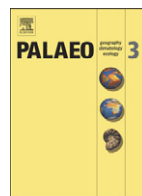




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Ecospace variability along a carbonate platform at the northern boundary of the Miocene reef belt (Upper Langhian, Austria)

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ABSTRACT

The south-western edge of the Leitha Mountains in the southern Vienna Basin (Austria) exposes parts of an Upper Langhian (Middle Badenian) shallow water (<30 m) carbonate platform. The study of its ecospace comprises sedimentological and palaeontological data of 4 up to 36 m thick carbonate sections of the Müllendorf quarries which have been logged and subjected to detailed investigation and sampling. The sedimentary record is dominated by coralline algal debris sands which represent 7 distinct lithofacies (bioclastic coralline algal-mollusc facies, *Hyotissa* facies, *Isognomon* facies, coral facies, rhodolith facies, bryozoan facies). All these facies are described in detail in respect to lithology and biota and are palaeoecologically interpreted. Striking features of these limestone successions are periodical intercalations of coral- and mollusc-rich horizons. Their formation had been triggered by water turbidity and low amplitude changes in relative sea level. These relations are especially interesting as the platform carbonates formed at the northern edge of the Langhian Peri-Mediterranean reef belt. Water turbidity, as ecological master factor, and depth played the fundamental role in ecosystem and community expression within ecospace. The lateral distribution and the ecological relations between the various facies types allow proposing an ecospace-occupation model.

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1. Introduction

Each level of organization occupies a specific volume (or functional region respectively) within an ecospace which is e.g. the ecosystem for the community or the niche for the species (Valentine, 1969; Brenchley and Harper, 1998). The term “ecospace” is commonly afflicted with functional meanings (e.g. Bambach, 1983; Novack-Gottshall, 2007) but used here only in sense of spatial (i.e., potential habitat available for the establishment of necessary ecologic interactions) connotation (sensu Buatois and Mángano, 1993). Several physical and chemical factors, which are on the one hand limiting and on the other hand modulating, influence geographical distributions of marine carbonate producing organisms within an ecospace (Brenchley and Harper, 1998).

Typical representatives of these carbonate producing organisms are corals and coralline algae. These were the main constituents of the Miocene carbonate platforms in Europe and also in the area of the Paratethys Sea. Causes for development of either coral reefs (s.s.) or coral bearing coralline algal limestones within the same ecospace are so far not considered for the Central Paratethys. A key location to

discuss this problem is the Leitha platform in the southern part of the Vienna Basin. Its limestones, broadly known as Leitha Limestones (sensu Keferstein, 1828), are dominated by coralline algal debris and have been deposited during Langhian and early Serravallian times (corresponding to the Badenian age of the regional Paratethyan stratigraphy; Steininger and Papp, 1978). The coral bearing strata at the south-western rim of the Leitha Mountains (Fig. 1a, b) are known for a moderately diverse coral fauna (e.g. Reuss, 1871). The former interpretation of these strata as coral reefs (e.g. Schaffer, 1908; Dullo, 1983; Tollmann, 1985) was re-evaluated and it was shown that the term coral carpets (sensu Reiss and Hottinger, 1984) is more appropriate (Piller and Kleemann, 1991; Piller et al., 1996, 1997; Riegl and Piller, 2000). A well studied locality is the Fenk quarry NNW of Grosshöflein (Burgenland province, N 47°50'42.65", E 16°28'36.04"). As type locality of the Badenian Leitha Limestone (Steininger and Papp, 1978) it comprises a ca. 20-m-thick succession of coralline algal limestones with frame-building coral carpets and non-frame-building biostromal coral communities with horizons of coral debris, in situ coral colonies and oyster/*Isognomon* horizons (Steininger and Papp, 1978; Piller and Kleemann, 1991; Riegl and Piller, 2000). A currently much larger outcrop, exposing a lateral time-equivalent succession of these units, is the Müllendorf quarry (Fig. 1c, d), well known for its fossil richness (Abel, 1928; Kühnelt, 1931; Reidl, 1937, 1941; Toth, 1950; Schaffer, 1961; Kühn, 1963; Kristan-Tollmann, 1964, 1966; Kleemann, 1982; Schultz, 2001, 2003, 2005; Kroh, 2005). In contrast to other limestones of the

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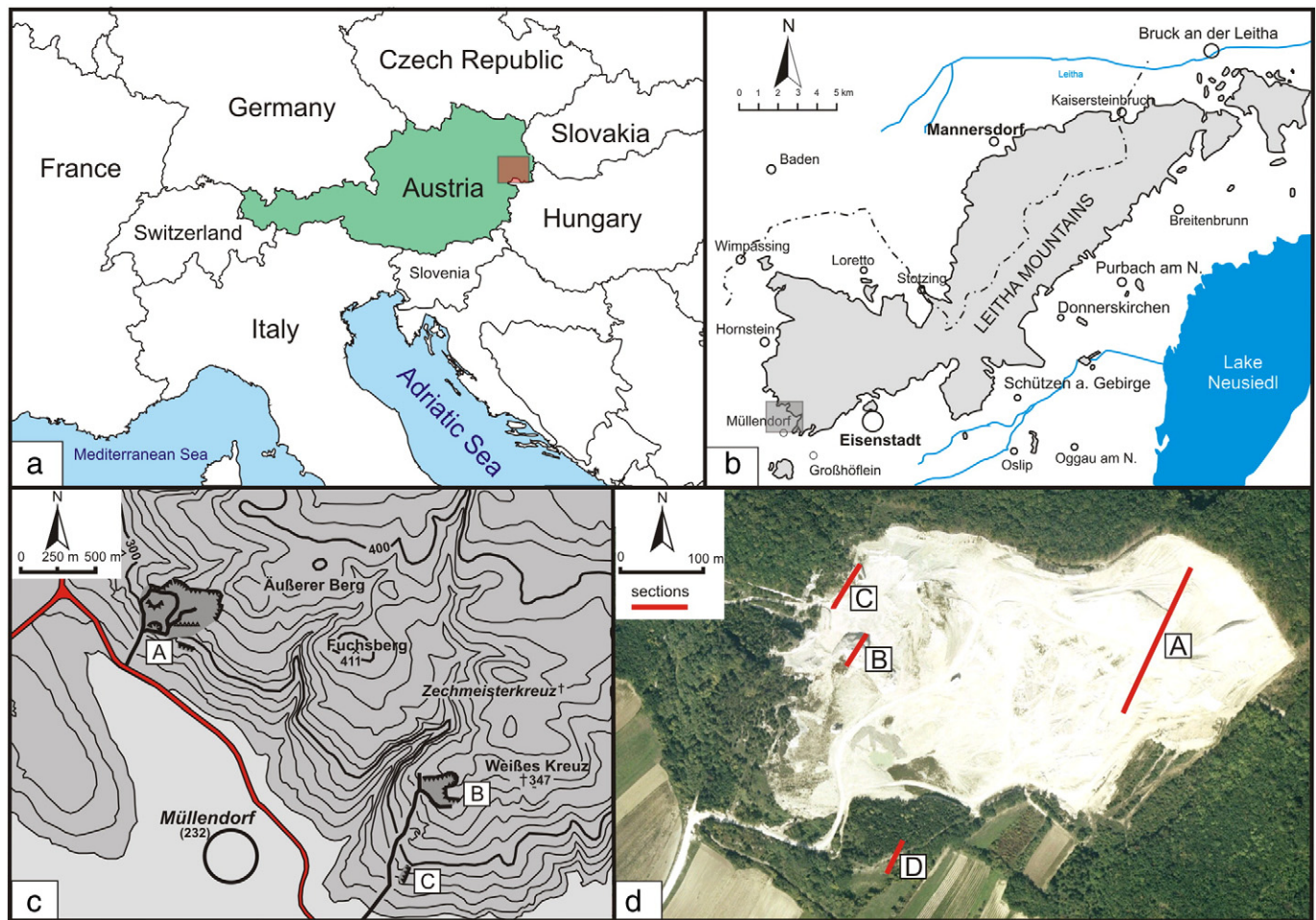


Fig. 1. Location of the studied area. **a** Map of Europe with Austria in the centre. The study area is highlighted with a brown rectangle. **b** Geographic map (inset in **a**) of the Leitha Mountains spanning the border region of Lower Austria and Burgenland provinces. **c** Map with contour lines (metres above sea-level) of the study area. (A) Müllendorf quarry system, (B) Upper Fenk quarry system, (C) Lower Fenk quarry. **d** Satellite image ((C)2010 Google) of the quarry system of the Mühlendorfer Kreidefabrik Margit Hoffmann-Ostenhof GmbH, corresponding to A in **c**. The studied sections are indicated by letters A–D. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Leitha Mountains, these show a soft, chalky appearance, (e.g. Reidl, 1937; Kapouněk, 1938), which is caused by post-depositional diagenetic leaching (Dullo, 1983).

The goal of this study is the reconstruction and recognition of environmental factors and their role in modulating a Langhian ecospace within which facies changes are the expression of altered ecospace utilization. Therefore, the sedimentary successions of the south-western part of the Leitha Mountains enable insights into dynamic near-shore environments of a Central Paratethyan carbonate platform where settlement of the sea-floor by corals or specific bivalve associations was limited to narrow niches. In addition, rhythmic bedding of coral and bivalve accumulations is a characteristic feature of these sediments.

2. Study area

The study area is located at the south-western edge of the Leitha Mountains in the Burgenland province between Hornstein and Großhöflein (Fig. 1b, c). The Leitha Mountains represent a mountain chain spanning ca. 35 km from southwest to northeast with a maximum width of ca. 17 km (Fig. 1b). The Leitha Mountains have a crystalline core dominated by mica schists of the Lower Austroalpine nappe system which is covered by Badenian and Sarmatian limestones (Pascher and Brix, 1994). During the Middle Miocene the Leitha Mountains formed a topographic high or island with extensive carbonate

production, giving rise to a carbonate platform (Tollmann, 1955; Dullo, 1983; Riegl and Piller, 2000; Schmid et al., 2001; Strauss et al., 2006; Harzhauser and Piller, 2010). The investigated sections (A: N47°51'29.65", E16°27'22.62"; B: N47°51'29.48", E16°27'4.87"; C: N47°51'31.38", E16°27'03.34") are located within and in the south (D: N47°51'20.65", E16°27'5.10") in a more basinwards position of the active quarry system (Fig. 1d) of the Mühlendorfer Kreidefabrik Margit Hoffmann-Ostenhof GmbH. Most of the limestones have a soft, light-colored, chalky character and underwent a complex diagenetic pathway. They passed through a freshwater phreatic environment, characterized by undersaturated waters flowing rapidly through the sediment, which allowed a leaching without coeval precipitation (Dullo, 1983). They contain high amounts of fossils with calcitic skeletons such as oysters, pectinids, echinoids and cirripedians (e.g. Suess, 1860; Reidl, 1937; Kroh, 2005) while shells of aragonitic skeletons are dissolved and commonly replaced by calcite (Suess, 1860; Kleemann, 1982; Dullo, 1983). These organisms are preserved as molds or steinkerns. The presence of corals, for example, is only documented as voids or sediment-filled corallites.

3. Materials and methods

This study combines sedimentological and palaeontological data. Four sections have been logged and subjected to detailed investigation and sampling within the study area that has an extension of ca.

500×500 m and exposes an up to 37-m-thick carbonate succession. Abundances of different taxa were obtained semiquantitatively with categories rare, frequent and dominant. Section A (Figs. 1d, 2, 3a–c) is located ca. 320 m to the E of section B (Figs. 1d, 2, 3a), which is sited ca. 50 m to the SE of section C (Figs. 1d, 2, 3a). Section D (Figs. 1d, 2, 3d) is situated outside of the active mining area ca. 300 m in the SSE of section B. For microfacies analyses 79 thin-sections have been prepared, followed by semiquantitative analyses classifying abundances of taxa with categories rare, frequent and dominant. Furthermore, for nanoplankton analyses three samples had been collected as well as three samples from the marly layers of the Upper Fenk quarry and 8 samples from the marl beds of the Lower Fenk quarry (cf. section of Pillar et al., 1996). The carbonate nomenclature follows Dunham (1962) and Embry and Klovan (1971); the classification of siliciclastic sediments is based on Wentworth (1922). The nomenclature of red algae growth forms is based on Woelkerling et al. (1993).

4. Sedimentary facies

The studied limestones are composed of coralline algal rudstones with packstone matrix, containing various biota. In some horizons changing amounts of terrigenous sediment occur.

4.1. Section A

The section (Figs. 1d, 2, 3a–c), starts with platy well-cemented limestones (bed 1) containing few poorly rounded crystalline pebbles. The fauna is represented by the large bivalves *Periglypta miocaenica* and *Spondylus crassicostata* with articulated shells of *Gigantopecten nodosiformis* and regular (*Eucidaris zeamays*) as well as irregular echinoids (*Aliaster cotteauui*, *Clypeaster campanulatus*, *Clypeaster scillae*, *Echinolampas hemisphaericus*, *Schizaster eurynotus*). To the top of bed 1 a fining upward trend concerning the terrigenous material can be observed. In bed 2 crustacean remains are common; to the east shell accumulations of articulated *Gigantopecten nodosiformis* are observed. The amount of quartz fine-sand in bed 3 is higher than in the bed below and increases slightly to the top where encrusting *Porites* (ca. 1 cm thickness) occur. Small rhodoliths are common, occasionally with crystalline pebbles as nuclei. To the east, the bed is characterized by mass occurrences of the bivalves *Isognomon maxillatus* and *Glycymeris deshayesi*. Bed 4, whose base is an erosive surface, starts with a 2-cm-thick marly horizon with pebble sized (\varnothing 0.2–0.5 cm) poorly rounded quartz and mica schists and highly fragmented mollusc shells; to the top articulated shells of *Gigantopecten nodosiformis* occur and the siliciclastic content decreases. Above an outcrop gap of ca. 1.2 m, limestone bed 5 contains few pebble-sized siliciclastics and *Eucidaris zeamays*. Upsection follows a succession of four beds (15–40 cm thickness) starting with accumulations of the bivalve *Hyotissa hyotis* at the base. These oysters are represented by large (15 cm long, 10 cm thick) articulated specimens, occasionally strongly bored by *Lithophaga laevigata*. The *Hyotissa*-horizon at the base of bed 7 can only be followed over ca. 9 m to the south-east. The amount of siliciclastics is low except for bed 9 where a slight increase can be observed to the top. Within bed 6 additionally many *Isognomon maxillatus* occur randomly dispersed while in bed 7 a horizon with debris of the corals *Porites* and *Tarbellastraea reussiana* (bored by the bivalve *Lithophaga laevigata* and settled by pyrgomatid barnacles) is developed. After a gap of ca. 1.6 m, the limestone (bed 10) contains few coarse grained siliciclastics.

Bed 11 starts with a *Hyotissa*-horizon, followed by a horizon of in situ coral colonies (\varnothing 10–30 cm) of branching (branch-diameter ca. 7 mm) *Porites* and few small *Tarbellastraea reussiana* colonies (diameter 4–5 cm). The corals are covered by another horizon of *Hyotissa hyotis*. Directly above this *Hyotissa*-horizon in situ *Tarbellastraea reussiana* colonies (\varnothing 10–30 cm) follow partly settling on the shells. Interspaces

between coral colonies and oysters are filled with coralline algal debris. Molluscs are represented by *Cypraea*, *Periglypta miocaenica* and *Acropsis*. Crystalline components are rare in the lower part, but increase to the top. The base of the following bed (12) is characterized by a 60-cm-thick horizon containing up to 40% poorly rounded and sorted pebble-sized siliciclastics (quartz and mica schist). This distinctive horizon can be followed in the quarry over a distance of ca. 320 m to the west and 60 m to the south-east. Its dipping is estimated with ca. 8° to the west. The echinoids *Parascutella gibbercula*, *Clypeaster campanulatus* and *Clypeaster calabrus* occur in this horizon which is overlain by another *Hyotissa*-horizon. Upsection in bed 12 the siliciclastic content decreases. Again, a *Hyotissa*-horizon is developed ca. 1.8 m from the base. The shells are often affected by *Lithophaga laevigata* borings. Rare thick branched rhodoliths (up to 7 cm in diameter) occur within the bed. Above follows a coralline algal limestone (bed 13) containing many colonies of *Tarbellastraea reussiana* (\varnothing 10–30 cm) and *Acanthastraea horrida* at the base and ca. 1.8 m from the base. The corals are highly affected by *Lithophaga laevigata* borings. At the top rare fragments of thin branching corals, probably *Stylocora exilis*, occur. Siliciclastics are rare in the entire bed. Similar to bed 12, bed 14 starts with coralline algal limestone containing poorly sorted siliciclastics (up to fine-gravel) in the lower 60 cm. Rhodoliths (\varnothing 2 cm) occur, often containing subrounded mica schist pebbles as nuclei. The siliciclastics show a fining upward trend (2–3 cm at the base, 5 mm at the top). The amount within the bed fluctuates: 10% (base), <5% (middle), 10% (top). In the upper part of the bed molluscs are very common, represented by many lucinids (e.g. *Codakia*), *Hyotissa hyotis*, double valved *Cardites partschi*, *Megacardita* and *Gouldia*, venerids and rare *Isognomon maxillatus*. A platy poritid colony (60 cm wide, 8 cm thick) occurs associated with the molluscs. Limestones directly above the coral colony are enriched in quartz fine-sand. Just below the top of the bed a *Hyotissa*-coquina including rare *Ostrea lamellosa* is developed. The following bed (15) again shows a high amount (60%) of siliciclastics at the base (poorly sorted pebble to cobble sized). Rhodoliths (\varnothing 2–3 cm) are common, occasionally with mica schist pebbles as nuclei. The siliciclastic content decreases to ca. 5% at the top. Molluscs such as *Conus*, *Xenophora*, *Periglypta miocaenica* and *Pinna tetragona* commonly occur while highly fragmented *Porites* branches are rare.

The topmost bed (Bed 16; Fig. 2) shows fluctuations from 1% to 5% in siliciclastic content. In the lower part *Gigantopecten nodosiformis* commonly occurs together with *Periglypta miocaenica*. The rare echinoids are represented by *Clypeaster scillae* and *Parascutella gibbercula*. Sphaeroidal rhodoliths (\varnothing 5–10 cm) are abundant in the entire bed. They are enriched in a horizon ca. 5.5 m above the base. Above the rhodolith horizon the siliciclastic content decreases to zero to the top.

4.2. Section B

Section B (Figs. 1d, 2, 3a) is dominated by a succession of well cemented limestones. The section starts with calcareous pebble-sized gravels (bed 1) characterized by a high content of limonite, followed by a coralline algal limestone (bed 2) with rhodoliths (\varnothing 2–3 cm) containing mica schist pebbles as nuclei. Single *Clypeaster campanulatus*, *Parascutella gibbercula* and *Clypeaster calabrus* occur. Bed 3 is characterized by a *Hyotissa*-horizon at the base and shell-accumulations ca. 40 cm above. *Acanthastraea horrida* colonies (\varnothing 10 cm) occur isolated, as well as fragments of *Tarbellastraea reussiana* (\varnothing <10 cm). At the base of bed 4, a densely packed *Hyotissa*-bed of ca. 10 cm thickness is developed; the oysters are usually double valved. In situ coral colonies (*Tarbellastraea* and *Porites*, \varnothing 10–30 cm) occur in two horizons. Ca. 1 m above the base a horizon with double valved *Hyotissa hyotis* is developed. The gastropod *Cheilea equestris* commonly occurs in the bed. Bed 5 again starts with a *Hyotissa*-horizon, whose shells are often bored by *Lithophaga laevigata*. Nodular bryozoans (\varnothing 1.5 cm) are enriched directly above the *Hyotissa*-horizon. The following horizon commonly contains in situ *Tarbellastraea*-colonies which are highly

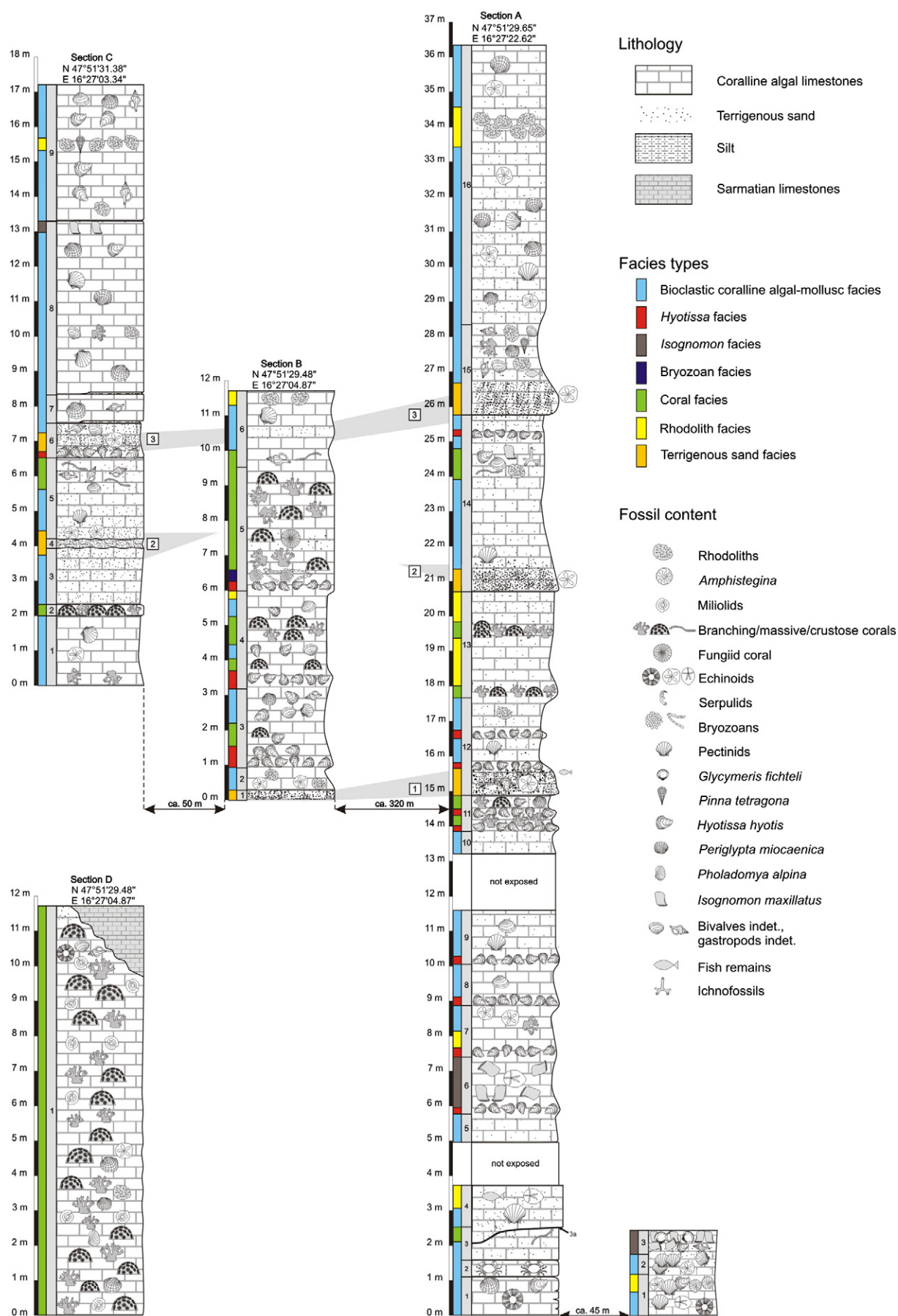


Fig. 2. Lithologic columns of sections A–D including sample numbers and GPS coordinates. Colors represent facies types. Three siliciclastic horizons (numbers in square boxes) are used for section correlation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

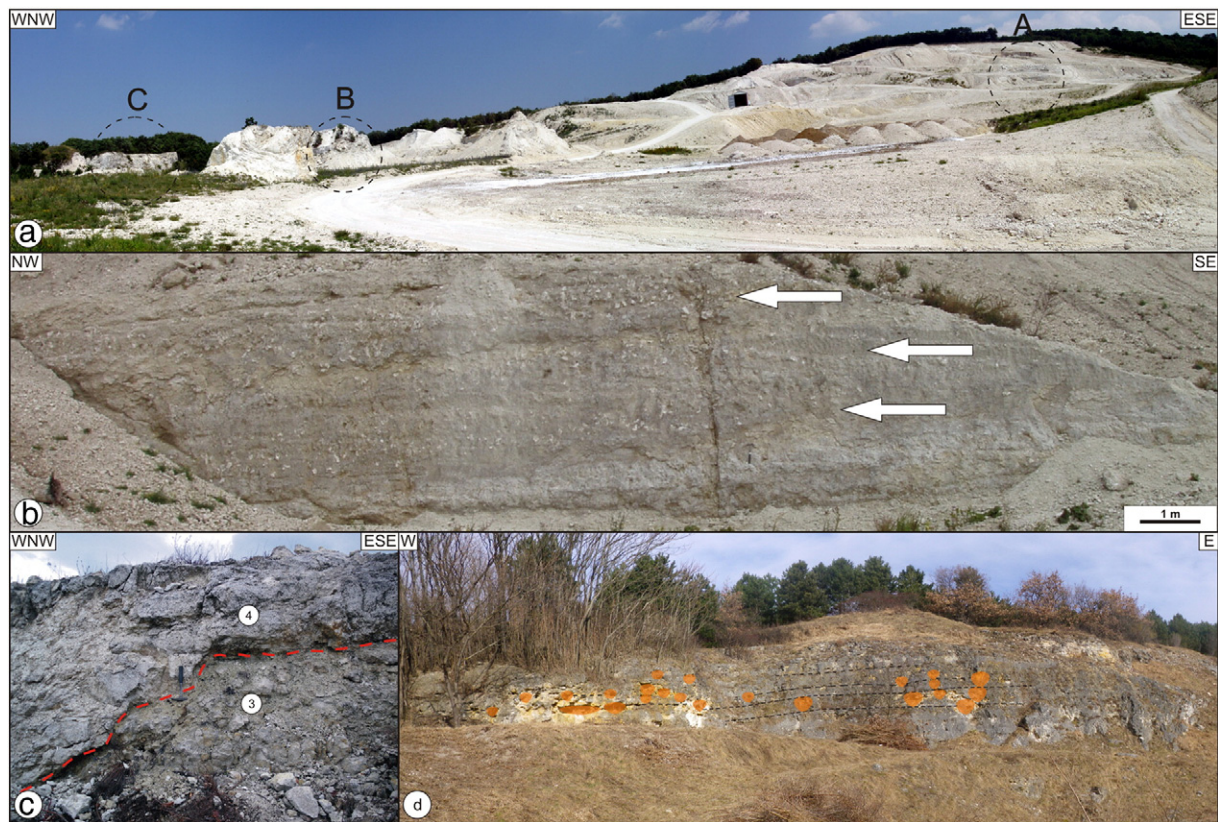


Fig. 3. Phototranssects of the Müllendorf quarries with geographic orientations. Positions of the sections are indicated in Fig. 1d. **a** Panorama of the active Müllendorf quarry system, display window from the WNW to the ESE ca. 280 m. Stippled circles mark sections A–C. **b** Beds 6–9 of section A. White arrows: *Hyotissa*-horizons. **c** Lower part of section A. The stippled red line traces the unconformable contact between bed 3 and 4. **d** Section D (ca. 30 m in longitudinal extension) showing indistinct bedding indicated with stippled lines. Orange: coral colonies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

affected by *Lithophaga laevigata* and cirripeds, less commonly by *Gastrochaena dubia*. *Porites* and *Acanthastrea horrida* are common too. A fungiid coral with a corallite diameter of ca. 17×16 cm could be detected in this horizon, where quartz fine-sand locally occurs in low amounts. The section terminates with bed 6 which contains common mollusc fragments of *Gigantopecten nodosiformis* and ostreids and steinkerns of gastropods. A horizon containing quartz fine-sand and rare mica schist pebbles (3–4 mm) is developed in the middle of the bed. Small rhodoliths (\varnothing 1 cm) are common at the top.

4.3. Section C

The lowest bed (Fig. 2) is characterized by *Porites* debris at its base while molluscs are common upsection. The following bed (2) is dominated by colonies (\varnothing 20–30 cm) of *Tarbellastraera reussiana* (affected by *Lithophaga laevigata* and settled by pyrgomatid barnacles). Bed 3 contains rare *Amphistegina* and the amount of siliciclastics increases from ca. 5% directly above the corals to ca. 20% towards the top. The bed is terminated by poorly sorted terrigenous coarse sand to fine-gravel (bed 4) containing echinoid remains. The following bed (5) is characterized by common *Echinolampas manzonii* at the base. It is overlain by a horizon with common steinkerns of gastropods (*Xenophora*, *Conus*, *Cassis*) and a subsequent horizon with crustose *Porites*. It is covered by coralline algal limestone containing quartz fine-sand. Bed 6 starts with a horizon of *Hyotissa hyotis* and *Ostrea lamellosa* followed by a limestone containing ca. 30% siliciclastics. The content of coarse siliciclastics decreases to the top, where residual clay is developed. Bed 7 contains common *Periglypta miocaenica* and small gastropod steinkerns (2–4 mm) and is again covered by residual clay.

Bed 8 (Fig. 2) starts with a limestone containing commonly *Periglypta miocaenica* and *Gigantopecten nodosiformis*. A horizon with *Porites* debris is developed ca. 1.7 m from the base. Above this horizon, shells of *Isognomon maxillatus* are common; they are found in situ (double valved) at the top. The bed terminates with a thin layer of residual clay. The top of the section (bed 9) is characterized by common small gastropod steinkerns and shell debris of ostreids. 2.1 m from the base rare *Pinna tetragona* occur in situ together with common large globular rhodoliths (\varnothing 4–7 cm).

4.4. Section D

Section D (Figs. 1d, 2, 3d) consists of massive coralline algal limestones which contain many in situ coral colonies of *Porites* (\varnothing 10–50 cm), *Tarbellastraera reussiana* (\varnothing 10–20 cm), and *Acanthastrea horrida* (\varnothing 10 cm) which are rarely affected by *Lithophaga laevigata*. The space between coral colonies is filled with coralline algal debris and often diffusely bedded (dipping 076/07). The molluscs *Periglypta miocaenica* and *Haliotis* are common within these fine-grained limestones which contain common miliolids (*Spiroloculina*, *Triloculina*) and alveolinids (*Borelis*). Remains of pycnodont oysters and steinkerns of small venerids and gastropods are common as well. Upsection interspaces between coral colonies are commonly filled with *Porites*-rubble. At the top of the section bioclastic grainstones (debris of bivalves, gastropods and echinoids) are developed and the amount of coral colonies (10–15 cm diameter) decreases. Globular rhodoliths occur in the entire bed. The top of the bed is characterized by low amounts of quartz middle- to fine-sand. The uppermost part of the section is unconformably covered by a Sarmatian limestone. It consists of a poorly cemented, well bedded coralline algal rudstone (thickness 6 m) of well rounded and well

sorted coralline algal debris with common quartz grains (5–7 mm diameter).

5. Stratigraphy

Stratigraphic correlation and dating of the coralline algal limestones of the south-western edge of the Leitha Mountains (Fenk and Müllendorf quarries) were based on foraminiferal assemblages. The foraminiferal fauna was first interpreted to correspond to the Upper Lagenidae Zone to *Bulimina–Bolivina* Zone of the regional ecozones (Papp and Turnovsky, 1953; Tollmann, 1955). Later, Steininger and Papp (1978) mentioned a correlation with the *Bulimina–Bolivina* Zone for the Fenk quarry based on uvigerinids. Whilst the later zone would indicate a late Badenian age and a correlation with nanoplankton zone NN6 (Hohenegger and Wagreich, 2012), the original dating could also indicate a middle Badenian age and a correlation with NN5. Herein, a calcareous nanoplankton assemblage from a marly interlayer of the Lower Fenk quarry (N 47°50′33.96″, E 16°28′22.58″) was analysed. The assemblage contains *Sphenolithus heteromorphus*, *Calcidiscus leptoporus*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Geminitella rotula*, *Helicosphaera carteri*, *Pontosphaera multipora*, *Reticulofenestra gelida*, *Reticulofenestra pseudumbilicus*, *Sphenolithus moriformis* and *Thoracosphaera saeae*.

The presence of *Sphenolithus heteromorphus* indicates nanoplankton zone NN5 according to Martini (1971) and Young (1998) and excludes a correlation with the *Bulimina–Bolivina* Zone. Additionally, the absence of *Helicosphaera waltrans* excludes the Lower Lagenidae Zone. Therefore, the sediments can be correlated to the Upper Lagenidae and *Spiroplectammina* zones (Fig. 4). The thin-bedded limestone-marl sequence of the Lower Fenk quarry represents time-equivalent “basinal” deposits of the Upper Fenk quarry (Piller et al., 1992). Furthermore a time-equivalent development of both locations, the Upper Fenk quarry and the Müllendorf quarries, is very likely as both limestone successions show similar facies successions (Piller and Vavra, 1991) and are situated at the same topographic level (Pascher and Brix, 1994).

6. Facies analysis and interpretation

Combining the results of field observations and microfacies analyses, seven facies types can be distinguished.

6.1. Bioclastic coralline algal–mollusc facies

The sediment (Fig. 5d) comprises coralline algal rudstones and floatstones with packstone matrix. The facies is marked by high amounts of bivalves and gastropods. Aragonitic shells are completely dissolved and preserved as imprints or steinkerns. Bivalves are represented by very common *Hyotissa hyotis*, common *Gigantopecten nodosiformis*, *Periglypta miocaenica*, *Glycymeris deshayesi*, common *Ostrea lamellosa*, *Spondylus crassicastra*, rare *Pinna tetragona* and cardids and very rare *Pholadomya alpina*. They are usually articulated and randomly distributed within the beds. *Gigantopecten nodosiformis* are often settled by balanids. Gastropods are represented by *Conus*, *Cheilea equestris*, *Cypraea*, *Xenophora* and *Turritellidae*. Locally (section A, beds 3, 7 and 15; section C, beds 1 and 8), coral debris can be found. *Clypeaster campanulatus*, *Clypeaster calabrus*, *Eucidaris zeamays* and *Parascutella gibbercula* are present. The foraminiferal fauna consists of common biserial textulariids, rare miliolids (*Triloculina*) and alveolinids (*Borelis*) and very rare *Amphistegina*. Celleporiform bryozoans occur in low amounts. The facies is characterized by common bioturbation. Siliciclastics occur in variable amounts within the beds. The facies is represented in section A (beds 1–5, 7–10, 12, 14–16), section B (beds 2–4, 6) and section C (beds 1, 3, 5–9).

Interpretation – The facies is similar to the mollusc subfacies of Wiedl et al. (2012). The common occurrence of *Gigantopecten nodosiformis* is typical for this facies. This bivalve preferentially settled on bioclastic carbonate platforms (Bongrain, 1988) which are occasionally characterized by increased siliciclastic content (Mandic and Piller, 2001). The mineralization of its shells correlates with high metabolic costs and implies favourable climate conditions (Grecian et al., 2000). Comparable to the mentioned mollusc associations are samples from

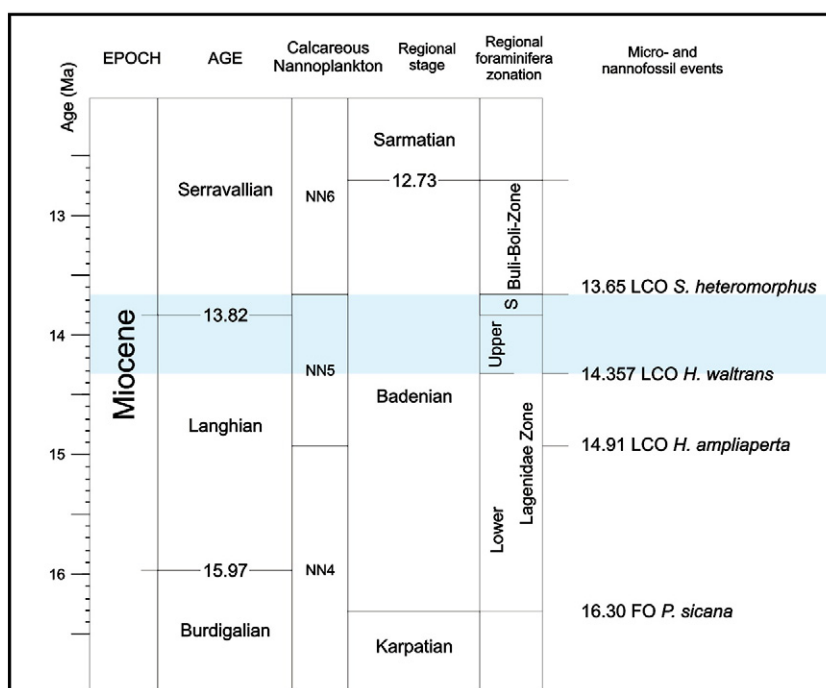


Fig. 4. Stratigraphic chart (modified after Hohenegger and Wagreich, 2012) with focus on Badenian geochronology and biozonations of calcareous nanoplankton and Central Paratethyan foraminifera zonations (S: *Spiroplectammina* Zone, Buli-Boli: *Bulimina–Bolivina* Zone). The studied sections are located within nanoplankton zone NN5 (highlighted in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the modern Red Sea (Zuschin and Hohenegger, 1998; Zuschin et al., 2009; Janssen et al., 2011). The apparent dominance of oysters and pectinids is caused by leaching processes which led to these accumulations (Dullo, 1983). *Eucidaris zeamays* is common; extant species of *Eucidaris* are abundant from the intertidal down to 20–30 m (Kier and Grant, 1965; Nebelsick, 1992; Hickman, 1998; Kroh, 2003 and references therein) which fits to the proposed water depth of Wiedl et al. (2012) for the mollusc subfacies.

6.2. *Hyotissa* facies

The *Hyotissa* facies (Fig. 5a, b) is exposed in sections A, B and C and is characterized by coralline algal rudstones or packstones with common occurrences of *Hyotissa hyotis*. They are accumulated in horizons of 10 to 40 cm thickness and show, especially within beds 5–9 of section A, repeated occurrences after 1–1.5 m; locally the shells are densely packed. Coarse siliciclastics are rare. Specimens of *Hyotissa* reach dimensions of more than 25 cm length with a shell thickness of more than 10 cm; often they are articulated and in life position. *Hyotissa* shells are frequently bored by *Lithophaga laevigata* (Fig. 5b) or clonid sponges. Specimens of *Hyotissa* < 5 cm are extremely rare. The *Hyotissa* facies, represented in sections A (beds 6–9, 10–12 and 14), B (beds 3–5), and C (bed 6) is predominantly adjacent to the bioclastic coralline algal-mollusc facies.

Interpretation — Gryphaeids are marine and estuarine suspension feeders which are cemented to hard subtidal substrata like rocks or dead corals, generally not being gregarious or reef-forming (Zuschin and Piller, 1997; Slack-Smith, 1998; Bieler et al., 2004; Mikkelsen and Bieler, 2008). The genus *Hyotissa*, commonly associated with corals, is strictly eu- and stenohaline and also stenotherm (Stenzel, 1971). *Hyotissa hyotis* often occurs in subtidal waters down to 30 m (Bieler et al., 2004; Mikkelsen and Bieler, 2008) but dense populations of *Hyotissa*-species commonly occur free lying on the substratum, under intertidal rocks and are commonly attached to dead and degraded coral colonies (Slack-Smith, 1998; Zuschin and Baal, 2007) in water depth < 10 m (e.g. Titschack et al., 2010). The geographical extension of extant *Hyotissa hyotis* covers tropical and subtropical waters of the Indo-Pacific (Slack-Smith, 1998; Zuschin and Oliver, 2003; Zuschin and Baal, 2007) and it occurs as neozoon in the Florida Keys (Bieler et al., 2004). High suspension load is very likely the reason for gigantism (up to 30 × 20 cm in dimension) of the specimens in Müllendorf; such phenomena have been observed in recent *Hyotissa hyotis* in the Red Sea where a change in suspension load in the water column induces shifts in bivalve assemblages (Zuschin and Piller, 1997). Furthermore, pioneer assemblages in eutrophic environments are characterized of oysters (as *Hyotissa*) and *Isognomon* (Hendry et al., 2001; Minchinton and McKenzie, 2008; Reuter and Piller, 2011). Similar fossil occurrences of *Hyotissa hyotis* are described from Neogene limestones of the South Florida Platform (Scott, 2001; Missimer, 2002), southwestern Turkey (İslamoğlu and Hakymez, 2010) and at Gebel Gharra in Egypt (Mandic and Piller, 2001) where — in the two latter cases — *Hyotissa hyotis* is associated with corals too.

Hyotissa-accumulations within the coralline algal limestones of Müllendorf have biostromal characteristics, composed of shells of almost the same size of which up to 60% are in place. Shell-displacement is very likely caused by water energy. Although *Hyotissa* occurs as well in other localities of the Leitha Mountains (Wiedl et al., 2012), frequent *Lithophaga*-borings in oysters are only reported from the Müllendorf quarry (Reidl, 1937; Kleemann, 1982). This may be caused by eutrophication of the waters which often stimulates bioerosion by date mussels (Highsmith, 1980). The *Hyotissa* facies is usually adjacent to the bioclastic coralline algal-mollusc facies, which very likely represents a deeper setting (see discussion below). The periodic occurrences of *Hyotissa*-horizons in Müllendorf rather point to high

population densities due to increased nutrients than to low sedimentation rates.

6.3. *Isognomon* facies

The facies (Fig. 5c) is characterized by the common occurrence of articulated shells of *Isognomon maxillatus* (ca. 10 cm in length), which form distinct coquinas within coralline algal rudstones with packstone matrix. They are usually preserved as steinkerns but occasionally remains of the calcitic shell are preserved. *Isognomon maxillatus* is associated with *Glycymeris deshayesi*. Coral debris (*Porites*) occurs as well. *Acervulina*-coralline algal macroids (Ø 0.5–1 cm) are common, as well as small gastropods and celaporiform bryozoans. The amount of siliciclastics is low in this facies. The rare and poorly preserved foraminifers are represented by textulariids and rotraliids. The facies is developed in sections A (bed 3 and 6) and C (top of bed 8) and associated with the bioclastic coralline algal-mollusc facies and *Hyotissa* facies.

Interpretation — *Isognomonidae* are typical shallow-water thermophilic epibionts (Yonge, 1968; Harzhauser et al., 2003). Modern *Isognomon* live in shallow water areas (Wilbur, 1983), even intertidally (Wilk and Bieler, 2009), and settle preferentially along submarine cliffs, on mangroves or even on mudflats (Whorff et al., 1995; Mikkelsen and Bieler, 2008; Printragoon and Tëmkin, 2008; Printragoon et al., 2008). Its occurrence within the Upper Fenk quarry is interpreted to indicate a shallow subtidal area with 1–5 m depth range (Riegl and Piller, 2000). *Isognomon* is interpreted as part of a pioneer assemblage in eutrophic habitats (Hendry et al., 2001; Minchinton and McKenzie, 2008; Reuter and Piller, 2011). The high amount of articulated shells, often in life position, indicates that these concentrations are autochthonous (Fürsich et al., 2009). Similar deposits in Spain, consisting of coralline algal-rhodolith rudstones together with *Isognomon*, had been interpreted as low-relief rocky shore deposits of the coastal belt (Braga et al., 2006). Suspension feeding *Isognomon* very likely benefited from nutrients and acted as pioneers in settlement of a shallow sea-floor with coralline algal sands similar to *Hyotissa*.

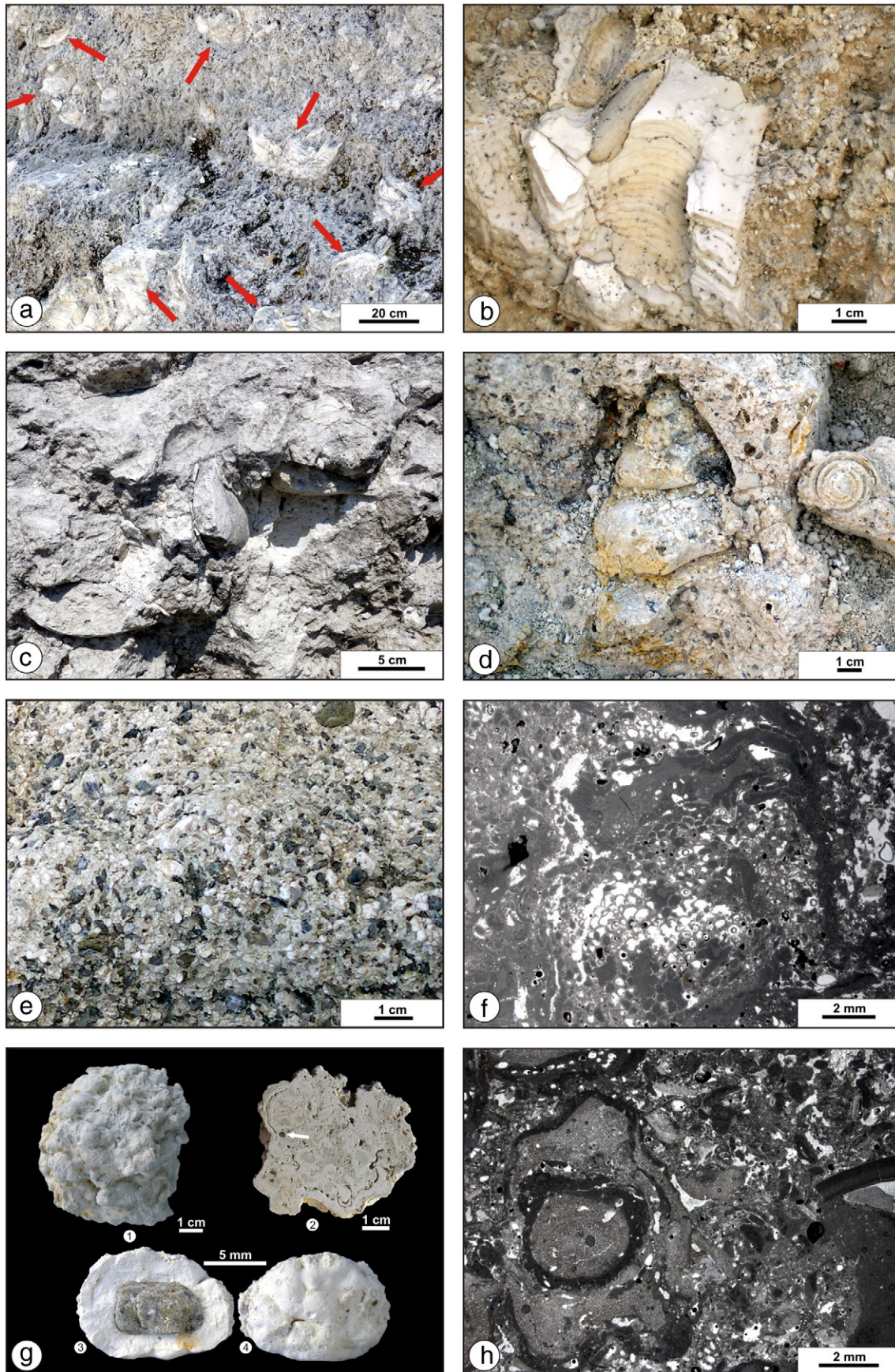
6.4. Bryozoan facies

The bryozoan facies (Fig. 5f) consists of densely packed poorly sorted coralline algal rudstones. They are dominated by debris of thin encrusting and fruticose coralline algae. Bryoliths (Ø 1.5 cm) occur in high amounts. Echinoid remains are rare, as well as molluscs except for oysters. Quartz (< 1 mm) is rare as are foraminifers. The facies is developed in section B (lower part of bed 5) and associated with the *Hyotissa* facies and the coral facies.

Interpretation — A similar facies (bryozoan subfacies) has been reported by Wiedl et al. (2012) from the Mannersdorf quarries. In contrast to the latter, foraminifers are subordinate and branched bryozoans are missing. In Müllendorf the facies is overlain by the coral facies. Coexistence of coral- and bryozoan-bearing assemblages was explained by variations in the productivity of surface waters (Moissette et al., 2007). A slightly deeper water depth, however, similar to the adjacent facies types, is very likely for this facies in Müllendorf as modern analogues are documented for the Apulian shelf along the shore in ca. 10–30 m water depth (Toscano and Sorgente, 2002). Increased nutrient levels probably lead to this heterotrophic-rich association in a lower water depth.

6.5. Rhodolith facies

This facies (Fig. 5g, h) is represented by coralline algal rudstones with packstone matrix containing sub-spheroidal laminar rhodoliths with diameters between 2 and 3 cm (sections B and C), sphaeroidal thin-branched rhodoliths between 5 and 10 cm (section A) and sphaeroidal laminar rhodoliths between 5 and 7 cm (section C). It



also contains *Acervulina*-coralline algal macroids with diameters of 0.5–3 cm (mostly > 2 cm). Interspaces between rhodoliths and macroids are filled with coralline algal debris. Fruticose and encrusting growth forms dominate coralline algae but thin encrusting growth forms are also common. Foraminifers are represented by rotaliids (*Amphistegina* and *Ammonia*), biserial textulariids and rare miliolids. Bryozoans are rare and commonly encrusted by coralline algae. The facies is represented in section A (beds 1, 4, 7, 13, 16) and section B (beds 4, 6) and section C (bed 9).

Interpretation — The facies has similarities with the rhodolite facies and the *Acervulina*-rhodolith subfacies described by Wiedl et al. (2012) from the north-eastern part of the Leitha Mountains. These authors indicated water depths of 10–20 m for the mentioned facies types, a similar water depth can be therefore assumed for this facies in Müllendorf.

6.6. Coral facies

Corals are represented by common in situ massive *Tarbellastra* *reussiana* and *Acanthastraea horrida* as well as bushy *Porites* colonies which are embedded in coralline algal rudstones with packstone matrix (Fig. 6a–d) dominated by fruticose growth forms. *Stylocora exilis* occurs very rare. One specimen of a large fungiid coral was detected (Fig. 6b). In sections A and B platy and encrusting poritids occur in association with coralline algae dominated by thin encrusting growth forms. The corals (in particular *Tarbellastra*) are bored by *Lithophaga laevigata* (Fig. 6c) and *Gastrochaena dubia*. Bivalves are represented by common Lucinidae (as *Codakia*), double valved *Cardites partschi*, *Megacardita*, *Gouldia*, venerids, *Hytissa hyotis*, *Acropsis*, rare *Periglypta miocaenica* and very rare *Isognomon maxillatus*. Gastropods are represented by *Cheila equestris*, *Cypraea*, *Haliotis* and *Turritellidae*. Occasionally, the corals settle on *Hytissa* shells and vice versa (Fig. 6d). Echinoid fragments are common. *Acervulina* occurs in low amounts encrusting fragments of *Porites*. Other foraminifers are rare except in section D where high amounts of miliolid foraminifers (*Spiroloculina*, *Triloculina*) occur, as well as biserial textulariids, rotaliids (*Elphidium*) and alveolinids (*Borelis*). *Thalassinoides* burrows (Ø 1–2 cm) are common. Locally quartz fine-sand is enriched; up to pebble-sized siliciclastics are rare. This facies is developed in section A (beds 3, 11, 13, 14), B (beds 3–6), C (beds 2, 5) and D (bed 1) and is associated with the bioclastic coralline algal-mollusc facies, the *Hytissa* facies, the bryozoan facies and the terrigenous sand facies.

Interpretation — The facies has similarities to coral interval 3 (sand with massive corals, dominated by *Tarbellastra reussiana*) and coral interval 5 (sand with occasional corals, few *Porites* branches) of Riegl and Piller (2000) described from the Upper Fenk quarry. In section B the facies follows directly above the bryozoan facies, similar to coral interval 5. The corals of interval 5 are interpreted as vestiges of a sparse *Porites* community on a subtidal soft- or firmground, similar to interval 3 of Riegl and Piller (2000), which represents unstable sandy substrata with individual massive coral colonies. Horizons with oyster-coral associations (section A, bed 11; section B, bed 3) are similar to coral interval 7 (oysterbeds and *Isognomon* alternating with branching corals) of Riegl and Piller (2000). Coral interval 7 has been interpreted as sparse-to-dense non-framebuilding coral community (sensu Geister, 1983) in a shallow subtidal environment

alternating with patchy bivalves (Riegl and Piller, 2000). The coral facies has also similarities with the Badenian coral facies of the Ukraine (Radwański et al., 2006).

Faviids and poritids are sediment-resistant corals which have advantages in areas of high re-suspension and re-settlement after stormy conditions (Riegl, 1999). Sediment resistance of a coral is mainly determined by growth form and polypar width (Sanders and Baron-Szabo, 2005). While large-polyped corals effectively reject sediment up to fine-gravel size, small-polyped species are more effective in rejection of clay to silt (Bak and Elgershuizen, 1976). Recent Australian *Acanthastraea echinata* show better sediment-rejection rates than poritids and also fungiids are very efficient at cleaning their surfaces (e.g. Hubbard and Pocock, 1972; Stafford-Smith, 1993). Contrary to the Upper Fenk quarry, where *Acanthastraea horrida* is subordinate (Riegl and Piller, 2000), in the Müllendorf area, *Acanthastraea horrida* is very common and probably could better compete with small-polyped corals due to its higher resistance to coarse sediments and smothering. A similar scenario is described for ecological successions of *Porites* and *Tarbellastra* of Tortonian reefs in Spain showing that *Porites* was able to colonize areas of soft substrate with fine siliciclastic load and also prepares the ground for succeeding *Tarbellastra* (Martin et al., 1989).

Langhian and Serravallian representatives of *Acanthastraea* in the Gulf of Suez did not occur at depths shallower than 5 m and had been the dominant corals around 10 m; poritids dominated (branching and columnar shallower than massive and domal) in 2.5–6 m and faviids showed their preferential occurrence in the shallowest habitats (Perrin, 2000).

Encrusting growth of corals, observed in sections A–C, is commonly a response to environmental conditions (Riegl and Piller, 2000) and flattening of coral colonies often indicates a decrease in light intensity (Titlyanov and Latypov, 1991) usually caused by high water turbidity. This was probably also the case in the upper part of bed 14 of section A and in bed 5 of section C, which show increased siliciclastic content and the presence of encrusting corals.

High affection of coral colonies by date mussels often goes along with eutrophication of the waters (Highsmith, 1980) and the nutrient supply for this assemblage of Müllendorf was probably favoured by currents (Kleemann, 1982; Piller and Kleemann, 1991). Most boring organisms are suspension feeders, however, extensive rates of sedimentation are detrimental to organism survival (Perry, 1996), and for example *Lithophaga* is intolerant to even minor amounts of sediment (Bromley and Asgaard, 1993). Other authors suppose that the infestation by bioeroders remains at comparable levels to that found in adjacent clear-water environments (Perry and Macdonald, 2002; Macdonald and Perry, 2003).

The foraminiferal-rich limestones of section D, located in a more basinward position related to the other sections, are characterized by a high density of corals. Due to this fact, the section had been interpreted as reef (Schaffer, 1908; Kapounek, 1935; Reidl, 1937; Kapounek, 1938; Tollmann, 1955) ignoring the fact that the coral colonies are usually isolated within a bedded coralline algal matrix and do not show a frame-building character. The development of grainstone matrices points to increased water energy (Flügel, 2004). Therefore the coral facies at this particular location had been developed in a distal, slightly deeper environment, influenced by increased water energy and hardly affected by terrigenous influx or increased

Fig. 5. a–h *Hytissa* facies. **a** Arrows indicate *Hytissa hyotis* shells within a coralline algal rudstone (section B, base of bed 3). **b** The calcitic shell of *Hytissa hyotis* bored by two *Lithophaga laevigata* (section A, bed 7). **c** *Isognomon* facies. Shell-accumulation of *Isognomon maxillatus* represented as steinkerns and shell remains; commonly the bivalves are in life position (section A, bed 3). **d** Bioclastic coralline algal-mollusc facies. Steinkerns of *Xenophora* and *Conus* within a coralline algal rudstone; the shells are completely dissolved (section C, bed 5). **e** Terrigenous sand facies (section A, bed 12). Coralline algal rudstone with poorly rounded pebble sized mica schists and quartz. **f** Bryozoan facies. Celleporiform bryozoans partly encrusted by red algae (section B, bed 5). **g–h** Rhodolith facies. **g** 1–2 Large sized rhodolith (Rh2): 1 Sphaeroidal laminar rhodolith (section C, bed 9) 2 Section through a sphaeroidal laminar rhodolith (section C, bed 9) binding mica schist grains (white arrow). 3–4 Small sized sub-sphaeroidal laminar rhodoliths of the terrigenous sand facies with a mica schist pebble as nucleus (Rh1, section C, bed 4). **h** *Acervulina*-coralline algal macroid within a coralline algal rudstone (section A, bed 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

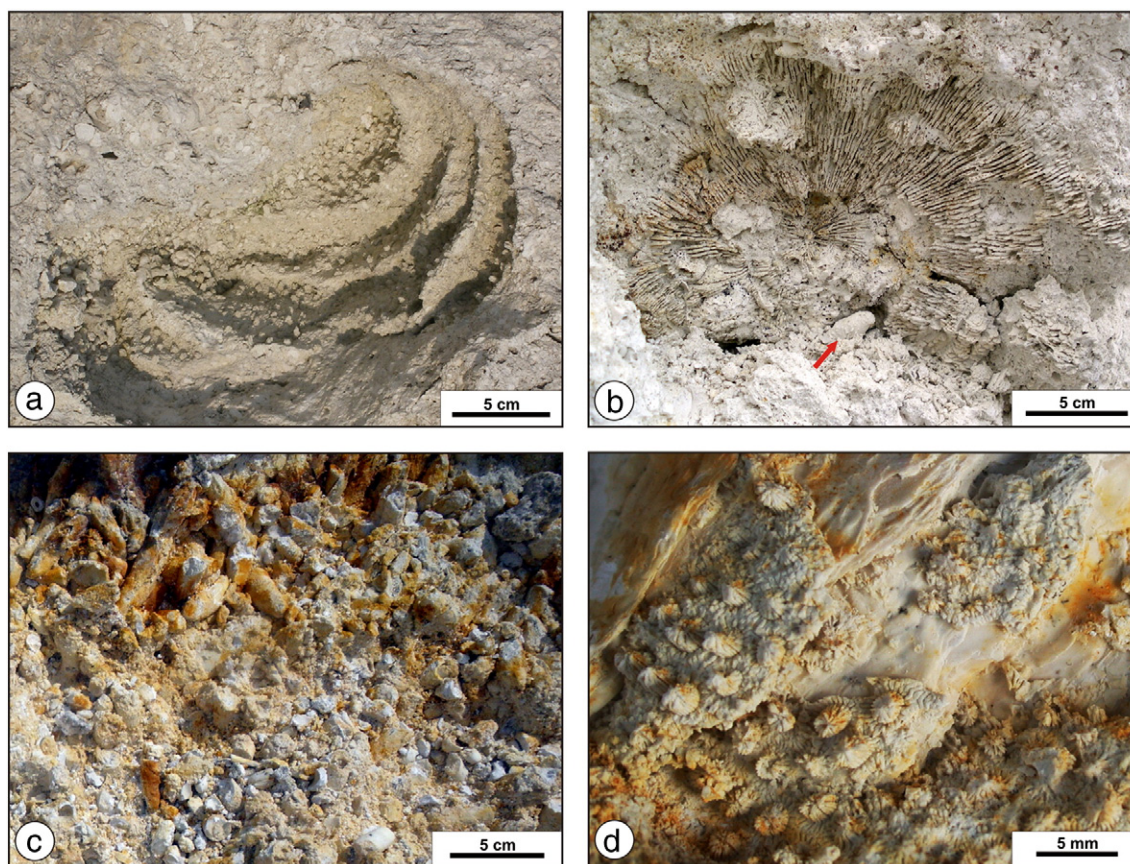


Fig. 6. a–d Coral facies. **a** Negative of a dissolved colony of *Tarbellastraea reussiana* with growth lines (section B, bed 3). **b** Negative of a dissolved fungiid coral (section B, bed 5) affected by *Lithophaga laevigata* (arrow). **c** Colonies of *Tarbellastraea reussiana* and *Porites* are often almost beyond recognition due to massive infestation of *Lithophaga laevigata* (section B, bed 5). **d** Coral–oyster association. Infillings of *Tarbellastraea reussiana* corallites on the surface of a *Hyotissa hyotis* shell (section A, bed 11).

nutrient levels. Summing up, the coral facies in general reflects a shallow subtidal habitat with moderate water energy and nutrient load in a water depth of ca. 5–10 m.

6.7. Terrigenous sand facies

The terrigenous sand facies (Fig. 5e) comprises three distinct beds dominated by subrounded poorly sorted breccias up to cobble sized mica schists or fine-sands with low amounts of coralline algae or coralline algal limestones with a siliciclastic content >20%. Commonly small rhodoliths (Ø 2 cm) occur with lithic nuclei. Echinoids are the predominant larger faunal elements, represented by *Parascutella gibbercula*, *Clypeaster campanulatus*, *Clypeaster calabrus* and *Echinolampas hemisphaericus*. The rare mollusc fauna consists of oyster debris. In thin sections coralline algal debris is characterized by fruticose and thin encrusting growth forms. Foraminifera are rare, locally, however, *Borelis* and textulariids are common. The facies is represented in sections A (beds 12, 14, 15), B (bed 1) and C (beds 4, 6) and is associated with the coral facies, the *Hyotissa* facies and bioclastic coralline algal-mollusc facies.

Interpretation – Poor sorting and subrounding of the lithic components of the terrigenous sand facies indicate a short transport. Echinoids are the dominant faunal elements. The common presence of the large sand dollars *Parascutella* and sea biscuits *Clypeaster* in the Caribbean is linked with mobile sand bottoms where seagrass and filamentous algae are rare or absent (Hendler et al., 1995). The facies is interpreted as the onset of a transgressive pulse after a relative sea-level lowstand, leading to increased reworking of terrestrial material.

7. Discussion

The depositional environment of Müllendorf reflects an ecospace along a gently sloping coralline algal-dominated carbonate platform. Recurrent coral (*Tarbellastraea reussiana*, *Acanthastraea horrida*, *Porites* and *Stylocora exilis*) and mollusc biostromes (*Hyotissa hyotis*, *Isognomon maxillatus*) are indicative for shallow subtidal, tropical environments. The limestones are clearly dominated by a coralline algal facies characterized by heterogeneous mollusc assemblages (bioclastic coralline algal-mollusc facies). Coral-rich horizons or monospecific bivalve accumulations (*Hyotissa*, *Isognomon*) are locally present. The occurrence of corals throughout the successions indicates persistence in ecological parameters within the ecospace as corals are sensitive to changes in temperature, sea-water chemistry or light (e.g. Roberts et al., 1982; Kleypas et al., 1999b; Marubini and Atkinson, 1999; Bergman et al., 2010). Intercalated horizons with terrigenics are interpreted as result of transgressive pulses, expressed in three distinct horizons.

7.1. Ecospace modulation – variation under different set-ups

Environmental factors such as light, temperature, nutrients and depth determine the range of organisms and communities within an ecospace (Brenchley and Harper, 1998). For instance, the dominance of coralline algae over corals in tropical environments has been explained as triggered by enhanced trophic resources (Johansen, 1981; Littler and Littler, 1984; Halfar and Mutti, 2005). As high nutrient levels had been hypothesized as reasons for mass occurrences of boring organisms in Müllendorf (Kleemann, 1982), this is also supported by accumulations of large-shelled *Hyotissa* and *Isognomon* which point to

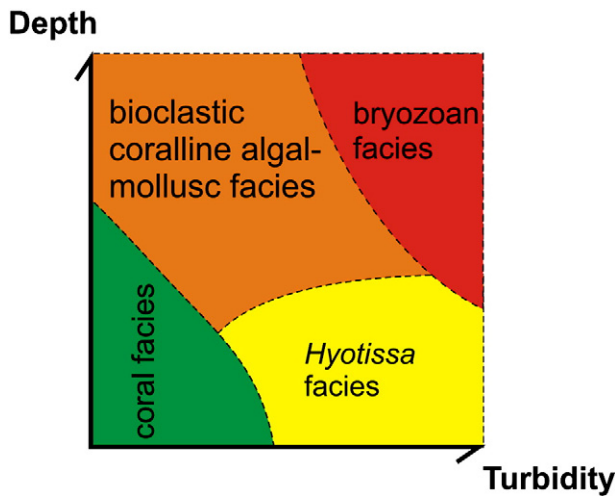


Fig. 7. Idealized ecospace-occupation model of depth-turbidity relationships influencing facies distribution (deduced of Fig. 8). With increasing depth and turbidity the bryozoan subfacies gains greater importance.

a beneficial food situation as well (see discussion above). But high nutrient supply has detrimental effects on coral communities as it stimulates plankton growth and as consequence causes increasing water turbidity (Hallock and Schlager, 1986). The common occurrence of large-polyped corals (*Tarbellastraea* and *Acanthastrea*) in Müllendorf, next to common *Porites*, a sediment-resistant coral in areas of high re-suspension (Riegl, 1999), refers to active sediment removal than passive one by increased water energy, which commonly prevents smothering of a reef system (Stafford-Smith, 1992; Jokiel, 2006). As water energy mainly influences sediment composition, accumulation and distribution (Bergman et al., 2010), conspicuous differences in siliciclastic content between the close-by sections B and C (cf. Figs. 1d, 2) point to a short current driven distribution of siliciclastics. Additionally, corals – representing biostromal coral communities (sensu Riegl and Piller,

2000) – probably caused slight changes in bottom topography and therefore influenced the distribution of siliciclastics, which underwent only a short transport (see above).

Influences of environmental factors on faunal communities within the ecospace of Müllendorf can be deduced from the ecological requirements of this biota discussed in chapter 6 and are best illustrated by a turbidity/water depth diagram (Fig. 7). A single parameter change (increased water turbidity) causes displacement of corals by the oyster *Hyotissa* while a change in two parameters, increased water turbidity and depth, causes the transition to deposits with common shallow-burrowing molluscs (bioclastic coralline algal-mollusc facies) and finally to sediments with common bryozoans (bryozoan facies). The common occurrence of facies formed in very shallow waters shows that water turbidity (determined by nutrient and/or terrigenous values) acted as strongest modulating factor (ecological master factor) in community expression in Müllendorf, followed by influences of water depth regulated by fluctuations in relative sea-level. Other important ecological factors as temperature, which is often documented as ecological master factor (Brett, 1971), had no apparent influence as the sedimentary records shows no indications for temperature changes during the observed time-interval. Based on the observed facies relations, gradations and reconstructed water depths for each facies an idealized ecospace-occupation model (Fig. 7) for similar shallow tropical carbonate platforms can be deduced from the Müllendorf case study. It illustrates the position and space of a facies within a depth-turbidity diagram. Facies relationships in multiple directions of the diagram can be produced in this way.

7.2. Cyclic sedimentation patterns

Cyclic stacking of sediments is visible in recurring transitions from the bioclastic coralline algal-mollusc facies either to oyster- or to coral-horizons. Such transitions are tied to low-amplitude relative sea-level oscillations, as the bioclastic coralline algal-mollusc facies has been formed in greater depth than the *Hyotissa*- and coral-horizons (see discussion above), whose individual formation is controlled by

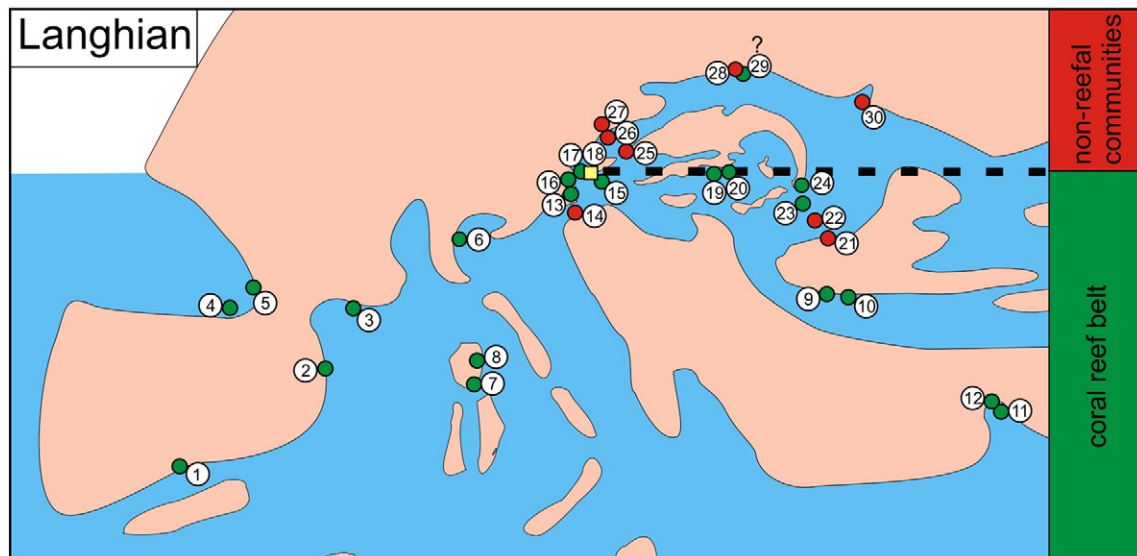


Fig. 8. Paleogeographical map of Europe during Langhian time (adapted after Rögl, 1999). The stippled black line shows the northern edge of the coral reef belt. Green dots indicate coral reefs; red dots indicate coral carpets or biostromal coral communities and single coral occurrences. The yellow square highlights the study area. Localities are given by numbers: 1 Murchas (Braga et al., 1996), 2 Sant Pau d'Ordal (Permanyer and Esteban, 1973; Calvet et al., 1994), 3 Hérault (Chevalier, 1961), 4 Saubrigues (Chevalier, 1961), 5 Manciet (Chevalier, 1961), 6 Torino Hills (Chevalier, 1961), 7 Balistra (Pedley, 1996 and further literature), 8 Aléria (Pedley, 1996 and further literature), 9 Ohrid (Okhrid) (Kojumdzieva and Strachimirov, 1960; Kojumdzieva, 1976), 10 Pleven (Kojumdzieva et al., 1978; Budd et al., 1996), 11 Oymapinar (Karabiyiçoğlu et al., 2005), 12 Tepeki and Köprücaş (Karabiyiçoğlu et al., 2005), 13 Retznei and 'Tittenbach' quarry (Friebe, 1991; Friebe, 1993; Reuter and Piller, 2011), 14 Duplek (Baron-Szabo, 1997), 15 Fertőrákos (Randazzo et al., 1999), 16 Wiesfleck (Kroh, 2007), 17 Soos-Lindkogel (Piller et al., 1991), 18 Müllendorf/Großhöflein (Dullo, 1983; Riegl and Piller, 2000), 19 Budapest area (Oosterbaan, 1990; Randazzo et al., 1999; Saint Martin et al., 2000), 20 Zebegény (e.g. Oosterbaan, 1990; Randazzo et al., 1999), 21 Bahna (Tiță, 2007), 22 Delinești (Tiță, 1999, 2000), 23 Lăpușiu de Sus (Rus and Popa, 2008), 24 Podeni (Saint Martin et al., 2007; Bucur et al., 2011), 25 Devínska Nová Ves (Švagrovský, 1978), 26 Židlochovice (Cicha, 1978), 27 Borač (Brzobohatý and Cicha, 1978), 28 Korytnica (Bałuk and Radwański, 1977; Roniewicz and Stolarski, 1991; Stolarski, 1991), 29 Grobie (Górka, 2002), 30 Maksymivka (Radwański et al., 2006).

turbidity. Therefore these recurring facies changes reflect high frequency shallowing-deepening sequences. However, neither field observations nor thin-section analyses allowed an interpretation whether these sequences reflect shallowing- or deepening-upward cycles. Transgressive-regressive cycles of higher order, bundling the prementioned oscillations, are indicated by changing amounts of siliciclastics.

7.3. The northern boundary of the Langhian Peri–Mediterranean reef belt

Coral reefs are typically associated with warm shallow seas (Veron, 1995) and their today's dispersal is restricted to the northern and southern tropics (e.g. Guilcher, 1988; Veron, 2000; Spalding et al., 2001). Nevertheless some coral communities extend beyond the tropics also into higher latitudes (e.g. Florida, Australia, Japan and Southern Africa) between a zone of ca. 30° N to 30° S (Kleypas et al., 1999a) but often fail to form reefs (Veron and Minchin, 1992). The Middle Miocene Climatic Optimum (e.g. Flower and Kennett, 1994; Böhme, 2003) led to an extension of the tropical belt and favoured the wide distribution of coral communities also throughout the Mediterranean and Central Paratethyan seas during Langhian time (Perrin and Bosellini, 2012). During the Langhian the Central Paratethys spanned a zone from ca. 40–47° N (Perrin and Bosellini, 2012). Coral reefs are documented from the entire Mediterranean and from the Central Paratethys up to the southern Vienna and Transylvanian basins (Fig. 8). From this distribution pattern of the circum-Mediterranean region a subdivision into two biogeographic areas during Langhian times is possible. The southern area is characterized by coral reefs (s.s.). Its northern boundary can be drawn from the Aquitaine Basin to the Vienna and Transylvanian basins (Esteban, 1996). Further to the north coral occurrences are characterized by coral carpets/assemblages or monospecific coral occurrences (Fig. 8). In this context the Leitha platform, which is situated at the edge of the coral reef belt, characterizes the transition zone between coral reefs to non-reefal coral communities – the second biogeographic unit. The development of exclusively non-reefal communities beyond the transition zone is very likely influenced by a distinct climatic north-south gradient well documented by molluscs and echinoids (Harzhauser et al., 2003; Harzhauser and Piller, 2007; Kroh, 2007). Górka (2002) interprets weathered material from an agricultural field at Grobie in Poland as reef core facies of a patch reef. However, in-situ reef-core facies is not documented and, according to the geographical position of other Badenian reefal and non-reefal communities (Fig. 8), an affiliation to the latter group is more appropriate. The distribution of corals in the Central Paratethys, being distinctly north of the Holocene tropical zone (Pisera, 1996), is thus clearly linked with the Middle Miocene Climatic Optimum, which supported the northward shift of tropical elements (Harzhauser et al., 2003). Langhian deposits of the Pannonian basinal system in Hungary, including coral patch reefs, had been interpreted as cool water limestones (Randazzo et al., 1999). But in consideration of the fact that tropical coral assemblages occurred even much further in the north, this interpretation is very unlikely.

8. Conclusion

We present a detailed key study on a Middle Badenian (upper Langhian) carbonate platform in the southern Vienna Basin. The investigated parts of the platform formed in a tropical near-shore environment with a maximum water depth of ca. 30 m. Predominant coralline algal limestones represent multiple biofacies, whose distribution was modulated by turbidity and water depth. This relation can be plotted in a depth-turbidity diagram and allows proposing an ecospace-occupation model for Miocene carbonate biofacies of shallow-water carbonate platforms. The sedimentary record, dominated by coralline algal debris sands, reveals stable climatic conditions during the observed time interval where water turbidity and depth acted as ecological master factors in modulating the ecospace. They were therefore responsible for facies changes from accumulations of shallow-water suspension feeding

Hytissa and *Isgnomon* to coral communities, represented by sediment-resistant taxa (*Acanthastrea*, *Tarbellastrea* and *Porites*). Furthermore, associated changes in water-depth, regulated by fluctuations in relative sea-level, were responsible for development of 7 facies types, represented by the bioclastic coralline algal-mollusc facies (the most common facies), *Hytissa* facies, *Isgnomon* facies, rhodolith facies, bryozoan facies, coral facies and terrigenous sand facies. Cyclic sedimentary patterns point to low-amplitude sea-level fluctuations. The platform was situated at the northern edge of the Langhian Peri–Mediterranean reef belt in the Central Paratethys, where coral reefs (s.s.) and non-reefal coral communities coexisted in the same ecospace while in closeby regions to the north only non-reefal coral communities existed.

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