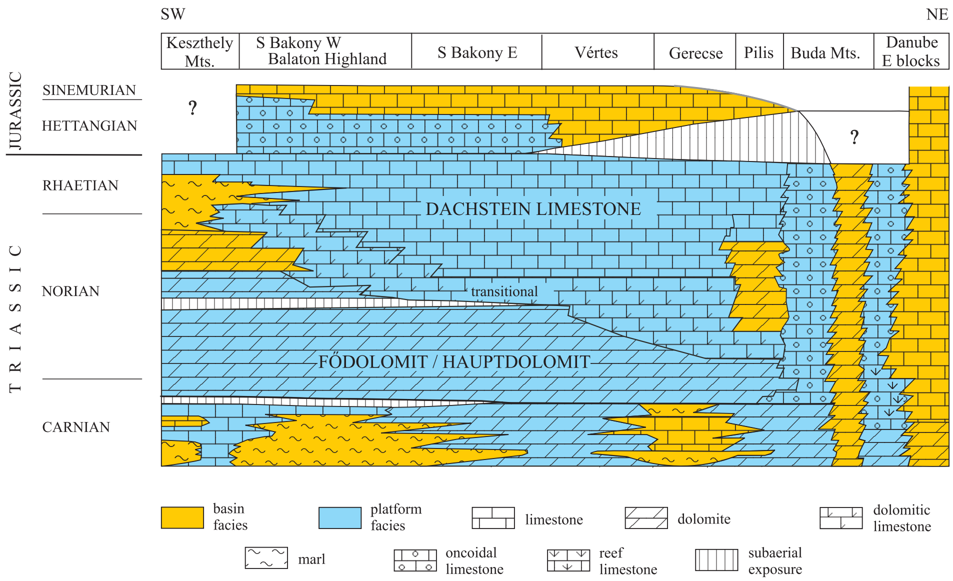


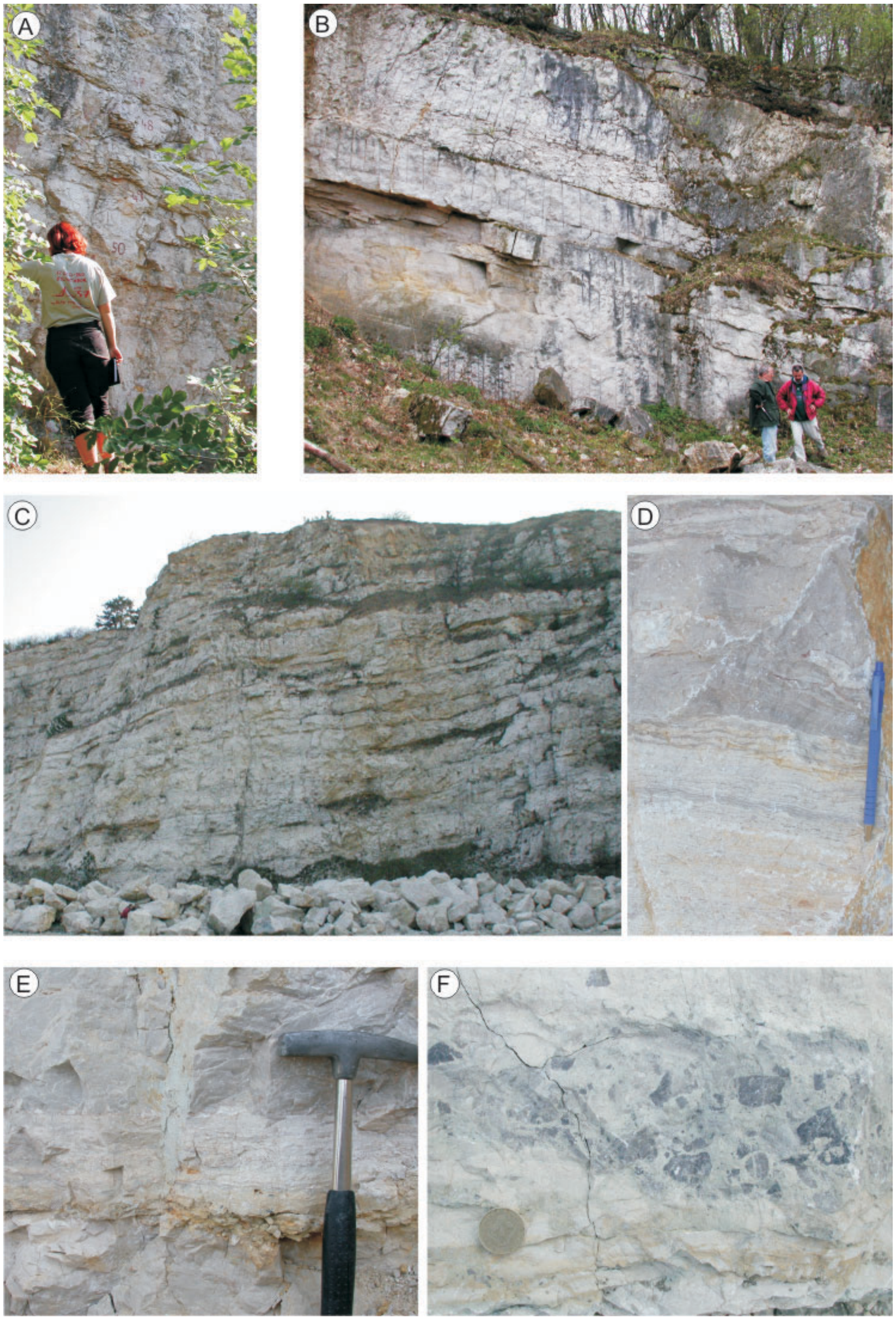
Fig. 4
Stratigraphic scheme of the Upper Triassic platform and basin facies in the Transdanubian Range (after Haas and Budai 1995, modified)

developed in the southwestern part of the TR (Kössen Basin; see Fig 4). The continent-encroaching platform was transformed into an isolated platform in the latest Norian (Haas 2002). The trend of increasing humidity continued leading to cessation of the early diagenetic dolomitization and growing importance of pedogenic alteration processes on the platform (Lofer cyclic Dachstein Limestone), and accumulation of fine siliciclastics in the coeval back-platform Kössen Basin.

Characteristics of Lofer cyclicity

In the TR the Upper Triassic inner platform successions are characterized by Lofer cyclicity. For the Dachstein Limestone the mean cycle thickness is 3.1 m (Schwarzacher and Haas 1986; Haas 1991). The mean thickness of the basic cycles

Plate 1 ⟶
A) cyclic dolomite beds, made up of alternation of Megalodont-bearing subtidal and stromatolite beds in the lower (latest Carnian) part of the Fődolomit/Hauptdolomit. Veszprém Aranyosvölgy Quarry, Bakony Mountains B) cyclic dolomite of Norian age. Csákánykő Quarry, Vértes Mountains, C) cyclic partially dolomitized succession, representing the upper part of the transitional unit between the Hauptdolomit and the s.str. Dachstein Limestone. Epöl Quarry, Gerecse Mountains. D) Transition between the stromatolitic peritidal and the subtidal facies. Epöl Quarry. E) cycle boundary; the subtidal bed (C facies) is truncated and the uneven erosional surface is covered by thin breccia in green clayey natrix that is overlain by a dm-thick stromatolite layer prograding upward into the subtidal facies. Epöl Quarry; F) black pebbles in the basal part of a cycle. Epöl Quarry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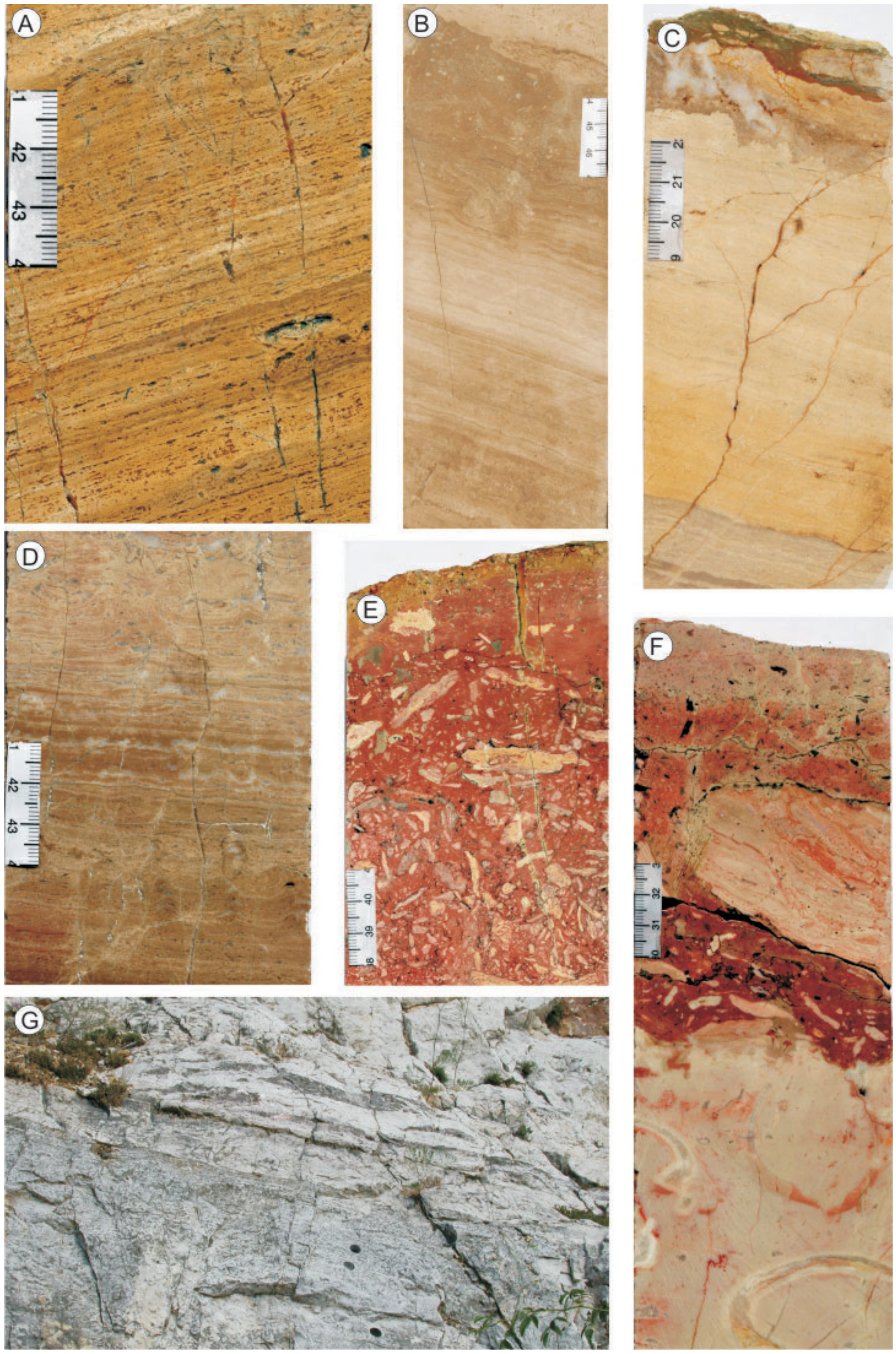
in the transitional Fenyőfő Member and in the Fődolomit Formation is practically the same.

In the 800–1200 m-thick Fődolomit Formation the cycles are usually made up of two basic facies types: microbial stromatolite (member B) and various subtidal facies (member C) (Plate 1A, B) with bioclastic, oolitic or peloidal wackestone or packstone texture or dolosparite without any recognizable texture. The cycles are generally bounded by uneven disconformity surfaces (d). Less than 10 cm of red, clayey argillaceous dolomite or a dolocrete horizon may appear above the disconformity. The cycle-bounding disconformity is either below the stromatolitic member or above it, or in many cases it lies within the stromatolitic facies, separating the regressive (B') and the transgressive (B) peritidal members. This means that the basic cycle pattern is d-B-C-B'-d, although truncated cycles (d-B-C-d) are common. Alternation of peritidal and subtidal facies without any erosional boundary surface (B-C-B-C) was also observed in a certain interval (Haas 2004). Occurrence of dolocrete caps indicates semiarid climatic conditions in the subaerial period. Early diagenetic pervasive dolomitization took place below the surface of the tidal flat in the unconsolidated mud. According to C and O isotope data, evaporated seawater may have been the dolomitizing fluid (Balog et al. 1999). However, it is probable that sulfate-reducing bacteria and cyanobacteria association in the microbial mat (Vasconcelos et al. 1995; Wright and Wacey 2005) also played a decisive role in the dolomitization process, along with the favorable climatic and hydrologic conditions.

There is a 100–300 m-thick transitional interval between the Fődolomit Formation and the typical Dachstein Limestone (Fenyőfő Member). It is characterized by calcareous dolomite and dolomitic limestone, and an alternation of dolomitized and non-dolomitized intervals (Plate 1C). The dolomitization is more pronounced at the lower part of the member where characteristics of the cycles are similar to those in the Fődolomit Formation. There is an upward-decreasing trend in the grade of dolomitization and it is accompanied by a general occurrence of the reddish or greenish argillaceous, commonly intraclastic supratidal facies (member A) above the disconformity, at the base of the cycles (Plates 1E, F, 2C). Thus the cycle-stacking pattern that is typical in the lower part of the Dachstein Limestone (d-A-B-C-B'-d) appears gradually. According to microscope observations and stable isotope studies (Haas and Demény 2002) dolomitization took place in unconsolidated sediments of a previously deposited

Plate 2 →

A) stromatolite (B facies) in the Fődolomit/Hauptdolomit. Core Ut-8 148.7 m, Ugod, Bakony Mts; B) stromatolite (B facies) in the lower transitional member of the Dachstein Limestone. Core Tbt-8, 42.8 m, Tatabánya, Gerecse Mts; C) disconformity surface with microkarstic features on a stromatolite bed; the uneven surface is covered by green marl with breccia. Core Tbt-8, 74.4 m, Tatabánya, Gerecse Mts; D) stromatolite (B facies) in Norian Dachstein Limestone. Core Cá-2 m, Császár, Vértes Mts. E) stromatolite intrabreccia in argillaceous limestone matrix (A facies) Core Po-89, 100.1 m Porva, Bakony Mts. F) truncated megalodont-bearing subtidal limestone (C facies) is overlain by argillaceous limestone with various intraclasts (A facies) Core Po-89, 390.5 m Porva, Bakony Mts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cycle, and along with downward percolation and seaward flow of the evaporated sea water, mixing of sea water and meteoric water may have also played a role in this process.

As was discussed above in the case of the dolomitized formations, the most important subaerial process is dolomitization itself. Karstification and accumulation of the reworked argillaceous weathering products show an opposite trend to the intensity of the early dolomitization.

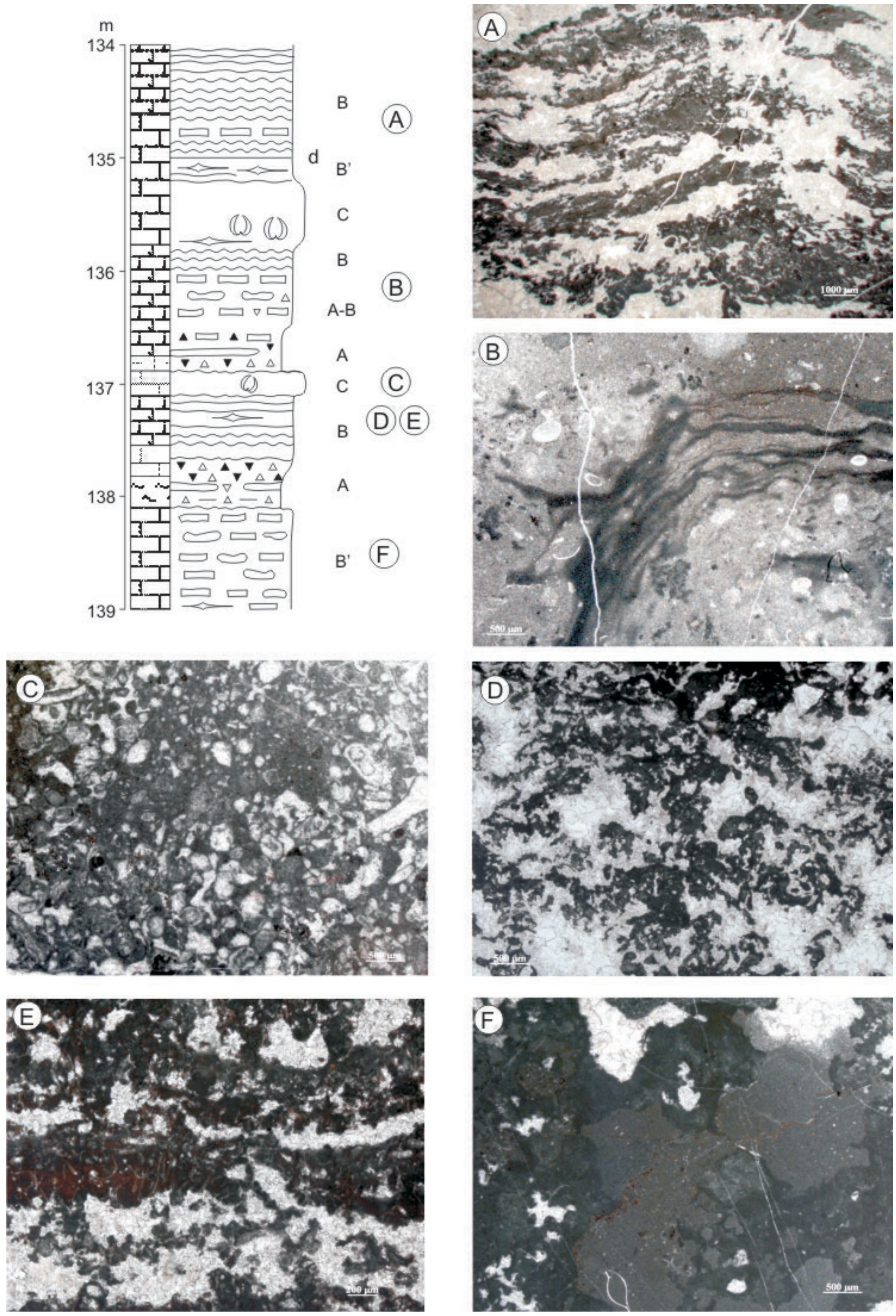
Based on characteristics of the Lofer-cycles, the Dachstein Limestone s. str. can be subdivided into two parts. The lower part corresponds approximately to the Middle to Upper Norian while the upper part corresponds roughly to the Rhaetian.

The lower, approximately 500–700 m thick part of the Dachstein Limestone s.str. is generally made up of fairly complete and symmetrical cycles (d-A-B-C-B'-A'-d) although truncated ones (d-A-B-C-B'-d or d-A-B-C-d) are also common (Haas 1991, 2004). The disconformity surfaces (d) are generally uneven, showing traces of karstic solution. Centimeter-sized solution cavities filled with reddish or greenish argillaceous limestone are common (Plates 2, 3, 4).

Between the subtidal beds of predominantly biopelmicrite wackestone or packstone texture (member C), facies types akin to those that were described by Fischer (1964) as A and B members were found (Plates 2, 3, 4, 5). The typical facies of the latter members are as follows a) argillaceous micrite, carbonate silt (dolosilt), clayey marl or marl, greenish or reddish; b) intraclastic argillaceous micrite, greenish or reddish, rarely with silt-sized quartz and mica. Ostracodes are usually common in the matrix. Millimeter to centimeter-sized rip-ups of microbial stromatolite and black pebbles are typical clastic components; pisoids and pisoidic lumps with Fe-oxide staining and coating also occur locally; c) microbial stromatolite; d) peloidal-microbial stromatolite with large amounts of tiny peloids, probably of microbial origin; e) stromatolite intrabreccia in a micritic matrix; f) micrite mudstone with scattered fenestral pores; g) ostracode wackestone, reddish, greenish or light gray. All of these facies types were formed on the tidal flat, representing various sub-environments (channel, intrachannel supratidal area, pond). Features suggesting incipient pedogenic alteration are common. Well-developed *in situ* paleosol was rarely found, but in the greenish or reddish, usually argillaceous layers that frequently overlie the disconformity surface (member A) redeposited remnants of subaerially modified and pedogenic deposits are common.

Plate 3 ⟶

Typical Lofer cyclic succession in Core Po-89 (134-139 m), and location of the presented microfacies. A) stromatolite with micro-tepee structure; B) nodular, argillaceous ostracode-bearing limestone; C) bioclastic wackestone-packstone; D) peloidal stromatolite with fenestral pores; E) peloidal stromatolite with filaments (calcified filamentous cyanobacteria); F solution pores in micritic host; the large solution pores filled by ostracode-bearing micrite internal sediment and sparite (geopetal fill). F) bioclastic grainstone (C facies)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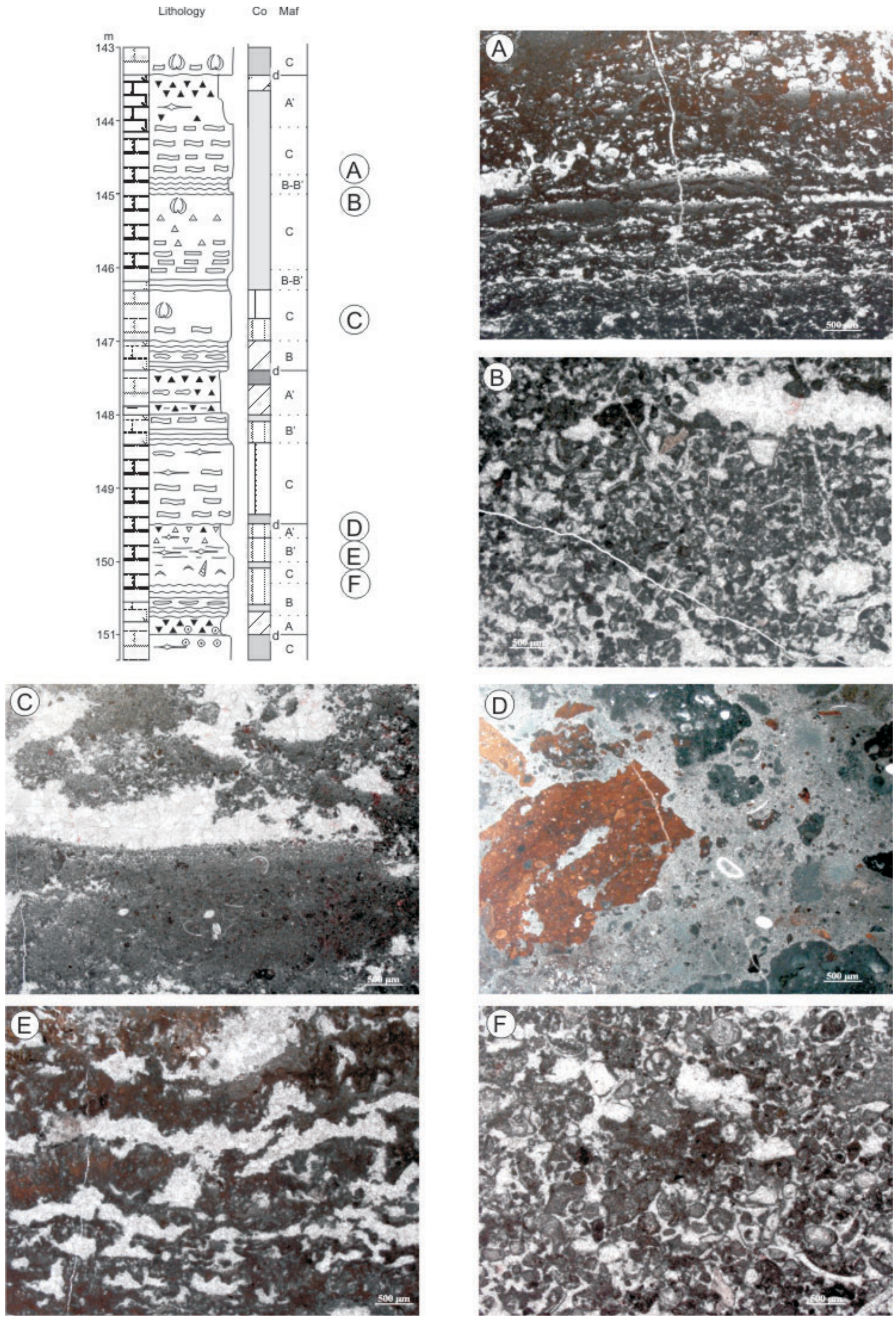
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In the upper, roughly 200 m-thick upper part of the Dachstein Limestone the basic facies characteristics of the Lofer-cycles do not change but there are remarkable differences in the composition of the cycles and in the thickness of the peritidal layers (Plate 6). The cycles are truncated as a rule, i.e. the regressive peritidal layers are generally missing. The thickness of the basal peritidal facies is usually reduced; it is not more than 10 cm. However, anomalously thick (1–2 m) peritidal facies consisting of pinkish or greenish argillaceous limestone layers also occur; these intervals are made up of thin, condensed cycles reflecting low accommodation, i.e. only very shallow, ephemeral inundation of the platform (Haas 1995a, b). The clayey horizons, which usually cover the microkarstic disconformity surfaces, are not pedogenic but probably windborne; the "paleosol" beds are actually inter/supratidal sediments that were affected only by weak pedogenic alteration (Mindszenty and Deák 1999).

Pelagonian Zone (s. l.)

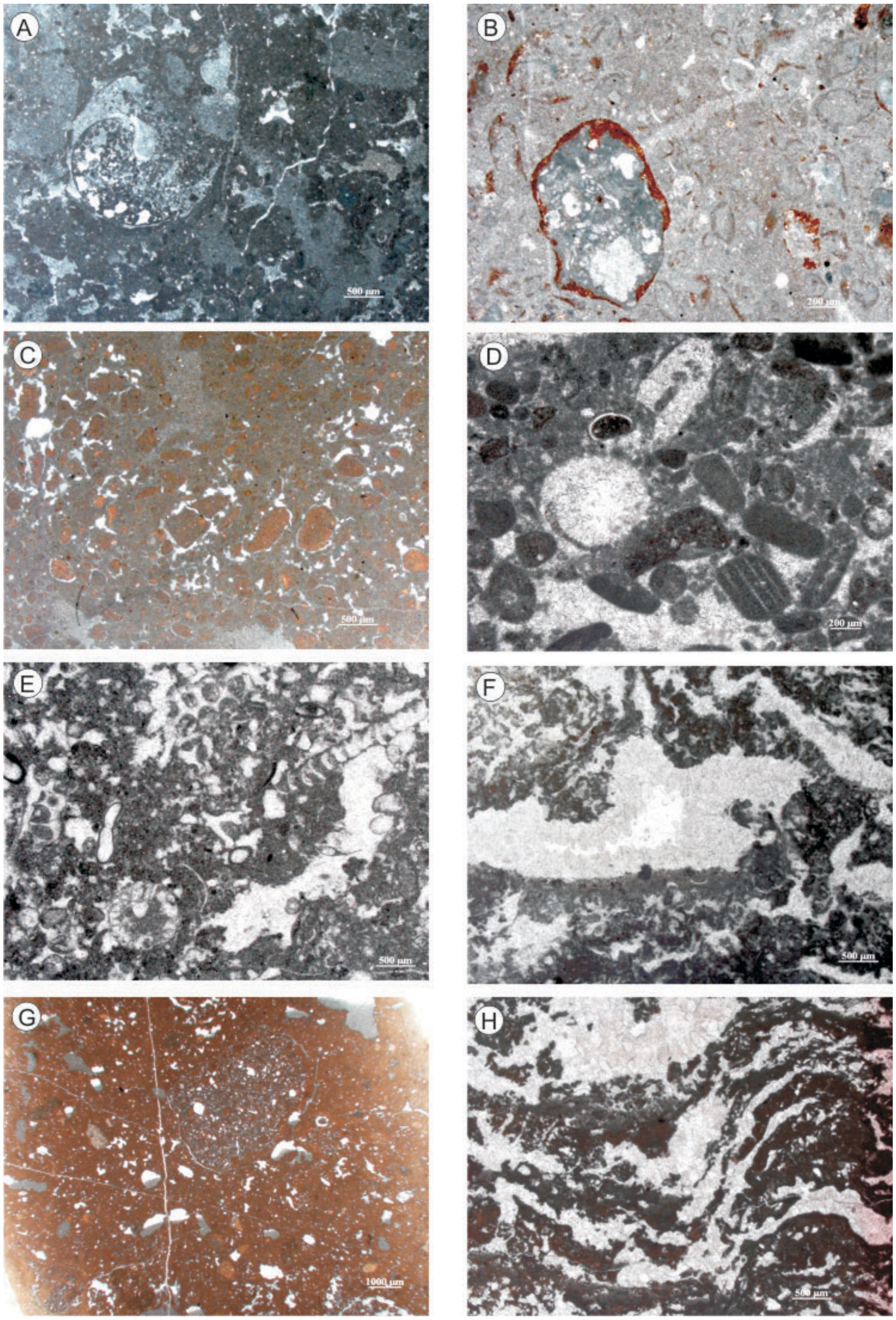
Geologic setting

The large Pelagonian carbonate platform was established in the early Middle Triassic and developed until the Late Jurassic (e.g. Brunn 1956; Bassoulet and Guernet 1970; Celet and Ferrière 1978; Papanikolaou and Zambetakis Lekkas 1980; Clément 1983; Sideris 1986; Celet et al. 1988). Extensional tectonics in the Ladinian led to drowning over large parts of the platform and development of an articulated topography (Ferrière 1982; Celet et al. 1988). Maximum extension of the platform environments occurred during the Late Carnian to Liassic interval (Celet et al. 1988; Haas and Skourtsis-Coroneou 1995). Disintegration and related drowning of the platform began in the late Early Jurassic and it was completed in the Late Jurassic (Celet et al. 1988), prior to tectonic emplacement of ophiolite nappes that took place in the Late Jurassic to Early Cretaceous (e.g. Mercier 1968; Jacobshagen 1979; Katsikatsos et al. 1986).

The thick Late Triassic–Early Jurassic platform carbonates crop out in several parts of the Pelagonian Zone in Greece (e.g. Argolis Peninsula, Attica-Beotia, Skopelos island) (Fig. 1), although different names have been used for their description (Late Triassic limestone or dolomite, Pantokrator limestone or Pantokrator Formation). However, all these platform carbonates display similar lithofacies and biofacies characteristics, suggesting that the carbonate platform

←Plate 4

Lofer cyclic succession in Core Po-89 (143-151 m), and location of the presented microfacies. A) planar stromatolaite with fenestral pores and sheet cracks (B facies); B) peloidal grainstone (C facies) containing solution pores with isopach sparite fill; C) large solution pores with ostracode-bearing micrite internal sediment and sparry calcite geopetal fill; D) Clasts of various origin in an ostracode-bearing argillaceous micrite matrix (A facies); a larger soil-clast is visible on the left side of the photo; E) stromatolite with amalgamated fenestral pores (B facies); F) bioclastic, peloidal grainstone (C facies)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F
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G
1000 µm
H
500 µm

evolved under similar conditions and that these features are very similar to that of the Dachstein-type platform carbonates widely present in the Alpine–Carpathian–Dinaridic region.

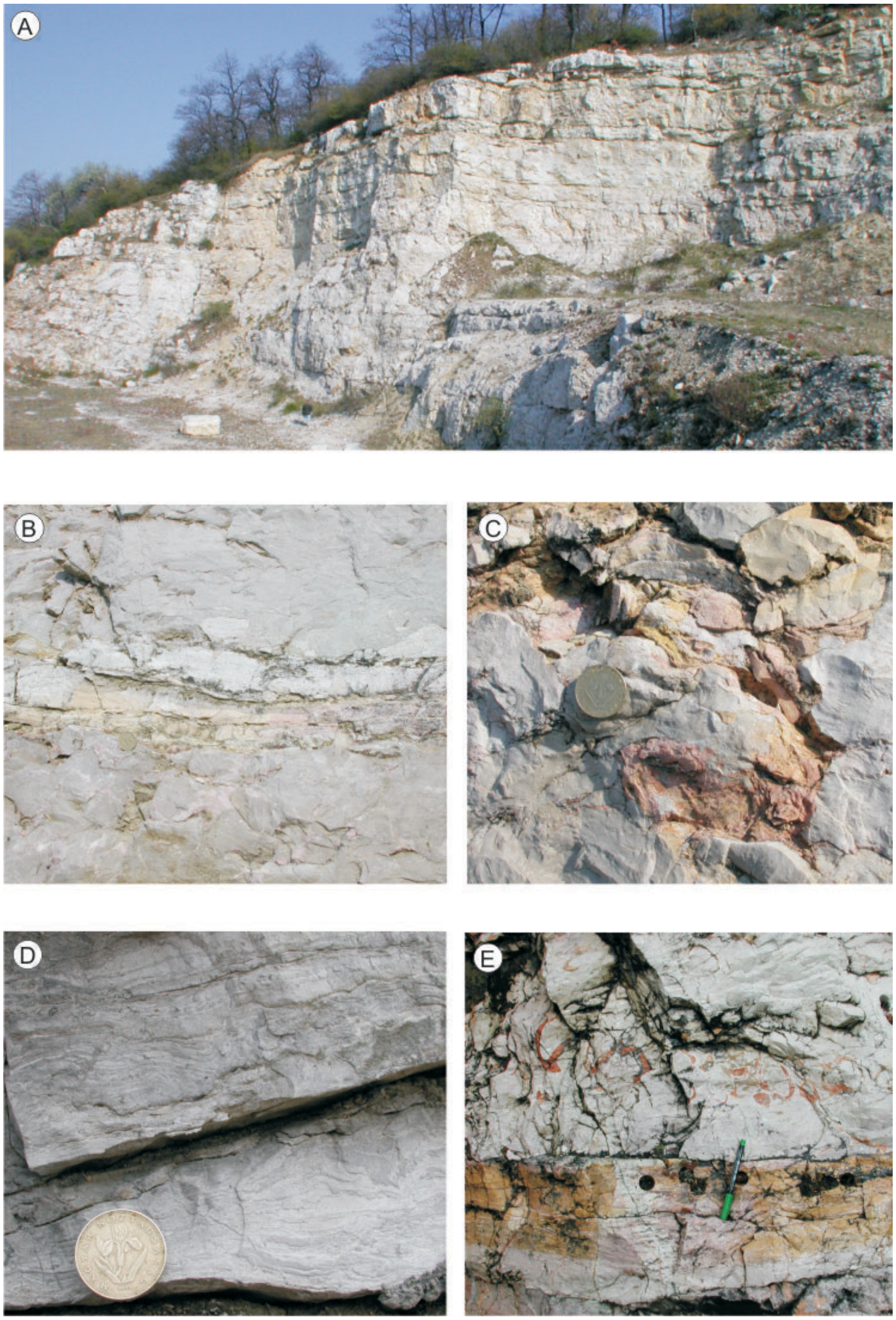
In the Hellenides analogous cyclic platform carbonates occur in coeval platform carbonate formations of the Parnassus Zone (Vartis-Matarangas et al. 1994) that was a part of the Pelagonian realm in the Triassic (Celet et al. 1988), as well as in the Ionian Zone (Epirus, Corfu island) (Renz 1955; IGRSS-IFP 1966) and in the Gavrovo-Tripolitza Zone (Kalpakis and Lekkas 1982; Kati et al. 2007; Pomoni-Papaioannou and Kostopoulou 2008). Furthermore, Late Triassic distinctive Lofer cyclothems have been described by Pomoni-Papaioannou et al. (1986) at Mt. Olympus, which are considered to be a part of the Gavrovo-Tripolitza platform, but which at present appears as a tectonic window beneath the Pelagonian Unit (Fleury and Godfriaux 1974).

Characteristics of the cyclic deposits at various locations

In the Argolis Peninsula (Peloponnese) (Fig. 1), the Late Triassic – middle Early Jurassic platform carbonates have been referred to as "Pantokrator limestone" ("Pantokratorkalk") (e.g. Renz 1955; Dercourt 1964; Süsskoch 1967; Bannert and Bender 1968; Bernoulli and Renz 1970; Vrielynck 1978; Bachmann and Risch 1979). The shallow marine carbonates are overlain by Middle-Late Jurassic pelagic facies ("Ammonitico Rosso", radiolarian chert) (e.g. Bachmann and Risch 1979; Baumgartner 1985; Gaitanakis and Photiades 1993; Bortolotti et al. 2003).

The Late Triassic-Middle Liassic successions are typified by cyclic peritidal-lagoonal deposits. Characteristic lithofacies of the Lofer cycle (e.g. stromatolites, loferites, megalodont-bearing limestone, dolocrete) were reported from several sections of the Pantokrator Formation in the Argolis Peninsula (e.g. Mt. Trapezona, Iria area, Mt. Koni and Mt. Dhidymon) (e.g. Schäfer and Senowbari-Daryan 1982; Vartis-Matarangas and Matarangas 1991; Gaitanakis et al. 2007; Pomoni-Papaioannou 2008). Late Triassic reef limestone (sponge-coral and coral reefs) analogous to that of the Dachstein reef facies also occurs in the Argolis Peninsula (Schäfer and Senowbari-Daryan 1982; Matarangas et al. 1995; Senowbari-Daryan et al. 1996), whereas it is absent or very rare at Mt. Dhidymon (Schäfer and Senowbari-Daryan 1982; Turnsek and Senowbari-Daryan 1994).

←Plate 5
Typical microfacies in Norian Dachstein Limestone, Core Po-89, Porva, Bakony Mts. A) pedogenically altered argillaceous micrite with patchy microsparitic rootcast fills (A facies) 227.4 m; B) Osctracode-bearing micrite with a Fe-oxyhydroxide coated intraclast (A facies) 257.1 m; C) pedogenic alteration; lumps with incipient circumgranular cement (A facies) 266.2 m; D) bioclastic packstone with fragments of calcareous algae (C facies) 272.6 m; E) larger solution cavity in stromatolite; it is geopetally-filled by ostracode-bearing micrite internal sediment and isopach sparite cement (B facies) 321.0 m; G) paleosol with lumps (glaebules) and tiny, geopetally-filled pores (A facies) 331.8 m; H) wavy stromatolite (B facies) 373.4 m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From the middle Liassic oolitic grainstone and algal-onkoid packstone (e.g. Dhimaina area, Sofikon-Angelokastron area) were reported (Dercourt 1964; Vrielynck 1978; Baumgartner 1985; Gaitanakis et al. 1985; Photiades and Skourtsis-Coroneou 1994; Matarangas et al. 1995).

The Upper Triassic peritidal carbonates were recently studied in the Dhidyma area, SW Argolis, by Pomoni-Papaioannou and Photiades (2007) and Pomoni-Papaioannou (2008). The succession is definitely cyclic, showing characteristics of the Lofer cyclicity (Fig. 5, Plates 7, 8, 9). It was deposited in the interior of a rimmed carbonate platform. The subtidal conditions were periodically interrupted by shorter or longer subaerial exposure episodes leading to incipient pedogenesis, calcrete formation, meteoric diagenesis, and early diagenetic dolomitization.

The subtidal carbonates (corresponding to Member C of the Lofer cycles) are represented by peloidal dolostone and dolomitic limestone with megalodontids and calcareous algae (wackestone, packstone) or by packstone/grainstone with benthic foraminifera and/or calcareous algae. They commonly lie disconformably on a flat erosional surface. The tidal-flat

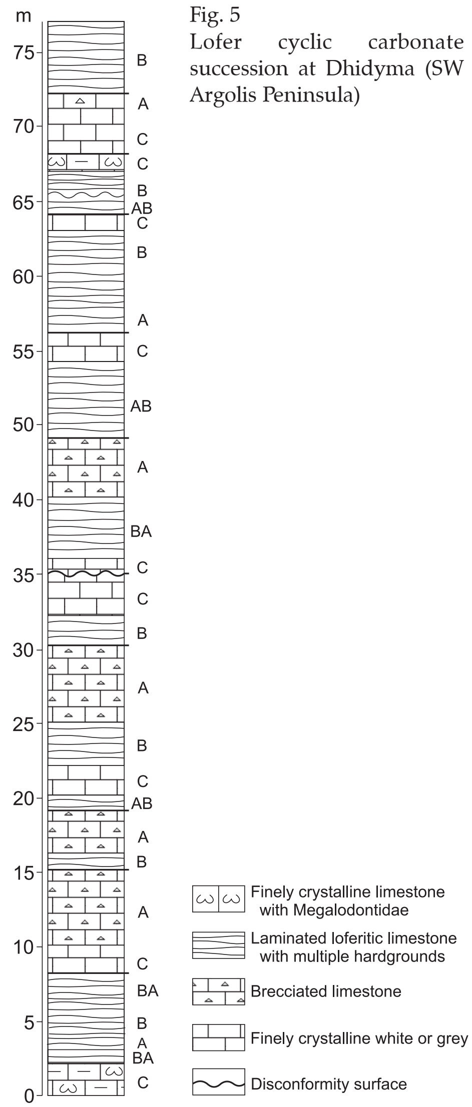

Fig. 5
Lofer cyclic carbonate succession at Dhidyma (SW Argolis Peninsula)

←Plate 6

A) Lofer cyclic Rhaetian Dachstein Limestone, Gorba Quarry, Gerecse Mts; B) truncated top of a subtidal bed; karstic solution pockets filled by pinkish micrite is visible below the disconformity surface that is overlain by a dm-thick laminated argillaceous limestone layer (A facies) and then by a stromatolite layer (B facies). Note the stromatolite rip-ups in the basal part of the overlying subtidal bed (C facies). Gorba Quarry, Gerecse Mts; C) karstic solution pocket with red argillaceous limestone fill. Gorba Quarry, Gerecse Mts; D) contorted, locally intraclastic stromatolite (B facies) Gorba Quarry, Gerecse Mts; E) Lofer cyclic succession in the uppermost part of the Dachstein Limestone (a few meters below the Triassic/Jurassic boundary). The basal stromatolite layer is overlain by subtidal containing in-situ embedded megalodonts. Tata, Kálvária Hill, Gerecse


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facies (Member B) consists of laminated-fenestral (stromatolitic), often dolomitic mudstone. It is usually overlain by dolocrete, pisoidic dolomite, or supratidal "soil conglomerate" in red, fine-grained matrix (Member A). These layers display varying evidence of intensive weathering and pedogenetic processes (e.g., laminar dolocrete, rhizolite-like structures, *in situ* breccia, solution cavities with geopetal fills, paleokarst features).

Some of the cycles studied display a shallowing-upward tendency, reflecting a regressive trend from subtidal/lagoonal (member C) to intertidal and supratidal (members B and A) settings. Most of the cycles are asymmetric and truncated (erosionally reduced) showing a d-A-B-C-d pattern. However, some of the cycles appear to be symmetric, i.e. the subtidal facies are underlain and overlain by peritidal loferites (d-A-B-C-B'-d). The early meteoric diagenesis (e.g. paleokarst dissolution cavities, dolocrete) often overprints the top of the supratidal and/or tidal flat deposits, implying periodical, relatively long-lasting subaerial exposure episodes (Strasser 1991).

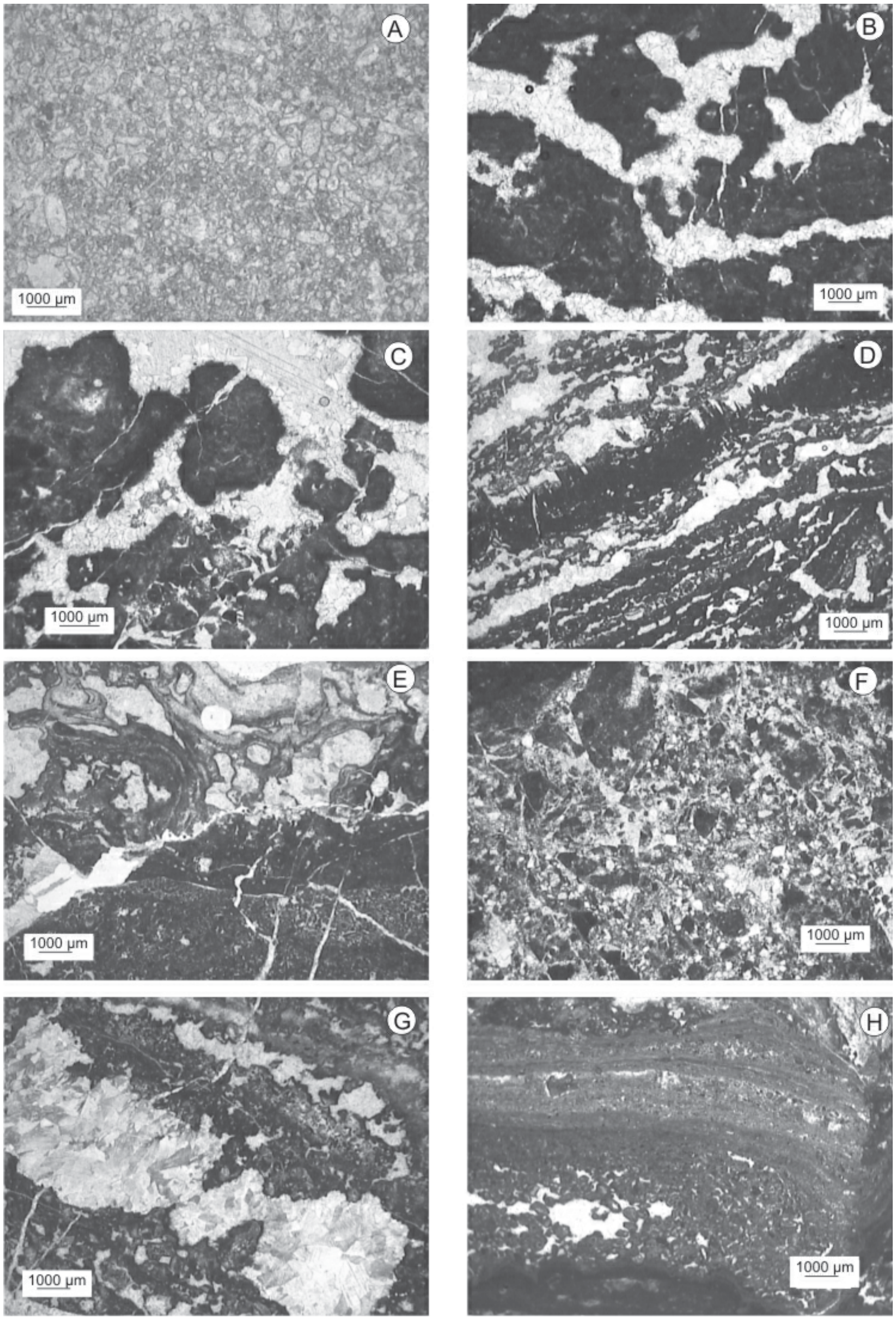
On Hydra Island near southern Argolis (Fig. 1) the Upper Triassic Pantokrator Formation is made up of Carnian to Norian reef limestone with coral-sponge and coral buildups, and of Norian to Rhaetian, partially dolomitized cyclic successions with alternating subtidal (megalodont-bearing, and algal-nodule) and tidal flat (pellet-loferite, and stromatolite) facies (e.g. Richter and Füchtbauer 1981; Schäfer and Senowbari-Daryan 1982, 1983; Kube et al., 1998; Turnsek and Senowbari-Daryan 1994; Richter et al. 1999). According to Kube et al. (1998) the Upper Carnian backreef facies is overlain by a Norian-Rhaetian Lofer-cyclic succession consisting mainly of BC-cycles.

Upper Triassic to Lower Jurassic platform carbonates were also reported from the area of Attica and Beotia (e.g. Negris 1911; Celet 1962; Koumandakis 1969; Christodoulou 1970; Bassoulet and Guernet 1970; Tataris 1972; Christodoulou and Tsaila-Monopolis 1972, 1975; Clément 1968, 1983) (Fig. 1). They are represented by bedded to massive white to gray limestone, dolomitic limestone and dolomite containing foraminifera (e.g. *Aulotortus, Triasina*) dasycladacean algae (e.g. *Gyroporella, Palaeodasycladus* mediterraneus) and megalodontid bivalves. Thick successions composed of meter-scale, mostly shallowing-upward peritidal cycles occur in northern Attica (Barattolo and Romano 2005; Romano et al. 2008; Bosence et al. 2009).

Middle Triassic to Upper Jurassic neritic limestone and dolomite of the non-metamorphic Pelagonian Zone are also recognized on Evia Island near Attica (e.g.

← Plate 7

Upper Triassic cyclic peritidal carbonates (Dhidyma area, Argolis Peninsula, Greece). A–B) stromatolites overlain by subtidal beds with megalodonts. C) intertidal microbial laminite (stromatolite) with flat lamination. D) subtidal layer with megalodont shells from the upper part of a cycle. E) Subaerial exposure-related facies with black intraclasts. F) large solution cavities with isopachous cement rims and filled with reddish material. Emersion-related layer overlain by subtidal facies. G–H) Lofer cyclic in the Dhidyma area. The subtidal beds are darker gray-beige, the inter-supratidal stromatolitic and loferitic horizons are lighter gray-white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Katsikatsos 1970; Kastikatsos et al. 1986) (Fig. 1). Platform carbonates assigned to the Pantokrator Formation and showing high-frequency shallowing-upward cyclicity were reported from NE Evia (Scherreiks 2000; Scherreiks et al. 2010).

Upper Carnian-Norian-Rhaetian dolomite rich in megalodontids and gastropods are present on Skopelos Island (Fig. 1) and in the adjacent areas (Skiathos Island, Magnesia Peninsula, eastern Othrys) (e.g. Papastamatiou 1964; Tataris 1975; Celet and Ferrière 1978; Ferrière 1982; Matarangas and Skourtsis-Coroneou 1989; Migiros 1990; Matarangas 1992). These Lofer-cyclic successions were formed in shallow subtidal/lagoonal to inter-supratidal settings, and subjected to very early diagenetic pervasive dolomitization (Matarangas 1992).

In summary, in the Pelagonian Zone (s. l.) the Upper Triassic to Liassic platform carbonates are composed of massive to poorly-bedded or well-bedded, light-colored to dark-gray limestone, dolomitic limestone, and dolomite. The faunal content and the sedimentary structures, textures and lithologies of these strata suggest depositional processes in various (sub)environments (ranging from shallow subtidal to tidal flat settings) of a large tropical, carbonate platform. In many places (e.g. Argolis Peninsula, Hydra Island, Evia Island) reefal facies were also recognized. The platform interior (lagoon) sediments consist mainly of wackestone-packstone hosting various benthic foraminifera, dasycladacean algae, gastropods, and bivalves. However, the subtidal series are intercalated by peritidal deposits. The presence of stromatolites, fenestral lamination, sheet-cracks and desiccation cracks suggest tidal flat setting. Karstic features, signals of meteoric diagenesis and pedogenesis are indicators of subaerial exposure. In many cases, the Pelagonian platform carbonates exhibit cyclic organization. The basic facies pattern and the meter-scale cyclicity show close similarity to those of the Lofer-cycles defined as Dachstein Limestone in the Alpine region. The interpreted depositional facies (subtidal, tidal flat facies and pedogenic horizons) correspond to the three typical lithofacies (members C, B and A) of the Lofer-cycles as defined by Fischer (1964). The elementary cycles generally show a shallowing-upward, regressive character, but deepening-upward and symmetric cycles (sensu Haas 1982) were also observed. In many cases the cycles are truncated due to subaerial erosion. Partially or completely dolomitized successions commonly occur but space and time distribution of the dolomitized sequences has not yet been determined.

The platform carbonates in the Pelagonian Zone represent an example of Dachstein-type depositional system which can be correlated to those developed

←Plate 8

Upper Triassic peritidal carbonates (Dhidyma area, Argolis Peninsula, Greece). A) Packstone/grainstone with benthic Forams (Aulotortinae?). B) Loferite with interconnected tubular and irregular fenestrae. C) Large shrinkage and/or dissolution cavities. D) Dolocrete crust with elongate fenestrae and wavy dissolution seam associated with pressure solution. E) Crusts with pisoid-like structure (top), microbial facies (base). F) Pseudo-microkarst filled by reworked intraclasts and sparite (vadose diagenesis). G) Laminar calcrete with alveolar-like texture, filled by blocky and/or drusy cement. H) Dolocrete directly overlying a subtidal facies

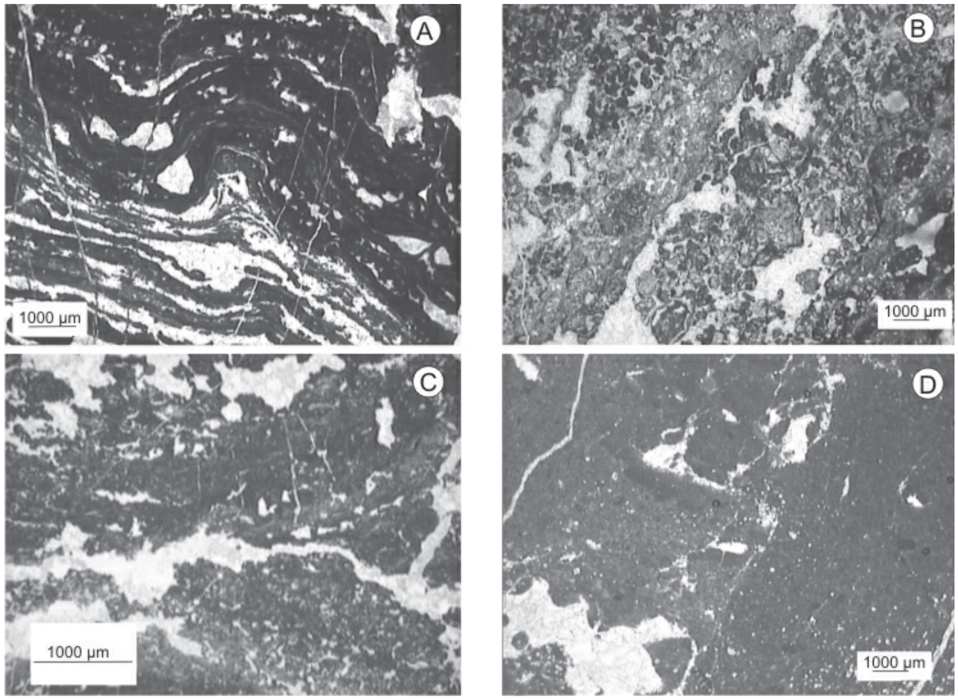

Plate 9
Upper Triassic peritidal carbonates (Dhidyma area, Argolis Peninsula, Greece). A) Laminar calcretes with irregular and wavy laminations, alternation of micritic and sparite laminae. B) Pellet-micronodular fabric. Large spar-filled solution pores and circumgranular cracks. C) Dolocrete crust. Irregular pores and elongated cavities filled by spar. D) Desiccated and microbrecciated dolomitized mudstone. Incipient glaebules, circumgranular cracking

along the margin of the western Neotethys during the Late Triassic or locally also in the Early Jurassic.

Comparison of the areas studied

In the Late Triassic extensive carbonate platform systems developed both in the Transdanubian Range (TR), Hungary and in the Pelagonian Zone (PG), Greece. In the TR the onset of the Dachstein-type platform evolution can be determined fairly exactly. It took place subsequent to upfilling of basins among smaller isolated platforms in the latest Carnian (late Tuvalian). In the PG this also happened in the Late Carnian but determination of the beginning of the platform evolution is less exact. In the northeastern part of the TR the carbonate platform was drowned at the Triassic-Jurassic boundary. Platform conditions persisted until the end of the Hettangian in the southwestern part of the TR but the Lower Jurassic segment is characterized by non-cyclic subtidal oncoidal limestone, implying an upward-deepening trend. In contrast, in the PG platform conditions continued until the early to middle Liassic, and the Liassic succession is typified by well-developed pedogenic features suggesting long lasting subaerial exposure intervals, i.e. an upward-shallowing trend.

Thick (1.5 to 2 km in the TR; 1 to 1.2 km in the PG) shallow-water carbonate successions (limestone, dolomitic limestone and dolomite) composed of cyclic lagoonal-peritidal facies formed in the wide inner platform zones of both regions. In the outer platform belt of the TR that was dissected by intraplatform basins, oncoidal limestone with small patch reefs developed. Platform margin reef tracts (Dachstein reef facies) might have existed but no exposure of larger reefs is known. In the PG typical Dachstein reef facies, which developed close to the platform margin, occur in several places.

The basic facies pattern and the general features of the meter-scale cyclicity observed both in the TR and the PG inner platform sequences show close similarity to that defined in the type locality of the Dachstein Formation in the Northern Calcareous Alps. The interpreted depositional facies, subtidal (e.g. bioclastic micrite), tidal-flat (e.g. microbial stromatolite) and pedogenic (e.g. calcrete-dolocrete, paleosol) horizons correspond to the three typical lithological members C, B and A of Fischer's (1964) Lofer cycle.

In the TR the Lofer cycles are generally bounded by uneven disconformity surfaces and their thickness is between 1 to 5 m (the mean value is about 3 m). The ideal TR Lofer cycle is symmetric (d-A-B-C-B'-A'-d) (Haas 1991, 2004). However, various stacking patterns including truncated, incomplete, and condensed cycles or even alternating peritidal and subtidal facies without disconformity are recognized. Truncated cycles consisting of B and C members are typical in the Fődolomit Formation but symmetric pattern (BCB') also occurs. The lower part of the Dachstein Limestone is still partially dolomitized and the stacking pattern of the cycles is transitional between the Fődolomit and the s. str. Dachstein Limestone. In the lower part of the s. str. Dachstein Limestone (Middle to Upper Norian) complete, symmetric cycles are common, but incomplete and truncated cycles are also present. The A and B members are usually relatively thick. In the upper (roughly Rhaetian) part of the Dachstein Limestone the truncated cycles are predominant and the A and B members are very thin or they are missing (Haas 2004). In the PG the thickness of the Lofer cycles is 1 to 5 m; they are commonly incomplete and their topmost parts preserve traces of subaerial weathering (karstic erosional surfaces). The observed stacking patterns include cycles with symmetric (sensu Haas 1982) or deepening-upward facies arrangement. However, in several cases, the regressive shallowing-upward asymmetric pattern is predominant.

In the TR, the Upper Carnian – Lower Norian cyclic lagoonal-peritidal carbonates (Fődolomit Formation) are completely dolomitized, whereas the Middle Norian to Rhaetian Dachstein Limestone is practically undolomitized (the B members are commonly slightly dolomitic) and there is a transitional, partially dolomitized unit of remarkable thickness (100–300 m) between them. The pervasive dolomitization took place during the subaerial exposure periods; modified sea water may have been the dolomitizing fluid; bacterial mediation may also have played a significant role. The change in the intensity of dolomitization reflects changes of climatic conditions from semi-arid (during formation of the Fődolomit Formation) to semi-humid (during formation of the Dachstein Limestone). As to the PG carbonates, completely or partially dolomitized and non-dolomitized successions were found in equal measure. The early diagenetic dolomitization is constrained by the observed features (e.g. well-preserved sedimentary structures, dolomite textures, facies associations).

Both in the TR and the PG, emergence-related erosional and diagenetic features have been preserved in the Late Triassic cyclic peritidal carbonates, which testify to repeated emersion episodes and related intense early meteoric modification. There is evidence for karstification and incipient pedogenesis. In the TR dolocrete caps are common in the Fődolomit Formation; calcrete and dolocrete are typical in the transitional member; and more or less clayey reddish or greenish *in situ* or reworked argillaceous paleosol layers characterize the Dachstein Limestone, but various calcrete types also occur locally. These differences suggest a long-term change in the climatic conditions as presented above. In the PG the coexistence and overlapping of karst features and calcrete-dolocrete beds reflects short-term climatic changes, i.e. alternating drier (calcrete-dolocrete) and wetter (karstic) climatic conditions.

The comparison of the cyclic TR and PG shallow-water platform carbonates, which were coevally accumulated in two distant segments of the western Neotethys realm, reveals the establishment of similar environmental conditions in the wide internal areas of large carbonate platforms under similar climatic conditions. Similarities in the litho- and biofacies, in the stacking pattern and thickness of the elementary cycles suggest allocyclic control, i.e. orbitally forced eustatic sea-level oscillation, and imply similar subsidence rates of the regions studied.

The essentially allocyclic control of the cyclicity is also suggested by signatures of subaerial exposure at the cycle boundaries. The karstic and early meteoric diagenetic features, which often overprint the top of the supratidal and/or subtidal deposits, imply sea-level fluctuations and repeated, relatively long-lasting exposure events (Haas et al. 2007; Pomoni-Papaioannou 2008). Consequently, these cycles probably record high-frequency eustatic sea-level oscillations, although the contribution of autocyclic mechanisms cannot be ruled out (Haas 1991; 1994; Haas et al. 2007; Pomoni-Papaioannou 2008; Romano et al. 2008; Bosence et al. 2009).

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