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ORIGINAL ARTICLE

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Facies dynamics in Eocene to Oligocene circumalpine carbonates

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Abstract A new concept, termed 'Facies Dynamics' (defined as changes of specific carbonate facies types in time and space, which are controlled by phylogenetic, ecological and geological parameters), is introduced. This concept aims to define and interpret spatial and temporal changes of carbonate facies patterns. It is based on Middle Eocene to Early Oligocene shallow-water carbonate facies types from the circumalpine area (north-eastern Italy, northern Slovenia, Austria and southern Bavaria), which are compared with respect to dominating biogenic components and their distributions along a shelf gradient. This comparison has lead to the distinction and definition of 14 Major Facies Types (MFTs), which are dominated by coralline algae, larger and smaller foraminifera, corals and bryozoans. The presence and distribution of these MFTs from three different time slices (Middle Eocene, Late Eocene and Early Oligocene) is compared. Nine aspects of facies dynamics are distinguished: origination, extinction, immigration, emigration, expansion, reduction, stasis, shift, and replacement of MFTs. These changes are controlled by regional changes in ecological parameters, but also by global events, especially extinction patterns at the Middle/Late Eocene boundary and at the Eocene/Oligocene boundary.

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Introduction

Shallow-water carbonate sediments are mainly formed by biotic and abiotic carbonate precipitation (Schlager 2003) and the carbonate facies types resulting from these processes are usually defined according to their dominant components (Flügel 2004). The high proportion of biotically controlled and biotically induced carbonate production makes carbonates and their facies types sensitive to factors that control the distribution and abundance of biotic components, which is a main difference to siliciclastic sediments (Flügel 2004). These biota are influenced by global and local (1) ecological (e.g., temperature, water chemistry, trophic resources), (2) geological (e.g., sea level, plate tectonics) and (3) phylogenetic (e.g., radiation, extinction) changes as well as by combinations of these factors (e.g., mass extinction caused by global changes, or increased trophic resources due to sea-level fall followed by sediment influx). Changes of these parameters affect changes of the biotic composition and the abundance of biota. Consequently, carbonate facies 'behave' dynamically, because facies-forming biota react to changes of controlling factors, which results in changing facies patterns in time and space. Well-known examples of this are (1) new facies-forming taxonomic groups inhabiting ecological niches of extinct taxa, (2) increasing water turbidity causing a shift of facies types formed by photo-autotrophic communities into shallower water, or (3) the expansion of tropical carbonate facies types (e.g., coral reefs) into higher latitudes during times of increased sea-surface temperatures (e.g., Kiessling et al. 2002).

This paper introduces 'Facies Dynamics' as a new concept and tool for carbonate facies analysis in its broadest sense, which is based on the well-known perception that carbonate facies are widely controlled by the carbonate-producing organisms (Flügel 2004). Facies dynamics is herein defined as 'changes of specific carbonate facies types in time and space, controlled by phylogenetic, ecological and geological parameters'. This is in contrast to former general carbonate facies models (e.g., Wilson 1975; Buxton and Pedley 1989), which are stationary and do not necessarily reveal changes through time. Other models that do include dynamic aspects (e.g., Spence and Tucker 1999) mainly aim to provide a sequence-stratigraphic framework. An overview of carbonate facies models was recently given by Flügel (2004).

Our concept is based on the temporal and spatial patterns of Major Facies Types (MFTs) of the circumalpine area, recently defined by Nebelsick et al. (2003). We describe the spatial and temporal changes of shallow-water carbonate facies within three time slices – Middle Eocene, Late Eocene and Early Oligocene – and discuss the potential controlling factors. The time span in question is of special interest as it crosses a period of two major extinction events at the Middle-Late Eocene (e.g., Hottinger 1983a; Aguirre et al. 2000) and at the Eocene/Oligocene boundaries (e.g., Berggren and Prothero 1992; Prothero 2003). This boundary corresponds to a global change from "Greenhouse" to "Icehouse" conditions (Ivany et al. 2003; Prothero 2003). Carbonates abound in the Paleogene, especially those dominated by coralline algae and larger foraminifera (Hottinger 1997; Bassi 1998; Geel 2000; Rasser 2000; Romero et al. 2002; Rasser and Nebelsick 2003). This corresponds to patterns of global carbonate platform areas which started with moderate values in the Paleocene to the Early Eocene, achieved a peak in the Middle Eocene and declined drastically in the Late Eocene to Early Oligocene (Kiessling et al. 2003). Reefs as such are very uncommon during this time, in fact, reaching a post-Cambrian low (Kiessling et al. 1999, 2003).

The base of our comparative analysis includes all known major and minor outcrops of Paleogene carbonates in the circumalpine area. Most of them have been studied in great detail in the last years by the authors and include some of the classic localities of Paleogene stratigraphy and facies studies (Fig. 1). These compiled studies include quantitative microfacies analyses (e.g., Rasser 2000; Nebelsick et al. 2001; Rasser and Nebelsick 2003) as well as studies on taxonomy, taphonomy and growth forms (e.g., Rasser and Piller 1999a; Nebelsick and Bassi 2000; Rasser and Nebelsick 2003). They provide basal data on various physical and biological controlling factors. Further data are taken from older literature. Facies dynamics during the Paleogene can be studied as major changes of facies composition and are not restricted to a single event. Additionally some facies types are found throughout, or in two of the three slices allowing their position along shelf gradient to be compared.

Study areas and geological background

The analysed carbonate facies originate from 13 different localities from the Eastern and Southern Alps (Fig. 2). These localities are from the following regions: Eastern Alps: The Helvetic Units with Kirchdorf, Eisenrichterstein, and the Salzburg Helvetic Zone; the autochthonous Molasse underground from Austria and Bavaria. Inner Alpine basins including the Lower Inn Valley, Enns Valley, Kirchberg am Wechsel, Wimpassing, and the Central Alpine Gosau Basin of Krappfeld. Localities in the Southern Alps include the Eastern and Western Lessini Shelf, and Eastern Colli Berici in northeastern Italy as well as the Gornji Grad area in northern Slovenia.

The Paleogene paleogeography of southern and central Europe is dictated to a high degree by the Tethys to the South (Fig. 1). The Tethys remained open in the Eocene and Oligocene allowing for continuous marine connection from the Indo-Pacific to the North Atlantic Oceans (Rögl 1998). In the Early Oligocene, the Alpine orogeny led to the rising of the Alps and subsequent separation of the Paratethys, a distinct marine biogeographic province to

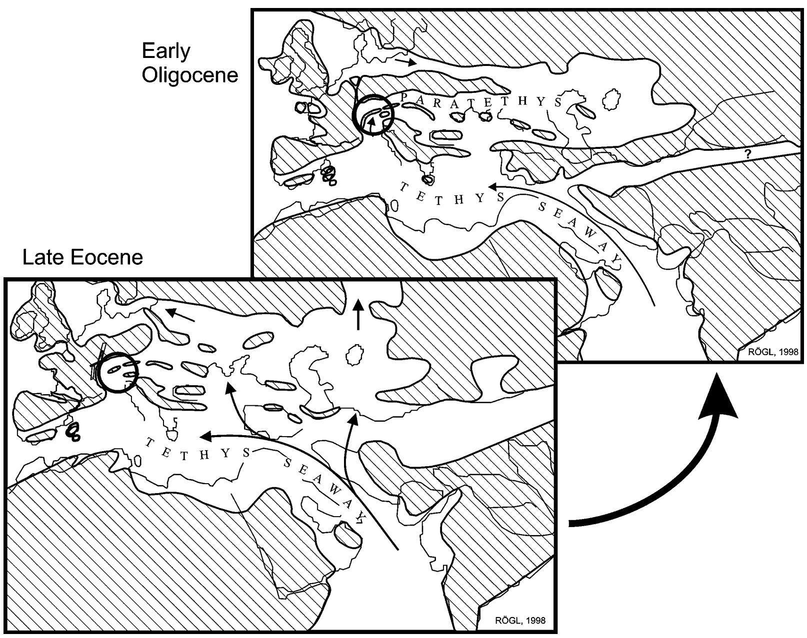


Fig. 1 Changes in paleobiogeography and position of the study area for the Late Eocene and Early Oligocene. The study area is designated by a circle. Maps based on Rögl (1998)

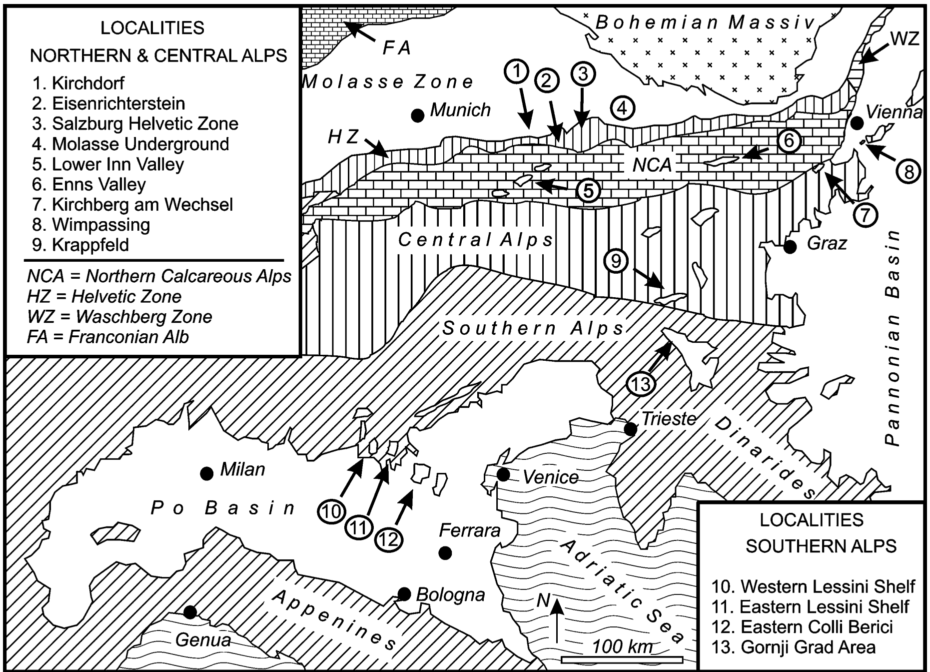


Fig. 2 Location of the studied profiles within the circumalpine area. Presence of Major Facies Types (MFTs) within the three studied time slices in the different localities of the study area. Crustose Cor. Algal = Crustose Coralline Algal

Major Facies Type	Localities														
	Middle Eocene					Late Eocene						Early Oligocene			
	3	9	10	11	12	1-3	4	6-8	10	11	12	5	11	12	13
1 Maerl							●		●	●			●	●	
2 Rhodolith		●	●	●	●	●	●		●	●	●		●	●	
3 Crustose Cor. Algal							●		●		●			●	
4 Coralline Algal Debris		●	●	●	●	●	●		●	●	●	●	●	●	●
5 Peyssonnelicaean							●								
6 Large *Nummulites*	●	●	●	●	●										
7 Small *Nummulites*		●	●	●	●		●	●	●	●	●		●	●	●
8 Orthofragminid			●	●	●		●	●	●	●	●				
9 *Orbitolites*				●											
10 Smaller Miliolid			●	●	●	●				●			●	●	●
11 Alveolinid			●	●							●				
12 Acervulinid		●		●		●	●			●					
13 Coral						●	●	●	●			●	●	●	●
14 Bryozoan							●			●	●	●			

the North of the Alps. The Paratethys was still connected, however, to the Tethys by means of marine connections. Exact geographic distributions as well as extent of marine sediments is difficult to ascertain due to the subsequent Alpine orogeny, which has led to radical reorganisation of tectonic units both in vertical and horizontal movements especially in the Eastern Alps. This movement is especially important in the Central and Northern Calcareous Alps. Eocene localities probably represent the remnants of a once-extensive shallow-water shelf environment, now only found in dispersed localities or represented as eroded boulders in younger sediments (e.g., Moussavian 1984) while Oligocene sediments were deposited in geographically widely separated depositional settings.

Eastern Alps

Geology

The Helvetic Zone and the authochthonous Molasse underground represent the southern margin of the European Shelf (Fig. 2). It was separated from the Alpine archipelago

(Gosau Basins, Inneralpine/Parautochthonous Molasse Basins) by the Penninic trough represented by deeper sediments including the flysch of the Flysch Zone. During the Cretaceous, subduction started on the southern margin of the Penninic Unit and continued until the Late Eocene. An older Alpidic phase, ranging from the Middle Cretaceous to the Late Eocene (Eoalpine orogeny; Wagreich 1995) can be differentiated from a younger Alpidic phase (Mesoalpine to Neoalpine), starting with the Late Eocene. The closure of the Penninic Ocean marks the beginning of the Molasse sedimentation in the Paratethys, which was separated from the Tethys by the rising Alpine chain. The Alpine Foredeep of the Molasse Zone separated a northern and the southern shelf and accommodated the erosional products from the uprising Alps. Piggy-back-basins (Inneralpine Molasse Basins) were formed along the northern Alpine thrust front (Steininger et al. 1986; Ortner and Singl 2001).

Stratigraphy

The Helvetic Zone forms a narrow zone extending from Switzerland to eastern Austria (Tollmann 1985). The best-known occurrences are situated near Salzburg (Gohrbandt 1963; Vogeltanz 1970; Rasser and Piller 1999b, c, 2001). Here coralline algal limestones of the upper-most Paleocene follow continental series of the Paleocene. Large nummulitids and orthophragminids characterize the overlying Ypresian to lowermost Bartonian limestones and sandstones. This succession is followed by a pelagic facies, called the "Stockletten" (Hagn 1981; Darga 1992).

The first marine sediments of the Molasse Zone are known from the Upper Eocene of the Molasse underground. These sediments, designated as the Perwang-Group by Wagner (1996), can be separated into a northern and a southern facies realm (Wagner 1980; Rasser 2000). The northern facies, which were deposited near the coast, contain siliciclastic series (*Cerithium*-beds, Amphing-Sandstone, Voidsdorf Formation) and diverse coralline algal facies ("*Lithothamnion* Limestone"). The latter are dominated by coralline branches, rhodoliths, and coralline bindstones. Additionally, peyssonneliaceans, nummulitids, and branching corals can be abundant. The southern facies are characterized by a succession from nummulite sandstones to orthophragminid marls, and finally to bryozoan marls (Rasser et al. 1999; Rasser 2000). Late Eocene sediments are overlain by Oligocene deep-water facies.

Paleogene neritic carbonates within the Northern Calcareous Alps are characteristically small-scaled occurrences, often only known from poorly dated, reworked clasts in Miocene conglomerates. These occurrences are usually separated into Gosau Basins and Inneralpine/Parautochthonous Molasse Basins (here group together into the Inneralpine basins). The Paleogene carbonates of the Lower Inn Valley are represented by Early Oligocene coralline algae-dominated facies (Hagn 1981; Stingl 1990; Nebelsick et al. 2001; Ortner and Singl 2001; Rasser and Nebelsick 2003). Coralline algae, branched corals, amphistigenids, and bryozoans can be abundant. Paleogene components of fluvial conglomerates near Radstadt/Pongau (Enns Valley) contain Late Paleocene coral limestones and Early to Middle Eocene detritical carbonates rich in nummulitids (Trauth 1918; Moussavian 1984). Parautochthonous boulders of Paleogene carbonates overlie the crystalline basement at Kirchberg am Wechsel in Lower Austria. They are dominated by large nummulitids and additionally contain orthophragminids and coralline algae; larger foraminifera indicate a Late Eocene age (Ebner et al. 1991). Finally, Late Eocene coralline algal limestones are known from Wimpassing in Burgenland (Trauth 1918; Papp 1958).

The Krappfeld Gosau Basin represents the southernmost Paleogene Gosau Basin. Due to its southern position, it forms a transitional element between the Northern Calcareous Alps and Southern Alps (Tollmann 1977; Wilkens 1989, 1991; Rasser 1994). The succession starts with the Paleocene continental Holzer Formation and grades into Late Paleocene to Early Eocene sandstones and nummulite marls of the Sittenberg Formation. The overlying Dobranberg Formation marks a transition to pure larger foraminiferal limestones. Basal parts of this formation are characterized by intercalations of *Alveolina* and nummulitic limestones with local intercalations of orthophragminid foraminifera (Wilkens 1989, 1991; Hillebrandt 1993). The nummulitid foraminifera are Early Eocene in age (Hillebrandt 1993). Coralline algae and encrusting foraminifera dominate the middle part of the succession where they form huge accumulations of rhodoliths and acervulinid macroids (Rasser 1994), which are thought to be of Ypresian to Lutetian in age (Wilkens 1989; see also Moussavian 1984).

Southern Alps

Geology

Inherited Permian-Jurassic tectonic structures derived during the collision between the Adriatic and European Plates dictate large-scale tectonics of the Lessini Shelf area (Doglioni and Bosellini 1987; Cassinis and Castellarin 1988). During the Paleogene, shallow-water carbonate sedimentation of the Lessini Shelf was initiated on topographic highs. This sedimentary pattern is the result from block-faulting of the former Liassic Trento Platform, a major structural and paleogeographic unit of the Adriatic Plate (Castellarin 1972; Bosellini 1989). The Colli Berici is the southwestern continuation of the Lessini Shelf (Corsi and Gatto 1967). Tectonic movements along the Periadriatic Lineament which separates the Southern from the Eastern Alps lead to the deposition of Paleogene sediments of the Gornji Grad area in Slovenia (Fodor et al. 1998; Placer 1999; Hanfland et al. 2004).

Stratigraphy

In northeastern Italy, shallow-water Middle Eocene to Oligocene successions (Mietto 1988; Antonelli et al. 1990) follow deeper water Late Cretaceous-Early Middle Eocene successions (Massari et al. 1976; Lehner et al. 1987). Four depositional sequences have been revealed by sequence stratigraphy analysis of the Paleogene successions from the western and eastern margins of the Lessini Shelf (Luciani et al. 1988; Luciani 1989; Trevisani 1997): Early-Middle Eocene (E1), Middle-Late Eocene (E2), Late Eocene-Early Oligocene (O1), and Late Oligocene (O2).

The Middle Eocene shallow-water carbonate successions consist of large nummulitic calcarenites and coralline-foraminiferal packstones which generally grade into smaller miliolid packstones/grainstones (Ungaro 1969; Garavello and Ungaro 1982; Papazzoni and Sirotti 1995). A regressive phase in the uppermost Middle Eocene (Bartonian) caused an emersion with brackish conditions in some areas the western Colli Berici (Ungaro and Bosellini 1965; Ungaro 1969) and Lessini Shelf (Frascari 1963). Late Eocene (Priabonian) carbonate deposits are mainly represented by small nummulitic calcarenites, coralline packstones, orthophragminid packstones/marls and bryozoan marls (Ungaro 1969; Antonelli et al. 1990; Bassi 1998). Larger foraminifera gradually disappear at the uppermost Bartonian. During the Priabonian, a dramatic increase in coralline algae is accompanied by common occurrences of small *Nummulites* and "*Operculina*".

A regressive phase is documented by a disconformity surface of the subaerially exposed Calcare di Nago platform at the Eocene–Oligocene boundary in the western Lessini Shelf. This is followed by basinal sediments of the Late Eocene–Early Oligocene "Marne di Bolognano" (Castellarin and Cita 1969; Luciani 1989). The Priabonian–Rupelian boundary in the eastern Lessini Shelf is marked by regressive deposits including bryozoan marls, sandstones and silty marls (Cita 1969; Setiawan 1983; Barbin 1988; Trevisani 1997). The Eocene–Oligocene boundary in the Colli Berici is also marked by bryozoan marls and marly calcarenites. Continuous marine sequences across the boundary have been recorded in Venetian neritic settings (Ungaro 1978; Garavello and Ungaro 1982) although the number of sedimentary hiatuses generally increase around the Eocene–Oligocene boundary (Pomerol and Premoli-Silva 1986).

The Calcareniti di Castelgomberto are Early to Middle Oligocene deposits which follow the Marne di Priabona both in eastern Colli Berici and in the Lessini Shelf. These carbonates consist of shallow-water, massive or irregularly bedded limestones and irregularly bedded calcarenites. Coralline algae, small benthic miliolid foraminifera, soritids and small *Nummulites*, massive and branched corals, molluscs and echinoids dominated the facies (Coletti et al. 1973; Geister and Ungaro 1977; Ungaro 1978; Frost 1981; Bosellini and Trevisani 1992; Bosellini and Stemann 1996). Both the Colli Berici and Lessini Shelf emerged towards the uppermost Rupelian.

Eocene terrestrial sediments and carbonates mark the beginning of a transgressive sedimentary succession of Paleogene sediments in Northern Slovenia. The Lower Oligocene shows marine siliciclastics and limestones of the Gornji Grad Beds. Carbonate facies are dominated by coralline algae, small *Nummulites*, small benthic foraminifera, corals and bivalves (Bassi and Nebelsick 2000; Bassi et al. 2000a; Nebelsick et al. 2000). An Early Oligocene age for the Gornji Grad Beds was recognized by Drobne et al. (1985) using larger foraminifera. The Gornji Grad Beds are followed by foraminiferal rich marls and volcanoclastics (Schmiedl et al. 2002; Hanfland et al. 2004).

Spatial and temporal distribution of Major Facies Types

This section summarizes spatial and temporal distribution patterns of fourteen Major Facies Types recognized in the study area. The dominant and eponymous components of these MFT's range from generic (e.g., *Acervulina*) to phylum rank (e.g., Bryozoa) and also include definitive growth forms (e.g., rhodoliths). Short descriptions of dominant and subordinate components as well as fabric are given in Fig. 3. The distribution of facies along a shelf gradient within each time slice is shown in Fig. 4. The position of the facies along the shelf gradient within the different time slices follows the primary literature (cited below) which localized the facies in the shelf setting. The interpretation of the facies position is based on the stratigraphic succession of the facies present and on interpretations of faunal and floral successions, but also on other factors such as terrigenous input, amount of turbulence and so on. Further characteristic as well as the specific distribution of different facies within the study area is given in Nebelsick et al. (2003).

MFT-1 Maerl Facies

Description and occurrence

Maerl designates sediments composed of coralline algal branches, rhodoliths, and their detritus. This type of sediment can be common in modern temperate and subarctic environments (Adey 1986; Freiwald et al. 1991; Freiwald 1995). In the study area, Maerl has a restricted occurrence to the Late Eocene of the Molasse underground (Rasser 2000) and the Early Oligocene of northeastern Italy.

Distribution patterns and changes

The Maerl Facies is characteristic of inner shelf environments. In the study area, the distribution is restricted to a single occurrence in each of the Late Eocene and Early Oligocene time slices. The scarcity of the facies is general in the Paleogene, which is surprising given its widespread distribution in present-day Mediterranean and North Atlantic environments (Bosence 1983b; Freiwald 1993; Bressan and Nichetto 1994; Rasser 2000). The restricted occurrence of this facies in fossil occurrences may be due to a lack of documentation since this facies has also been identified as a "coralline debris" or "coralline calcarenite" deposit. It may also be due to changes in growth form strategies of the coralline algal taxa, which produce this facies.

MFT-1: Maerl Facies

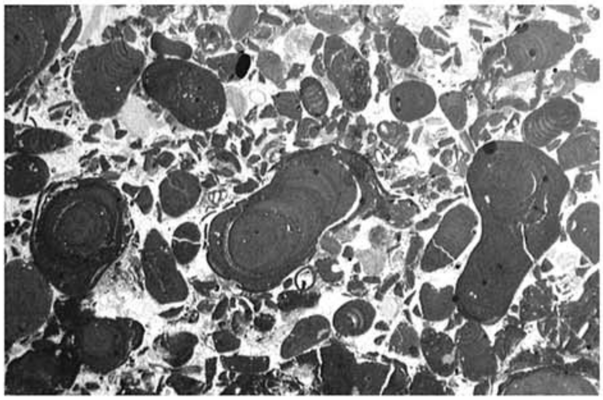
Dominant Components Coralline algal branches and detritus

Subordinate Components: *Nummulites*, smaller miliolids, textulariid foraminifera

Texture: Rudstones with packstone and grainstone matrix

Fabric: Massive and unbedded, no orientation or gradation

Molasse Underground - Late Eocene
Thin section: 215; Ma1 - width of figure: 12.7 mm



MFT-2: Rhodolith Facies

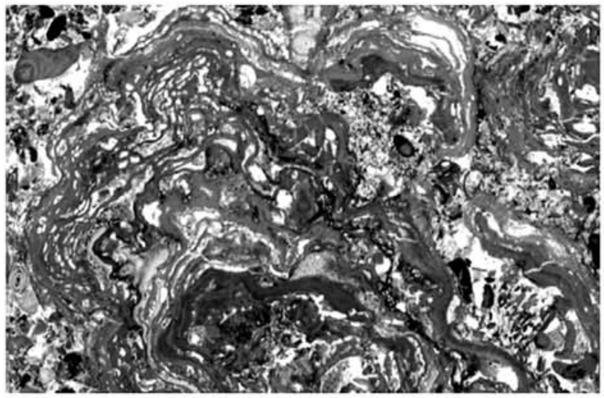
Dominant Components: Non-geniculate coralline algae, peyssonneliacean algae, encrusting acervulinid foraminifera

Subordinate Components: Serpulids, *Haddonia*, bryozoans

Texture: Rudstones with packstone and grainstone matrix

Fabric: Various rhodolith shapes: spherical, ellipsoidal, discoidal and boxwork; encrusting and protuberant algal growth forms

Molasse Underground - Late Eocene
Thin section: 217; Ma1 - width of figure: 30 mm



MFT-3: Crustose Coralline Algal Facies

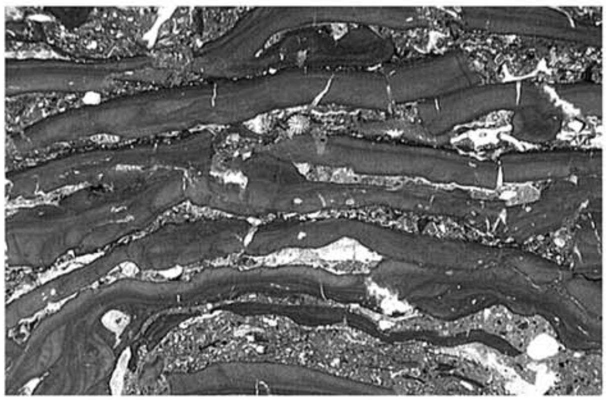
Dominant Components: Encrusting coralline algae, rhodoliths, encrusting corals, nummulitids locally abundant

Subordinate Components: Smaller miliolid and textulariid foraminifera, bryozoans, peyssonneliacean algae, echinoderms, serpulids

Texture: Meter thick bindstones composed of 0.5 to 1 mm thick algal crusts

Fabric: Algal crusts usually horizontally orientated

Molasse Underground - Late Eocene
Thin section: 207; Ma1 - width of figure: 12.7 mm



MFT-4: Coralline Algal Debris Facies

Dominant Components: Coralline algal debris, larger foraminifera, bryozoans, corals

Subordinate Components: Peyssonneliacean algae, molluscs, smaller benthic foraminifera (rotaliids, textulariids), peloids, siliciclastics

Texture: Rudstones with grainstone or packstone matrix

Fabric: No bedding or grading, various types of sorting

Molasse Underground - Late Eocene
Thin section: 206; Ma1 - width of figure: 12.7 mm

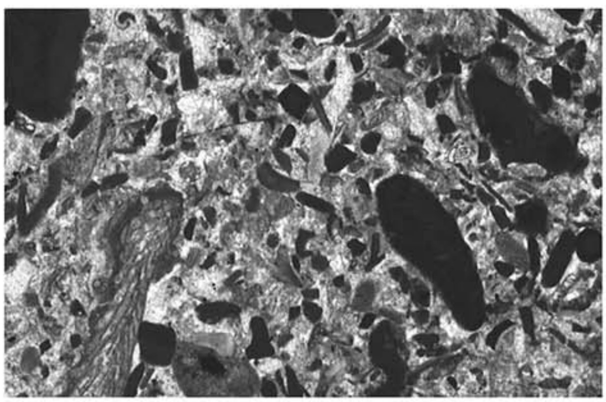


Fig. 3 Description of circumalpine, Middle Eocene to Late Oligocene Major Facies Types (MFTs) including dominant components, subordinate components, texture, fabric and typical thin section view. Microphotographs of MFT-9 and MFT-11 taken from Ungaro (2001)

MFT-5: Peyssonneliacean Facies

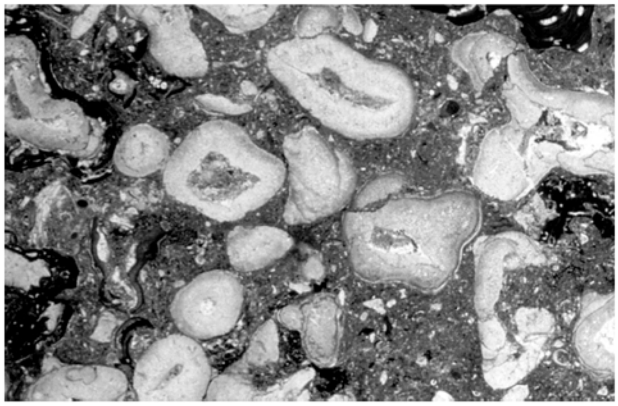
Dominant Components: *Polystrata alba* forming rounded aggregates

Subordinate Components: Coralline algae

Texture: Rudstones with grainstone or packstone matrix

Fabric: No bedding or grading, various types of sorting

Molasse Underground - Late Eocene
Thin section: 300; Gei - width of figure: 12.1 mm



MFT-6: Large *Nummulites Facies*

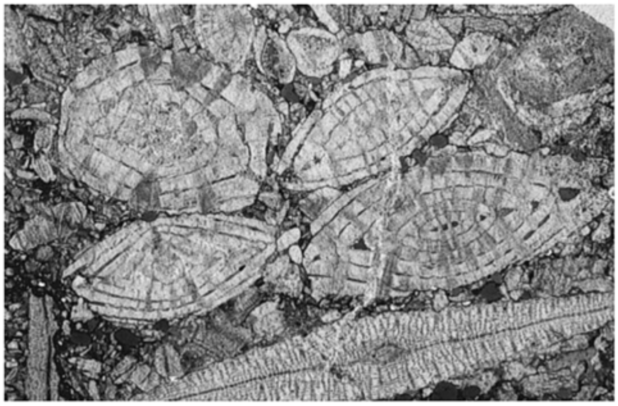
Dominant Components: Various species of large *Nummulites*

Subordinate Components: Other larger and smaller benthic foraminifera, molluscs, bryozoans, decapods, echinoids

Texture: Rudstones with packstone matrix

Fabric: Both orientated and chaotic fabrics

Helvetic Zone, Vorarlberg - Middle Eocene
Thin section: vbg982g - width of figure: 7.5 mm



MFT-7: Small *Nummulites* Facies

Dominant Components: Various species of small *Nummulites*

Subordinate Components: Coralline algal debris, other larger and smaller benthic foraminifera, bivalves, echinoids, brachiopods, corals

Texture: Packstones and rudstones with packstone/grainstone matrix or siliciclastic matrix

Fabric: Graded bedding can occur

Molasse Underground - Late Eocene
Thin section: 323; Hmbg1 - width of figure: 12.1 mm

MFT-8: Orthophragminid Facies

Dominant Components: Large, thin, disc-shaped and saddle shaped orthophragminids

Subordinate Components: Larger and smaller benthic foraminifera (rotaliids and textulariids), bivalves, coralline algal crusts, planktic foraminifera can be present

Texture: Rudstones with wackestone to packstone matrix

Fabric: Horizontal orientation usually present

Molasse Underground - Late Eocene
Thin section: 329; Hmbg1 - width of figure: 13 mm

Fig. 3 Continued

MFT-9: *Orbitolites* Facies

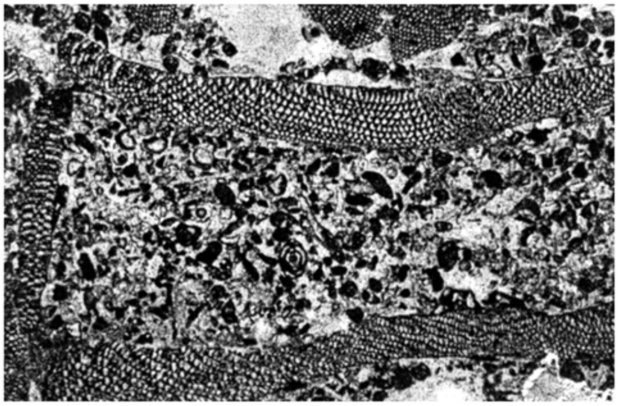
Dominant Components: *Orbitolites* tests and small miliolid foraminifera

Subordinate Components: Peneroplid foraminifera, bivalves and gastropods

Texture: Rudstones with packstone to grainstone matrix

Fabric: Graded bedding present

Eastern Lessini Schelf - Middle Eocene
Thin section: Novella - width of figure: ca. 12 mm



MFT-10: Smaller Miliolid Facies

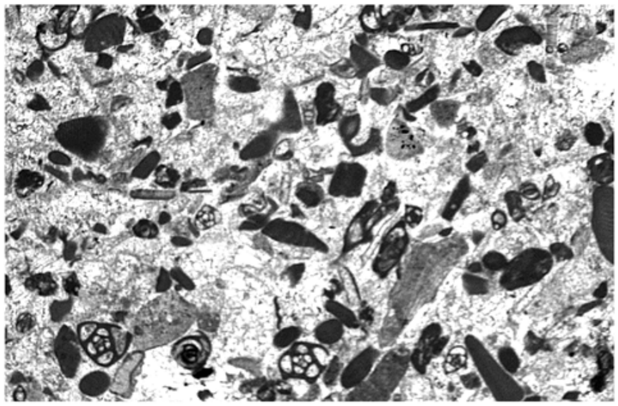
Dominant Components: Diverse small benthic miliolid foraminifera, peneroplid, and alveolinid foraminifera

Subordinate Components: Textulariid foraminifera, *Sphaerogypsina*, bivalves, echinoderms, geniculate and non-geniculate coralline algae

Texture: Packstones and grainstones

Fabric: No grading, sorting or orientation

Gornji Grad Area - Early Oligocene
Thin section: KO5 - width of figure: 5.5 mm



MFT-11: Alveolinid Facies

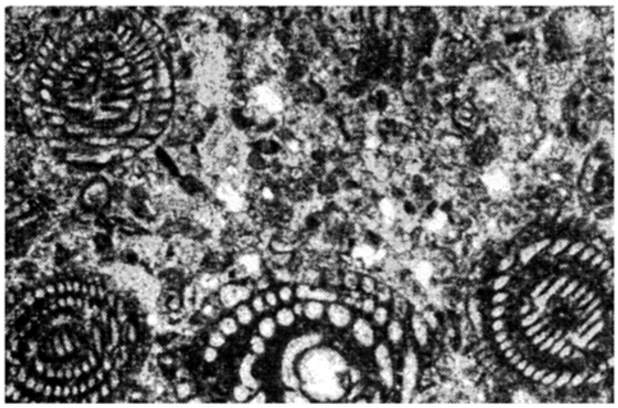
Dominant Components: Alveolinids, small miliolids, asterigerinids, nummulitids

Subordinate Components: Small benthic foraminifera,echinoids, coralline algae

Texture: Packstones and grainstones

Fabric: Both oriented and chaotic fabrics

Eastern Lessini Schelf - Middle Eocene
Thin section: Novella - width of figure: ca. 12 mm



MFT-12: Acervulinid Facies

Dominant Components: Acervulinid macroids formed by *Acervulina ogormani* and *A. linearis*, tubular aggregates of *A. multiformis*

Subordinate Components: Macroids also contain coralline algae, serpulids and homotrematid foraminifera, larger and smaller miliolid foraminifera

Texture: Rudstones

Fabric: Macroids up to 10 cm in diameter with laminar-encrusting growth-forms, no grading, sorting, or orientation

Molasse Underground - Late Eocene
Thin section: 323; Hmbg1 - width of figure: 12.1 mm

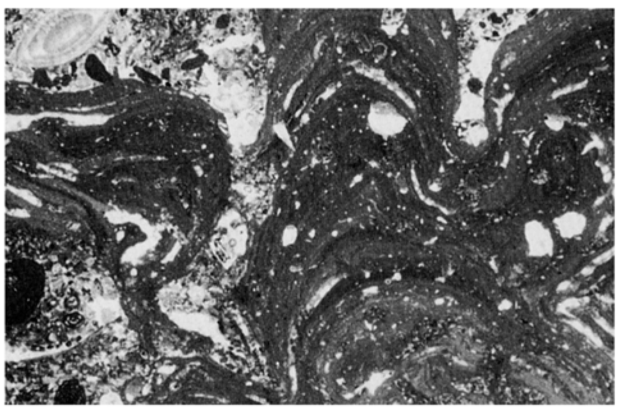


Fig. 3 Continued

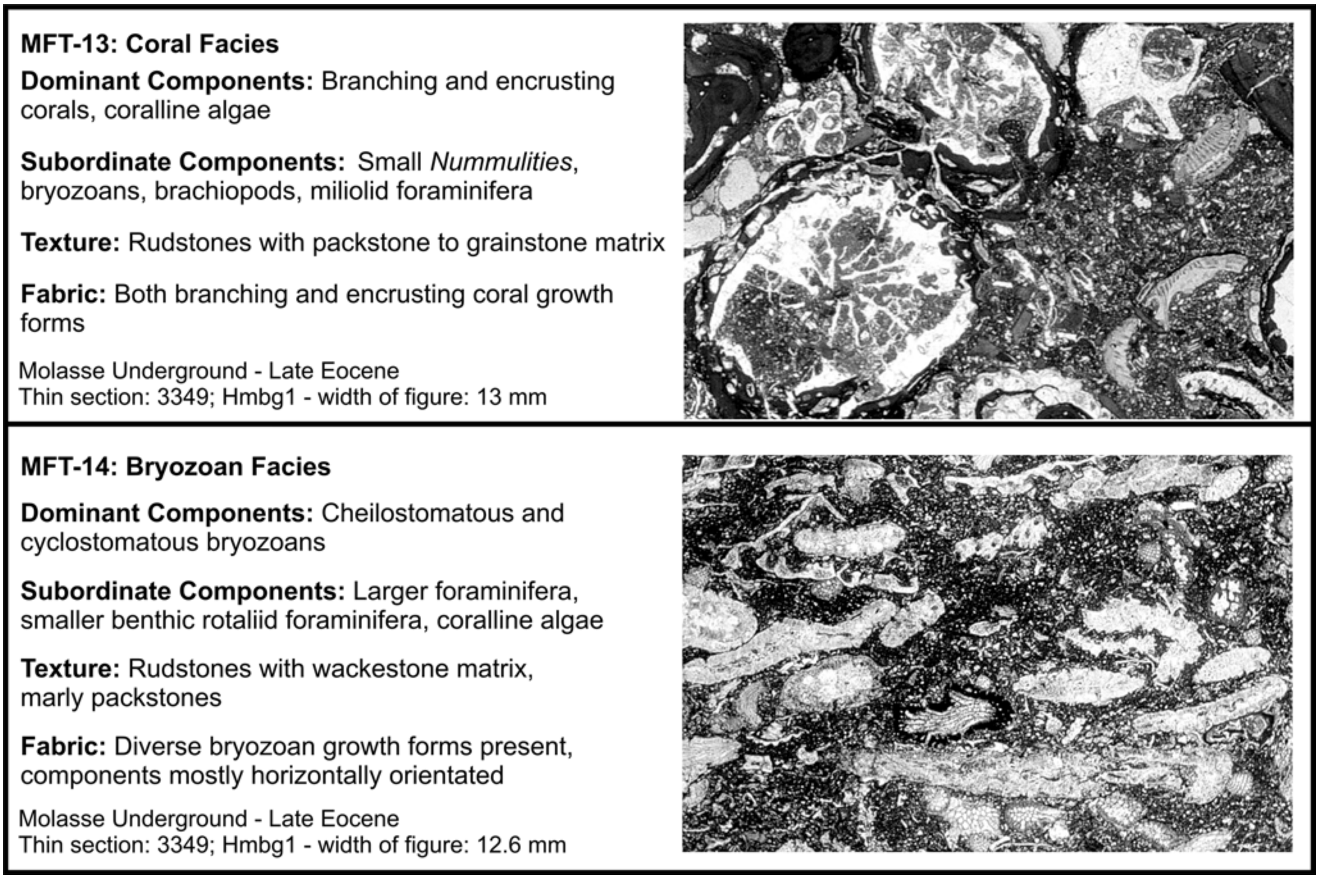


Fig. 3 Continued

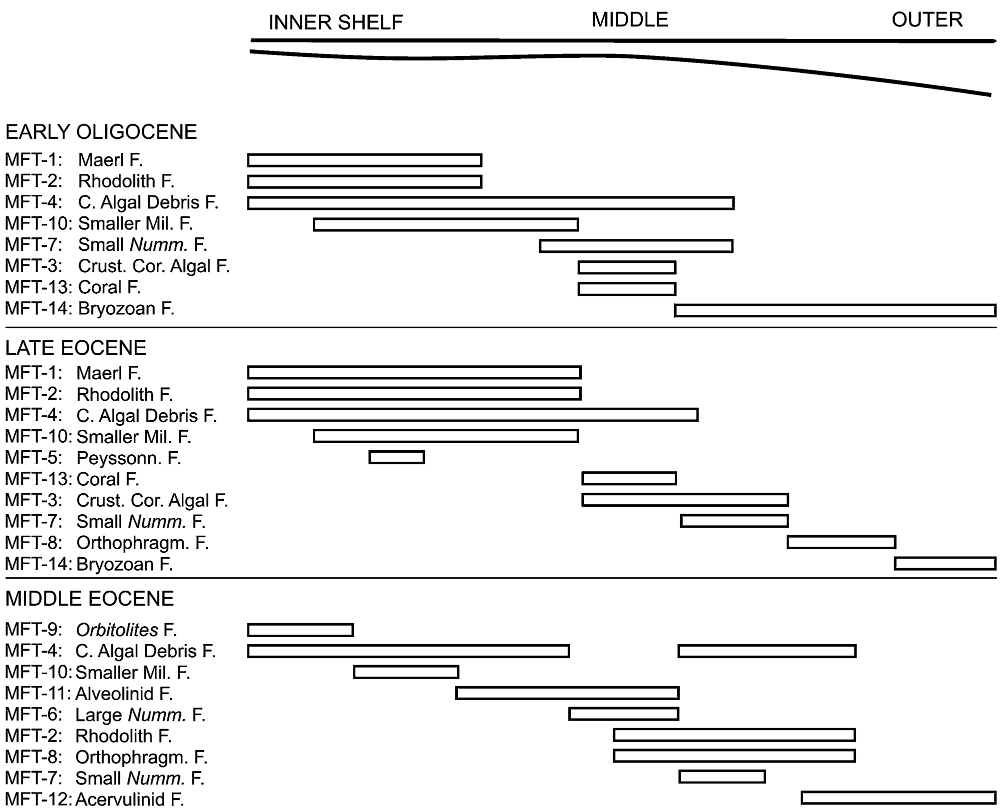


Fig. 4 Distribution of Major Facies Types along a shelf gradient in three studied time slices: Middle Eocene, Late Eocene and Early Oligocene (C. Algal Debris, Coralline Algal Debris; Smaller Mil., Smaller Miliolid; Crust. Cor. Algal, Crustose Coralline Algal; Small *Numm*., Small *Nummulites*; Large *Numm*., Large *Nummulites*; Peysosonn., Peyssonneliacean; Orthophrag., Orthophragminid)

MFT-2 Rhodolith Facies

Description and occurrence

The Rhodolith Facies, dominated by unattached nodules constructed predominantly of non-geniculate coralline red algae (Bosence 1983a), shows a wide distribution throughout the study area (Ungaro 1978; Garavello and Ungaro 1982; Bosellini and Trevisani 1992; Darga 1992; Rasser 1994, 2000; Bassi 1995, 1998). The size and shape as well as inner arrangement and taxonomic composition of the rhodoliths are highly variable. They can reach sizes up to 10 cm and show spherical, ellipsoidal, discoidal, or boxwork shapes.

Distribution patterns and changes

While this facies is typical of middle shelf environments of the Middle Eocene, its Late Eocene to Early Oligocene distribution is restricted to the inner shelf and the latter is even more restricted than the former.

Similar to the Maerl Facies described above, the taxonomic inventory of rhodolith-forming algae is mostly unclear. A high-diversity rhodolith-forming flora with a wide range of paleoecological requirements could be responsible for the changing distribution of this facies and probably explains the wide distribution of this facies on the shelf gradient as a whole. It is, however, noticeable that the onshore shift is accompanied by the disappearance of the Large *Nummulites* Facies, Alveolinid Facies, and *Orbitolites* Facies. In fact, the Rhodolith Facies replaces these facies during the Late Eocene and Early Oligocene.

MFT-3 Crustose Coralline Algal Facies

Description and occurrence

This facies consist of bindstones constructed by millimetre-scale lamination of coralline algae. Binding coralline algae are abundant in present-day tropical and non-tropical environments (Bosence 1985; Steneck et al. 1997) and can form a structural relief above the surrounding substrate (see Rasser and Piller 2004). This facies has a restricted distribution to the autochthonous Late Eocene of the Molasse underground with bindstones formed by *Phymatolithon* sp. and *Neogoniolithon* sp. (Rasser 2000; Rasser and Piller 2004) and to the Late Eocene of the Colli Berici where bindstones are formed by *Lithothamnion* spp. (Bassi 1995). These bindstones are in part comparable with Miocene representatives from Malta (Bosence and Pedley 1982) and the present-day "Coralligene de Plateau" (e.g., Bosence 1985).

Distribution patterns and changes

This facies, which first appeared in the Late Eocene as a whole, is characteristic of the inner and middle shelf. It does not show any spatial changes through time. The presence of binding coralline algae in a middle ramp setting can be seen to reflect suitable substrates, high nutrient supply and low turbulence conditions (Bassi 1995; Rasser and Piller 2004).

MFT-4 Coralline Algal Debris Facies

Description and occurrence

This facies which is dominated by the debris of various species of coralline algae is common and occurs in almost all of the studied areas. This facies can occur in a wide variety of environmental settings though not in the deeper outer shelf. It usually represents an unstable substrate detrimental for the development of sessile communities and frameworks.

Distribution patterns and changes

Although the facies distribution is wider in the Middle Eocene compared to the other time slices, there is no distinct distribution of this widespread MFT.

MFT-5 Peyssonneliacean Facies

Description and occurrence

This facies is dominated by the peyssonneliacean red alga *Polystrata alba*, which occur as small, monospecific subspherical aggregates and crusts. This facies is only known from the Late Eocene of the Molasse underground and is interpreted to have been deposited in an exceedingly low-energy environment with a muddy substrate of the inner shelf (Rasser 2000, 2001).

Distribution patterns and changes

This facies is restricted to the Late Eocene, although this species as such shows a wide stratigraphic distribution (Moussavian 1984; Bassi 1997). It thus cannot be excluded that this facies also exists in the Middle Eocene and Early Oligocene in areas outside of the study area.

MFT-6 Large *Nummulites* Facies

Description and occurrence

This facies which is dominated by one or a few species of large-sized *Nummulites* tests shows a wide geographic distribution, but is restricted to the Middle Eocene. This facies is characterized by a number of different *Nummulites* species (see Schweighauser 1953; Ungaro 1969; Hagn 1981; Schaub 1981; Garavello and Ungaro 1982; Hillebrandt 1993; Papazzoni and Sirotti 1995; Rasser and Piller 2001). *Nummulites* tests are major contributors to Eocene sediments in particular during the Middle Eocene when they reached diameters approaching 150 mm (e.g., *Nummulites millecaput*). The general interpretation of these deposits as parautochthonous accumulations forming in shoals or bars (Arni 1965; Aigner 1983, 1985; Matteucci and Pignatti 1990) has also been applied to the occurrence in the study area (Schaub 1981; Wilkens 1989). Racey (2001) summarized the complex relationships between larger foraminifera typical of Early Cenozoic carbonate platforms and concluded that *Nummulites* occupied a broad range of open-marine environments on both ramps and shelves, and were generally absent from more restricted waters. Beavington-Penney and Racey (2004) have recently discussed published observations (particularly those relating to *Nummulites*) within the context of modern studies.

Distribution patterns and changes

This MFT is restricted to Middle Eocene middle shelf environments in the study area. Its absence in the Late Eocene and Early Oligocene is caused by the extinction of larger *Nummulites* species at the Middle/Late Eocene boundary. The mid-shelf environment occupied by the Large *Nummulites* Facies is replaced by the Crustose Coralline Algal Facies and the Coral Facies in the Late Eocene.

MFT-7 Small *Nummulites* Facies

Description and occurrence

The main components of this facies are small *Nummulites* species accompanied by other larger and smaller benthic foraminifera (see Nebelsick et al. 2003 for species compilation). This facies is widely distributed throughout the study area (Schweighauser 1953; Papp 1958; Castellarin and Cita 1969; Ungaro 1969, 1978; Cita 1975; Schaub 1981; Garavello and Ungaro 1982; Luciani 1989; Wilkens 1989, 1991; Bosellini and Trevisani 1992; Rasser et al. 1999; Bassi and Nebelsick 2000; Bassi et al. 2000b). The Small *Nummulites* Facies represents parauthochtonous, reworked and re-sedimented inner platform deposits (Arni 1965; Aigner 1985; Matteucci and Pignatti 1990), the beginning of a deepening upward sequence in the Molasse underground (Rasser 2000).

Distribution patterns and changes

This MFT shows a slight expansion and an on-shore shift from the Middle Eocene to the Early Oligocene. This expansion is accompanied by an on-shore reduction of the Maerl (MFT-1) and Rhodolith Facies (MFT-2).

MFT-8 Orthophragminid Facies

Description and occurrence

This facies, which is dominated by large thin disc-shaped and saddle-shaped larger foraminifera, is widespread in Middle and Upper Eocene of the study area (Schweighauser 1953; Castellarin and Cita 1969; Setiawan 1983; Darga 1992; Bassi 1998; Bassi et al. 2000b; Rasser 2000). Open-shelf conditions are typical for orthophragminid assemblages (Sirotti 1978; Fermont 1982; Buxton and Pedley 1989; Eichenseer and Luterbacher 1992; Beavington-Penney and Racey 2004; Cosovic et al. 2004) with assemblages dominated by *Discocyclina* found in shallower water than *Asterocyclina* dominated ones (Less 1987).

Distribution patterns and changes

This MFT is restricted to the Middle to Late Eocene due to the extinction of orthophragminids at the Eocene/Oligocene boundary. From the Middle to the Late Eocene, the distribution of this facies is reduced to an offshore position; this reduction of facies distribution is accompanied by the first occurrence of the Crustose Coralline Algal Facies and Coral Facies, which occupy the middle shelf environment formerly occupied by the Orthophragminid Facies. An on-shore expansion of the Bryozoan Facies occupies the space left after the extinction of the orthophragminids.

MFT-9 *Orbitolites* Facies

Description and occurrence

The *Orbitolites* Facies is dominated by the name giving larger porcellaneous foraminifera. This facies is restricted to uppermost Middle Eocene of the eastern Lessini Shelf (Garavello and Ungaro 1982). The environment of deposition has been interpreted as shallow water or possibly hypersaline (Hottinger 1983a; Eichenseer and Luterbacher 1992).

Distribution patterns and changes

This MFT is restricted to the Middle Eocene since *Orbitolites* became extinct at the Middle/Late Eocene boundary. The space formerly occupied by this MFT is occupied by the Maerl and Rhodolith Facies in the Late Eocene and Early Oligocene.

MFT-10 Smaller Miliolid Facies

Description and occurrence

The packstones and grainstones of the Miliolid Facies are dominated by a wide range of foraminifera (see Nebelsick et al. 2003 for species compilation). This facies has a widespread distribution (Castellarin and Cita 1969; Ungaro 1969, 1978; Cita 1975; Garavello and Ungaro 1982; Setiawan 1983; Bosellini and Trevisani 1992; Darga 1992; Bassi and Nebelsick 2000) and represents a shallow-water setting with high hydrodynamic and high light intensity (Buxton and Pedley 1989).

Distribution patterns and changes

This distribution of this MFT is more expanded in the Early Oligocene, compared to the Middle Eocene. However, there is a lack of record for the Late Eocene in the study area.

MFT-11 Alveolinid Facies

Description and occurrence

This facies is dominated by alveolinid foraminifera which form massive to bedded packstones to rudstones in the Middle Eocene at the western and eastern Lessini Shelf (Hottinger 1960; Drobne 1977).

Distribution patterns and changes

This MFT is restricted to the inner to middle shelf environments of the Middle Eocene. This facies disappears with the extinction of larger alveolinids and the decrease in species diversity of the family at the Bartonian–Priabonian boundary. Its position along the shelf is replaced by the Rhodolith Facies, Crustose Coralline Algal Facies, Coralline Algal Debris Facies and Coral Facies in the Late Eocene.

MFT-12 Acervulinid Facies

Description and occurrence

The Acervulinid Facies is characterized by macroids dominated by *Acervulina ogormani*. The macroids (*sensu* Hottinger 1983b) reach sizes up to 10 cm in diameter and show a laminar-encrusting growth form. This MFT is restricted to the Middle Eocene of the Krappfeld (Rasser 1994) and the Eastern Lessini Shelf (Ungaro 1996).

Distribution patterns and changes

Due to the extinction of *A. ogormani* in the Early Bartonian, this MFT is restricted to the Middle Eocene and is characteristic of outer shelf environments. The Bryozoan Facies replaces the Acervulinid Facies in the Late Eocene outer shelf.

MFT-13 Coral Facies

Description and occurrence

This MFT is dominated by branching and encrusting corals together with coralline algae. It shows a wide geographic distribution in the Late Eocene and Early Oligocene in the study area (Geister and Ungaro 1977; Ungaro 1978; Frost 1981; Bosellini and Russo 1988; Bosellini and Trevisani 1992; Darga 1992; Bosellini and Stemann 1996; Bosellini 1998; Bassi and Nebelsick 2000; Rasser 2000). Corals are mostly present as isolated corals in muddy environments or in coral carpets or thickets (see Nebelsick et al. 2003 for discussion of different occurrences). It is important to note, however, that corals do not form entire reef bodies in the studied areas.

Distribution patterns and changes

Although corals can also be locally abundant in pre-Late Eocene sediments, this MFT is unknown in the Middle Eocene of the study area. Together with the Crustose Coralline Algal Facies, the Coral Facies replaces the Large *Nummulites* Facies and Alveolinid Facies on the mid-shelf.

MFT-14 Bryozoan Facies

Description and occurrence

The Bryozoan Facies occurs in different outer to mid-shelf settings of the Late Eocene and Early Oligocene (Ungaro 1969, 1978; Setiawan 1983; Rasser 2000; Nebelsick et al. 2001; Rasser and Nebelsick 2003).

Distribution patterns and changes

The Bryozoan Facies is absent in the Middle Eocene. This MFT replaces the Acervulinid Facies in the Late Eocene and reveals a distinct on-shore expansion in the Early Oligocene. This on-shore expansion is accompanied by a replacement of the Orthophragminid Facies which disappears at the Eocene/Oligocene boundary, an onshore shift of the Small *Nummulites* Facies, and an on-shore reduction of the Crustose Coralline Algal Facies.

Facies dynamics

The facies types summarized above provide a broad data base for the definition and interpretation of MFT patterns, which results in the facies dynamics concept given below. Facies dynamics is defined as changes of specific carbonate facies types in time and space, which are controlled by phylogenetic, ecological and geological parameters.

Changes in the position of Major Facies Types can be seen when comparing the distribution of facies along the shelf gradient from the inner to the outer shelf. Nine aspects of facies dynamics were distinguished: origination, extinction, immigration, emigration, expansion, reduction, stasis, shift, and replacement (Figs. 5–7). Six of these categories are processes than can be seen in the change of relative position of a single facies along the shelf gradient; one of these (facies stasis) delimits no change of relative position; two categories (shift and replacement) result from a combination of other processes.

Facies origination

Definition: First appearance of a Major Facies Type.

Examples: The Maerl Facies (MFT-1) and Crustose Coralline Algal Facies (MFT-3) in the Late Eocene (Fig. 7) are not reported to occur anywhere before, which may indicate facies origination. Alternatively, this pattern may simply be an artefact of their lack of recognition. Phylogenetic evolution among the coralline algal floral spectrum may have led to species which are likely to produce the observed growth forms (e.g., Rasser and Piller 2004), but more rigorous taxonomic studies are needed to decide this. These growth forms are ultimately controlled by factors such as substrate and turbulence conditions.

Notes: The first appearance of a dominant, name-giving biotic component can be caused by (1) the phylogenetic origination of a specific species (“Facies origination”); (2) the increased relative importance of an already extant taxon; or the (3) development of a particularly successful ecophenotype or growth form within an already existing taxon. The first appearance of a dominant, name-giving taxon can be caused by factors such as the phylogenetic origination of a specific species and its increasing relative importance due to ecological changes (climate, palaeoceanography), or the development of a particularly successful ecophenotype or growth form (e.g., coralline algae) within an already existing taxon. There are, however, no reliable indications for *de facto* facies origination in the studied areas.

Facies extinction

Definition: Global disappearance of a particular carbonate facies.

Examples: The Alveolinid Facies (MFT-11) disappears in the Early Bartonian (late Middle Eocene) due to extinction of larger alveolinid foraminifera (Fig. 5). The Acervulinid Facies (MFT-12) disappears in the Early Bartonian (late Middle Eocene) due to the extinction of *A. ogormani* (Fig. 5). The Large *Nummulites* Facies (MFT-6) disappears at the Middle Eocene/Late Eocene boundary due to the extinction of larger *Nummulites* species (Fig. 5). The *Orbitolites* Facies (MFT-9) disappears at the Middle Eocene/Late Eocene boundary due to the extinction of the genus *Orbitolites* (Fig. 5). The Orthophragminid Facies (MFT-8) disappears at the Late Eocene/Oligocene boundary due to extinction of orthophragminids (Fig. 5).

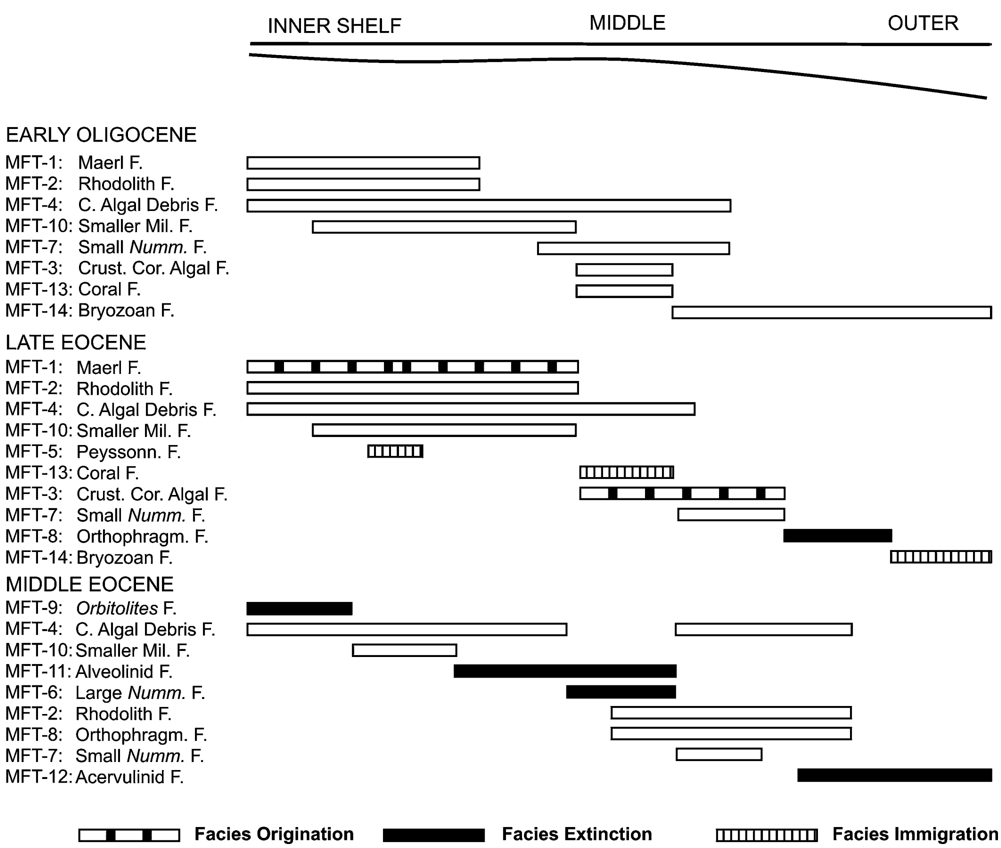


Fig. 5 Facies development of facies origination, extinction and immigration. See Fig. 4 for abbreviations

Fig. 6 Facies development of facies expansion, reduction stasis and emigration. See Fig. 4 for abbreviations

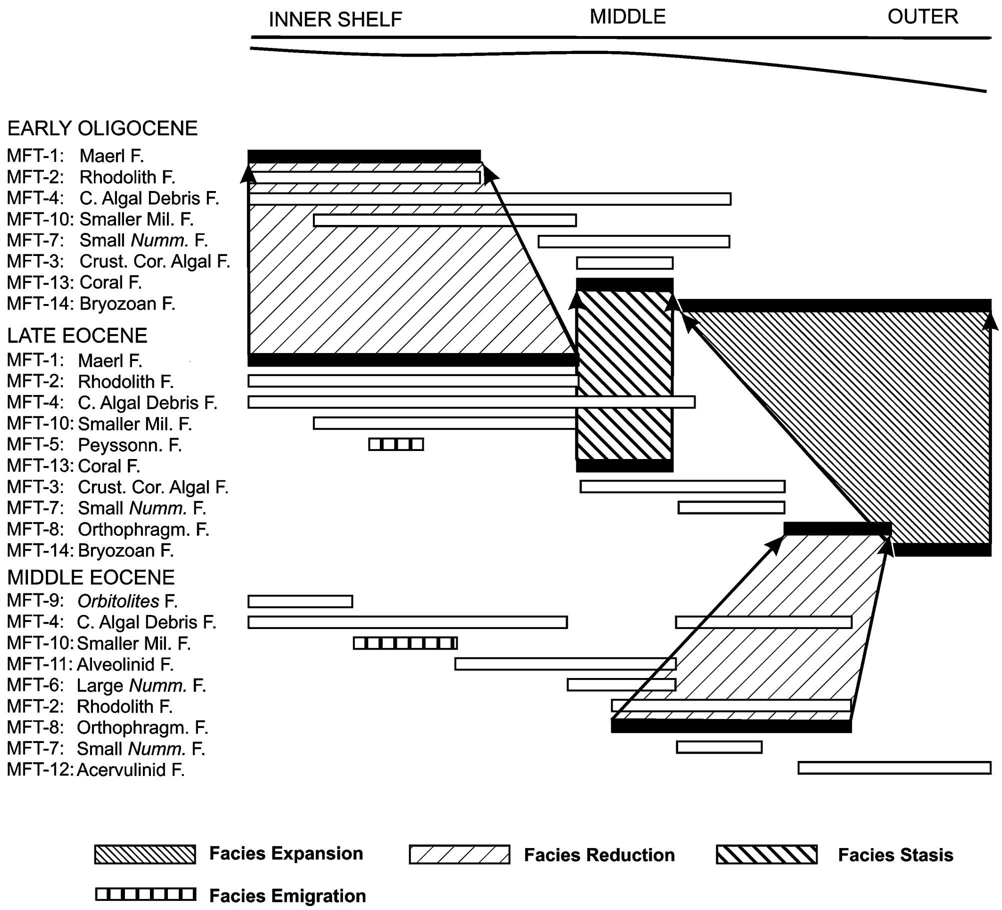
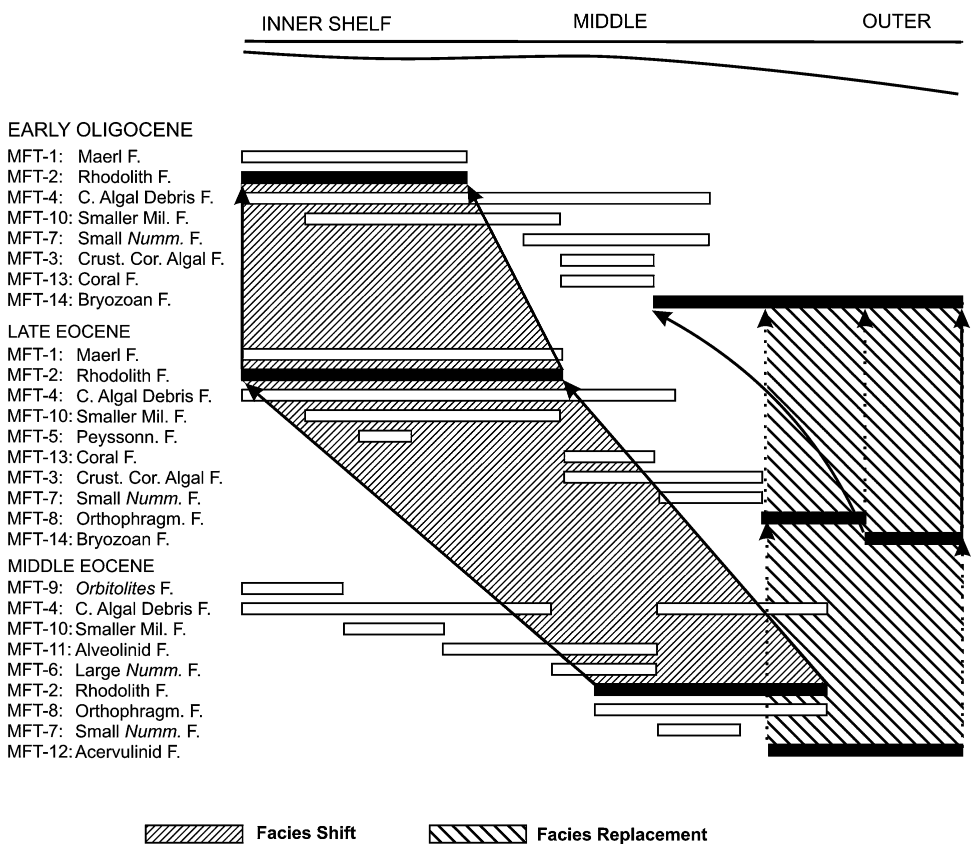


Fig. 7 Facies development of facies shift and replacement. See Fig. 4 for abbreviations



Notes: As for facies origination, there can be several causes for facies extinction such as the outright extinction of the taxon in question, a reduced relative abundance of the dominant biota without recovery, or a reduced relative abundance of the dominant growth form.

Facies immigration

Definition: Immigration of an already existing facies into an area. Facies immigration implies that the facies in question already existed in another depositional area before appearing in the study area.

Examples: Three facies types which appear in the Late Eocene are known from older deposits of the studied areas (Fig. 5). These facies are the Peyssonneliacean Facies (MFT-5; e.g., Moussavian 1984), the Coral (MFT-13) and the Bryozoan Facies (MFT-14). Especially coral- and bryozoan-dominated facies types are known from various occurrences world-wide even since the Paleozoic (Kiessling et al. 1999, 2003). The Smaller Miliolid Facies (MFT-10) appears again in the Early Oligocene after having disappeared at the Middle Eocene/Late Oligocene boundary.

Notes: This process depends especially on paleobiogeographic factors, such as changing paleogeographic conditions and the formation of appropriate ecosystems that had been absent before. Too little data is known about the Maerl (MFT-1) and Crustose Coralline Algal Facies (MFT-3) both of which appear in the Late Eocene in the study area to judge whether they immigrate from surrounding areas or represent facies origination (see above).

Facies emigration

Definition: Disappearance of a facies in an area without global disappearance. These correspond to Major Facies Types, which continue to exist, but outside the study area.

Examples: Both the Peyssonneliacean (MFT-5) and Smaller Miliolid Facies (MFT-10) are present in the Middle Eocene but disappear in the study area in the Late Eocene (Fig. 6). These are not caused by extinction as they are common within other coeval occurrences in the Tethys (e.g., Caus 1976; Drobne 1979; Travé et al. 1996; Romero et al. 2002) or in later stages (e.g., Henson 1950). The Smaller Miliolid Facies, in fact, returns to the study area in the Early Oligocene (Ungaro 1978).

Notes: This process is caused by changing ecological conditions within the area of study and is thus of regional importance. It may be caused by the disappearance of appropriate ecosystems due to paleoceanographic and local climatic (e.g., upwelling, nutrients) or geological aspects (e.g., sediment influx, tectonics). Ecological replacement by competitive immigrants can also lead to facies immigration.

Facies expansion

Definition: Spatial expansion of a facies along an environmental gradient through time. This is accompanied by the disappearance, emigration, reduction, or shift of another MFT (see below).

Examples: The Small *Nummulites* Facies (MFT-7) shows an on-shore expansion from the Middle Eocene to the Early Oligocene (Fig. 6). The Bryozoan Facies (MFT-14) also shows an onshore expansion in the same time span (Fig. 6).

Notes: The expansion of a dominating biotic component into an geographic adjacent areas will be governed by the presence of appropriate ambient ecological conditions (e.g., nutrients, light, substrate) as well as by other MFTs that already occupy these areas in the sense of ecological competition of the dominating components.

Facies reduction

Definition: Spatial reduction of a facies along an environmental gradient through time.

Examples: The Orthophragminid Facies (MFT-8) shows an off-shore reduction from the Middle to the Late Eocene (Fig. 6). The Maerl Facies (MFT-1) is reduced on-shore in the Early Oligocene (Fig. 6).

Notes: This process can be related to a gradual reduction of the importance of a facies delimiting component through time. This can eventually lead to total extinction (as in orthophragminids), or may reflect general changes in environmental conditions within the specific study area.

Facies stasis

Definition: Static spatial position of a facies within a particular depositional environment through time.

Examples: The Crustose Coralline Algal Facies (MFT-3) and Coral Facies (MFT-13) are static in their position along the shelf from the Late Eocene to Early Oligocene (Fig. 6). The overall position of the Coralline Algal Debris Facies (MFT-4) is more or less static with slight on-shore reduction in the Late Eocene with a slight off-shore expansion in the Early Oligocene (Fig. 6).

Notes: see comments concerning facies expansion.

Facies shift

Definition: Spatial shift of a facies along an environmental gradient through time.

Examples: The Rhodolith Facies (MFT-2) show a shift from the outer/middle to the inner shelf in the Late Eocene and finally even more landward in the Early Oligocene (Fig. 7). The Orthophragminid Facies (MFT-8) reveals a slight off-shore facies shift (as well as a facies reduction) from the Middle to Late Eocene (Fig. 7). The Small *Nummulites* Facies (MFT-7) reveals a slight on-shore shift as well as an expansion in the Early Oligocene (Fig. 7).

Notes: This represents a combination of different processes defined above. A shoreward shift results from a corresponding onshore expansion and offshore reduction of facies position; an basinward shift results from a corresponding offshore expansion and reduction of facies position.

Facies replacement

Definition: Spatial replacement of one facies by another through time – necessarily accompanied by disappearance, emigration, reduction, or shift of the replaced facies.

Examples: The Bryozoan Facies (MFT-14) not only replaces the Acervulinid Facies (MFT-12) from the Middle to Late Eocene but also the Orthophragminid Facies (MFT-8) from the Late Eocene to Early Oligocene (Fig. 7). The immigrating Coral Facies (MFT-13) and Crustose Coralline Algal Facies (MFT-3) replace the Large *Nummulites* Facies (MFT-6) and Alveolinid Facies (MFT-11) in the middle Shelf from the Middle to Late Eocene (Fig. 7). The Orthophragminid Facies (MFT-8) is partially replaced by the Crustose Coralline Algal Facies (MFT-3) from the Middle to the Late Eocene (Fig. 7).

Notes: As in facies shift, this category results from a combination of different processes.

Facies dynamics in the study area

Five major patterns showing combined processes of facies dynamics take place in the study area between the three designated time slices.

1. This facies shift of the Rhodolith Facies (MFT-2) from the outer/middle to the inner shelf from the Middle to the Late Eocene follows the disappearance of the *Orbitolites* Facies (MFT-9), Large *Nummulites* Facies (MFT-6) and Alveolinid Facies (MFT-11) at the Middle/Late Eocene boundary due to the extinction of their respective major components.
2. In the middle shelf, the disappearance of Large *Nummulites* Facies (MFT-6) and Alveolinid Facies (MFT-11) is accompanied by a replacement with the first appearance of the Coral Facies (MFT-13) and Crustose Coralline Algal Facies (MFT-3) in the Late Eocene.
3. The Orthophragminid Facies (MFT-8) shows an off-shore facies shift (as well as a facies reduction) from the Middle to Late Eocene accompanied by an immigration of and partial replacement by the Crustose Coralline Algal Facies (MFT-3).
4. The Small *Nummulites* Facies (MFT-7) shows an on-shore expansion from the Middle Eocene to the Early Oligocene, probably because of the on-shore facies reduction of the Rhodolith Facies (MFT-2).
5. The appearance and expansion of the Bryozoan Facies (MFT-14) is accompanied by two instances of facies disappearance linked to component extinction. The appearance of the Bryozoan Facies (MFT-14) at the outer shelf in the Late Eocene is accompanied by the disappearance of Acervulinid Facies (MFT-12) at the Middle/Late Eocene boundary. The landward facies expansion of the Bryozoan Facies (MFT-14) during the Early Oligocene is facilitated by the disappearance of Orthophragminid Facies (MFT-8) at the Eocene/Oligocene boundary as these larger foraminifera go extinct. This expansion may have also been facilitated by changes in ecological conditions along the shelf gradient for example changes in temperatures of nutrient regimes at this boundary.

Discussion

The MFT patterns presented herein are based on the following data: (1) paleoenvironmental interpretations of the cited literature, which were based on vertical facies successions and paleoecological considerations, and (2) a most plausible distribution along a standardized carbonate platform model with the distribution of MFTs between two ecological end members: the inner-most highest-energetic inner shelf, on the one hand, and the lower photic zone of the outermost shelf, on the other. Based on this, standardized MFT patterns were defined by Nebelsick et al. (2003), which provided the base for a dynamic, integrative model for the distribution of facies types in time and space presented herein. The necessary generalization was possible due to the integration of carbonate facies data from different geological realms that were affected by different types and degrees of ecological and geological changes. Despite these differences, it is interesting to recognize that there are larger-scaled patterns recognizable over the whole study area.

One restriction that biases our model of facies dynamics on first glance may be the involvement of different taxonomic ranks and features. For example, the Coralline Algal Debris Facies is based both on a high taxonomic rank as well as on sediment type. The Large *Nummulites* Facies is based on a higher generic rank, whereas the Acervulinid Facies based on the dominance of a single species. This ambiguity is based on the vastly different potential for identification of different taxa in thin section, but also on differing taxonomic concepts for some groups (i.e., coralline algae, some larger foraminifera). Two aspects, however, justify the definition of Major Facies types as well as an analysis of their changes through time based on differing taxonomic levels: (1) this study reflects the taxonomic state of research and more detailed data are not available; (2) each described MFT reflects a particular carbonate facies element that by itself is well known from many parts of the world and is easily recognizable even by non-specialists. Especially the latter aspect increases the usefulness of a dynamic facies concept, because it can be applied on a wide scale and allows global comparisons.

The dynamic facies concept presented here shows the importance of the biological developments for facies distribution of carbonate systems. These developments include the origination and extinction of specific taxa, the migration of taxa to different environments or geographic areas, changes in growth form morphologies and adaptation to new environments. Facies dynamics are highly controlled by phylogenetic aspects. Facies extinction is especially a direct consequence of the extinction of taxa in the study area. It is important to note, however, that the origination of one facies does not automatically correspond with the first appearance of the name-giving taxon – and the extinction of one facies is not necessarily caused by the extinction the dominant biota. Other aspects, especially the relative abundance of taxa (controlled by ecological factors) can play a more important role.

Spatial change of facies types does not necessarily imply a change of environmental conditions such as water depth. Organisms can adapt to different conditions through time and thus change their ecological distribution, which may or may not be seen in changes in taxonomic make-up within groups. Many of the observed changes in facies distribution may be due to combined factors driven both phylogenetically and ecologically. For example, the disappearance of one MFT by extinction of the dominating component can allow for the ecological expansion of another dominating component along with an accompanying change in the Major Facies Type.

The facies dynamics approach allows different areas from varying tectonic histories and exposure to be compared. The 13 different areas include for example the well, exposed largely undisturbed northern Italian outcrops, with the relatively undisturbed albeit subsurface data from the Molasse basement to the highly tectonized setting of the Lower Inn Valley or Gornji Grad Basin. These areas have, up till now, not been specifically compared with one another over their whole geographic and stratigraphic range. This former shortcoming is due not only to stratigraphic uncertainties, but also to the lack of detailed microfacies analysis, without which it is difficult to compare environmental settings. If facies patterns in a distinct time slice can be standardized, then deviations from this pattern between two localities can be used to discern variations in background ecological controlling factors be they abiotic or biotic in nature. For example, during the Early Oligocene, the facies pattern of the Gornji Grad area shows a lower facies diversity than those from the Monti Lessini. This difference is probably due to ecological controlling factors such as high terrigenous input (Nebelsick et al. 2000) which constrain the diversity of the Slovenian benthic communities and therefore the variation of facies present.

The most important tectonic development during this time is the isolation of the Paratethys from the Tethys in the Early Oligocene through the plate tectonic movements and the raising of the Alpine chain. This is reflected in a differentiation of facies development between north and south of the Alps. The Bryozoan Facies, for example, is present in the Lower Oligocene of the Lower Inn Valley (Nebelsick et al. 2001; Rasser and Nebelsick 2003), but missing in the Gornji Grad area of Slovenia (Nebelsick et al. 2000). The Slovenian carbonates conversely have a more diverse calcareous algal flora (10 genera, 12 species) than in the Lower Inn Valley (5 genera, 6 species) and a richer foraminiferal fauna including, for example, peneroplids which are typical for warm-water regions (e.g., Betzler et al. 1997). These variations in floral and faunal content as well as facies character may reflect differences in temperature and nutrient supply with lower temperatures and higher nutrients supply being present north of the nascent Alpine chain as reflected in the Lower Inn Valley than south of this barrier as seen in the Gornji Grad area. More detailed investigations over the whole study area with a comparison of specific components are needed, however, to support such general statements.

An important result of this study is the fact that the changes identified in this study usher in the modern pattern of carbonate facies and their distribution. Facies patterns in the Middle Eocene are clearly different than those present today while all the facies present in the Early Oligocene in the study area can be found in Recent environments. Although larger foraminifera are significant contributors to sediments in modern tropical carbonate environments (e.g., Reiss and Hottinger 1984; Hohenegger 2000), they do not dominated to the extent that they did in the Eocene as far as diversity and lateral extent of facies is concerned. The geometry of carbonate accumulations in the Eocene in extensive shoal-like accumulations (Arni 1965; Aigner 1983, 1985; Matteucci and Pignatti 1990) was thus radically different than the morphologically distinct build-ups dominated by scleractinian in present day coral reef environments. Coralline algae can also dominate and delimit facies in recent environments, but more so in non-tropical settings (e.g., Bosence 1985; Freiwald 1993, 1995; Freiwald et al. 1991) than in tropical environments. Carbonate shelves dominated by scleractinian coral reefs first become common during the Late Oligocene at least in the Caribbean area (Frost and Langenheim 1974; Kiessling et al. 2003). Extending the Facies Dynamic concepts to areas outside the study area should help to substantiate these statements.

As the Eocene/Oligocene boundary belongs to the most significant extinction events in the Phanerozoic, it is of interest to reflect how this event affected the make-up and distribution of facies patterns. As seen in this study, major changes of facies patterns are caused by the extinction events of larger foraminiferal taxa at the both the Middle Eocene/Late Eocene boundary (Hottinger 1983a; Aguirre et al. 2000) and at the Eocene/Oligocene boundary (Berggren and Prothero 1992; Prothero 2003). These extinction events are thus not restricted to a single boundary. Additionally, the extinction events are more important at the Middle Eocene/Late Eocene (four facies disappear) than at the Eocene/Oligocene boundary (one facies disappears). This may seem counterintuitive as the major climatic changes are known to occur at the Eocene/Oligocene boundary (Zachos et al. 1994, 2001). This pattern, however, is also seen in other faunal groups such as molluscs where different extinction patterns are known for warm-water and cool-water mollusc taxa particularly at the Middle/Late Eocene boundary with a loss of tropical taxa and drop in species richness (e.g., Hansen 1992; Nesbitt 2003).

The facies dynamics concept as presented here can be used as a tool to demonstrate how facies and their denominating components change in relative importance and position along a shelf gradient through time. These changes can then be related to global, regional or local controlling factors. It is shown in this study how carbonate facies react to major extinction events and other developments including the evolution of novel taxa or growth form strategies among existing taxa. The next step is to expand this concept to facies outside of the study area and to other time slices.

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References

Adey WH (1986) Coralline algae as indicators of sea-level. In: van de Plasche O (ed) Sea-level research: a manual for the collection and evaluation of data. Free Univ Geo Book, Norwich, pp 229–280

Aguirre J, Riding R, Braga JC (2000) Diversity of coralline red algae: origination and extinction patterns from the Early Cretaceous to the Pleistocene. Paleobiology 26:651–667

Aigner T (1983) Facies and origin of nummulitic buildups: an example from the Giza Pyramids Plateau (Middle Eocene, Egypt). N Jb Geol Paläontol Abh 166:347–368

Aigner T (1985) Biofabrics as dynamic indicators in nummulite accumulations. J Sediment Petrol 55:131–134

Antonelli R, Barbieri G, Dal Piaz GV, Dal Pra A, De Zanche V, Grandessa P, Mietto P, Sedea R, Zanferani A (1990) Note illustrative della carta geologica del Veneto 1:250.000. Regione Veneto, Dip Geol Paleont Geof Univ Padova, 31 pp

Arni P (1965) L'évolution des Nummulitinae en tant que facteur de modification des dépots littoraux. Mém Bur Rech Géol Min 32:7–20

Barbin V (1988) The Eocene–Oligocene transition in shallow-water environment: the Priabonian stage type area (Vicentin, Northern Italy). In: Premoli Silva I (ed) E/O meeting, Ancona, October 1987. Spec Publ Int Subcomm Paleogene Strat 2:163–171

Bassi D (1995) Crustose coralline algal pavements from Late Eocene Colli Berici of northern Italy. Riv Ital Paleont Stratigr 101:81–92

Bassi D (1997) Vegetative anatomy and paleoecology of *Polystrata alba* (Pfender) Denizot, 1968 (Cryptonemiales, Peyssonneliaceae) from the Upper Eocene of northern Italy. Rev Paléobiol 16:309–320

Bassi D (1998) Coralline algal facies and their palaeoenvironments in the Late Eocene of northern Italy (Calcare di Nago). Facies 39:179–202

Bassi D, Nebelsick JH (2000) Calcareous algae from the Lower Oligocene Gornji Grad Beds of Northern Slovenia. Riv Ital Paleont Stratigr 106:99–122

Bassi D, Woelkerling WJ, Nebelsick JH (2000a) Taxonomic and biostratographical re-assessment of *Subteranniphylum* Elliott (Corallinales, Rhodophyta). Palaeontology 43:405–425

Bassi D, Cosovic V, Papazzoni CA, Ungaro S (2000b) The Colli Berici. In: Bassi D (ed) Shallow water benthic communities at the Middle-Upper Eocene boundary. Southern and north-eastern Italy, Slovenia, Croatia, Hungary. Field trip guidebook of the 5th meeting IGCP 393 IUGS-UNESCO. Ann Univ Ferrara, Suppl Sci Terra, pp 43–57

Beavington-Penney SJ, Racey A (2004) Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. Earth-Sci Rev 67:219–265

Berggren WA, Prothero DR (1992) Eocene–Oligocene climatic and biotic evolution: an overview. In: Prothero DR, Berggren WA (eds) Eocene–Oligocene climatic and biotic evolution. Princeton University Press, Princeton, pp 1–28

Betzler C, Brachert T, Nebelsick JH (1997) The warm temperate carbonate province: facies, zonations and delimitations. Courier Forschinst Senckenberg 201:83–100

Bosellini A (1989) Dynamics of Tethyan carbonate platforms. In: Crevello PD, Wilson JL, Sarg JF, Read JF (eds) Controls on carbonate platform and basin development. SEPM Spec Publ 44:3–13

Bosellini FR (1998) Diversity, composition and structure of Late Eocene shelf-edge coral associations (Nago Limestones, Northern Italy). Facies 39:35–40

Bosellini FR, Russo A (1988) The Oligocene *Actinacis* coral community of the Southern Alps (Italy): temperature *vs*. terrigenous control. Proceedings of the 6th international coral reef symposium, Townsville, Australia, pp 385–391

Bosellini FR, Stemann TA (1996) Autoecological significance of growth form in the scleractinian *Actinacis rollei* Reuss (Oligocene, Lessini Mountains, Northern Italy). In: Cherchi A (ed) Autoecology of selected fossil organisms: achievements and problems. Boll Soc Ital Paleontol Spec Vol 3:31–43

Bosellini FR, Trevisani E (1992) Coral facies and cyclicity in the Castelgomberto Limestone (Early Oligocene, Eastern Lessini Mountains, Northern Italy). Riv Ital Paleontol Stratigr 98:339–352

Bosence DWJ (1983a) Description and classification of rhodoliths. In: Peryt TM (ed) Coated grains. Springer, Berlin, pp 217–224

Bosence DWJ (1983b) The occurrence and ecology of recent rhodoliths: a review. In: Peryt TM (ed) Coated grains. Springer, Berlin, pp 225–242

Bosence DWJ (1985) The "Coralligène" of the Mediterranean – a recent analog for Tertiary coralline algal limestones. In: Toomey DF, Nitecki MH (eds) Paleoalgology: contemporary research and applications. Springer, Berlin, pp 216–225

Bosence DWJ, Pedley HM (1982) Sedimentology and palaeoecology of a Miocene coralline algal biostrome from the Maltese Islands. Palaeogeogr Palaeoclimatol Palaeoecol 38:9–43

Bressan G, Nichetto P (1994) Some observations on the maërl distribution in the northern Adriatic Sea. Acta Adriat 35:15–20

Buxton MWN, Pedley HM (1989) A standardized model for Tethyan Tertiary carbonate ramps. J Geol Soc 146:746–748

Castellarin A (1972) Evoluzione paleotettonica sinsedimentaria del limite tra "Piattaforma veneta" e "Bacino lombardo" a nord di Riva del Garda. Giorn Geol 38:11–212

Cassinis G, Castellarin A (1988) Il significato delle linee della Gallinera e della Giudicarie sud nella geologia dell'Adamello e zone circostanti. Atti Ticinensi Sci Terra 31:446–462

Castellarin A, Cita MB (1969) La coupe priabonienne de Nago (Prov. Trento) et la limite Éocène-Oligocene. Mém Bur Rech Géol Min 69:93–117

Caus E (1976) Alguns macroforaminifers del Biarritzià català. Bull Inst Catal Hist Nat 40:23–29

Cita MB (1969) Le Paléocène et l'Eocène de l'Italie du nord. Mém Bur Rech Géol Min 69:417–429

Cita MB (1975) Stratigrafia della Sezione di Possagno. In: Bolli HM (ed) Monografia micropaleontologica sul Paleogene e l'Eocene di Possagno, Provincia di Treviso, Italia. Schweiz Paläontol Abh 97:9–32

Coletti F, Piccoli G, Sambugar B, Vendemiati Dei Medici MC (1973) I molluschi fossili di Castelgomberto e il loro significato nella paleoecologia dell'Oligocene veneto. Mem Inst Geol Min Univ Padova 28:1–32

Corsi M, Gatto GO (1967) 4, Tettonica. In: Bosellini A, Carraro F, Corsi M, De Vecchi GP, Gatto GO, Malaroda R, Sturani C, Ungaro S, Zannetin B (eds) Note Illustrative della Carta geologica d'Italia, Foglio 49 "Verona". Serv Geol Ital, pp 35–39

Cosovic V, Drobne K, Moro A (2004) Paleoenvironmental model for Eocene foraminiferal limestones of the Adriatic carbonate platform (Istrian Peninsula). Facies 50:61–75

Darga R (1992) Geologie, Paläontologie und Palökologie der südostbayerischen unter-priabonen (Ober-Eozän) Riffkalkvorkommen des Eisenrichtersteins bei Hallthurm (Nördliche Kalkalpen) und des Kirchbergs bei Neuberern (Helvetikum). Münchner Geowiss Abh A 23:1–166

Doglioni C, Bosellini A (1987) Eoalpine and mesoalpine tectonics in the Southern Alps. Geol Rundsch 77:734–754

Drobne K (1977) Alvéolines paléogènes de la Slovénie et de l'Istrie. Schweiz Paläontol Abh 99:1–132

Drobne K (1979) Paleocene and Eocene beds in Slovenia and Istria. In: Drobne K (ed) 16th European Micropaleontology Colloq, Ljubljana, pp 49–63

Drobne K, Pavlovec R, Drobne F, Cimerman F, Sikic L (1985) Some larger foraminifera from the Upper Eocene and basal Oligocene beds in north Slovenia. Geologica Glasnik, Herald Geol Bull 28:77–117

Ebner F, Sachsenhofer F, Schwendt A (1991) Das Tertiär von Kirchberg am Wechsel. Mitt Natw Ver Steiermark 121:119–127

Eichenseer H, Luterbacher HP (1992) The marine Paleogene of the Tremp region (NE Spain)—Depositional sequences, facies history, biostratigraphy and controlling factors. Facies 27:119–152

Fermont WJJ (1982) Discocyclinidae from Ein Avedat (Israel). Utrecht Micropaleontol Bull 27:1–173

Flügel E (2004) Microfacies of carbonate rocks, analysis, interpretation and application. Springer, Berlin

Fodor L, Jelen B, Márton E, Skaberne D, Car J, Vrabec M (1998) Miocene–Pliocene tectonic evolution of the Slovenian Periadriatic fault: implications for Alpine-Carpathian extrusion models. Tectonics 17:690–709

Frascari F (1963) La trasgressione priaboniana nel Vicentino orientale. Giorn Geol 30:219–231

Freiwald A (1993) Coralline algal maerl frameworks - Islands within the phaeophytic kelp belt. Facies 29:133–148

Freiwald A (1995) Sedimentological and biological aspects in the formation of branched rhodoliths in northern Norway. Beitr Paläontol 20:7–19

Freiwald A, Henrich R, Schäfer P, Willkomm H (1991) The significance of high-boreal to subarctic Maerl deposits in Northern Norway to reconstruct Holocene climatic changes and sea level oscillations. Facies 25:315–340

Frost SH (1981) Oligocene reef coral biofacies of the Vicentin, northern Italy. In: Toomey DF (ed) European fossil reef models. SEPM Spec Publ 30:483–539

Frost SH, Langenheim RL (1974) Cenozoic reef biofacies. Northern Illinois University Press, De Kalb

Garavello AM, Ungaro S (1982) Studio biostratigrafico e paleoecologico della serie eocenica di Pradipaldo nella zona pedemontana meridionale dell'Altipiano di Asiago (Vicenza). Geol Rom 21:655–675

Geel T (2000) Recognition of stratigraphic sequences in carbonate platform and slope deposits: empirical models based on microfacies analysis of Paleogene deposits in southeastern Spain. Palaeogeogr Palaeoclimatol Palaeoecol 155:211–238

Geister J, Ungaro S (1977) The Oligocene coral formations of the Colli Berici. Eclogae Geol Helv 70:811–823

Gohrbandt K (1963) Paleozän und Eozän des Helvetikums nördlich von Salzburg. In: Grill R, Kollmann K, Küppers H, Oberhauser R (eds) Exkursionsführer für das Achte Europäische Mikropaläontologische Kolloquium in Österreich. Geol Bundesanst, Vienna, pp 47–57

Hagn H (1981) Die Bayerischen Alpen und ihr Vorland in mikropaläontologischer Sicht. Geol Bavar 82:408

Hanfland C, Läufer AL, Nebelsick JH, Mosbrugger V (2004) The Paleogene Smrekovec Basin and related volcanism (Slovenia): sedimentology, geochemistry, and tectonic evolution. N Jb Geol Paläontol Abh 232:77–125

Hansen TA (1992) The patterns and causes of molluscan extinction across the Eocene/Oligocene boundary. In: Prothero DR, Berggren WA (eds) Eocene–Oligocene climatic and biotic evolution. Princeton University Press, Princeton, pp 341–348

Henson FRS (1950) Middle Eastern Tertiary Peneroplidae (Foraminifera) with remarks on the phylogeny and taxonomy of the family. PhD Thesis, University of Leiden, 70 pp

von Hillebrandt A (1993) Nummuliten und Assilinen aus dem Eozän des Krappfeldes in Kärnten (Österreich). Zitteliana 20:277–293

Hohenegger J (2000) Coenoclines of larger foraminifera. Micropaleontology 46:127–151

Hottinger L (1960) Recherches sur les Alvéolines du Paléocène et de l'Eocène. Schweiz Paläontol Abh 75–76:1–243

Hottinger L (1983a) Processes determining the distribution of larger foraminifera in space and time. Utrecht Micropaleontol Bull 30:239–253

Hottinger L (1983b) Neritic macroid genesis, an ecological approach. In: Peryt TM (ed) Coated grains. Springer, Berlin Heidelberg New York, pp 38–55

Hottinger L (1997) Shallow benthic foraminiferal assemblages as signals for depth of their deposition and their limitations. Bull Soc Géol France 168:491–505

Ivany LC, Nesbitt EA, Prothero DR (2003) The marine Eocene–Oligocene transition: a synthesis. In: Prothero DR, Ivany LC, Nesbitt EA (eds) From greenhouse to icehouse: the marine Eocene–Oligocene transition. Columbia University Press, New York, pp 522–534

Kiessling W, Flügel E, Golonka J (2002) Phanerozoic reef patterns. SEPM Spec Publ 72:774

Kiessling W, Flügel E, Golonka J (2003) Patterns of Phanerozoic carbonate platform sedimentation. Lethaia 36:195–226

Kiessling W, Flügel E, Golonka J (1999) PaleoReef maps: evaluation of a comprehensive database on Phanerozoic reefs. AAPG Bull 83:1552–1587

Lehner BL, Knappertsbush MW, Heer PH (1987) Biostratigraphy, lithostratigraphy and sedimentology of the Maiolica Lombarda and the Scaglia Lombarda on the West side of Lake Garda (northern Italy). Mem Sci Geol 34:1–35

Less G (1987) Paleontology and stratigraphy of the European Orthophragminae. Geol Hung (Palaeontol) 51:1–373

Luciani V (1989) Stratigrafia sequenziale del Terziario nella catena del Monte Baldo (Province di Verona e Trento). Mem Sci Geol 41:263–351

Luciani V, Barbujani C, Bosellini A (1988) Facies e cicli del Calcare di Nago (Eocene superiore. Trentino meridionale). Ann Univ Ferrara, NS 1(4):47–62

Massari F, Medizza F, Sedea R (1976) L'evoluzione geologica dell'Area euganea tra il Giurese superiore e l'Oligocene inferiore. Mem Inst Geol Min, Univ Padova 30:174–197

Matteucci R, Pignatti JS (1990) The taphonomy of *Nummulites*. In: Robba E (ed) Proceedings of the 4th symposium on ecology and paleoecology of the benthic communities, Sorrento 1988. Turin, Mus Reg Sci Nat Torino, pp 183–198

Mietto P (1988) Aspetti geologici dei Monti Berici. In: Signum P (ed) I Colli Berici. Natura e civiltà. Padua, Edizioni, pp 13–23

Moussavian E (1984) Die Gosau- und Alttertiär-Gerölle der Angerberg-Schichten (Höheres Oligozän, Unterinntal, Nördliche Kalkalpen). Facies 10:1–86

Nebelsick JH, Bassi D (2000) Diversity, growth-forms and taphonomy: key factors controlling the fabric of coralline algal dominated shelf carbonates. In: Insalaco E, Skelton PW, Palmer TJ (eds) Carbonate platform systems: components and interactions. Geol Soc Spec Publ 178:89–107

Nebelsick JH, Bassi D, Drobne K (2000) Microfacies analysis and palaeoenvironmental interpretation of Lower Oligocene, shallow-water carbonates (Gornji Grad Beds, Slovenia). Facies 43:157–176

Nebelsick JH, Stingl V, Rasser M (2001) Autochthonous facies and allochthonous debris flows compared: Lower Oligocene carbonates of the Lower Inn Valley (Tyrol, Austria). Facies 44:31–46

Nebelsick JH, Rasser M, Bassi D (2003) The development of facies patterns of Middle Eocene to Lower Oligocene circum-alpine shallow-water carbonate environments. In: Prothero DR, Ivany LC, Nesbitt EA (eds) From greenhouse to icehouse. The marine Eocene–Oligocene transition. Columbia University Press, New York, pp 471–491

Nesbitt EA (2003) Changes in shallow-marine faunas from the Northeastern Pacific Margin across the Eocene/Oligocene boundary. In: Prothero DR, Ivany LC, Nesbitt EA (eds) From greenhouse to icehouse. The marine Eocene–Oligocene transition. Columbia University Press, New York, pp 57–70

Ortner H, Singl V (2001) Facies and basin development of the Oligocene in the Lower Inn Valley, Tyrol/Bavaria. In: Piller WE, Rasser MW (eds) Paleogene of the Eastern Alps. Österr Akad Wiss Schriftenr Erdwiss Komm 14:153–196

Papazzoni CA, Sirotti A (1995) Nummulite biostratigraphy at the Middle/Upper Eocene boundary in the Northern Mediterranean area. Riv Ital Paleontol Stratigr 101:63–80

Papp A (1958) Vorkommen und Verbreitung des Obereozäns in Österreich. Mitt Geol Ges Wien 50:251–270
Placer L (1999) Contribution to the macrotectonic subdivision of the border region between Southern Alps and External Dinarides. Geologija 41:223–255
Pomerol C, Premoli-Silva I (1986) Terminal Eocene events. Developments and stratigraphy. Elsevier, Amsterdam
Prothero DR (2003) Pacific coast Eocene–Oligocene marine chronostratigraphy: a review and an update. In: Prothero DR, Ivany LC, Nesbitt EA (eds) From greenhouse to icehouse: the marine Eocene–Oligocene transition. Columbia University Press, New York, pp 1–13
Racey A (2001) A review of Eocene nummulite accumulations: structure, formation and reservoir potential. J Petrol Geol 24:79–100
Rasser MW (1994) Facies and palaeoecology of rhodoliths and acervulinid macroids in the Eocene of the Krappfeld (Austria). Beit Paläontol 19:191–217
Rasser MW (2000) Coralline red algal limestones of the Late Eocene Alpine Foreland Basin in Upper Austria: component analysis, facies and palecology. Facies 42:59–92
Rasser MW (2001) Influence of bottom stability and sediment input on growth forms of *Polystrata alba* (red algae) from the Late Eocene Alpine Foreland: a new tool for the reconstruction of sedimentary environments. Palaios 16:532–538
Rasser MW, Nebelsick JH (2003) Provenance analysis of allochthonous Oligocene coralline algal assemblages: a quantitative approach. Palaeogeogr Palaeoclimatol Palaeoecol 201:89–111
Rasser MW, Piller WE (1999a) Application of neontological taxonomic concepts to Late Eocene coralline algae (Rhodophyta) of the Austrian Molasse Zone. J Micropaleontol 18:67–80
Rasser MW, Piller WE (1999b) Lithostratigraphische Neugliederung im Paläogen des österreichischen Helvetikums. Abh Geol Bundesanst 56:699–712
Rasser MW, Piller WE (1999c) Die klassischen Profile des Paläogen des Haunsberg-Helvetikums (Salzburg): Die Typusprofile von Olching-Formation, Kroisbachgraben-Subformation, und Frauengrube-Subformation. Abh Geol Bundesanst 56:713–722
Rasser MW, Piller WE (2001) Paleogene of the Eastern Alps – an introduction. In: Piller WE, Rasser MW (eds): Paleogene of the Eastern Alps. Österr Akad Wiss Schriftenr Erdwiss Komm 14:5–11
Rasser MW, Piller WE (2004) Crustose algal frameworks from the Eocene Alpine Foreland. Palaeogeogr Palaeoclimatol Palaeoecol 206:21–39
Rasser MW, Less G, Báldi-Beke M (1999) Biostratigraphy and facies of the Late Eocene of the Western Austrian Molasse Zone with special reference to the larger foraminifera. Abh Geol Bundesanst 56:679–698
Reiss Z, Hottinger L (1984) The Gulf of Aqaba: ecological micropaleontology. Ecol Stud 50. Springer, New York
Rögl F (1998) Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). Ann Nathist Mus Wien 99A:297–310
Romero J, Caus E, Rosell J (2002) A model for the palaeoenvironmental distribution of larger foraminifera based on late Middle Eocene deposits on the margin of the South Pyrenean basin (NE Spain). Palaeogeogr Palaeoclimatol Palaeoecol 179:43–56
Schaub H (1981) Nummulites et Assilines de la Téthys Paléogène. Taxonomie, phylogénèse et biostratigraphie. Schweiz Paläontol Abh 104–106:1–236
Schmiedl G, Scherbacher M, Bruch A, Jelen B, Nebelsick JH, Hemleben H, Mosbrugger V, Rifelj H (2002) Paleoenvironmental evolution of the Paratethys in the Slovenian Basin during the late Paleogene. Int J Earth Sci 91:123–132
Schlager W (2003) Benthic carbonate factories of the Phanerozoic. Int J Earth Sci 92:445–464
Schweighauser J (1953) Mikropaläontologische und stratigraphische Untersuchungen im Paleocaen und Eocaen des Vicentin (Nord-Italien). Schweiz Paläontol Abh 70:1–97
Setiawan JR (1983) Foraminifera and microfacies of type Priabonian. Utrecht Micropaleontol Bull 29:1–161
Sirotti A (1978) Discocyclinidae from the Priabonian type section (Lessini Mountains, Vicenza, Northern Italy). Boll Soc Paleont Ital 17:49–67
Spence GH, Tucker M (1999) Modelling carbonate microfacies in the context of high-frequency dynamic relative sea-level and environmental change. J Sediment Res 69:947–967
Steininger FF, Wessely G, Rögl F, Wagner L (1986) Tertiary sedimentary history and tectonic evolution of the Eastern Alpine Foredeep. Gior Geol Ser 3, 48:285–297
Steneck RS, Macintyre IG, Reid RP (1997) A unique algal ridge system in the Exuma Cays, Bahamas. Coral Reefs 16:29–37
Stingl V (1990) Die Häringer Schichten vom Nordrand des Unterinntaler Tertiär Beckens (Angerberg/Tirol): Fazies, Sedimentpetrographie und beckengenetische Aspekte. Geol-Paläont Mitt Innsbruck 17:31–38
Tollmann A (1977) Geologie von Österreich 1. Deuticke, Vienna, 766 pp
Tollmann A (1985) Geologie von Österreich 2. Deuticke, Vienna, 523 pp
Trauth F (1918) Das Eozänvorkommen bei Radstadt im Pongau und seine Beziehung zu den gleichaltrigen Ablagerungen bei Kirchberg am Wechsel und Wimpassing am Leithagebirge. Denkschr KK Akad Wiss Wien, Math-Natw Kl 95:171–278
Travé A, Serra-Kiel J, Zamarreño I (1996) Paleoecological interpretation of transitional environments in Eocene carbonates (NE Spain). Palaios 11:141–160
Trevisani E (1997) Stratigrafia sequenziale e paleogeografia del margine orientale del Lessini Shelf durante l'Eocene superiore (Prealpi Venete, province di Vivenza e Treviso). Stud Trentini Sci Nat, Acta Geol 71:145–168
Ungaro S (1969) Étude micropaléontologique et stratigraphique de l'Éocene supérieur (Priabonian) de Mossano (Colli Berici). Mém Bur Rech Géol Min 69:267–280
Ungaro S (1978) L'Oligocene dei Colli Berici. Riv Ital Paleont 84:199–278
Ungaro S (1996) Adaptive morphological strategy of *Gypsina* (encrusting foraminifer). In: Cherchi A (ed) Autecology of selected fossil organisms: achievements and problems. Boll Soc Paleont Ital, Spec Vol 3:233–241
Ungaro S (2001) Le biofacies paleogeniche ed eoceniche dei Monti Lessini (Veneto, Italia). Ann Univ Ferrara, Sez Sci Terra 9:1–40
Ungaro S, Bosellini A (1965) Studio micropaleontologico e stratigrafico sul limite Eocene–Oligocene nei Colli Berici occidentali. Ann Univ Ferrara NS 9(3):157–183
Vogeltanz R (1970) Sedimentologie und Paläogeographie eines eozänen Sublitorals im Helvetikum von Salzburg (Österreich). Verh Geol Bundesanst 1970:373–451
Wagner L (1980) Geologische Charakteristik der wichtigsten Erdöl- und Erdgasträger der oberösterreichischen Molasse Teil I: Die Sandsteine des Obereozäns. Erdöl Erdgas Z 96:338–346
Wagner L (1996) Stratigraphy and hydrocarbons in the Upper Austrian Molasse Foredeep (active margin). In: Wessely G, Liebl W (eds) Oil and gas in alpidic thrustbelts and basins of Central and Eastern Europe. EAGE Spec Publ 5:217–235
Wagreich M (1995) Subduction tectonic erosion and late Cretaceous subsidence along the northern Austroalpine margin (Eastern Alps, Austria). Tectonophysics 242:63–78
Wilkens E (1989) Entstehung von Großforaminiferen-Akkumulationen, Biofabric-Entwicklung und Bioklastaggregaten im Alttertiär des Sonnberges. Arbeitstag Geol Bund, pp 100–106
Wilkens E (1991) Das zentralalpine Paläogen der Ostalpen: Stratigraphie, Sedimentologie und Mikrofazies Großforaminiferen reicher Sedimente (2 Anlagen). PhD Thesis, University of Hamburg
Wilson JL (1975) Carbonate facies in geologic history. Springer, New York
Zachos JC, Scott LD, Lohmann KC (1994) Evolution of early Cenozoic marine temperatures. Paleoceanography 9:353–387
Zachos J, Pagani M, Sloan L, Thomas E, Billups K (2001) Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292:686–693