Late Oligocene algal limestones on a mixed carbonate-siliciclastic ramp at the southern margin of the Bohemian Massif (Upper Austria)

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Abstract: The Upper Oligocene (Chattian, Lower Egerian) Linz Sands of the sand pit 'Treul' in Steyregg (near Linz, Upper Austria) contain a >40 m thick succession of siliciclastic and carbonate sediments. They are characterized by a low diversity of facies and components. Microfacies and granulometric analyses allowed the designation of four facies: coralline algal rudstone facies, terrigenous – coralline algal rudstone facies, miogypsinid facies, and siliciclastic facies. Siliciclastics derive from the crystalline basement and show a wide range of grain size from sand to boulders. Main carbonate components are coralline algae, benthic foraminifers (especially miogypsinids) and oysters. The identification of *Miogypsina formosensis* YABE & HANZAWA and its delimitation from *M. complanata* SCHLUMBERGER and *M. bantamensis* TAN SIN HOK reveals that the studied sequence was deposited between 25 and 24 million years b. p. Granulometrical and paleoecological studies as well as actualistic comparisons allowed the interpretation of the sedimentary environment. The studied sediments were deposited on a mixed carbonate-siliciclastic ramp close to or above fair weather wave base. Vertical and lateral transitions from siliciclastics to carbonates suggest trends from proximal to distal environments and thus backstepping of the ramp. These frequent transitions are either caused by relative sea-level changes due to local tectonics, or by temporal variations of siliciclastic sediment input during continuous subsidence.

Zusammenfassung: Die Linzer Sande des oberen Oligozäns (Chattium, unteres Egerium) in der Sandgrube 'Treul' in Steyregg nahe Linz (Oberösterreich) weisen eine >40 m mächtige Abfolge von Siliziklastika und Karbonaten mit einer geringen Diversität an Faziesbereichen und Komponenten auf. Mikrofazielle und granulometrische Analysen ermöglichten die Definition von vier Faziesbereichen: Corallinaceen Rudstone Fazies, Terrigene Corallinaceen Rudstone Fazies, Miogypsiniden Fazies und Siliziklastische Fazies. Die Siliziklastika entstanden durch Verwitterung des Kristallins des Böhmischen Massivs und weisen ein Korngrößenspektrum von Sand bis Blockwerk auf. Die wichtigsten Karbonatkomponenten sind coralline Rotalgen, benthische Foraminiferen (vorwiegend

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Miogypsiniden) und Austern. Die Bestimmung von *Miogypsina formosensis* Yabe & Hanzawa und ihre Abgrenzung von *M. complanata* Schlumberger und *M. bantamensis* Tan Sin Hok zeigen ein Alter von 25 bis 24 Millionen Jahren an. Granulometrische und paläökologische Studien weisen auf die Ablagerung auf einer gemischten karbonatisch-siliziklastischen Rampe nahe oder innerhalb der Schönwetter-Wellenbasis hin. Vertikale und laterale Übergänge von Siliziklastika zu Karbonaten repräsentieren Übergänge von proximalen zu distalen Ablagerungsräumen. Diese wurden entweder durch relative Meeresspiegelschwankungen, oder durch temporär variierenden siliziklastischen Sedimenteintrag verursacht.

Keywords: Oligocene, Carbonate – Siliciclastic Carbonate Ramp, Grain Size Analysis, Coralline Algae, Miogypsinid Foraminifera, Molasse Zone

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1. INTRODUCTION

Upper Oligocene shallow water carbonates are particularly rare in the Alpine region. One of the scarce examples is represented by the coralline algal limestones of the sand pit 'Treul' in Steyregg, next Linz (Upper Austria), which is situated at the southern margin of the Bohemian Massif. Although this sand pit represents a classic locality of the Linz Sands (e.g., Grill, 1937; Spillmann, 1947), the intercalated algal limestones are poorly known (Roetzel et al., 1991). These sediments contain coralline algae growing in a mixed carbonate-siliciclastic environment, and the algae dominated facies can be compared with the present-day 'maerl'. Although this type of carbonate-siliciclastic sediment is well known from present-day environments of the Northern Atlantic (e.g., Scoffin, 1988) and the Mediterranean (e.g., Adey, 1986), and recently has been recorded from the Brazilian Shelf (Testa & Bosence, 1998), fossil analogues are rare.

Besides the fact that the sediments of Steyregg represent one of the very few Upper Oligocene carbonate sequences of the Central Paratethys, they provide the possibilities for: 1) high resolution biostratigraphy using miogypsinid larger foraminifers; 2) paleoecological analyses of coralline algae in a fossil 'Maerl' facies; 3) studying rapid facies changes in a shallow water, near shore environment along a rugged crystalline coastal morphology; and 4) helping to complete our picture of the complex Oligo-Miocene lithological successions of the Molasse Zone.

We studied this mixed carbonate-siliciclastic succession by means of a detailed outcrop analysis, granulometry of the siliciclastics and carbonate microfacies analysis. The aim of this study was to combine different methodological approaches for the reconstruction of facies patterns that are unique in this area.

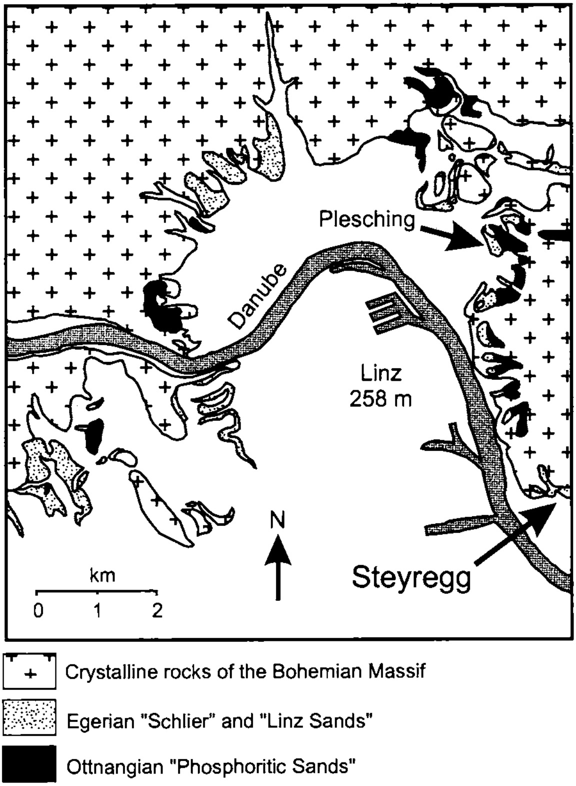

Fig. 1:
Geological map of the study area and its surroundings (after Schaffer & Grill, 1951). The sand pit "Treul" in Steyregg is lying at the southeastern edge of the "Linz Bay".

2. STUDY AREA

The studied profiles of the Linz Sands are located in the sand pit "Treul" in the village of Steyregg, which is situated north of the river Danube, SE of Linz (Fig. 1). The ca. 1 km^2 large sand pit is located at the base of the Pfenningberg, north of the village centre. The 30 m high walls at the base of the pit are formed by the purely siliciclastic sands. Towards the top, they interfinger with mixed carbonate – siliciclastic beds, which are the object of the present study (Fig. 2).

The study area is situated in the SE of the "Linz Bay", which formed an embayment of the Oligo-Miocene Molasse Sea along the margins of the crystalline Bohemian Massif (Fig. 1). The study area played an important role in the history of investigations on the Linz Sands (Grill, 1937; Spillmann, 1947), although their interfingering with algal limestones have only recently been recognized. Roetzel et al. (1991) reported the presence of mixed terrigenous/carbonate sequences characterised by coralline algae and the larger foraminifer *Miogypsina formosensis* in Steyregg as a particular unit within the Linz Sands. This foraminifer has also been used as a stratigraphic indicator in the Linz Sands at the nearby locality Plesching (Steininger, 1969; Rögl & Steininger, 1970, 1975). Sedimentological and petrographical studies in the study area were conducted by Kandharosa (1995).

3. GEOLOGICAL BACKGROUND

3.1. Paratethys and Molasse Basin

The study area is situated in the Upper Austrian Molasse Basin, at the southern margin of the Bohemian Massif. The first known marine transgression in the Alpine Foreland Basin during the Late Eocene was caused by subsidence of the underground due to the Alpine orogeny (Wagner, 1996a; Rasser, 2000). The periodic isolation and presence of a distinct bioprovince in the Paratethys lead to the development of regional stratigraphic stages (see Steininger, 1976; Steininger et al., 1985; Berggren et al., 1995; Rögl & Rupp, 1996; Rögl, 1998). High subsidence rates in the Early Oligocene caused deeper water conditions enabling the entrance of boreal deep water faunas into the Molasse Basin (Dohmann, 1991; Rögl in Wagner, 1996b). The subsequent development of banded marls, nannoplankton ooze and fish shales is expected to be caused by an upwelling system (Parish 1982; Dohmann, 1991; Wagner, 1996b; Krhovsky et al., this volume). The influx of warm Mediterranean water masses into the Paratethys during the Early and Late Egerian are marked by the appearance of lepidocyclinid and miogypsinid larger foraminifera as well as Indopacific corals (Rögl, 1998).

An overview of the lithostratigraphy and facies has been given by Wagner (1996b). During the Oligocene, a facies differentiation was established in the Molasse Zone with the shallow marine Linz and Melk Sands in the north (Roetzel, 1983) and basinal sediments of the "Älterer Schlier" (Eferding Fm. after Wagner, 1996b) interfingering with turbidites of the Puchkirchen Formation to the south (Kollmann, 1977; Kollmann & Malzer, 1980; Brix et al., 1977; Malzer, 1981) (see fig. 1). The Linz Sands are discontinuously overlain by the "Phosphoritsande" (Plesching Fm. after Wagner, 1996b) (Roetzel, 1983; Faupl & Roetzel, 1990).

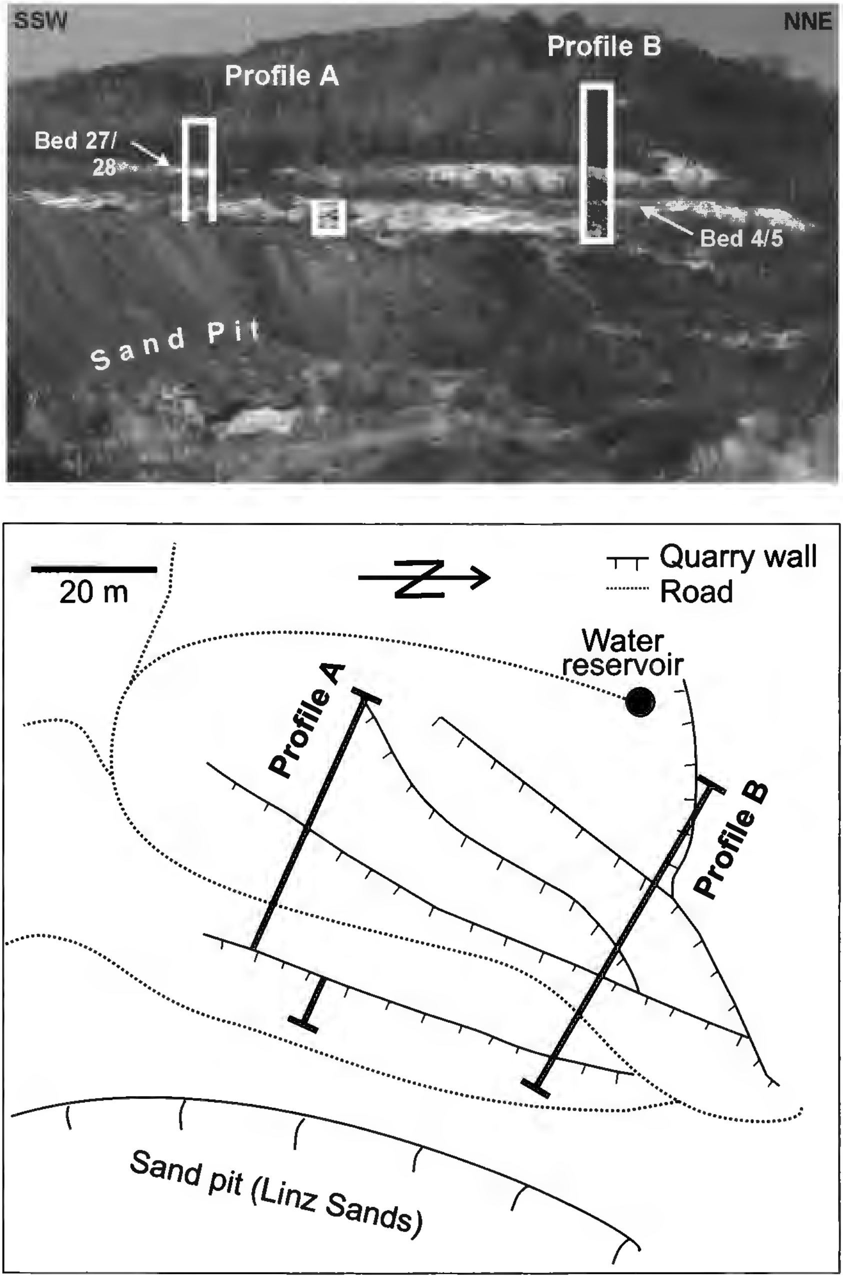

Fig. 2: Photo and sketch map of the studied part of the sand pit 'Treul', south of the "Pfenningberg" in Steyregg. The position of the two profiles (compare Fig. 3) is marked. Note that the apparent high inclination in 'profile A' is only caused by an oblique perspective; inclination is ca. 5°.

3.2. Facies of the Linz and Melk Sands

The Linz and Melk Sands are dominated by weakly consolidated to unconsolidated, light gray to yellow brown, medium to coarse sands; fine to medium gravels are subordinate (ROETZEL, 1983). These sediments, which are mined in many sand pits, have been well studied since the middle of the 19th century due to the occurrence of fossils, especially vertebrates (e.g., FITZINGER, 1842; EHRLICH, 1855; BENEDEN, 1865; SUESS, 1891). Investigations on the Linz Sand, as well as Molasse sediments in general, have, however, usually concentrated on mapping and stratigraphy. The first geological summaries of the Linz area are known from EHRLICH (1852, 1855) and COMMENDA (1900). A number of more recent investigations have been conducted on both vertebrates and invertebrates (GRILL, 1937; SCHADLER, 1945; SIEBER, 1953; STEININGER, 1969, 1975; KÜPPER & STEININGER, 1975; RÖGL & STEININGER, 1970; FUCHS & GRÜN, 1980).

The facies of Linz and Melk Sands were interpreted as near-shore and deeper circalittoral sediments by STEININGER (1975). Mollusc associations (*Glycimeris latiradiata – Turritella venus – Pitar beyrichi*) show a faunal succession ranging from the shore line (with terrestrial faunal elements) to a deeper environment (BALDI, 1973; STEININGER, 1975). Heavy mineral analyses show that the main source area of the Linz and Melk Sands is the adjoining Bohemian Massif. Very short transport distances are suggested by the poor sorting and high angularity of these particles (ROETZEL, 1983; KANDHAROSA, 1995). ROETZEL (1991) suggested that the Melk Sands were deposited in an upper littoral position. KANDHAROSA (1995) interpreted the siliciclastic part of the Linz Sands and the interfingering carbonate/siliciclastic sequences in Steyregg as littoral to circalittoral deposits affected by rapid sea-level changes.

4. MATERIAL AND METHODS

The 'Treul' sandpit contains 5 terraces on its northern face (Fig. 2). Two profiles were measured and sampled (Fig. 3). 'Profile A' is compiled from four of the five terraces and is 29 m long; 'profile B' crosses all five terraces and is 41 m long. The distance between 'profile A' and 'profile B' is about 50 m. The co-occurrence of limestones, siliciclastics as well as mixed carbonate-siliciclastic sediments requires different methodological approaches and results in the use of varying nomenclatures (compare DUNHAM, 1962; FOLK, 1962, 1974; FÜCHTBAUER, 1974). We refer the term 'terrigenous' sediments to those consisting of more than 50% siliciclastic material; 'limestones' contain less than 50% siliciclastic material.

4.1. Grain size analyses

Grain size analysis was conducted by sieving. Both consolidated and unconsolidated sediments were included. Consolidated samples were first treated with 1n hydrochloric acid to remove the carbonate. Gravel sized particles (larger than 2 mm) were dry sieved by hand. Sand sized particles (63 µm –2 mm) were separated in phi steps by dry sieving in an ultrasonic sieving apparatus. The silt – sand – gravel triangular plot (Fig. 4) was used for characterizing the sediment (FÜCHTBAUER, 1959; MÜLLER, 1961). The determina-

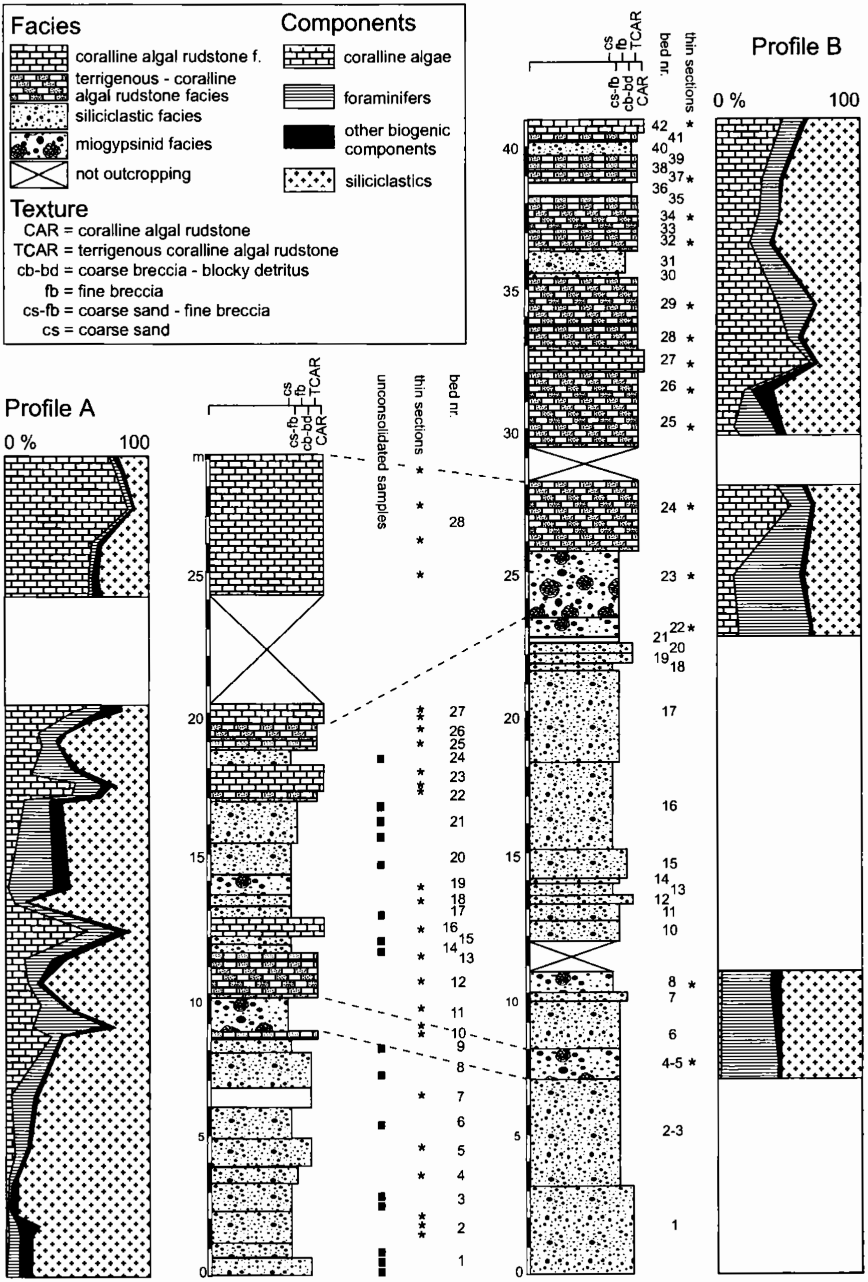

Fig. 3: Facies, texture, and main components of 'profile A' and 'profile B'. Asterisks mark the positions of thin sections taken from consolidated samples, black squares mark the position of unconsolidated samples. Main components are only shown for consolidated samples. Hatched lines indicate correlations of beds as revealed from outcrop analysis.

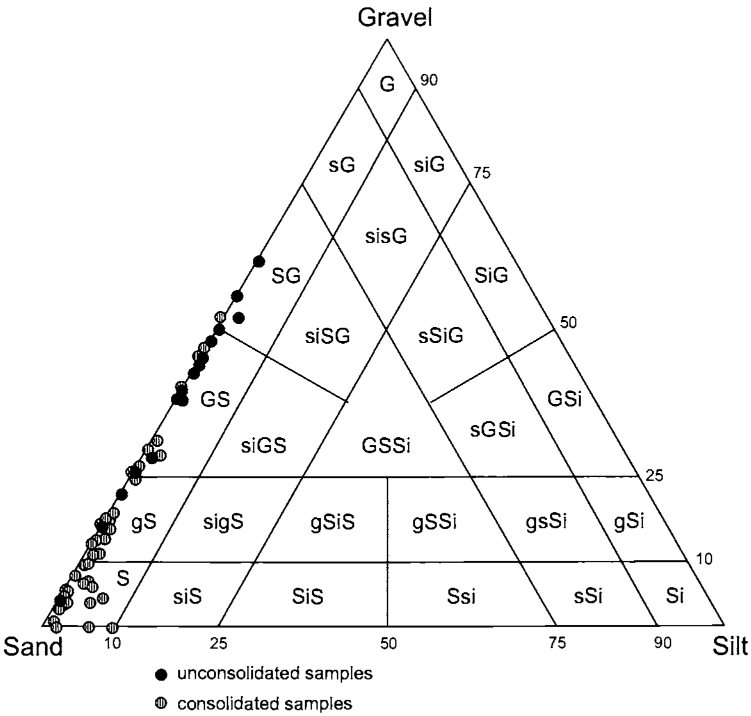

Fig. 4: Samples of mixed – siliciclastic sediments plotting in a silt – sand – gravel diagram (after Füchtbauer, 1959; Müller, 1961). Note that consolidated and unconsolidated samples show the same range.

tion of roundness followed comparative charts. The calculation of arithmetic mean, standard deviation and skewness (Fig. 5) follows Marsal (1967); CM distributions (Fig. 6) follow Passega (1957, 1964) and Passega & Byramjee (1969). Terminology for sorting coefficients follows Friedman (1961). The description of sediments using the log-probability-curve (Fig. 7) allows the definition of different transport modes (e.g., Sindowsky, 1957; Walger, 1961; Moss, 1962, 1963; Visher, 1969; Glaister & Nelson, 1974).

4.2. Microfacies analyses

Poorly consolidated sediments were impregnated with resin to allow thin sectioning. Quantification of 64 thin sections was conducted using the grain bulk point counting method with 350 to 700 counts, at a distance of 1 mm. Samples displaying a higher diversity of components were counted with higher numbers than homogenous samples. 19 different categories were counted, including 15 biogenic component types, terrigenous particles, micrite, sparite and voids. The results of the point counts are shown in Fig. 3.

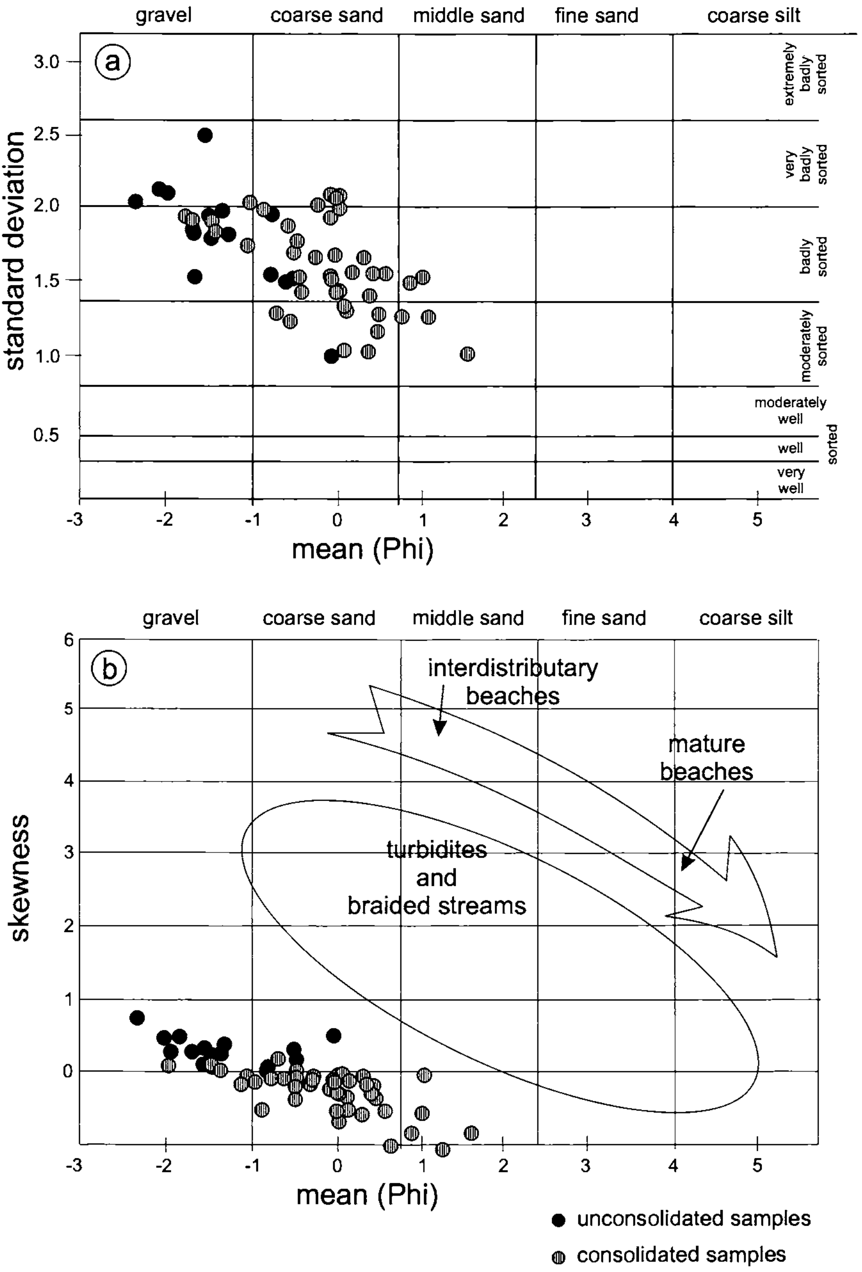

Fig. 5: Correlation between mean, standard deviation and skewness of consolidated and unconsolidated sediments (after Friedman, 1961). Note that the siliciclastics of consolidated sediments (sands) are finer-grained and better sorted than those of the unconsolidated sediments.

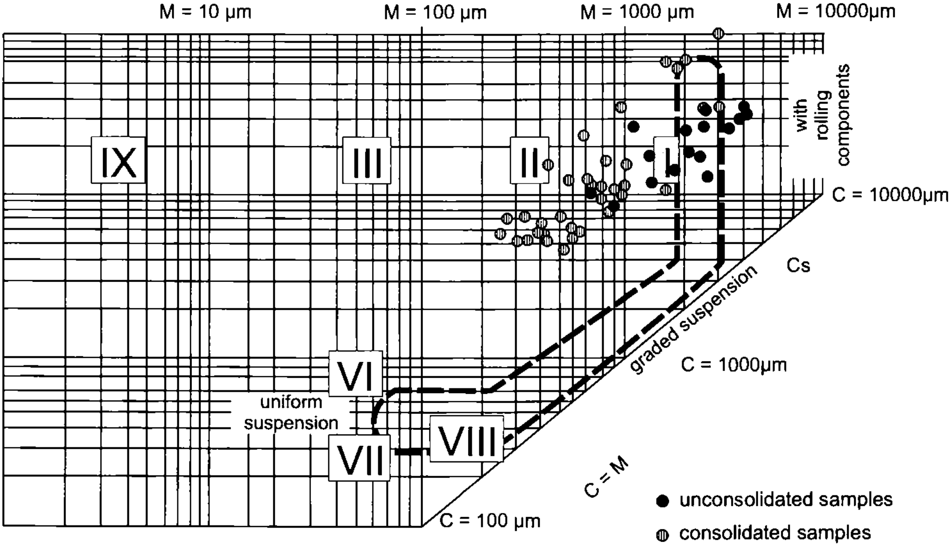

Fig. 6: CM-diagrams after Passega (Passega, 1957, 1964; Passega & Byramjee, 1969). Sediments in field I and II point to coastal or near shore position.

4.3. Miogypsinid taxonomy

A remarkable abundance of miogypsinid foraminifers allowed high resolution biostratigraphy. The large number of individuals revealed adequate sections for the study of growth parameters.

Since Drooger (1952), the evolution of miogypsinids is one of the most valuable tools for the middle Oligocene to Middle Miocene biostratigraphy. Like in other rotaliid larger foraminifers, the evolutionary principle is the so called "nepionthic acceleration". Drooger established a technique of calculating median values (Mx) of the nepiont apparatus, which is one of the most important taxonomic features of miogypsinids. The nepiont apparatus is the inner ring of median chambers next to the first two median chambers: the Proto- and Deuteroconch. The species differentiation is achieved by assessing the average number (Mx) of chambers. After Drooger (1966), miogypsinid species are defined as: Mx >17 = *M. complanata*, Mx: 17–13 = *M. formosensis*, Mx 13–10 = *M. bantamensis*.

76 foraminifers from 15 thin sections were measured in the current study, which allowed designation of Mx changes across the composite section (Fig. 8). The stratigraphic ranges of different Oligocene to Miocene miogypsinid species after Drooger & Laagland (1986) are shown in Fig. 9.

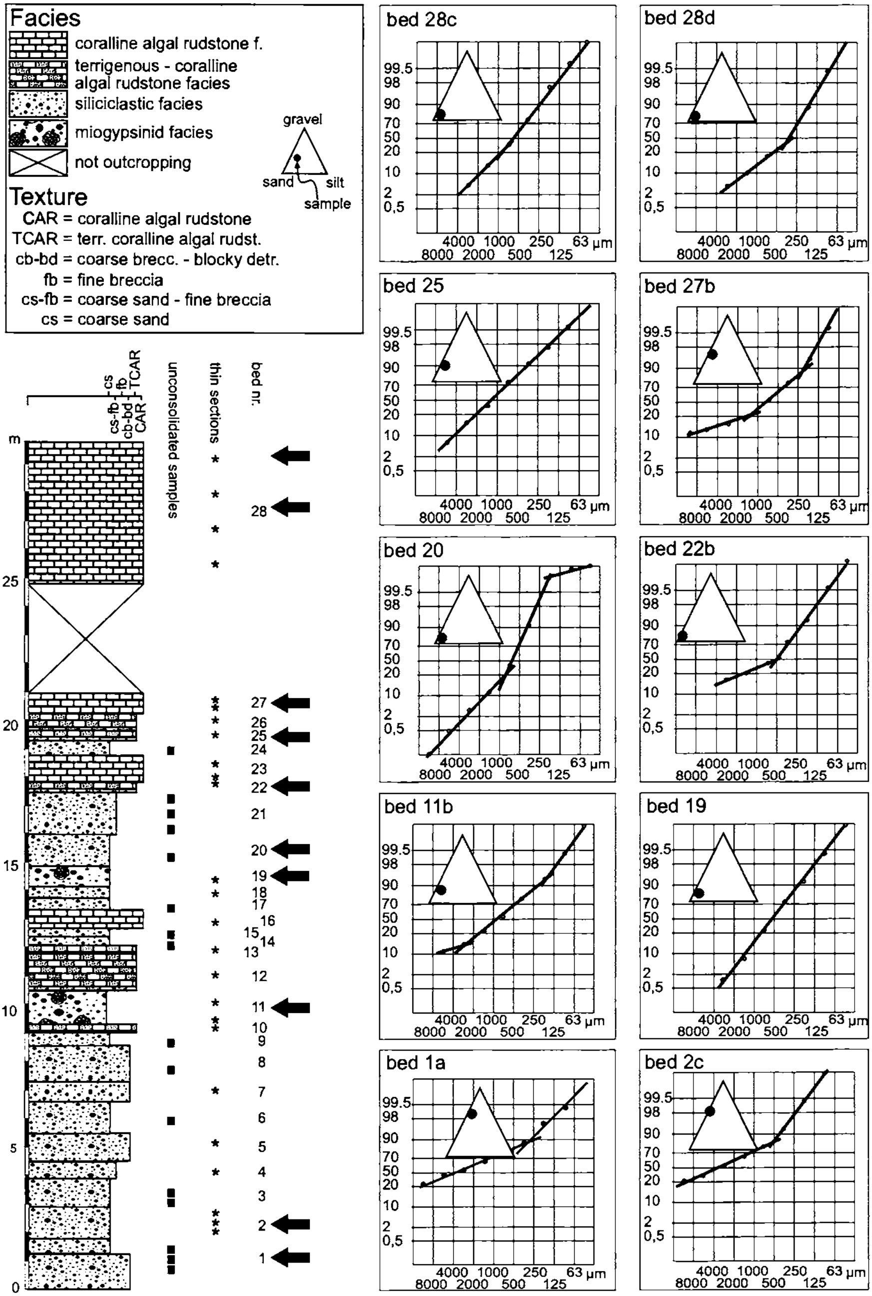

Fig. 7: Log-normal grain size distribution in 'profile A' reveal that there are no fundamental difference between consolidated and unconsolidated sediments, but between siliciclastic and algal dominated sediments. For details see text.

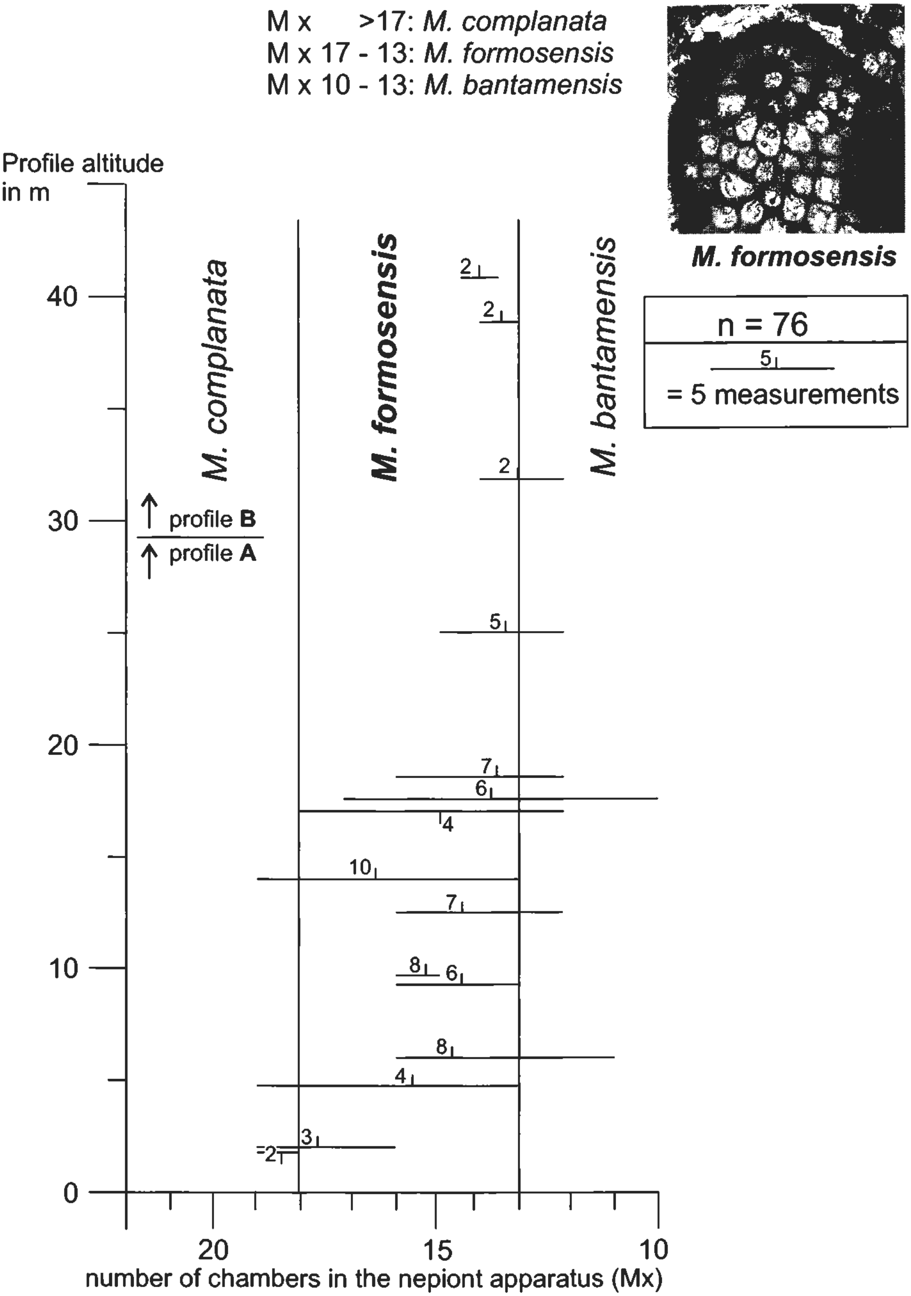

Fig. 8: Biometry of miogypsinids and definition of species by the average number of median chambers in the nepiont appartus (Mx). Note the trend of Mx from the base towards the top.

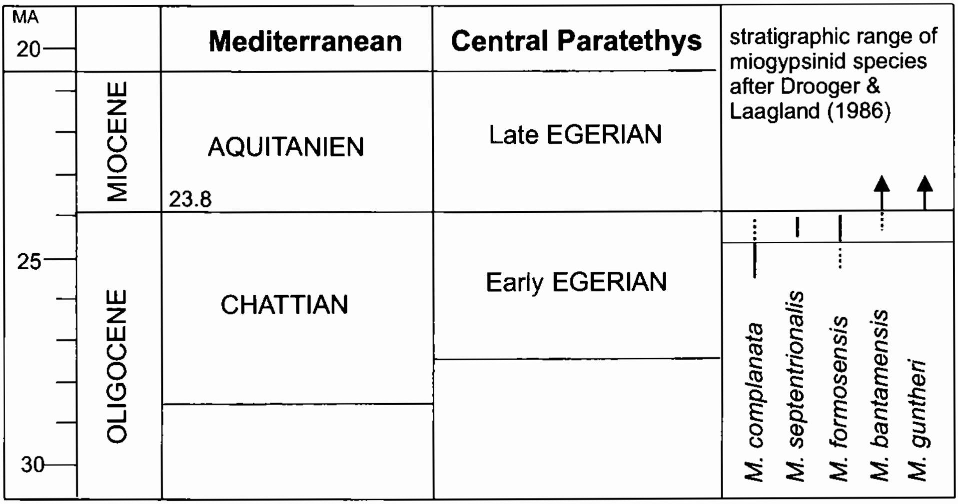

Fig. 9: Biostratigraphy after Drooger & Laagland (1986) reveal that the studied sediments of Steyregg were deposited approximately between 25 and 24 million years b. p.

5. RESULTS

5.1. Profiles

'Profile A' starts with a thick succession of siliciclastic dominated sediments, composed of blocky to coarse sandy sediments. The middle part of the profile is characterised by intercalations of beds rich in siliciclastics, those rich in miogypsinids as well as mixed siliciclastic/coralline algal occurrences. The latter become more common towards the top of the profile, which is terminated by a massive bed (at least 9 m thick) dominated by coralline algae. Two cycles with increasing coralline algae abundance separated by coarse terrigenous sands can be recognized.

The basal beds of 'profile B' are dominated by siliciclastics and miogypsinid foraminifera; coralline algae never become abundant. As in 'profile A', the succession starts with blocky detritus. No trend in grain size is visible. Miogypsinids can be locally common, while coralline algae generally become more abundant towards the top of the profile. The co-occurrence of siliciclastics and coralline algae characterises the upper part of this profile. Three thin beds of coarse terrigenous sands are intercalated towards the top of the profile.

Carbonates are generally more abundant in the south, what is visible between 'profile B' in the north and 'profile A' in the south. In the area of 'profile B', the bed 2–3 grades from unconsolidated siliciclastics in the north to better consolidated sicliciclastic sediments rich in oysters, in the south. Also the overlying bed 4–5 grades from pure siliciclastics in the north to miogypsinid rich sediments in the south. Due to the outcrop situation, only two beds could be correlated between 'profile A' and 'profile B'. The above mentioned miogypsinid rich sediments of bed 4–5 in 'profile B' can be correlated with bed 11 of 'profile A' without remarkable facies changes. Beds 23 and 24 of 'profile B' can be traced to beds 27 and 28 of 'profile A'.

5.2. Siliciclastics and grain size analyses

Siliciclastics derive from weathered crystalline rocks and show a wide range of grain size from sand to boulders. They are dominated by angular to subangular quartz grains and feldspars, present as isolated crystals and larger composite grains. Boulders up to 30 cm in size can be locally abundant. Conglomerate layers with well rounded pebbles also occur.

The grain size analyses plot between gravel and sand in the silt – sand – gravel triangular diagram (Fig. 4). The siliciclastics of consolidated sediments (sands) are finer-grained and better sorted than those of the unconsolidated sediments (gravely sands and sandy gravels) (Fig. 5). The amount of silt and clay is low in all sediments and never exceeds 10%. In general, the siliciclastic portions of the studied sediments represent gravel as well as coarse and middle sand. Their arithmetic means are between –2.5 and +1.5, their standard deviations between 1.0 and 2.6. The sorting ranges from moderate to very bad (only bed 20 shows a better sorting with subrounded sand sized grains). The skewness of the sediments lies between –1.0 and +0.7.

The CM-diagram (Fig. 6) shows a distribution within the fields I and II, where bedload transport (field I) and bedload / graded suspension transport (field II) prevails (PASSEGA & BYRAMJEE 1969). Unconsolidated and consolidated sediments differ again by a greater proportion of bedload transport in the former and graded suspension in the latter; however, they show a broad range.

The log-probability curves of consolidated and unconsolidated sediments do not show fundamental differences (Fig. 7). There are, however, differences between siliciclastic and algae dominated sediments. Most of the log-probability curves are composed of two distinct populations of bedload and graded suspension transport mode. Populations corresponding to suspending transport are mostly missing. The designation of bedload and graded suspension, respectively, coincides with the grain size composition. Coarse grained siliciclastics (e.g., beds 1a & 2c) posses two populations with bedload and graded suspension. In finer siliciclastic sediments (e.g., bed 19) there is just one population corresponding to graded suspension. The log-probability curves of bed 20 are remarkably different from the rest of the studied sediments in showing three distinct populations.

Siliciclastic components in algal dominated sediments (e.g., beds 28c & d) consist of sandy grain sizes, within which two populations (bedload and graded suspension) can be recognised. In some of the distributions, the graded suspension population can be seen to consist of two sub-populations: a badly sorted population of coarse sediments and a better sorted population of fine sediments (e.g., beds 11 b, 27 b). This can be interpreted as a result of winnowing effects caused by wave agitation.

5.3. Biogenic components

The main biogenic components are coralline algae and benthic foraminifera (Fig. 3). Coralline algae are dominated by species of the subfamily Melobesioideae (*Lithothamnion* div. spec. and *Mesophyllum* sp.). *Spongites* sp. and *Lithoporella melobesioides* (FOSLIE) FOSLIE (subfamily Mastophoroideae) are rare. ROETZEL et al. (1991) additionally mentioned *Lithothamnion operculatum* (CONTI) CONTI. Coralline algae are most abundant in 'profile A', where they account for up to 80% of the rock content. In terrigenous dominated sediments, coralline algae are represented by abraded fragments (Pl. 1, Fig. 2). They are best preserved in the terrigenous rich coralline algal sediments where complete branches occur. Algal crusts around biogenics or crystalline pebbles reach a thickness of a few mm, but they are rare.

Foraminifera are dominated by the larger benthic foraminifer *Miogypsina* YABE & HANZAWA (Pl. 2, Fig. 1), which can be facies characteristic (see below). The restriction of foraminifera to thin sections made taxonomic identifications difficult. 21 different taxa were distinguished, mostly smaller benthic forms including 4 textulariids, 7 miliolids, and 10 rotaliids. The following taxa can be tentatively identified upon comparison with CICHA et al. (1998): *Asterigerinata planorbis* (d'ORBIGNY), *Marginulina behmi* (REUSS), *Sphaerogypsina globulus* (REUSS), and *Elphidium* sp. A single, relative large, unidentified agglutinated foraminifera (probably *Dorothia* sp.) is restricted to the terrigenous rich, coralline algal sediment (Pl. 2, Fig. 3).

Oysters occur throughout the profile and can be concentrated in distinct layers. Other subordinate biogenics include rare gastropods, ostracods, balanid plates, different forms of encrusting bryozoans and sea urchin spines.

5.4. Miogypsinid taxonomy

The measurements of Mx values (Fig. 8) confirms the dominance of *Miogypsina formosensis* in the sections as reported by ROETZEL et al. (1991). But the Mx value of *M. formosensis* differs in lower and upper parts of the composite profile. Distinct vertical trends can be recognized: The lower part of the profile is characterized by higher Mx values (0–18 m: Mx = 15.44) than in the upper part (19–41m: Mx = 13.84). These lower values mark the transition from *M. complanata* to *M. formosensis*, while the higher values reveal a trend from *M. formosensis* to *M. bantamensis.*

5.5. Facies analysis

Four different facies (Pl. 1) were recognized based on the dominating components (Pl. 2): 1) siliciclastic facies, 2) miogypsinid facies, 3) terrigenous – coralline algal rudstone facies, and the 4) coralline algal rudstone facies. Within the profiles (Fig. 3), the facies show rapid vertical and lateral changes. For example, the coralline algal facies in bed 27–28 of 'profile A' can be traced in the outcrop to the terrigenous coralline algal and miogypsinid facies of beds 23 and 24 of 'profile B'.

5.5.1. Siliciclastic facies

This facies is dominated by siliciclastics, while biogenic components are subordinate. The biogenic content is lowest in unconsolidated parts of the profiles, where only a few small remains of gastropods and some echinoid spines were found. Coralline algae (up to 20%) are represented by abraded fragments of branches. Rare moulds of aragonitic bivalves (up to 5 cm) and gastropods are present. Sporadic oyster beds with limited lateral extension contain both single and double valved specimens, which reach sizes up to 15 cm.

5.5.2. Miogypsinid facies

The miogypsinid facies is primarily siliciclastic, but is rich in miogypsinid foraminifers. They reach up to 35% of the total sediment. Other biogenic particles are subordinate, their abundance and diversity are comparable with the siliciclastic facies. The beds show a varying degree of consolidation. The miogypsinids are mostly fragmented and reveal no preferred orientation.

5.5.3. Terrigenous – coralline algal rudstone facies

The content of coralline algae in the terrigenous – coralline algal rudstone facies ranges from 20 to 50%. The algae are represented by well preserved, fragmented branches reaching lengths of up to a few millimeters. Other components are represented by siliciclastics with a smaller mean grain size (sands) than in the siliciclastic and miogypsinid facies. Consolidation is very good, resulting in hard, platy weathering beds. Other biogenic components are subordinate.

5.5.4. Coralline algal rudstone facies

The coralline algal rudstone facies is dominated by densely packed coralline algal detritus. Coralline algae occur in abundances higher than 50%, sometimes up to 80%. The siliciclastic particles are arenitic; silt sized particles are less abundant than in the terrigenous – coralline algal rudstone facies. Siliciclastic pebbles can, however, occur and can be encrusted by thin layers of coralline algae. Other biogenics are subordinate. Pressure solution is very common. The high degree of compaction makes the original fabric difficult to discern, but most algal branches seem to be fragmented.

5.5.5. Diagenesis

The beds composed of coarse sediments show highly varying degrees of consolidation. Beds dominated by siliciclastic sediments range from weakly to well consolidated. Sediments rich in coralline algae are always well consolidated. The thickness and content of individual beds are highly variable and single beds can show lateral changes within tens of meters. Cements are represented by meteoric-phreatic, blocky calcite, which fills up interparticle and intraparticle pore spaces. Marine cements are absent.

6. DISCUSSION

6.1. Biostratigraphy

The evolution of miogypsinids allows high resolution biostratigraphic correlations from the middle Oligocene to Middle Miocene (Drooger, 1952, 1966). Coarse siliciclastic sediments do not usually favor the preservation of stratigraphically relevant microfossils. The well preserved miogypsinids thus provide a good possibility to date the sediments under study here. Papp (1963, 1975) compiled the occurrence of miogypsinids in the Paratethys. Küpper (1975) described *M. complanata* from the 'Lower Puchkirchen

Series'. *M. formosensis* is known from the Plesching locality in Austria (Rögl & Steininger, 1970; Steininger, 1975), from Slovenia (Papp, 1954) and Hungary (Baldi, 1975). One of the main differences is, that the study area is the only known locality where miogypsinids occur in rock-forming quantities. Specimens of Plesching show an Mx of 15.15 (10–19); specimens of Slovenia an Mx of 15.1 (12–18) and those of Hungary an Mx of 15.0 (13–16).

According to Drooger & Laagland (1986), the transition from *M. formosensis* to *M. bantamensis* (Fig. 9) took place before the end of the Early Egerian / Chattian. The presented biometric studies on miogypsinids thus indicate a late Early Egerian (latest Oligocene) age. If sedimentation started soon after the first appearance and ended soon after the last appearance of *M. formosensis*, we can then assume a time span of ca. one million years in which sedimentation of the studied sediments took place (Fig. 9).

6.2. Environmental parameters revealed by siliciclastics

The lack of distinctive sedimentary structures in the studied sediments is most probably due to bioturbation. Interpretations of the studied sedimentary environment therefore focused on grain size parameters and carbonate facies. The siliciclastics can be derived from erosion of the crystalline rocks of the Bohemian Massif, which is supported by heavy mineral analyses (Kandharosa, 1995). The immediate proximity of the crystalline coastline is additionally indicated by the outcrop position close to the Bohemian Massif, the occurrence of large crystalline boulders and the large grain sizes of terrigenous sediments in general.

Skewness is seen as a very sensitive factor for facies interpretation (Friedman, 1961, 1967, 1979) with respect to the depositional environment. For the studied sediments, the plot of skewness values against mean values (Fig. 5) excludes deposition on a beach, within turbidites, as well as in braided streams. It suggests, however, an environment very close to the land. The CM-diagrams (Fig. 6) also point to deposition in a coastal or near shore position. The log-probability curves (Fig. 7) confirm this result and additionally reveal information regarding transport modes and energy levels. The fact that both consolidated and unconsolidated sediments show similar grain size distributions indicates that they were affected by the same environmental parameters of agitation by waves within, or close to, the fair weather wave base. Some of the studied sediments are indicative for winnowing by waves. Wave agitation blows and sorts well finer sediment fractions, but it leaves less sorted remains out of a graded suspension carpet (Visher, 1969).

Grain size parameters exclude deposition on a shore line (compare Kandharosa, 1995), which would show a much better sorting than the studied sediments, especially in the graded suspension population. As the studied sediments originate from weathering of the nearby Bohemian Massif, the gravel portion is often well developed and usually badly sorted, as seen in the grain size distributions. This excludes the presence of strong tidal currents, which would have caused a better sorting of coarse sediments. The siliciclastic portions of the coralline algal rudstones show a better sorted graded suspension population, although this sediment is generally finer than in the siliciclastic facies. This may indicate a reduced energy level in the coralline algal rudstone facies.

The only influence of river sediments seems to be preserved in bed 20 of 'profile A', which shows well rounded grains and a log-probability curve differing from all other samples. It shows a clear proportion of grains transported by suspension, which is characteristic for river sediments (VISHER, 1969).

6.3. Paleoecology and diagenetic bias

Paleoecological interpretations of the studied sediments suffer from diagenetic bias. The degrees of diagenetic consolidation are highly variable. The source of carbonate available for the granular calcite cements is represented by the leached aragonitic molluscs which are only present as moulds. Studies on recent algal sediments have shown the common presence of aragonitic molluscs, which potentially serve as a sources for carbonate cementation (e.g. FREIWALD, 1993; WEHRMANN, 1994). Aragonite is rapidly leached under freshwater conditions, causing precipitation of calcite cements (FOLK, 1974) close to the areas of production.

The coralline algal dominated facies of the study area are comparable to present-day Maerl, which is best known from the Mediterranean and the Northern Atlantic (BOSENCE, 1983a, 1983b, 1984; FREIWALD et al., 1991; WEHRMANN, 1994; FREIWALD, 1993, 1995; FREIWALD & HENRICH, 1994). Maerl is composed of rhodoliths, coralline algal branches, as well as their detritus. In the turbid, high-energy waters of western Europe, Maerl mostly occurs in protected bays at depth of 1–10 m. In lower-energy and clear waters of the Mediterranean they are more characteristic in depths down to 40 m; but they are also reported from 180 m (ADEY, 1986). While Maerl sediments in protected areas are characterised by large, fragile branched rhodoliths (ADEY, 1986), those of higher energetic (tidal currents) areas are composed of interlocking coralline branches forming megaripples (SCOFFIN, 1988). In the northeastern Atlantic, 10 to 30 cm high Maerl banks form a loose framework os interlocking branched coralline algae. This framework grows in sheltered parts of bays at depths of 1–8 m; in the Mediterranean at depths of 30–40 m (BOSENCE, 1983b). Features comparable to the coralline algal rudstone facies are also known from fossil temperate coralline algal gravels and algal-bearing quartz sandstones from the Late Eocene of New Zealand as reported by MACGREGOR (1983). These have been interpreted as a cold- and clear-water, near-shore algal facies swept by weak tidal currents, at 0–12 m depth.

Miogypsinids are rare elements in the Paratethys, being more important in the Mediterranean. As Tethyan elements, miogypsinids are expected to record temporal marine connections between the warm Mediterranean Sea and the cooler northern Paratethys (RÖGL, 1998). Following actualistic comparisons, miogypsinid foraminifers have been interpreted to have carried algal symbionts and lived in shallow waters of less than 30 meters (HOTTINGER, 1997). The very high abundance of miogypsinids in the miogypsinid facies is probably a result of transport or winnowing due to current activity. Their generally high abundance probably reveals warmer influences within a longer period of a cooler climate.

6.4. Sedimentation rate, sea-level and ramp geometry

According to the biostratigraphic results (Fig. 9), the studied ca. 40 m thick sediments were deposited during a time span of about one million years. This result reveals deposition of only ca. one meter within 25.000 years, suggesting the occurrence of sedimentary breaks and/or times of erosion within the studied sequence. However, there are no indications for condensed beds or horizons, and therefore the positions of the possible hiatus is/are unknown.

KANDHAROSA (1995) suggested that the described sequence was deposited under the influence of rapid sea-level changes: low stands producing carbonate-free terrigenous sediments in a littoral position, while sequences rich in coralline algae where formed when rising sea-level flooded the area. Such events could explain the occurrence of erosive events within the described succession, although the eustatic sea-level curves (HAQ et al., 1988) give no indications for rapid sea-level changes within the interval of 25 and 24 m. a. (compare Fig. 9). However, the studied sediments were deposited along the southern border of the Bohemian Massif, which was tectonically active during the Oligocene to Lower Miocene (BACHMANN et al., 1997). Faulting may have caused locally changing subsidence rates, which finally resulted in relative sea-level changes that are not reported from other localities.

The main types of carbonate platforms are isolated platforms, rimmed shelfs, homoclinal and distally steepened ramps (AHR, 1973; READ, 1985; WRIGHT & BURCHETTE, 1998). The transition from the studied sediments to the basin is not exposed, but their mixed carbonate/siliciclastic character suggests that the platform geometry is represented by a homoclinal ramp. Both rimmed shelves and distally steepened ramps would require the existence of carbonate build-ups, which are unknown from the study area. Distally steepened ramps in siliciclastic environments can also be caused by the underground topography. However, the huge thickness of the Linz Sands suggests that the ramp geometry was independent from the underground relief. The vertical succession from siliciclastic dominated sediments at the base to carbonate sediments at the top indicates backstepping of the ramp (DOROBEK, 1995) during transgression; this means that the coastline moved towards the north.

6.5. Facies patterns and environmental reconstruction

Sedimentary and paleontological data show that the studied sediments were deposited in a shallow water environment predominantly influenced by wave agitation, which was situated very close to a rugged crystalline coastline. The influence of wave agitation suggests deposition close to or above the fair weather wave base, which allows the interpretation of an inner or highest middle ramp setting. Both the vertical and the lateral (from north to south) successions from siliciclastics to algal limestones represent changes from proximal to distal environments. The vertical trend thus represents backstepping of the ramp. This interpretation is supported by the grain size data, which suggest that the development from siliciclastic facies to algal dominated facies was accompanied by a reduction of hydrodynamic energy.

The described sedimentary features broadly correspond to sediments described from the present-day NE Brazilian coast (TESTA & BOSENCE, 1998). As in the current study, the environment is characterised by a low diversity of carbonate components, a mixture of siliciclastics and coralline algae on a ramp and a derivation of siliciclastics from submarine reworking of the underground. Moreover, relatively rapid sea-level changes occur.

The present-day analogue and the above discussions of biogenic and siliciclastic components suggest reconstruction of the depositional scenario. During relative sea-level lowstands, erosion prevails and large boulders are deposited close to the shoreline. Wave agitation may cause formation of submarine dunes or bars. The following transgression caused stabilization of the substrate due to decreased wave exposure, and thus enabled growth of coralline algae (compare TESTA & BOSENCE, 1998). Wave agitation still occured and caused the fragmentation of coralline algae as well as their admixture with siliciclastic material. Maerl fields with a lateral extension of tens of meters may have occurred. Interlocking coralline algal branches stabilized the siliciclastic dunes or bars. The miogypsinid facies and oyster beds were most probably also deposited during a higher sea-level stand. After this, a sea-level fall occurred and increased wave agitation again caused erosion and transport of siliciclastic sediment bodies over the Maerl fields. This caused a cessation of coralline algal growth. However, intensive sea-level falls may have led to erosion due to the reduced accommodation space. In this way, the low total sedimentation rate can be explained.

However, the described successions and the sedimentary breaks do not necessarily require rapid sea-level changes. They can also occur in an environment characterized by continuous subsidence and / or continuous relative sea-level rise. Such a setting could be influenced by temporal changes of siliciclastic sediment input into the studied environment. Times of low sediment input allowed growth of maerl dunes, as described above. High sediment input then led to burial and cessation of coralline algal growth. Taking a stable sea-level, the low accommodation space affected erosion and removal of the sediment, which caused hiatus represented by bedding planes. A subsequent time of low sediment input again allowed formation of laterally extensive maerl fields.

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Plate 1

Fig. 1: Siliciclastic facies with badly sorted crystalline components. Sample 20 / bank 2.

Fig. 2: Siliciclastic facies with coralline algae debris (a.d.). Sample 58 / bank 28b.

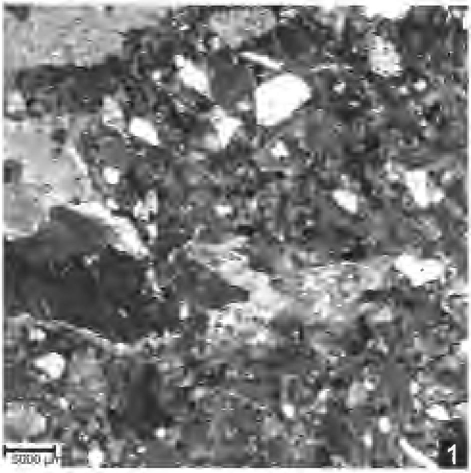
Fig. 3: Miogypsinid facies showing densely packed miogypsinids as well as crystalline components. Sample 33 / bank 11.

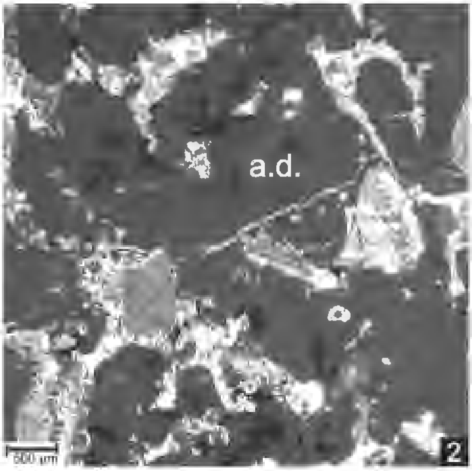
Fig. 4: Terrigenous coralline algal rudstone facies. A branch of a coralline algae fragmented by compaction. Sample 58 / bank 28b.

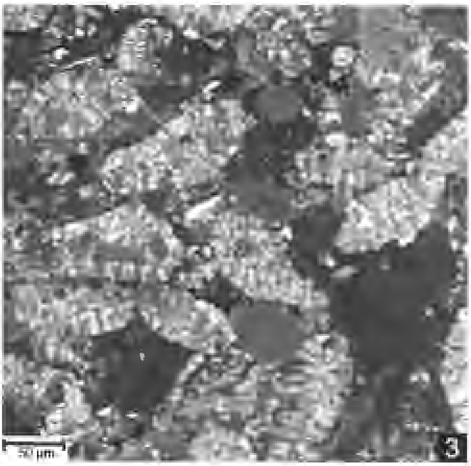
Fig. 5: *Asterigerinata planorbis* in the siliciclastic facies. Sample 27 / bank 5.

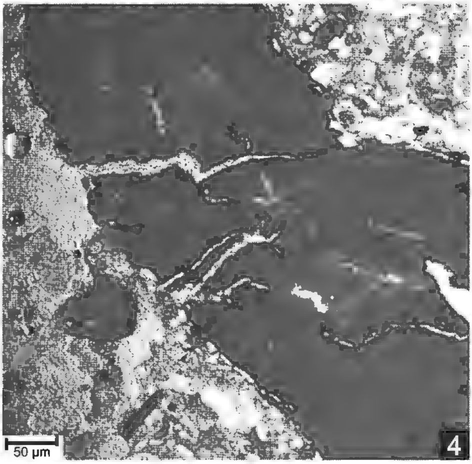
Fig. 6: Cyclostome bryozoa in the siliciclastic facies. Sample 62 / lateral equivalent to bank 28 a.

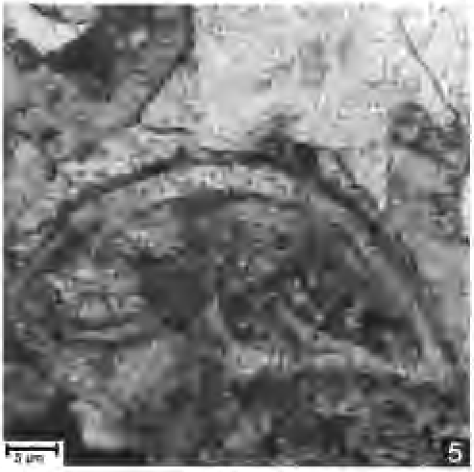
Plate 1











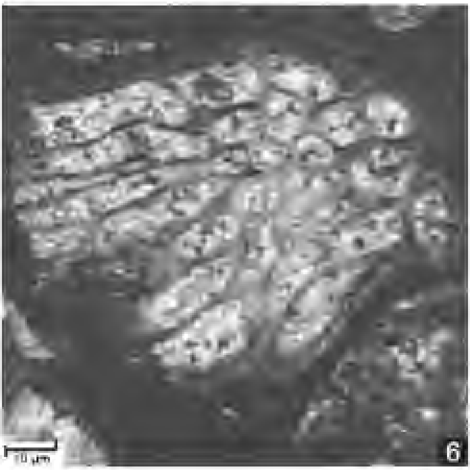


Plate 2

Fig. 1: Median area of a *Miogypsina formosensis*. Sample 51 / bank 23 b.

Fig. 2: Unidentified foraminifer of the siliciclastic facies. Sample 27 / bank 5.

Fig. 3: This textularinid foraminifer, probably *Dorothia* sp., is restricted to the terrigenous coralline algal rudstone facies. Sample 57 / bank 28 a.

Fig. 4: Milliolinid smaller foraminifer in the terrigenous coralline algae rudstone facies. Sample 54 / bank 26.

Fig. 5: *Sphaerogypsina* sp. occurs in all facies, but is most abundant in the siliciclastic facies. Sample 56 / bank 27 a.

Fig. 6: *Amphistegina* sp. in the coralline algal rudstone facies but it appears in all other facies. Sample 50 / bank 23 a.

Plate 2