Facies patterns, subsidence and sea-level changes in ferruginous and glauconitic environments: the Paleogene Helvetic shelf in Austria and Bavaria

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Abstract: The Paleogene Helvetic Shelf in Austria and Bavaria comprises a variety of siliciclastic and carbonate pelagic and shallow water sediments. The shallow water carbonates, which are characterized by ferruginisation and glauconitisation, are unique in the Eastern Alps. Five carbonate facies as well as four biota-bearing siliciclastic facies can be differentiated. In general, carbonate and siliciclastic facies contain the same components, characterized by coralline algae, nummulitid and orthophragminid foraminifera, ooids, and subordinate smaller foraminifera.

The Paleocene comprises pure siliciclastic Danian to Thanetian sediments, with the first ferruginous particles in the Thanetian. These sediments are overlain by massive Thanetian algal limestones, which are characterized by glauconitisation without ferruginisation. Heavy ferruginisation started in the Ypresian. The main ferruginous particles are larger foraminifera and ooids. Glauconitisation is particularly absent during the Ypresian. Only the Lutetian carbonate facies reveals a co-occurrence of glauconitisation and ferruginisation.

The facies patterns can be related to tectonic events in the Helvetic Zone, sea-level changes and subsidence. The Paleocene of the eastern part of the Helvetic Zone is characterized by a low subsidence rate and a relative sea-level fall until the Thanetian. From the Thanetian to the Early Ypresian, a relative sea-level rise occurred, but the subsidence rate is still as low as during the whole Paleocene. An angular disconformity between Paleocene algal limestones and Eocene ferruginous foraminiferal limestones corresponds to a tectonic event ('Laramide 3') at the Paleocene/Eocene boundary. During the Middle Ypresian, another relative sea-level fall occurred, despite an increasing subsidence rate. This regression is terminated at the Ypresian/Lutetian boundary, which corresponds to the end of the Laramide tectonic phase. From the Lutetian to the Priabonian, the relative sea-level rose continuously, with a distinctly increasing subsidence rate starting at the Lutetian/Bartonian boundary.

Zusammenfassung: Der helvetische Schelf wird im Paläogen von Österreich und Bayern durch eine Vielfalt von siliziklastischen und karbonatischen Sedimenten charakterisiert, die in unterschiedlichen Wassertiefen abgelagert wurden. Die Seichtwasserkarbonate sind durch ihre Eisenvererzung und Glaukonitisierung einzigartig in den Ostalpen. Fünf Karbonatfazies und vier biogenführende silizi-

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klastische Fazies können unterschieden werden. Die wichtigsten Karbonatkomponenten sind coralline Rotalgen, nummulitide und orthophragminide Großforaminiferen, Ooide und - untergeordnet – Kleinforaminiferen.

Das Paleozän wird durch rein siliziklastische Sedimente vom Danium bis zum Thanetium bestimmt. Noch im Thanetium werden die Siliziklastika durch mächtige Algenkalke überlagert, die glaukonitisiert sind aber keine Eisenimprägnierung aufweisen. Starke Eisenvererzung beginnt mit dem Ypresium, wobei Großforaminiferen und Ooide die stärkste Vererzung zeigen. Glaukonitisierung fehlt im Ypresium. Allein die Karbonatfaziesbereiche des Lutetium zeigen sowohl Glaukonitisierung als auch Eisenvererzung.

Die Faziesverteilung kann aus dem Zusammenspiel der tektonischen Entwicklung der Helvetischen Zone, dem eustatischen Meeresspiegel und der lokalen Subsidenzrate erklärt werden. Im Paleozän herrschten im Ostteil der Helvetischen Zone geringe Subsidenzraten und ein relativer Meeresspiegelabfall bis ins Thanetium. Vom Thanetium bis ins Frühe Ypresium kam es zu einem relativen Meeresspiegelanstieg, die Subsidenz war aber immer noch so gering wie während des gesamten Paleozäns. An der Paleozän/Eozän-Grenze kam es zu einer Winkeldiskordanz zwischen den paleozänen Algenkalken und den eisenvererzten Foraminiferenkalken des Eozäns, die zeitlich mit einem tektonische Ereignis ('Laramische Phase 3') übereinstimmt. Im Mittleren Ypresium kam es erneut zu einem Meeresspiegelabfall bei zunehmender Subsidenzrate. Die daraus resultierende Regression findet an der Ypresium/Lutetium-Grenze ihr Ende, die mit dem Ende der Laramischen tektonischen Phase zusammenfällt. Vom Lutetium an kommt es zu einem kontinuierlichen Meeresspiegelanstieg bis in das Priabonium, eine deutlich zunehmende Subsidenz ist ab der Lutetium/Bathonium-Grenze zu beobachten.

Keywords: Carbonate Facies Patterns, Glaucony, Ferruginisation, Paleogene, Helvetic Shelf, Eastern Alps

Contents

1. INTRODUCTION

The Helvetic Zone in Austria and Bavaria was part of the Helvetic Shelf and as such part of the Alpine Foreland. This foreland was formed by subduction of the European Plate under the African – Adriatic Plate during the Alpine orogeny (PREY, 1980; WAGNER, 1998; KURZ et al., this volume). During the Paleogene a wide carbonate platform with characteristic shallow water carbonate sediments was developed in the Helvetic Zone of Austria and Bavaria. Similar sediments are also known to the west from Switzerland (HERB, 1988) and from the Waschberg Zone in Austria to the east (SEIFERT, 1980).

These sediments are characterized by the most intensive ferruginisation and glauconitisation known from Cenozoic shallow water carbonates of the Eastern Alps and by ooidal limestones otherwise rare in the Paleogene (VOGELTANZ, 1970; OBERHAUSER, 1995). Although these sediments show a wide distribution and are well known from literature, their occurrences are scarce due to Alpine tectonics and the knowledge on their nature and origin is particularly poor.

The current study aimed to investigate the carbonate facies of the eastern part of the Helvetic Zone and the factors influencing their distribution. We present a detailed documentation and analysis of the shallow water carbonate occurrences in Vorarlberg, Bavaria, Salzburg, and Upper Austria. The discussion focuses on the carbonate platform geometry, the meaning of ferruginisation and glauconitisation, as well as on the relationships between facies patterns, tectonics, sea-level changes, and subsidence. Finally, we present an interpretation of the subsidence history in the study areas and a reconstruction of the Thanetian to Lutetian depositional environments.

2. MATERIAL, METHODS AND NOMENCLATURE

We studied ca. 350 thin sections from all known localities of the Helvetic Zone in Austria from which Paleogene shallow water carbonates have been reported. Additionally, we studied representative occurrences from Bavaria. Samples are stored at the Institute of Geology and Paleontology, Karl-Franzens-University of Graz, Austria.

Carbonate nomenclature was used after DUNHAM (1962) and EMBRY & KLOVAN (1972), which can be well applied to ironstones (YOUNG, 1989a). All terms referred to iron and ferruginised allochems used in the current paper are summarized by YOUNG (1989a; see also FLÜGEL, 1982, for related carbonate components); ironstones are rocks of greater than 15 wt. % iron; ooids are spherical or ellipsoidal grains, less than 2 mm in diameter, having one or more regular concentric laminae covering any nucleus; spastoliths are plastically deformed ooids; peloids are grains of fine-grained material, up to several mm in diameter, without recognizable internal structure. We additionally use the prefix 'iron-' in order to indicate that an allochem is ferruginous (e.g., iron-ooid, iron-peloid). Bioclasts are fragmented fossils, unfragmented equivalents are termed biota (compare FLÜGEL, 1982). The term sand/sandstone refers to quartzsand/-sandstone, while 'arenitic' refers to sandy grain size (compare TUCKER, 1985).

Nomenclature of glauconitic sediments is used after ODIN & MATTER (1981) and FISCHER (1990). ODIN & MATTER pointed to the nomenclatural problem that 'glauconite' is a mineral species, which is not necessarily the main mineral in green grains; therefore, the authors suggested the application of the term 'glaucony' to the facies. Glaucony grains are classified according to FISCHER (1990): authigenic glaucony, also called primary glaucony, is formed in situ (autochthonous); perigenic glaucony was subjected to short transportation (parautochthonous); allogenic glaucony, also called detrital or secondary glaucony, was formed elswhere (allochthonous).

3. GEOLOGICAL BACKGROUND AND PALAEOGEOGRAPHY

The geology of the Helvetic Zone in Austria (Eastern Helvetic Zone), was summarized by PREY (1980: 189 ff.), TOLLMANN (1985: 300 ff.), OBERHAUSER (1995), and KURZ et al. (this volume). The Helvetic Zone was named after its prominent development in Switzerland, north of the Rhone-Rhine valley. In Austria, sediments of the Helvetic Zone show a more or less continuous development from the Jurassic to the Late Eocene. Comparable successions are known from the adjacent central Helvetic Zone in Switzerland (HERB, 1988), as well as from the Waschberg Zone in the East (SEIFERT, 1980). Towards the south, the Helvetic Zone grades into the Ultrahelvetic Zone.

The development of the Helvetic shelf was influenced by the Alpine orogeny. Collisional processes caused subduction of the European Plate below the African – Adriatic Plate within the Penninic Realm. The subduction caused the formation of the Alpine Foreland Basin with a more or less E – W striking basin axis and a corresponding E – W striking shore line (PREY, 1980; WAGNER, 1998). Sedimentation in the Helvetic Zone ceased in the Late Eocene, when it was completely overthrusted by the northward moving Alpine nappe system (HAGN, 1981).

A generalized section of the Helvetic Zone shows Danian to Upper Thanetian siliciclastic pelagic sedimentation, followed by uppermost Thanetian algal limestones. They are overlain by Ypresian to Lutetian ferruginous larger foraminifera limestones and siliciclastic sediments. Deep marine conditions occur from the Bartonian to the Priabonian; they are characterized by the marly "Stockletten" (Traub, 1938, 1953; Vogeltanz, 1970; Hagn, 1981; Prey, 1983, 1984), which are represented by 'globigerinid marls' in Vorarlberg (Bertle et al., 1986). Sedimentation ceased at the Eocene/Oligocene boundary.

Most authors suggest that the Paleogene Helvetic shelf as well as the adjacent Ultrahelvetic Zone and Rhenodanubian Flysch Zone were morphologically structured by several submarine swells and island chains. The northernmost one was represented by the Intrahelvetic Swell (Hagn, 1954, 1981; Vogeltanz, 1970), which separated a Northern (Adelholzen facies) and a Southern (Kressenberg facies) Helvetic facies unit. Emersion of this swell from latest Maastrichtian to Middle Eocene time caused a sedimentary gap in the Northern Helvetic Zone, while sedimentation continued in the Southern Helvetic Zone (Hagn, 1981: 48). The Pre-Vindelician island chain (Traub, 1953: 33) marked the transition from the Helvetic Zone into the Ultrahelvetic Zone. The Ultrahelvetic Zone is again subdivided into a Northern Ultrahelvetic Facies, characterized by marls, and a Southern Ultrahelvetic Facies, characterized by carbonate-free clays (Hagn, 1981: 40). The Southern Ultrahelvetic Facies was separated from the adjacent turbiditic Flysch Zone by the Cetic Island Ridge (Hagn, 1960, 1981: 40).

4. STUDY AREAS AND STATE OF RESEARCH

A general overview on the Helvetic Zone in Austria has been presented by Prey (1980), Tollmann (1985) and Oberhauser (1995), a lithostratigraphic overview has been given by Rasser & Piller (1999a), including newly defined lithostratigraphic units. The studied occurrences and additional localities mentioned in the text are shown in Fig. 1.

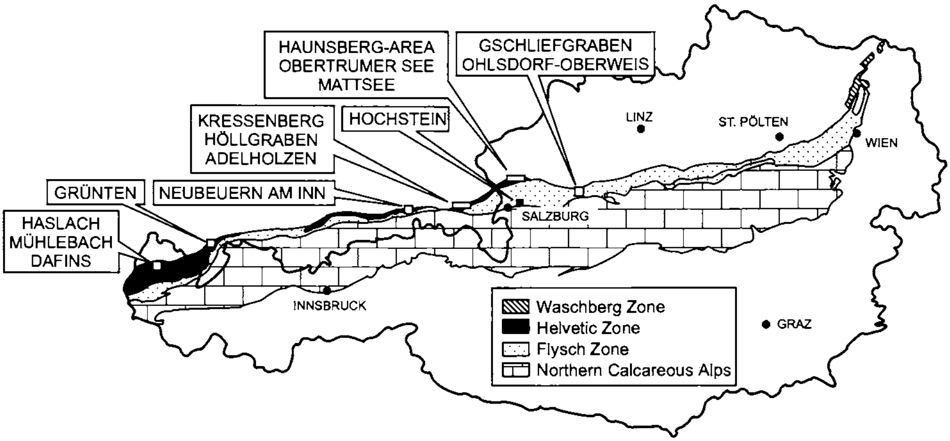


Fig. 1: Study areas and other localities mentioned in the text.

4.1. Vorarlberg

The carbonates of Vorarlberg are poorly studied. An overview was given by Richter (1978), Bertle et al. (1986), and Oberhauser (1991, 1995).

Most occurrences of the Helvetic Zone in Vorarlberg are tectonically isolated; all of them are considered to be part of the Southern Helvetic facies. Only at the Mühletobel, near Dafins (Oberhauser, 1991: 24) does a measurable section exist. Isolated blocks of nummulite limestones are reported from the Sünseralpe (Felber & Wyssling, 1979), the Dornbirner Ach between Dornbirn and Gütle (Richter, 1978: 67; Bertle et al., 1986: 9), Mühlebach (Bertle et al., 1986: 9), Bad Haslach (Bertle et al., 1986: 9, 10; Friebe, 1995a, 1995b), as well as the Steckenweg at Breitenberg – Klienfelsen, next Hohenems (Bertle et al., 1986: 10). We visited all of these localities, but today Paleogene limestones crop out only at the localities Mühletobel – Dafins, Mühlebach, and Bad Haslach.

4.2. Bavaria

Classical studies were carried out in the Kressenberg area by, e.g., Gümbel (1861) and Schlosser (1925), followed by those of Hagn (1967, 1981), Hagn & Wellnhofer (1973), and Ziegler (1975, 1983). Only a few publications deal with other Bavarian localities, such as Grünten (Reis, 1926; Ziegler, 1983) and Neubeuern am Inn (Hagn & Darga, 1989).

Outcrops with both Northern and Southern Helvetic sediments are reported from Bavaria. The locality Höllgraben near Adelholzen (Hagn, 1981: 130) represents the main occurrence of the Northern Helvetic facies. The other most important localities of Bavaria, Sonthofen–Grünten (Reis, 1926; Ziegler, 1983), Neubeuern am Inn (Hagn & Darga, 1989), Katzenloch (Hagn, 1981: 115), as well as Kressenberg (Hagn, 1981: 99, cum. lit.) are part of the Southern Helvetic facies. We only studied the most typical localities: Adelholzen, Katzenloch, and Kressenberg. The localities Grünten and Neubeuern widely correspond to the facies of Kressenberg, however, general knowledge is poor (for review Rasser & Piller, 1999a).

4.3. Salzburg

Overviews were given by Gohrbandt (1963) and Vogeltanz (1970). Biostratigraphic studies were conducted by Gohrbandt (1963), Kuhn & Weidich (1987), and Kuhn (1992), lithological and palaeontological studies by Götzinger (1936), Traub (1938, 1953, 1990), Vogeltanz (1968, 1970, 1972), Tichy (1980), and Rasser & Piller (1999b). Documentations of macrofossils are presented in Moosleitner (1988), Merbeler (1988), and Schultz (1998).

Sediments of the Northern Helvetic Zone are reported from Nußberg, north of the Haunsberg. All other studied localities are part of the Southern Helvetic facies. The best studied area is the Haunsberg including the localities Kroisbach, Frauengrube, sand pit Schlößlbruch, Schlößlfelsen, as well as some less important localities (Traub, 1953, 1990; Vogeltanz, 1970, Kuhn, 1992; Rasser & Piller, 1999b). Due to the ESE – WNW striking direction of the Helvetic Zone in this area, the occurrence of the Haunsberg continues into the area around Obertrumer See and Mattsee (Vogeltanz, 1970). As the facies patterns at the eastern localities are similar to the Haunsberg (Vogeltanz, 1970), where a complete succession is cropping out, the current study is restricted to the latter. Another important, but small-scaled and poorly studied, locality is the Hochstein at the Heuberg, east of the town Salzburg. It is assigned to the Southern Helvetic facies (Prey, 1980).

4.4. Upper Austria

Paleogene Helvetic carbonates in Upper Austria are highly isolated. Only two areas with occurrences of loose blocks are known: Ohlsdorf-Oberweis N' of Gmunden (Prey, 1984) and Gschliefgraben SSE' of Gmunden (Prey, 1983). Although the localities are well described, the loose blocks of Ohlsdorf-Oberweis could not be found. Two localities with loose limestone blocks are described from the Gschliefgraben: Gaisrücken and Lidringgraben (Northern Helvetic facies); the blocks of Gaisrücken, however, are currently not exposed. The only Paleogene section of the Gschliefgraben area is known from the Rote Kirche (Southern Helvetic facies).

5. REMARKS ON BIOSTRATIGRAPHY

The algal limestones of the Fackelgraben Mb. ('Unterer Lithothamnienkalk') were previously assigned to the Late Paleocene (Hagn, 1981). Latest results on biostratigraphy of the Haunsberg and Kressenberg area were published by Kuhn (1992). He found evidence for an Early Eocene age, based on planktic foraminifera. This was an unexpected result, since all other algal limestones of the Helvetic Zone are of Late Paleocene age – except those reworked in the Late Eocene 'Stockletten' (Darga, 1992). Kuhn (1992) defined the Paleocene/Eocene boundary by the last appearance of *Morozovella velascoensis*, which corresponds to the zonal scheme of Berggren et al. (1995). However, Kuhn points out that *M. subbotinae*, another biostratigraphically important species, does not occur.

Recent results of J. Egger (Egger, unpublished data), however, again revealed a Thanetian age based on calcareous nannoplankton (NP 9) from marly interlayers of the Fackelgraben Mb. As this coincides with other studies on algal limestones of Dafins (Oberhauser, 1991), Kressenberg (Hagn, 1981) and the adjacent Waschberg Zone (Seifert, 1980), we consider the Fackelgraben Mb. to be of Late Paleocene age.

6. RESULTS

6.1. Sedimentary components

Siliciclastic components are dominated by poorly to well rounded, arenitic quartz grains (Pl. 1, Figs. 5–8). Lithoclasts are very rare.

Only ferruginous **ooids** are known, non-ferroan ooids do not occur. Fe-ooids can be multi- or unilayered (Pl. 1, Figs. 1–4). The nuclei, which are represented by siliciclastics or bioclasts, are always Fe-impregnated. Composite grains composed of ooids can occur (Pl. 1, Fig. 2); these grains show multiple ooidal layers.

Composite grains with an amorphous, ferruginous binding agent, can be composed of ooids and bioclasts (Pl. 1, Fig. 2). They can be coated by ferruginous laminae.

Rhodoliths are defined as unattached nodules with a size of >2 cm (Adey, 1986) which predomantely (>50%) consist of calcareous red algae (Bosellini & Ginsburg, 1971; Bosence, 1983; Adey, 1986). Nuclei are represented by bioclasts. Rhodoliths are mostly laminar and are composed of encrusting coralline algae, peyssonneliacean algae, encrusting acervulinid foraminifera, as well as rare encrusting bryozoans (Pl. 2, Fig. 1). Their diameter can reach more than 5 cm.

Algal debris is represented by fragmented coralline algae. They can be well to poorly rounded, their size ranges from fine-arenitic to (rarely) ruditic (Pl. 2, Figs. 2, 3; Pl. 1, Figs. 5, 6, 8). Debris of other algae is unknown.

Larger foraminifera are dominated by nummulitids (Pl. 2, Figs. 4–6), usually accompanied by orthophragminids (Pl. 2, Figs. 5, 6). The latter can also dominate some samples. The shapes of both nummulitids and orthophragminids range from small lenticular (Pl. 2, Fig. 6; Pl. 1, Fig. 7) to large (up to >5 cm) discoidal tests (Pl. 2, Fig. 5). Chambers can show glaucony cements. Larger foraminifera are frequently impregnated by Fe (Pl. 1, Fig. 4), especially in reworked specimens. Other larger foraminifera are not abundant; they are represented by unidentified, fragmented, rotaliids.

Smaller foraminifera are generally rare in the studied samples, only globigerinids can be locally important (Pl. 2, Figs. 7, 8). Textulariids and miliolids (Pl. 2, Fig. 2) are especially rare and are not characteristic for any facies.

Besides algae and foraminifera, pycnodont bivalves can be locally abundant, especially in the Kroisbach Mb. of the Haunsberg and at the base of the Fackelgraben Mb. Additional biota are fragmented encrusting bryozoans, isolated serpulids, as well as rare fragmented corals.

6.2. Glauconitisation and ferruginisation

Authigenic glaucony is represented by arenitic grains with a characteristically cracked habit (Fischer, 1987), as well as by glaucony cement; the latter is usually restricted to chambers of foraminifera and bryozoans. Detritic glaucony is also arenitic, but characterized by rounded, elongated grains. Colors vary from brightish green to dark, brownish green under the microscope.

Iron impregnations are abundant in the foraminifera dominated facies. Ferruginisation is known from all types of bioclasts, as well as from peloids; the matrix is never affected by ferruginisation. Fractures within siliciclastic grains can also be ferruginized. Ferruginisation and iron coatings of unrounded bioclastics lead to well rounded components.

6.3. Facies

Based on the abundance of above described sedimentary features, we were able to distinguish nine different facies. The characterization of the particular facies and the relative abundance of components are summarized in Tab. 1 and 2.

	Rhodoliths	Algal debris	Nummulitids / Orthophragminids	Other larger foraminifera	Smaller foraminifera	Bryozoa	Terrigenics	Authigenic glauconite	Ooids	Fe-impregnations
Rhodolith Facies	++++	+++	(++)		(+)	+	(+)	+		
Algal Debris Facies		++++	(++)		(+)	(+)	(++)	(+)		
Algal Debris Sandstone Facies		++	(+)				++++	(+)		(+)
Larger Foraminifera Facies		(+)	++++	(+)	(+)	(+)	(+)	(+)	(+)	(++)
Foraminiferal Sandstone Facies		(+)	++				++++	(+)		(++)
Foraminifera-Ooid Sandstone Facies			++				++++		++	++
Ooid Facies							(+)		++++	++
Ooid Sandstone Facies							++++		++	(++)
Smaller Foraminifera Facies					++++			+		(+)

Tab. 1: Carbonate facies of the eastern part of the Helvetic Zone and relative abundance of sedimentary features. Brackets indicate that the mentioned features do not occur in all samples.

6.3.1. Rhodolith facies

Nomenclature: Rhodolith floatstones and rudstones, partly terrigenous, with nummulitid-orthophragminid grainstone-packstone matrix or bioclastic packstone-grainstone matrix.

Description: Main components are rhodoliths with a diameter of up to 5 cm. Nummulitids and orthophragminids can be up to 30 mm in diameter and are unfragmented. Additional components are other larger rotaliid foraminifera and smaller foraminifera, especially textulariids. Fragmented bryozoa and siliciclastic components can occur, detritic and authigenic glaucony is always present. Ooids are absent (Pl. 2, Fig. 1).

Occurrence: Basal part of the Dafins section, Haunsberg (Fackelgraben Member), Hochstein.

Comparisons: The facies of Dafins differs from the other occurrences by the terrigenous components. Facies features of Haunsberg and Hochstein are highly similar.

Stratigraphy: Thanetian (chapter 5).

6.3.2. Algal debris facies

Nomenclature: Coralline algal packstones and grainstones (Pl. 2, Figs. 2, 3).

Description: Main components are arenitic, fragmented, partially rounded algal fragments, as well as small nummulitids and orthophragminids in some samples. Siliciclastics are rarely abundant. Additional components are bryozoan fragments (Pl. 2/3) and authigenic glaucony. Smaller foraminifera are rare, globigerinids are known from one sample of the Gschliefgraben area. Fe-ooids are absent, detritic glaucony is restricted to one sample of the Dafins profile.

Occurrence: Dafins, Katzenloch, Kressenberg (Fackelgraben Member), Hochstein, Lidringgraben (Gschliefgraben).

Comparisons: Authigenic glaucony is restricted to Dafins. Samples from Kressenberg are characterized by terrigenous components and by the absence of foraminifera; in contrast, samples of Hochstein contain nummulitids and orthophragminids, but lack siliciclastic components. The Gschliefgraben locality is also characterized by siliciclastic components, but larger foraminifera are restricted to a few samples.

Stratigraphy: Thanetian (chapter 5); biostratigraphic data from Katzenloch, Hochstein and Lidringgraben are missing, but most probably they represent the same age as the rhodolith facies. Eocene algal limestones are not known from the Helvetic Zone.

6.3.3. Larger foraminifera facies

Nomenclature: Nummulitid-orthophragminid grainstones-packstones or nummulitid-orthophragminid floatstones-rudstones with nummulitid-orthophragminid grainstone-packstone matrix or with bioclastic packstone-grainstone matrix (Pl. 2, Figs. 4–6).

Plate 1

Fig. 1: Ooid facies. Sample kress 98-02-3. Image width: 7.5 mm.

Fig. 2: Ooid facies showing a composite grain composed of ooids and an unidentified foraminifera, bound together by an amorphous ferruginous binding agent. Sample kress 7. Image width: 2 mm.

Fig. 3: Ooid facies showing a peloid with small siliciclastic grains incorporated. Sample kress 98-2-3. Image width: 2 mm.

Fig. 4: Ooid facies showing ooids and a part of an impregnated nummulitid. Sample hau 98-3a. Image width: 2 mm.

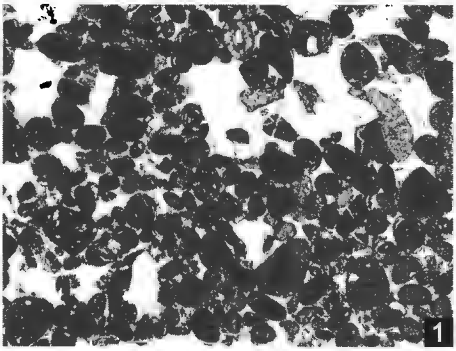
Fig. 5: Ooid sandstone facies. Sample cr 1. Image width: 7.5 mm.

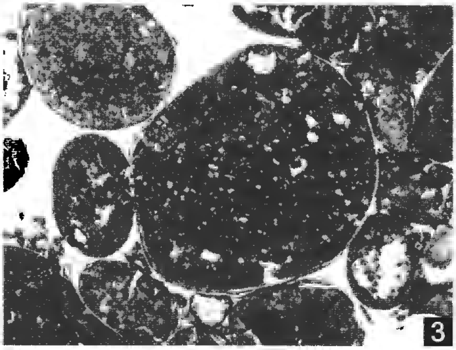
Fig. 6: Foraminifera-ooid sandstone facies. Sample hau 98-1a. Image width: 7.5 mm.

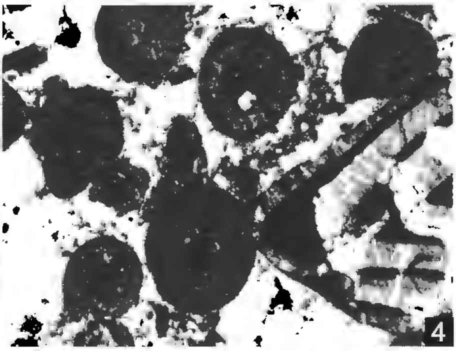
Fig. 7: Foraminifera sandstone facies. Note the more lenticular tests compared to the Larger foraminifera facies. Sample hau 98-5a. Image width: 7.5 mm.

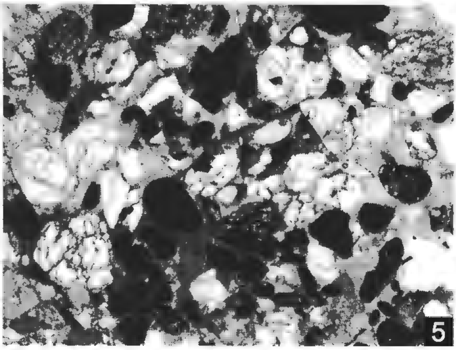
Fig. 8: Algal debris sandstone facies. Sample gsl 98-1h. Image width: 7.5 mm.

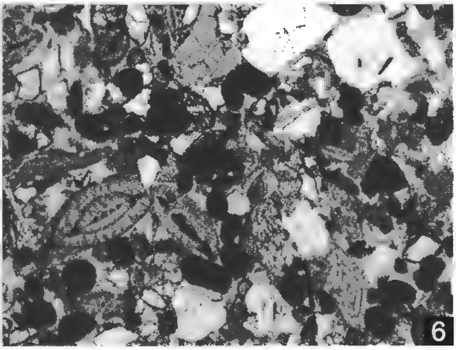
Plate 1

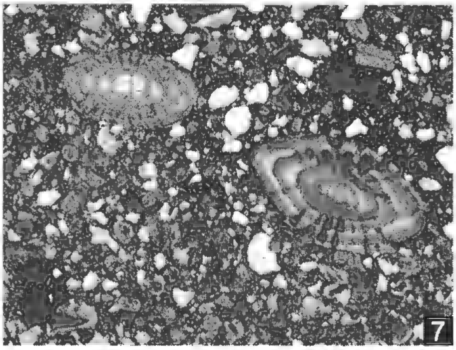


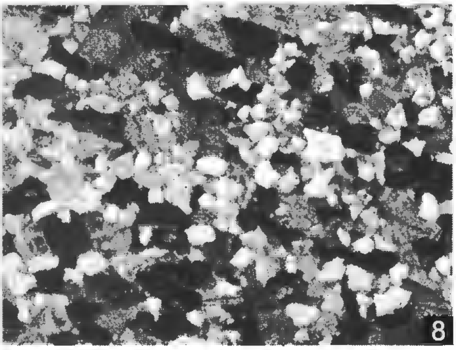












Description: Main components are nummulitids and orthophragminids with a diameter of up to >40 mm; unfragmented foraminifera are predominantely large with flat tests. Siliciclastics can occur. Additional components are unidentified small rotaliid foraminifera, fragmented bryozoans, as well as authigenic and detritic glaucony. Ooids are restricted to a few samples of Hochstein and Haunsberg. Smaller foraminifera are usually absent. Ferruginisation of bioclasts can be locally abundant.

Occurrence: This is the most widespread facies. It is known from all localities, except Dafins.

Comparisons: Ferruginisation is absent in Mühlebach, and in a few samples of Haslach, Katzenloch, Höllgraben, and Lidringgraben. In Kressenberg and Haunsberg, glaucony is restricted to Kressenberg and Weitwies Mb., respectively; they also show ferruginisation. Nummulitids and orthophragminids of the locality Katzenloch are predominantely flat and large (>40 mm), those from Vorarlberg are mostly lenticular and only up to 20 mm in diameter. Occurrences in Vorarlberg and Hochstein lack siliciclastic components. The Northern Helvetic occurrence of Höllgraben-Adelholzen contains the largest nummulitids known from the study area (Pl. 2, Fig. 5); Fe-impregnations are absent, but glaucony occurs. Generally, the samples of Höllgraben correspond to those of other Lutetian larger foraminifera facies (Kressenberg, Salzburg localities, Katzenloch), although ferruginisation occurs in localities of Kressenberg and Salzburg.

Stratigraphy: Ypresian and Lutetian. The occurrences of Vorarlberg are expected to represent Ypresian to Lutetian age (Bertle et al., 1986), but biostratigraphic data are missing. The occurrences of Katzenloch and Höllgraben represent Lutetian age (chapter 6.4.2); both Ypresian and Lutetian ages are known from the Kressenberg area and from Salzburg (Rasser & Piller, 1999a cum. lit.). The larger foraminifera facies of the Rote Kirche (Gschliefgraben) most probably represents Lutetian age (chapter 6.4.4).

Plate 2

Fig. 1: Rhodolith facies, showing detail of a laminar rhodolith. Image width: 7.5 mm. Sample hau 14.

Fig. 2: Algal debris facies with miliolid smaller foraminifera. Sample gsl 98-1-b2. Image width: 7.5 mm.

Fig. 3: Algal debris facies with a bryozoan bioclast at the lower left part and a sparitic groundmass. Sample katz 98-g2. Image width: 7.5 mm.

Fig. 4: Larger foraminifera facies of the Southern Helvetic Zone in the Kressenberg area showing nummulitid foraminifera. Sample kress10. Image width: 7.5 mm.

Fig. 5: Larger foraminifera facies of the Northern Helvetic Zone. Sample holl 3. Image width: 7.5 mm.

Fig. 6: Larger foraminifera facies of the Southern Helvetic Zone in Vorarlberg. Sample vbg 98-2g. Image width: 7.5 mm.

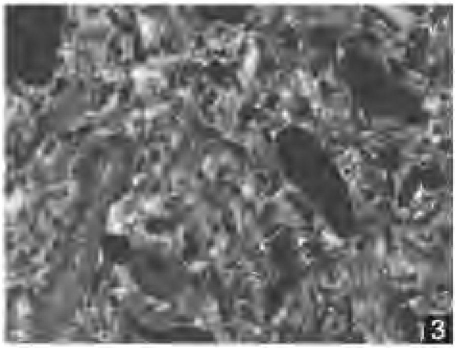
Fig. 7: Smaller foraminifera facies. Sample daf 98-10. Image width: 7.5 mm.

Fig. 8: Detail of fig. 7 showing poorly preserved globigerinid foraminifera. Sample daf 98-10. Image width: 2 mm.

Plate 2


1


2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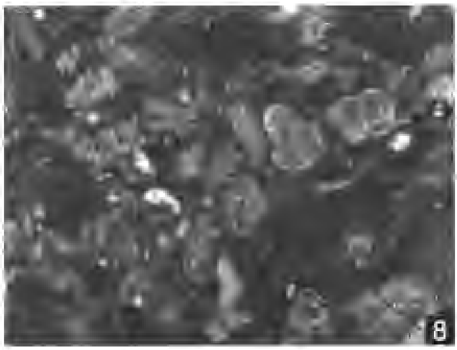

8

6.3.4. Smaller foraminifera facies

Nomenclature: Smaller foraminifera packstones (Pl. 2, Figs. 7, 8).

Description: Main components are unidentified bioclasts. Globigerinid foraminifera are never abundant but characterize most samples of this facies. Unidentified, fragmented hyaline foraminifera can also be abundant. Additional components are authigenic and detritic glaucony, which is present in all samples. Ferruginisation is rare.

Occurrence: Haslach, Mühlebach, Dafins, and Rote Kirche (Gschliefgraben)

Comparisons: Fe-impregnations are restricted to the Rote Kirche.

Stratigraphy: The smaller foraminifera facies in Vorarlberg is not dated but gradually develops from Thanetian (NP 9) rhodolith facies (OBERHAUSER, 1995). Also the age of the other occurrences is unknown.

6.3.5. Ooid facies

Nomenclature: Fe-ooid grainstone (Pl. 1, Figs. 1–4).

Description: Main components are multilayered ooids and ferruginised, fragmented bioclasts (mostly larger foraminifera), as well as large, flat unfragmented larger foraminifera; the latter are never ferruginised. The nuclei of ooids are difficult to recognize due to ferruginisation. Peloids can be abundant; they are well rounded, small siliciclasts can be incorporated (Pl. 1, Fig. 3). The ooid nuclei are arenitic with irregular shapes; they are represented by fragmented bioclasts or rarely siliciclasts. Composite grains with an amorphous, ferruginous binding agent can be composed of ooids and bioclasts. Siliciclastic components are present in most samples. Glaucony is absent.

Occurrence and Comparisons: Restricted to Kressenberg and Haunsberg; samples show the same sedimentary features.

Stratigraphy: Ypresian (RASSER & PILLER, 1999a cum. lit.).

6.3.6. Ooid sandstone facies

Nomenclature: Quartzsandstone with Fe-ooids and carbonate cement (Pl. 1, Fig. 5).

Description: Main components are poorly rounded siliciclastic grains. Additional components are multilayered ooids, peloids, and unidentified non-ferruginized bioclasts. Bivalves are abundant in one sample.

Occurrence: Restricted to Haunsberg (Kroisbach Member).

Stratigraphy: Thanetian (RASSER & PILLER, 1999a cum. lit.).

6.3.7. Foraminifera-ooid sandstone facies

Nomenclature: Quartzsandstone with larger foraminifera and Fe-ooids (Pl. 1, Fig. 6).

Description: Beside siliciclastic components, nummulitids, orthophragminids, ooids and peloids can be locally abundant. The unfragmented larger foraminifera are small and lenticular. Ferruginisation of bioclasts occurs.

Occurrence: Haunsberg (Frauengrube Member and Kressenberg Mb.) and Kressenberg (Sankt Pankraz Mb.).

Stratigraphy: Ypresian and Lutetian (Fig. 2).

6.3.8. Foraminifera sandstone facies

Nomenclature: Quartzsandstone with larger foraminifera (Pl. 1, Fig. 7).

Description: Beside quartz grains, nummulitids and orthophragminids can be abundant. In a few samples, coralline algal fragments occur. Foraminifera are usually lenticular. Glaucony is rare, ferruginisation occurs in most samples.

Occurrence: Haslach, Katzenloch, Kressenberg, Haunsberg, Lidringgraben (Gschliefgraben).

Comparisons: All occurrences show almost similar sedimentary features. Coralline algal fragments are restricted to one sample of Katzenloch.

Stratigraphy: Ypresian to Lutetian age in Vorarlberg (chapter 6.4.1). The ages of the Bavarian (chapter 6.4.2) and Upper Austrian (chapter 6.4.4) occurrences are unknown. Ypresian and Lutetian ages are proven for localities in Salzburg (Fig. 2).

6.3.9. Algal debris sandstone facies

Nomenclature: Quartzsandstone with coralline algal debris (Pl. 1, Fig. 8).

Description: Arenitic coralline algal debris and a few small orthophragminids and nummulitids occur. Ferruginisation is absent.

Occurrence: Kressenberg (Fackelgraben Member), Haunsberg, Hochstein, Lidringgraben (Gschliefgraben).

Comparisons: Authigenic glaucony is restricted to Haunsberg and Lidringgraben.

Stratigraphy: The age of most occurrences is unknown (chapter 6.4), but most probably they represent synchronous facies equivalents of the Thanetian rhodolith facies. Eocene algal facies are unknown from the Helvetic Shelf.

6.4. Facies Distribution

Tab. 2 summarizes the spatial distribution of facies and the differences between the particular localities.

6.4.1. Vorarlberg

The **Dafins – Mühletobel** section represents the only measurable section of algal limestones in Vorarlberg and the facies has not yet been described. OBERHAUSER (1991: 24) reports NP 9 (Upper Paleocene) from a not defined marl layer within this section. According to OBERHAUSER (1995: 400), the algal limestones overlay the Wang Beds and grade distally into the Fraxen Greensands.

The 12 m long section starts with a two meters thick, unbedded, greyish coralline algal limestone made up of rhodolith facies. The basal part is characterized by rhodolith

	Vorarlberg			Bavaria			Salzburg		Upper Austria	
	Haslach	Mühlebach	Dafins	Katzenloch	Höllgraben	Kressenberg	Haunsberg	Hochstein	Lidringgraben	Rote Kirche
Rhodolith Facies			t, g				g	g		
Algal Debris Facies			g	▨		t		▨	t	
Algal Debris Sandstone Facies						▨	g	▨	g	
Larger Foraminifera Facies	g, (Fe)	g		t, g	g	Fe, t, g	Fe, t, (g)	(t), Fe	(t), g	Fe, g
Foraminiferal Sandstone Facies	Fe			(g), (Fe)		Fe	Fe		g, (Fe)	
Foraminifera-Ooid Sandstone Facies						Fe	Fe			
Ooid Facies						t, Fe	(t), Fe			
Ooid Sandstone Facies							(Fe)			
Smaller Foraminifera Facies	g	g	g							g, Fe

Tab. 2: Facies distribution in the described occurrences. t = terrigenous carbonate facies; g = contains authigenic glaucony; Fe = contains Fe-impregnation of biogenics. Brackets indicate that the mentioned features do not occur in all samples.

float- to rudstones with a bioclastic packstone matrix. Rhodoliths are dominated by the genus *Sporolithon*. The foraminifers *Acervulina ogormani* Douvillé and very rare specimens of *Haddonia heissigi* Hagn, as well as the peyssonneliacean red alga *Polystrata alba* Pfender, rare encrusting bryozoans and rare serpulids can contribute to the rhodoliths. One rhodolith nucleus is represented by a fragmented coral, other nuclei are not known. The bioclastic matrix is characterized by coralline algal fragments and small orthophraminids. Authigenic and detritic glaucony occur. Towards the upper part of this bed, rhodoliths become smaller and the matrix is dominated by microsparite; bioclasts in this part are characterized by fragmented coralline algae, bryozoans, corals, and small orthophragminids, as well as a few glaucony grains. A 60 cm thick dm-bedded limestone, composed of smaller foraminifera facies, follows after a not exposed interval of 1.10 m. It is represented by a globigerinid packstone with a low amount of siliciclastic grains. Components are dominated by planktic foraminifers as well as detritic and authigenic glaucony. A 10 cm thick bed, which follows over another not exposed interval of 90 cm, is characterized by the same facies, although well-rounded coralline algal detritus is also present. After another covered interval, an 8 m thick succession of a massive, dark greyish limestone with green sand layers and lenses in the upper part, characterizes the upper part of this section (smaller foraminifera facies). The facies is characterized by packstones, again often dominated by planktic foraminifers. Orthophragminids or textulariid foraminifera can occur in the middle part of this bed. Coralline algae are characterized by well-rounded detritus. Detritic and authigenic glaucony occurs.

Loose blocks in the river Mühletobel additionally bear algal debris facies, which could not be found in the studied section. Most probably it represents a lateral facies equivalent of the rhodolith facies.

Algal limestones in Vorarlberg are restricted to the described section of Dafins. All isolated occurrences are characterized by foraminifers, mostly by larger foraminifera. Iron-impregnations are almost restricted to secondary fractures; the biota are rarely impregnated and iron-ooids are absent. The larger foraminifera dominated facies widely correspond to those reported in the literature. According to OBERHAUSER (1991: 22) all nummulite beds of Vorarlberg are of Late Ypresian to Early Lutetian age.

The **Mühlebach** locality is characterized by the larger foraminifera facies and the smaller foraminifera facies. These facies correspond to the nummulite beds with *Assilina placentula* and pectinid beds reported by BERTLE et al. (1986: 9) and are interpreted to be of Ypresian to Lutetian age. At Mühlebach these limestones are represented by three, tectonically repeated, highly inclined, morphological ridges, surrounded by marly sediments. Topographically, the smaller foraminifera facies is overlain by larger foraminfera facies in all three ridges; the stratigraphical base could not be determined.

Limestones from **Bad Haslach** are characterized by the larger foraminifera facies, the smaller foraminifera facies, and the foraminifera sandstone facies. They correspond to the nummulite beds of BERTLE et al. (1986: 9) and OBERHAUSER (1991: 24; 1995: 407). OBERHAUSER (1991) reported *Assilina exponens* and *Nummuites gallensis*, which are interpreted as Ypresian to Lutetian in age. The limestones of Bad Haslach and Hohenems (the latter could not be found in the course of the current study) are surrounded by marls (NP 15–16, Middle to lowermost Upper Eocene); the contact between these marls and the limestones could, however, be of tectonic nature! The larger foraminifera facies is comparable with the Mühlebach locality.

6.4.2. Bavaria

The section of the **Kressengraben** in Bavaria (Fig. 2), near to Neukirchen/Siegsdorf, is a classical locality for the Paleogene of the Helvetic Zone (HAGN, 1981; KUHN, 1992) and is the type locality of the Kressenberg Formation (RASSER & PILLER, 1999a). The Paleocene Olching Fm. is at least 15 m thick, the base is not exposed. It is characterized by sandy marls with sandstone layers and glaucony accumulations; both the abundance of sandstone layers and the general carbonate content increase upsection. Beds in the topmost part are up to 0.5 m thick. The Olching Fm. is overlain by the Kressenberg Fm. The Kroisbach Member, which is the basal part of the Kressenberg Fm., is currently not exposed in the Kressengraben section. After this covered interval of ca. 3 m, the Fackelgraben Member is represented by 10 m thick algal detritus grainstone to packstone. Additionally, fragments of echinoderms, rare bryozoans and serpulids, as well as accumulations of bivalves occur. Foraminifera are particularly absent. In contrast to the Haunsberg area, the Fackelgraben Mb. of the Kressenberg is characterized by algal debris facies. The Frauengrube Member is characterized by siliciclastic Fe-ooid pack-

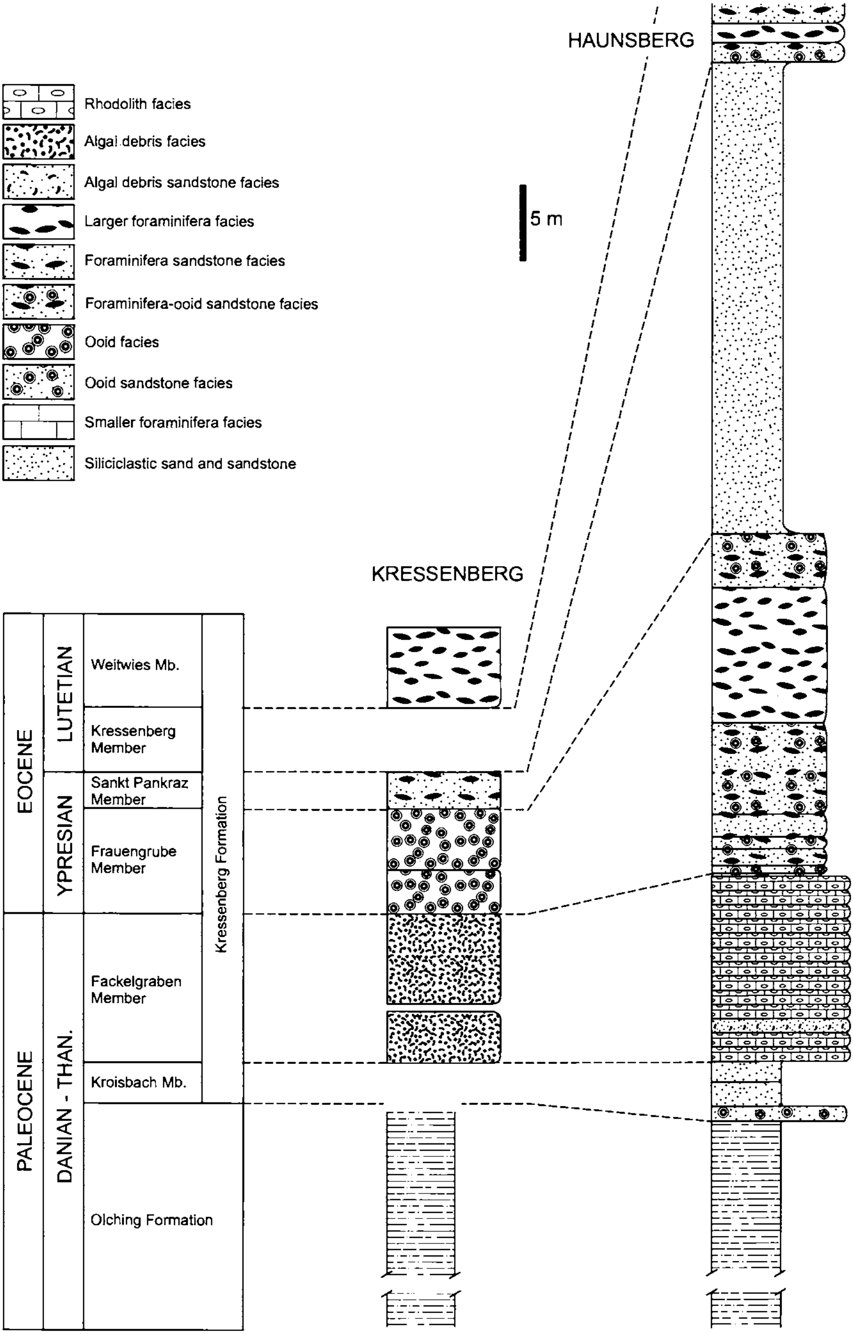


Fig. 2: Sections of the Kressenberg and Haunsberg area. After Rasser & Piller (1999a), but revised chronostratigraphic correlation.

stones (ooid facies), whereby the abundance of siliciclastics decreases upsection. Fe-impregnated orthophragminids and nummulitids can form local accumulations. The St. Pankraz Member is represented by coarse quartz sandstones with a red matrix, containing Fe-impregnated larger foraminifera and ooids (foraminifera-ooid sandstone facies); glaucony is absent. The Kressenberg Mb. represents one of the most characteristic sediments of the Kressenberg. It was mined for iron. However, to date, it is not exposed in the Kressengraben and could therefore not be regarded in the current study. The Weitwies Member is characterized by nummulitid packstones and floatstones (larger foraminifera facies). Only a few nummulitids show Fe-impregnations, ooids are rare. Both detritic and authigenic glaucony occurs; in the described section, it is restricted to this member.

Additionally, the foraminiferal sandstone facies is known from loose blocks; it could not be attributed to one of the studied members. Also the algal debris sandstone facies is known only from loose blocks; it is supposed to represent a facies analogue of the algal debris facies.

In loose blocks of the **Katzenloch** locality, the algal debris facies, the larger foraminifera facies, and the foraminiferal sandstone facies could be identified. Algal debris facies lacks siliciclastic components, larger foraminifera, and glaucony. The larger foraminifera facies contains siliciclastic components, authigenic glaucony and glaucony cement, as well as rare smaller foraminifera. Foraminifera sandstone facies could be found in only two samples; one contains Fe-impregnations and algal debris, the other authigenic glaucony. Facies of the loose blocks, which represent debris from a historical mine (REIS, 1898), were described by HAGN (1978: 186 ff.). The foraminiferal sandstone facies corresponds to the Kressenberg Mb. ('Schwarzerz-Schichten' of HAGN), the glauconitic larger foraminifera facies with the Weitwies Mb. ('Nebengestein' of HAGN). The algal debris facies was not described by the cited authors. We expect it to represent the equivalent of the Fackelgraben Mm in this area.

The **Höllgraben locality near Adelholzen** is characterized by poorly consolidated, glaucony bearing, larger foraminifera facies. This corresponds to the Upper Lutetian Middle Adelholzen beds of HAGN (1981: 130 ff.). The marly Upper Adelholzen beds (NP16 after HAGN, 1981: 131) were not found in the current study. They are referred to the Northern Helvetic Zone.

6.4.3. Salzburg

The described section of the **Haunsberg** area represents a composite profile (Fig. 2), combined from different localities (see also RASSER & PILLER, 1999a, b). Olching Fm., Kroisbach Mb., as well as the basal part of the Fackelgraben Mb., are outcropping in the Kroisbachgraben; the higher parts of the Fackelgraben Mb., the Frauengrube Mb., as well as the basal parts of the St. Pankraz Mb. are outcropping at the locality Frauengrube. The complete St. Pankraz Mb. is outcropping at its type locality, the Schlößlfelsen at St. Pankraz; the topmost part of the underlying Frauengrube Mb., as well as the basal part of the overlying Kressenberg Mb. are also exposed there. Finally, the basal parts of the Kressenberg Mb. are outcropping in the sand pit next to St. Pankraz. Parts of this section were described by VOGELTANZ (1970) and RASSER & PILLER (1999a, b).

The Olching Fm. represents an at least 57 m thick succession of well-bedded argillaceous marls with sand layers and lenses. Biota include molluscs, serpulids, and plant remains; trace fossils and corals are rare. The 3.8 m thick Kroisbach Mb., which represents the basal part of the Kressenberg Fm., is characterized by basal coarse quartzsandstones with calcite cements, Fe-ooids and brachiopods (formerly "Cranien-sandstein") which are overlain by coarse sands with glaucony (formerly "Gryphaeen-bank"). The Kroisbach Mb. is rich in pycnodont bivalves. The basal part is represented by ooid sandstone facies. The ca. 16 m thick Fackelgraben Mb. is dominated by rhodoliths, coralline algal debris, orthophragminids, and nummulitids (rhodolith facies); authigenic and detritic glaucony occur, terrigenous components, ooids, as well as Fe-impregnations are absent. The limestone is dm- to 50 cm-bedded with marl intercalations; thickness and abundance of these intercalations increase upward. The bedding thickness, as well as the bedding planes of algal limestones are very consistent throughout the Salzburg occurrences (Vogeltanz, 1970). The carbonate facies is dominated by rhodolith rudstones with grainstone and packstone matrix; only one bed at the base is composed of algal debris sandstone facies. Rhodoliths are dominated by encrusting coralline red algae; the encrusting foraminifer *Acervulina ogormani* and the peyssonneliacean red alga *Polystrata alba* occur subordinately.

The Frauengrube Mb. discordantly overlies the Fackelgraben Mb. with a >10° angular disconformity. Sediments of the Fackelgraben Mb. are reworked at the basal 20 cm of the Frauengrube Mm (Rasser & Piller, 1999b). The Frauengrube Mb. is characterized by ca. 22.5 m thick, red to brown, unbedded limestones. Main components are nummulitids, siliciclastics, Fe-ooids, and orthophragminids. Components are frequently Fe-impregnated, glaucony is absent. The carbonate facies is comparable to that of Kressenberg section, although Fe-ooids are particularly less abundant in the Haunsberg area. The basal ca. 10 m, as well as the topmost 2.5 m are represented by foraminifera sandstone facies and ooid sandstone facies. 10 m between them are composed of larger foraminifera facies. Glaucony is absent in the Frauengrube Mb. The Sankt Pankraz Mb. is completely different from the Kressenberg. In the Haunsberg area it is characterized by 31.5 m thick, weakly consolidated, well sorted quartz sands. The Kressenberg Mb. is characterized by more than 5 m thick limestones, terminated by a fault. It is composed of foraminifera-ooid sandstone facies, larger foraminifera facies, and foraminifera sandstone facies; in contrast to underlying units, the larger foraminifera facies of the Kressenberg Mb. contains authigenic glaucony. The topmost parts of this unit, as well as the overlying Weitwies Mb., are not outcropping today.

Additionally, the ooid facies, which is characteristic for the Frauengrube Mb. of the Kressenberg, but unknown from the described section of the Haunsberg, is known from loose blocks of the sand pit. It is not clear, whether it comes from the Frauengrube or Kressenberg Mb.

The **Hochstein at Heuberg**, east of the town of Salzburg, shows a relatively high facies diversity: rhodolith facies, algal debris facies, algal debris sandstone facies, and larger foraminifera facies were detected. Prey (1980: 296) gave an Eocene age for this section, biostratigraphical studies have not yet been conducted. According to Prey, this locality represents an undisturbed section, composed of 6 m thick algal limestones overlain by 5 m thick nummulite limestones. The rhodolith facies contains authigenic glaucony and corresponds to the rhodolith facies of the Haunsberg area. The algal debris facies contains larger foraminifera and lacks siliciclastic components and is therefore not comparable to any other algal debris facies of the studied areas. The larger foraminifera facies contains iron-impregnations and very rare ooids; it lacks siliciclastic components and glaucony. The succession can be compared with the occurrences of Kressenberg and Haunsberg. Facies composition suggests that algal bearing facies represents the Fackelgraben Mb., and the larger foraminifera facies may correspond to the Frauengrube Mb.

6.4.4. Upper Austria

A high variety of facies was found in the loose blocks of the locality **Lidringgraben** in the **Gschliefgraben** area. All samples of the algal debris facies contain siliciclastics, glaucony is absent; larger and smaller foraminifera are restricted to a few samples. Algal debris sandstone facies contains authigenic glaucony and larger foraminifera. The larger foraminifera facies contains siliciclastics and authigenic glaucony, but iron impregnations are absent. The foraminiferal sandstone facies contains authigenic glaucony and, in some samples, iron impregnations. These facies correspond to the sediments described by PREY (1983: 107, 117). PREY reported an Eocene age for this facies, but biostratigraphic data are missing. Due to the absence of iron impregnations in the larger foraminifera facies, it shows more similarities with the Northern Helvetic Zone, than with the Southern Helvetic Zone, in which foraminifera bearing facies always contain iron impregnations.

Only the larger foraminifera facies and the smaller foraminifera facies occur at the **Rote Kirche** locality. The larger foraminifera facies contains detritic glaucony, authigenic glaucony, and glaucony cement; in contrast to samples from the Lidringgraben, it contains iron impregnations and siliciclastics are rare. The smaller foraminifera facies shows iron impregnation of bioclasts, as well as detritic glaucony, authigenic glaucony, and glaucony cement. The locality Rote Kirche represents a section with several meters thick glauconitic marls and sandy marls, with ferruginous intercalations (PREY, 1983: 103). This section is Paleocene to Early Eocene in age and it is overlain by Early Eocene 'nummulite limestone' (larger and smaller foraminifera facies of the current study). The ferruginous intercalations, which are no longer outcropping and which therefore could not be studied here, are represented by 'iron oolites' and one 'iron-rich nummulite limestone'. PREY (1983: 105) reported NP 12 (Middle Ypresian) from the marly facies just below the 'nummulite limestone'. The marls and the ferruginous intercalations therefore represent facies analogues of the Frauengrube Mb. or/and the Sankt Pankraz Mb. The larger foraminifera facies of this locality can only be compared with the foraminifera facies of the Lutetian Weitwies Mb.

In the Gschliefgraben area, the glauconitic facies, which is characteristic for the Northern Helvetic Zone, is today situated south of the ferruginous sediments, characteristic for the Southern Helvetic Zone. This is in contrast to the general situation in Bavaria and Austria. Although the Gschliefgraben area is tectonically highly complex, PREY (1983: 125) refuses a tectonical explanation for this situation. Instead, he suggests that the present-day position corresponds to the Paleogene situation. This indicates, that sediments typical for the Northern Helvetic Zone can even be deposited south of those characteristic for the Southern Helvetic Zone (PREY, 1983).

7. DISCUSSION

The studied Paleogene sediments of the Helvetic Zone were deposited on the southern margin of the European Plate. Towards the south, they pass into deep water sediments of the Ultrahelvetic Zone and the Rhenodanubian Flysch Zone. Subduction of the European Plate below the Austroalpine nappe system took place in the Penninic Ocean. This succession from shallow water sediments in the north to deep water sediments in the south was probably caused by downbending due to tectonic loading of the Austroalpine nappe system (e.g., OBERHAUSER, 1980; KURZ et al., this volume). Such flexural downbending of the crust due to tectonic loading is typical for foreland basins and usually leads to the formation of carbonate ramps (AHR, 1973; READ, 1985; DOROBEK, 1995). The following environmental interpretations are based on facies patterns of a ramp, which are less influenced by sea-level changes compared to rimmed shelves (BURCHETTE & WRIGHT, 1992).

7.1. The meaning of ferruginisation

Crustose and oolithic ironstones can be formed in terrestrial (pedogenic) (SCHWARZ & GERMANN, 1993) or marine environments (VAN HOUTEN, 1992). Terrestrial ironstones are represented by crusts, ooids and pisoids, which can be transported into marine environments. They differ from marine equivalents by more complex internal structures and repeated coating of fractured pisoids (YOUNG, 1989a, for review). Most marine ironstones are represented by ooids and ferruginised allochems, like those of the current study. They are either formed in near-shore, partly lagoonal, environments, or in oolite bars (YOUNG, 1989a, for review).

Requirements for ironstone formation are (1) availability of iron, usually by lateritic weathering of sediments or igneous rocks in tropical/subtropical terrestrial environments, or by volcanic activities; (2) low sedimentation rate to prevent burying of iron particles; (3) shallow water depth; (4) oxigenic environments (YOUNG, 1989a, b; VAN HOUTEN, 1992; STURESSON et al., 2000).

For the current study, the iron source is represented by lateritic weathering of the crystalline hinterland, as suggested by VOGELTANZ (1970) and HAGN (1981). Although a few bentonites in Paleogene deep-water deposits of Austria indicate volcanic activities, the amount of iron introduced by volcanic activity can be expected to be insufficient (for discussion see EGGER et al., 1997). Low sediment supply is indicated by the absence of siliciclastics in most ferruginised rocks. Shallow water depths, associated with an oxigenic environment and high hydrodynamic energy, are indicated by the occurrence of oolites and well rounded ferruginized particles.

7.2. The meaning of glauconitisation

Glauconitisation is an intra-grain process (FISCHER, 1987). The starter material needs to be highly porous (either by primary porosity, fracturing, dissolution, or by borings). The original material disappears by dissolution. EHLMANN et al. (1963) and ODIN & MATTER (1981) point out that different genetic stages can occur within one sample. Glauconitisation requires a confinement, which produces a micro-environment which is different from the surrounding environment. Therefore, glauconitisation mostly starts in the inner parts of larger grains, which causes the internal cracks (ODIN & MATTER, 1981).

Climatic conditions seem to be negligible for glauconitisation (ODIN & MATTER, 1981). Biotic interaction is also not important, but water chemistry produced by organic matter plays a crucial role (HARDER, 1989). Main requirements are (1) availability of iron; detrital iron is supplied to the sea by streams, usually from lateritic weathering of the hinterland (HARDER, 1989), as well as by exhalations from volcanoes and rifts (ODIN & MATTER, 1981); (2) appropriate particles as precursors (e.g., bioclasts, siliciclasts) (ODIN & MATTER, 1981; FISCHER, 1987, 1990); (3) low sedimentation rates, because glauconitisation occurs close to the sediment – water interface of marine environments (ODIN & MATTER, 1981; FISCHER, 1987; HARDER, 1989); the break in sedimentation and the time required for glauconitisation is 10^3 to 10^6 years; (4) water chemistry: glauconitisation occurs in anoxic (HARDER, 1989) or at least low-oxygenated (ODIN & MATTER, 1981) marine waters; (5) low water energy, because a high water energy leads to well-oxygenated conditions; (6) water depth: today, glauconitisation occurs at 60–500 m, rarely down to 800 m water depth (ODIN & MATTER, 1981); in the tropics usually >125 m (PORRENGA, 1967); generally, a greater water depth is required, because it implicates low hydrodynamic energy and low sedimentation rate. The mode of glaucony formation is currently subject of discussion (CHAFETZ & REID, 2000).

The Paleogene was a time of widespread glaucony formation (ODIN & MATTER, 1981). Glauconitisation is typical for transgressional environments (ODIN & MATTER, 1981; FISCHER, 1987), because suitable starter material reaches a greater water depth with suitable low sedimentation rate and low oxygenation. Consequently, glauconitisation of typical shallow-water grains indicates a transgression. In contrast, glauconitisation of planktic foraminifera does not indicate transgression.

For the current study, the availability of iron and the required low sedimentation rate were discussed above, and starter material occurs in sufficient quantities in most rocks. Required low sedimentation rate is indicated by the absence of siliciclastic particles in most glauconitic rocks. Higher water depth, related to low water energy and – probably – to low oxygenation is reflected by the globigerinids associated with glauconitisation in the smaller foraminifera facies, as well as by the dominance of large, flat nummulitids and orthophragminids in the glaucony bearing parts of the larger foraminifera facies.

In summary, glauconitisation and ferruginisation have several requirements in common. Both of them require iron availability and low sedimentation rates. The main differences are that glauconitisation only occurs in low energetic, low oxygenic environments of deeper water, whereas ferruginisation occurs in well oxygenated, higher energetic environments.

7.3. Sea-level changes, tectonics and subsidence

Shallow water facies distribution is primarily controlled by sediment input, subsidence rate, and sea-level changes; sediment accomodation space is controlled by a combination of regional tectonics and eustatic sea-level changes (HAQ et al., 1988). This chapter discusses the possible influence of Paleogene sea-level changes and regional tectonics on the studied facies patterns.

7.3.1. Tectonics

The Paleogene was a time of ongoing orogeny in the Eastern Alps. The overthrusting of the Austroalpine nappe system onto the European Plate caused subsidence in the Alpine Foreland. The question arises, to which extent the Helvetic shelf and its carbonate systems were influenced by Alpine tectonic events, and which sedimentary/geological features observed in the current study can be explained by tectonics.

The Helvetic Zone was separated from the Eastern Alps by the Penninic trough. During the Cretaceous, subduction started in the Penninic Unit, which lasted until the Late Eocene. OBERHAUSER (1980) differentiated between an older Alpidic phase, ranging from the middle Cretaceous to the Late Eocene (Eoalpine orogeny, WAGREICH, 1995, cum. lit.), and a younger Alpidic phase (Mesoalpine to Neoalpine), starting with the Late Eocene. The Alpine Gosau Group reflects continuous sedimentation from Paleocene to Early/Middle Eocene without distinctive tectonic events (WAGREICH, 1995). This coincides with the 'Laramide orogenic phase' (TOLLMANN, 1964: 240; ZIEGLER, 1987), which represented a time of minor nappe thrusting and cannot be recognized in the Austroalpine Realm, but in the Helvetic Zone.

The classification of Laramide phases after TOLLMANN (1964) is of relevance for the current study, since the 'Laramide 3' (TOLLMANN, 1964), characterized by turbidites in the Ultrahelvetic Zone, is the only event that corresponds to the particular angular disconformity between algal limestones of the Fackelgraben Mb. and ferruginous limestones of the Frauengrube Mb. According to OBERHAUSER (1995: 379), the 'Laramide 3' corresponds to a rapid westward movement of the Alpine Nappe system, which started at the Paleocene/Eocene boundary. The end of the 'Laramid phase' coincides with a remarkable eustatic short term sea-level fall and the end of high siliciclastic input in the Helvetic Zone (Fig. 3).

The 'Laramide phase' is followed by the 'Illyric phase' (Middle/Late Eocene boundary) and the 'Pyrenide phase' (Eocene/Oligocene boundary) (TOLLMANN, 1964: 240 f.; OBERHAUSER, 1980. 44 ff.). The termination of shallow-water carbonate deposition and the change to deep-water sedimentation reflected by the Stockletten, may be correlated to the 'Illyric phase' (HAGN, 1981: 49). Finally, the total overthrusting of the Helvetic Zone during the Late Eocene/Early Oligocene was caused by the 'Pyrenide phase'.

7.3.2. Sea-level changes and subsidence

Following the sea-level charts of HAQ et al. (1988), the Late Cretaceous long term sea-level fall continued until the latest Paleocene. After a remarkable short term sea-level fall in the middle Thanetian, a long term transgression starts, with three regressive short term excursions along the Paleocene/Eocene boundary. As discussed by EGGER et al. (1997), this transgression started within the NP9 (uppermost Thanetian). This coincides with the succession from rhodolith facies to glauconitic smaller foraminifera facies in Vorarlberg, which was dated with NP9. In the Haunsberg and Kressenberg area, the equivalent deeper water sediments are not preserved due to the process causing the angular disconformity between the Fackelgraben and Frauengrube Members.

After a maximum in the Early Ypresian, the long term sea-level falls again until the Bartonian/Priabonian boundary. Another remarkable short term regressive excursion is reported from the Late Ypresian and Early Lutetian. It can be correlated with the high siliciclastic input reflected in the Sankt Pankraz Mb.

During the middle Lutetian, the coast line advanced towards the north and the Northern Helvetic Zone reveals the first marine Paleogene sediments. This event cannot be correlated with the eustatic sea-level curve, which shows a regressive trend during the Lutetian. Although the long term sea-level falls until the Bartonian/Priabonian boundary, the deep marine Stockletten sedimentation already started at the beginning of the Bartonian.

In summary, there are some features which cannot be explained only by eustatic sea-level changes, or regional tectonics, respectively. As worked out by Haq et al. (1988), the interplay of eustatic sea-level changes and local subsidence leads to the relative local sea-level. For example, a regressive phase with a subsidence rate higher than the eustatic sea-level fall, leads to a relative sea-level rise. Fig. 3 summarizes the relations between eustatic sea-level changes and subsidence rate discussed below. The relative sea-level changes are estimated from the facies patterns; in correlation with the eustasy, this leads to the subsidence rates.

7.4. Spatial and temporal facies pattern

The following interpretations are predominantly based on the occurrences in Bavaria and Salzburg (compare Fig. 2), because these represent the best studied and most complete sections. Sea-level changes and their influence on sedimentary facies are summarized in Fig. 3.

7.4.1. Paleocene marls terminated by ooidal sandstones

The Paleogene succession in the studied areas starts with Paleocene marls and marly sands of the Olching Formation. They develop directly from the Upper Cretaceous 'Gerhartsreiter Schichten' (Traub, 1953, 1990; Rasser & Piller, 1999a). The abundance of sands and sand beds intercalated into the marls increases upward (Rasser & Piller, 1999b); the succession is terminated by ooidal sandstone facies, which is, however, only known from the Haunsberg area.

The coarsening-upward trend, as well as the termination by ooid-bearing sandstones indicate a shallowing of the depositional system. This fall of the relative sea-level corresponds to the long term transgressive trend of the eustatic sea-level curve (Fig. 3), which indicates that subsidence during the Paleocene was low. Otherwise, the facies patterns should reveal a relative sea-level rise. During the latest Paleocene, a long term sea-level rise occurred. Following the mode of ironstone formation, the ooidal sandstone facies was deposited before this transgression.

7.4.2. Thanetian algal limestones

Ooidal sandstone facies of the Haunsberg is overlain by Thanetian glauconitic sands rich in pycnodont bivalves, which continuously develop into rhodolith facies. Consistent thickness of algal limestones and the absence of siliciclastics refuse the interpretation of rhodolith mounds in a siliciclastic environment of former studies (Kuhn, 1992, cum. lit). Rhodolith beds in the Salzburg localities show very consistent bedding. This indicates

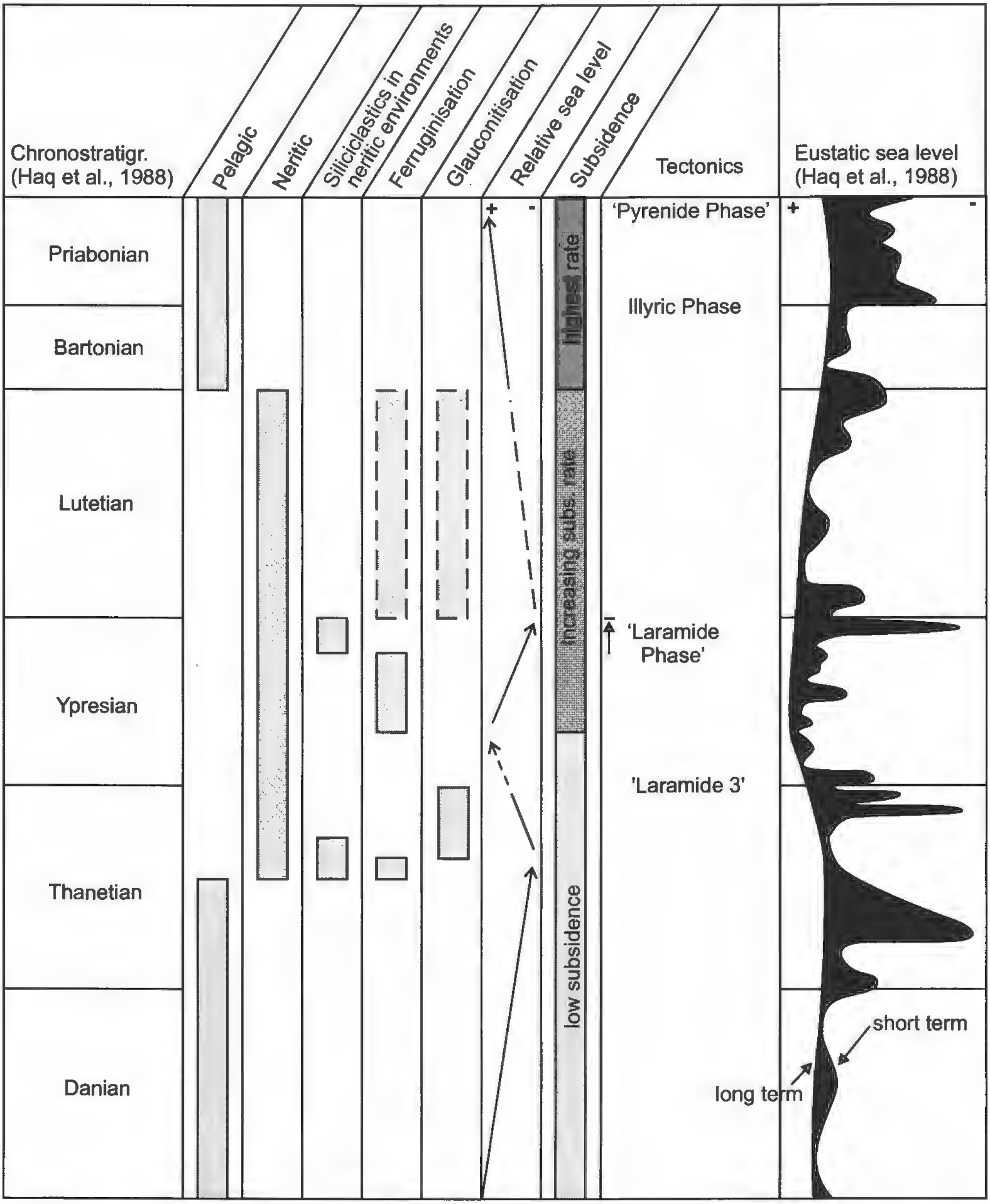


Fig. 3: Relations between sedimentary features, sea-level changes and subsidence in the Paleogene of the eastern part of the Helvetic Zone. The subsidence rates are estimated from relations between the relative sea-level changes as expressed by facies patterns and the eustatic sea-level changes after Haq et al. (1988). Hatched lines in the Lutetian indicate that the exact stratigraphical position of Kressenberg Mb. and Weitwies Mb. is unknown.

that the intercalated marl is an autochthonous sediment (suspension) and not caused by pressure solution. Upward increasing abundance and thickness of marl beds indicate that the input of argillaeceous sediment increases. In Vorarlberg, the rhodolith facies grades into smaller foraminifera facies rich in globigerinids and glaucony (NP 9 after OBERHAUSER, 1991), which suggests a deepening-upward of the environment. In the Salzburg localities, the absence of sediments and the angular disconformity at the Paleocene/Eocene boundary indicate that the sedimentary equivalents of the Vorarlberg smaller foraminifera facies were probably eroded during the Ypresian.

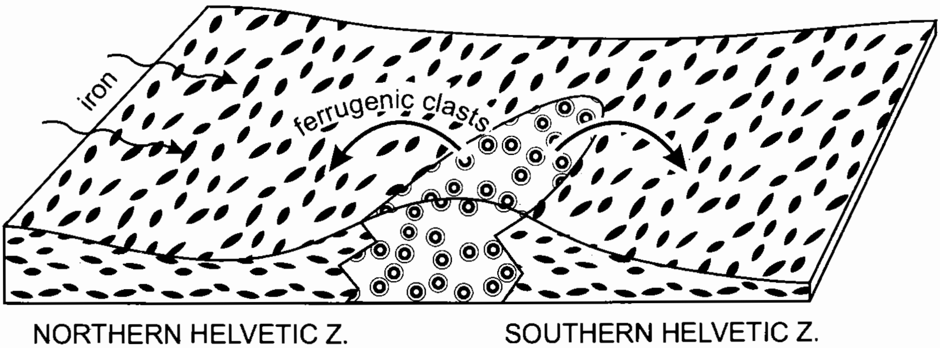
All of the described sedimentary features, including the presence of glaucony, suggest an increasing water depth. The occurrence of algal quartz sandstones and algal debris facies in different occurrences indicates proximal and distal environments (Fig. 4). The suggested deepening-upward trend coincides with the long term eustatic sea-level rise which started in the Late Paleocene (NP 9: EGGER et al., 1997) and lasted until the Early Ypresian. The relative sea-level corresponds to the eustatic sea-level. This indicates that the subsidence rate was again relatively low.

7.4.3. Ypresian time of ferruginisation

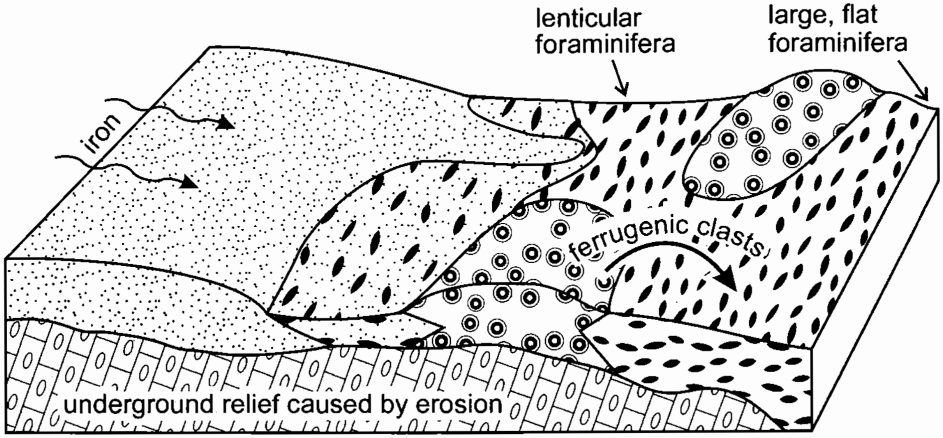
There are several arguments why the ferruginised Ypresian limestones were deposited in a lower water depth than underlying algal limestones: (1) ferruginisation requires input of detritic iron from the hinterland into a shallow marine environment; (2) ooid formation requires much higher hydrodynamic energy than rhodolith formation; (3) high input of siliciclastics at the top of the Ypresian succession.

The textural features of the described ooids exclude formation in a terrestrial environment. Consequently, they were formed in marine waters. A low net sedimentation rate is necessary for the described ferruginisation of bioclasts, as well as for the ooid formation. The overall abundance of silicilastics in most limestones reveals a general high sediment input into the carbonate system (compare VOGELTANZ, 1970). This is one evidence for the existence of high-energetic topographic highs, on which iron-ooid formation and iron-impregnation took place. The other evidence is the angular disconformity between the algal limestones and the iron-bearing succession, which was first described by RASSER & PILLER (1999b). The outcrop Frauengrube reveals that the Frauengrube Mb. transgressed over the inclined Fackelgraben Mb. We suggest that the lithified, inclined, and eroded beds of algal limestones caused a submarine structural relief with local highs favourable for ferruginisation (Fig. 4).

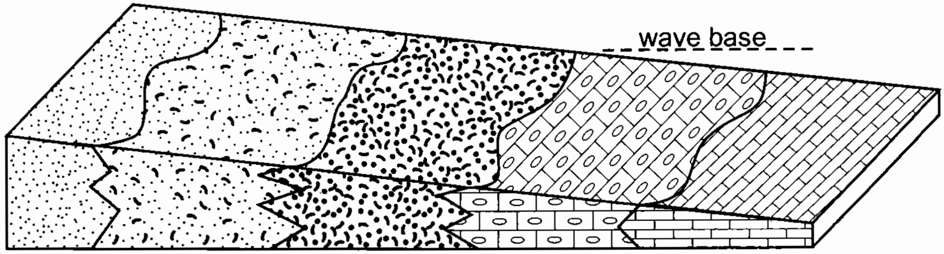
Very big, flat, and unfragmented larger foraminifera of the larger foraminifera facies indicate very low hydrodynamic energy (HOTTINGER, 1983; HOHENEGGER, 1994; 1995). This is, however, contradictive with the occurrence of high-energy iron ooids and ferruginized allochems in the same samples. Consequently, this facies is interpreted to represent a mixture of two different environments. This could be caused by an input of iron components into the relatively deeper water where the larger foraminifera lived, or simply by a lateral facies change into a more protected environment (Fig. 4). Morphologically different types of unfragmented, uncoated and poorly impregnated larger foraminifera lived in the larger foraminifera and ooid bearing quartz sandstone: they are usually lenticular. This growth form is typical for higher energetic environments (HOTTINGER, 1983; HOHENEGGER, 1994, 1995), as reflected by the accompanying quartz grains.



LUTETIAN



YPRESIAN, SOUTHERN HELVETIC ZONE



THANETIAN, SOUTHERN HELVETIC ZONE

Fig. 4: Stationary models of Paleogene carbonate facies patterns of the eastern part of the Helvetic Zone. The separation between the Northern and the Southern Helvetic Zone occurred during the Lutetian. For signatures compare Fig. 2.

The Ypresian ferruginisation is terminated by sand bodies of variable thickness. Sands of the Sankt Pankratz Mb. of Haunsberg represent subtidal sand bodies, which show a high fluvial influence and a high degree of reworking (VOGELTANZ, 1970: 425). They are laterally thinning and disappear.

This facies distribution indicates a shallowing-upward from ooid bars surrounded by deeper larger foraminifera sediments to the sand bodies of the Sankt Pankraz Mb. The Middle Ypresian age of these ferruginous foraminiferal limestones (P 7? after KUHN, 1992) coincides with the long term eustatic sea-level fall starting during the Middle Ypresian (Fig. 3). The high input of siliciclastics can be correlated with a short term regression during the latest Ypresian.

The accommodation space necessary for deposition of 22 m of ferruginized limestones and the overlying 32 m thick sands in Salzburg localities requires an increased subsidence rate due to the eustatic sea-level fall. Consequently, the subsidence rate was much higher than during the Paleocene and the Early Ypresian.

7.4.4. Lutetian co-occurrence of ferruginisation and glauconitisation

Lutetian limestones are represented in the Kressenberg Mb. and Weitwies Mb. During the Middle Lutetian, the coast line advanced towards the north and the Northern Helvetic Zone showed first marine deposits in the Paleogene. A problem is that the Lutetian represents a time span of about seven million years, which is represented by only ca. 10 m of limestones in the studied areas. Poor biostratigraphic dating give no evidence for their exact stratigraphic position within the Lutetian. Therefore, the correlation with eustatic sea-level changes is difficult.

Kressenberg Mb. and Weitwies Mb. show both ferruginisation and glauconitisation. Like in the older units, the larger foraminifera are very large and flat, indicating the same situation as for the Frauengrube Mb. The occurrence of glaucony and the lower frequency of ferruginisation indicate, however, that ooid bars are subordinate compared to the Fackelgraben Mb. and that surrounding larger foraminifera facies were deposited in deeper water under more reduced energy conditions.

Despite the stratigraphical problems, the whole Lutetian represents a time of long term sea-level fall. This is, however, contradictive with the described facies patterns indicating a relative sea-level rise. Therefore, the increased subsidence rate suggested for the Ypresian, continues during the Lutetian. This coincides with the flooding of the Northern Helvetic Zone, which represents a backstepping typical for transgressions on carbonate ramps (DOROBEK, 1995).

7.4.5. Bartonian termination of shallow water development

Shallow water carbonate deposition of the Lutetian is terminated by Bartonian to Priabonian deep water conditions ('Stockletten'). The ongoing backstepping is proven by a shift of carbonate ramp deposits towards the north, into the Molasse underground; these deposits can be reworked as olistoliths into the Stockletten (BUCHHOLZ, 1989; DARGA, 1992; RASSER, 2000).

The long term eustatic sea-level decreases until the Early Priabonian, followed by a rise until the Eocene/Oligocene boundary. The regressive eustatic trend, associated with very high relative sea-level stands in the whole Helvetic Zone indicates a much higher subsidence rate than in the stratigraphically older deposits. Several distinct short-term global sea-level falls in the Priabonian, as well as the beginning of the Pyrenide phase, may have caused the olistolithic reworking of shallow water sediments into the Stockletten.

7.5. The origin of the iron – how many swells?

Most authors suggested the existence of an Intrahelvetic Swell, which separated the Northern and the Southern Helvetic Zone (HAGN, 1954, 1981; VOGELTANZ, 1970). The main argument for the existence of this swell was the origin of detritic iron necessary for ferruginisation of bioclasts and formation of iron-ooids. During the Lutetian, the occurrence of ferruginisation was restricted to the Southern Helvetic Zone, the Northern Helvetic Zone only revealed glauconitisation. Therefore, the cited authors suggest, that a swell between these zones must have existed, on which lateritic weathering led to the input of detritic iron into the Southern Helvetic Zone.

As discussed above, however, glauconitisation also requires the input of detritic iron. This indicates that the iron could have been transported from the northernmost coastline into both the Northern and the Southern Helvetic Zone. This does not indicate that the Intrahelvetic Swell did not exist. We suggest, however, that most arguments for its existence are no longer evident.

8. CONCLUSION

The eastern part of the Paleogene Helvetic Zone represents a carbonate ramp with a distinct facies pattern that is controlled by an interplay of tectonic events, eustatic sea-level changes, and subsidence. Our results suggest the following reconstruction:

The Paleocene in the eastern part of the Helvetic Zone was a time of tectonic quiescence. It was characterized by a relative sea-level fall until the Thanetian, characterized by a coarsening-upward of pure siliciclastic sediments terminated by ooidal sandstones. During the Thanetian, a relative sea-level rise occurred, which most probably lasted until the beginning of the Ypresian. This transgression caused formation of glauconitic algal- and smaller foraminifera limestones. Both of these relative sea-level changes can be correlated with the eustatic sea-level curve. Consequently, subsidence was low to absent. Tectonic events at the Paleocene/Eocene boundary ('Laramide 3') coincides with a particular angular disconformity between Thanetian algal limestones and Ypresian ferruginous foraminiferal limestones.

During the Middle Ypresian, another relative sea-level fall occurred, which is characterized by thick ferruginous foraminiferal limestones and ferruginous oolites overlain by massive siliciclastics. This coincides with a eustatic sea-level fall. The high siliciclastic input can be correlated with a short term eustatic regression during the latest Ypresian. The necessary accommodation space suggests an increased subsidence rate compared to Paleocene to Early Ypresian time. The carbonate ramp environments are characterized by ooid shoals surrounded by foraminiferal limestones. As glauconitisation was absent during this period, the preserved facies reflect very shallow, well oxygenated environments. The Ypresian relative sea-level fall was most probably terminated by the end of the 'Laramide phase' at the Ypresian/Lutetian boundary.

Due to poor biostratigraphic data, the Lutetian development cannot be dated confidently. Facies characteristics of the Lutetian foraminiferal limestones overlying the last significant siliciclastic development of the Late Ypresian suggest a relative sea-level rise during the Lutetian. As the eustatic sea-level was falling during this time, the subsidence rate was still higher than during the Paleocene. This higher subsidence rate caused backstepping of the carbonate ramp and the first Paleogene transgression of the Northern Helvetic Zone. Larger foraminifera limestones of the Lutetian are the only sediments of the whole succession, which show a co-occurrence of glauconitisation and ferruginisation. This suggests the occurrence of submarine shoals, on which ferruginisation occurred. Ferruginous particles were shed into the surrounding deeper glauconitic foraminifera sediments. These facies interpretations suggest that the existence of an Intrahelvetic Swell is not necessary for the development of the described facies.

Due to the development of deep marine conditions in the Bartonian, this relative sea-level rise continued. The ongoing eustatic sea-level fall across the Lutetian/Bartonian boundary requires a highly increased subsidence rate compared to Paleocene to Lutetian time.

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