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Sequence stratigraphy in a mixed carbonate-silicilastic depositional system (Middle Miocene; Styrian Basin, Austria)

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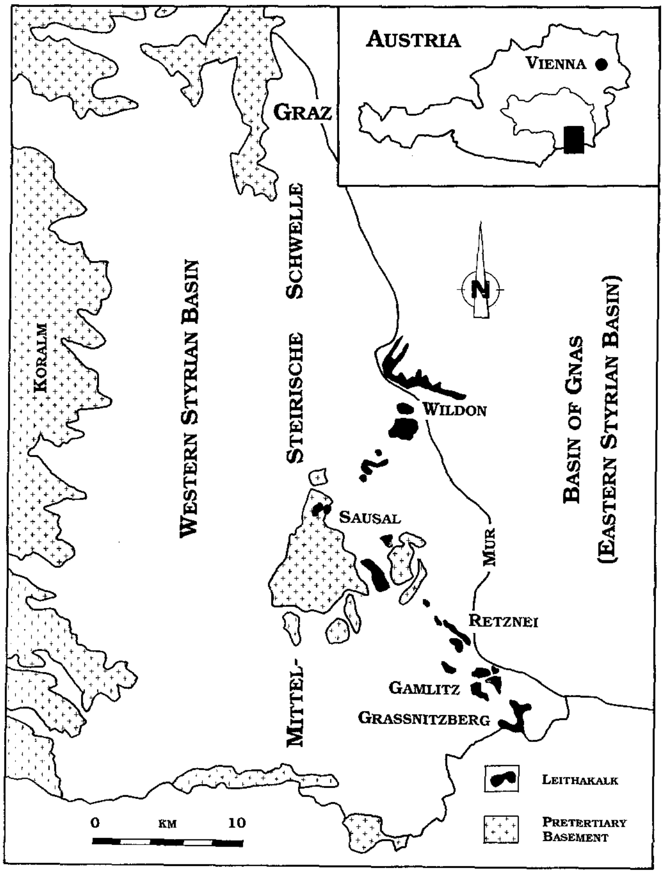
Abstract The mixed carbonate-siliciclastic Weißenegg (Allo-) Formation records three depositional sequences corresponding approximately to the TB 2.3, TB 2.4 and TB 2.5 global cycles. Sea-level fluctuations were of the order of at least 30 m. Siliciclastic lowstand systems tracts comprise lignite deposits, reworked basement and tidal siltstones (above a tectonically enhanced sequence boundary) as well as coastal sand bars. Coastal sands of the transgressive systems tract contain distinct layers of well cemented nodules. They are interpreted as the first stage in hardground formation and record superimposed minor sea-level fluctuations. Coral patch reefs and rhodolith platforms developed during transgressive phases and were subsequently drowned and/or suffocated by siliciclastics during early highstand. Shallowing upwards siliciclastic parasequences, each terminated by a bank of rhodolith limestone, form the (late) highstand systems tract. The limestone beds record superimposed fourth-order transgressive pulses. Occasionally a carbonate highstand wedge developed. Lowstand carbonate shedding occurred where the top of a platform which suffered incipient drowning during highstand was near sealevel again during the following lowstand. Late highstand delta progradation is common.

Key words Sequence stratigraphy – Mixed carbonate siliciclastic system – Styrian Basin, Austria

Introduction

The Styrian Basin (Austria) is the westernmost embayment of the Central Paratethys. A mixed carbonate-siliciclastic depositional system developed during the Badenian. In areas of low terrigenous influx coral reefs and coralline algal platforms were established on swells (Fig. 1; Friebe, 1990; 1991a). They were separated by siliciclastics. Autocyclic processes played an important role in the interaction between carbonate and siliciclastic sedimentation (Friebe, 1991a). Furthermore, a major tectonic event which controlled facies distribution during the Lower Badenian occurred in the latest Karpatian (Friebe, 1991b). During the Badenian tectonic activity was low. Sedimentation largely kept pace with subsidence. The Badenian deposits of the Styrian Basin

Fig. 1. Location of the study area and distribution of carbonate build-ups (Leithakalk); redrawn after Friebe (1990)



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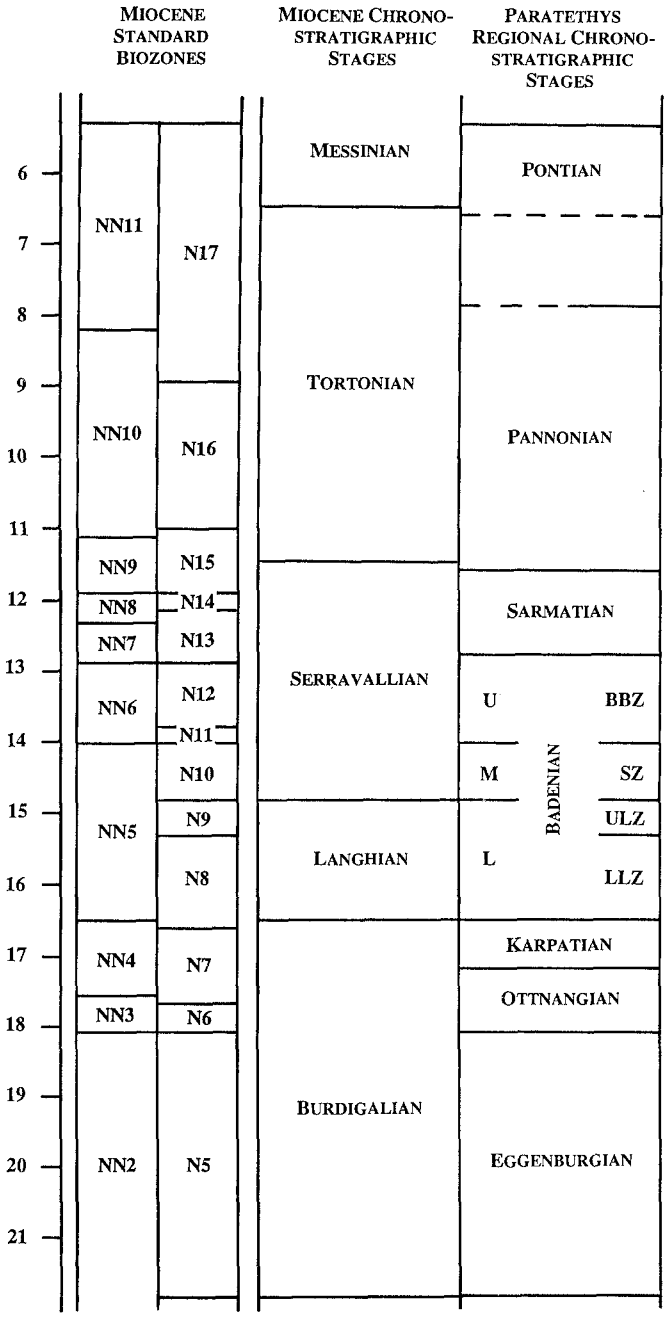


Fig. 2. Current correlation of the regional chronostratigraphic stages of Central Paratethys with Miocene standard chronostratigraphic stages and biozones according to Steininger et al. (1990). Note that there are major differences especially in the absolute age, between the Steininger et al. (1990) and the Haq et al. (1987) correlation tables (see also Fig. 14). LLZ = Lower Lagenid Zone; ULZ = Upper Lagenid Zone; SZ = Spiroplectammina Zone; BBZ = Bulimina–Bolivina Zone

provide an excellent opportunity to study the impact of sea-level changes on a mixed carbonate-siliciclastic depositional system.

As the Central Paratethys is characterized by its own faunal and tectonic evolution, regional (bio-)chronostratigraphic stages were defined (Fig. 2; summary in Rögl and Steininger, 1983). Correlation with the international standard stages suffers from the increasing endemism of the Paratethyan aquatic biota. Sequence stratigraphy could thus provide additional information to solve this problem (Tari et al., 1992).

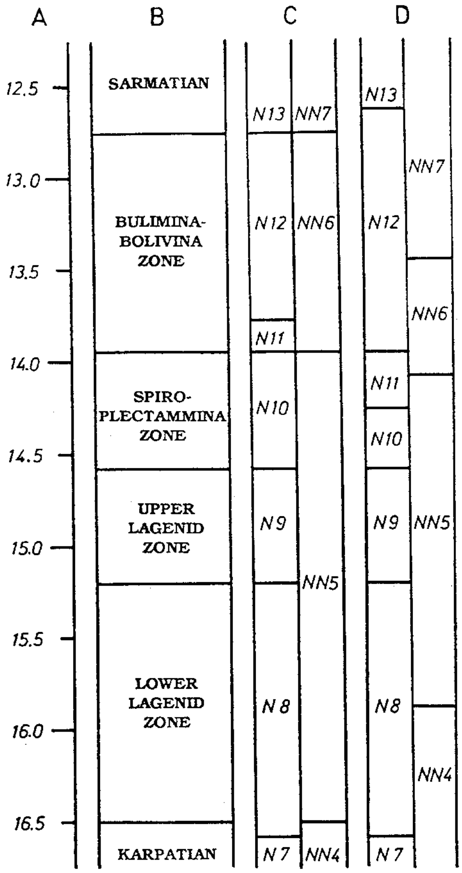
Geological Setting

The Styrian Basin, the westernmost of the Intra-Carpathian Neogene Basins (Central Paratethys), is separated from the Pannonian Basin by the Südburgenländische Schwelle. Pull-apart processes (Flügel, 1988) as well as blocktilting in connection with a 'continental escape' in the Eastern Alps (Neubauer and Genser, 1990; Ratschbacher et al., 1991) lead to its formation during the Ottnangian (Ebner et al., 1992; for correlation of the regional chronostratigraphic stages of the Central Paratethys with the Mediterranean stages, see Fig. 2 and Rögl and Steininger, 1983; Steininger et al., 1990). Its sedimentary record mainly consists of siliciclastics ranging from the Ottnangian to the Pontian. The Karpatian to Lower Badenian volcanism of the Eastern Styrian Basin (Flügel, 1988) is probably related to the back-arc regime of the Pannonian Basin (Horvath and Berkheimer, 1983; Royden, 1988). Carbonate sedimentation occurred both in the Badenian and Sarmatian (Kollmann, 1965). The latter is of only local importance.

The Badenian Leithakalk, which is also found in large parts of the Vienna and other Intra-Carpathian Basins (Papp et al., 1978), consists of shallow marine limestones of various microfacies formed mainly by coralline algae and corals. Minor sediment contributors are foraminifera, bryozoa, molluscs and sea urchins (Steininger and Papp, 1978; Dullo, 1983; Friebe, 1990). They form isolated carbonate bodies situated on morphological highs within the basins which are separated by siliciclastics.

In the Styrian Basin Leithakalk outcrops are confined to the vicinity of the islands of the Mittelsteirische Schwelle (Sausal Mountains), which separate the Eastern from the Western Styrian Basin (Figs. 1 and 3). The Leithakalk is also found in wells fringing the volcanic complexes of the Eastern Styrian Basin (Kollmann, 1965). Carbonate build-ups plus their siliciclastic surroundings are integrated in the Weißenegg (Allo-) Formation (Friebe, 1990). A detailed description of carbonate microfacies is given by Dullo (1983). Models for the interactions between carbonates and siliciclastics have been presented by Friebe (1991a).

Fig. 3. Lithostratigraphy and depositional sequences of the Badenian deposits in the Styrian Basin. A = Absolute age; B = chronostratigraphic zones and stages of the Central Paratethys; C = biozones according to Steininger et al. (1990); D = biozones according to Rögl and Steininger (1983)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C
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14.0
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SPIRO-PLECTAMMINA ZONE
UPPER LAGENID ZONE
LOWER LAGENID ZONE
KARPATIAN
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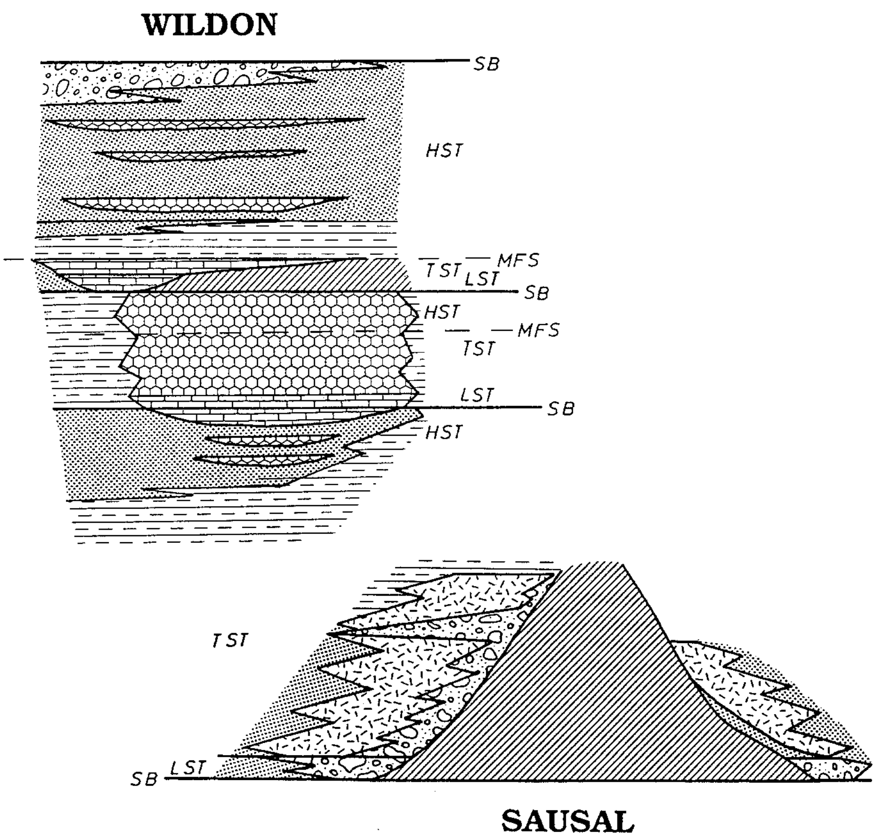
NN4


WILDON
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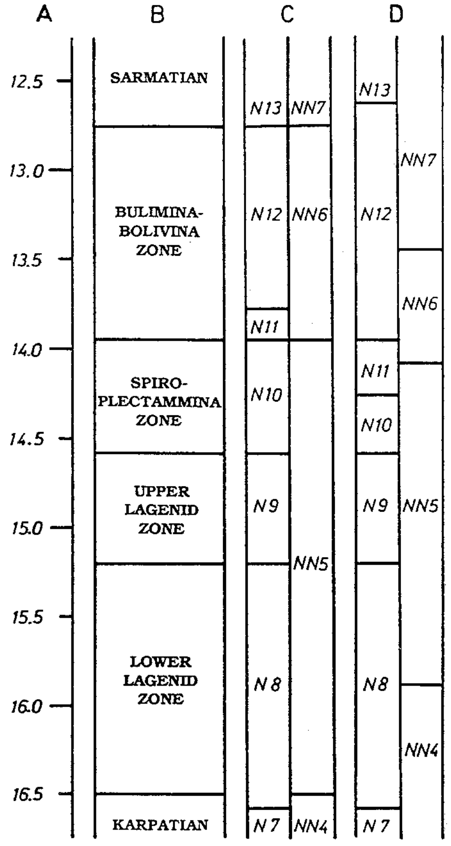
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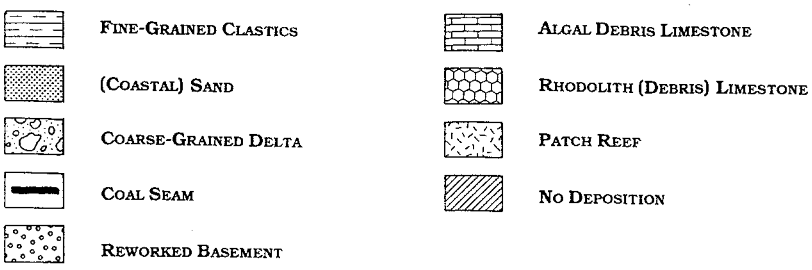
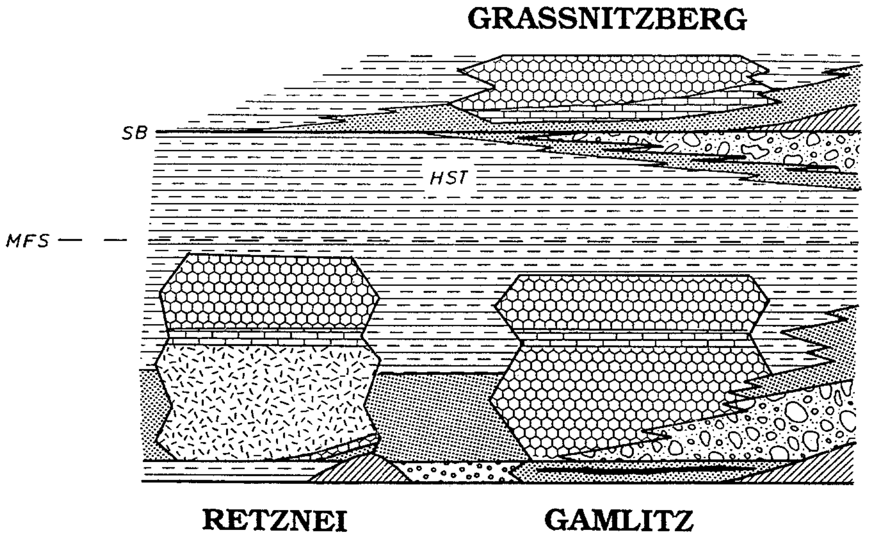

Fine-Grained Clastics
(Coastal) Sand
Coarse-Grained Delta
Coal Seam
Reworked Basement
Algal Debris Limestone
Rhodolith (Debris) Limestone
Patch Reef
No Deposition


GRASSNITZBERG
SB
HST
MFS
RETZNEI
GAMLITZ

Facies Distribution

Near the Mittelsteirische Schwelle (Sausal Mountains) five areas of Leithakalk sedimentation can be distinguished (north to south, Figs 1 and 3; Friebe, 1990): (1) The Leithakalk platform of Wildon (Upper Lagenid Zone to Bulimina-Bolivina Zone); (2) patch reefs fringing the islands of the Sausal Mountains (Lagenid Zone); (3) the Leithakalk platform and patch reef of Retznei (Lagenid Zone); (4) the Leithakalk build-up of Gamlitz (Lagenid Zone); and (5) the Leithakalk platform of Graßnitzberg (Spiroplectammina zone)

Lagenid Zone = Lower Badenian (Retznei, Gamlitz, Sausal)

During the latest Karpatian and Lower Badenian, facies distribution patterns were influenced by an inherited relief generated by erosion following tectonic activity in the late Karpatian (Fig. 4; Friebe, 1991c).

In the south the unconformity is overlain by a thin horizon of sandy conglomerate to gravelly sandstone of latest Karpatian age. Siltstone cobbles derived by the reworking of the basement are often bored by bivalves (*Gastrochaenolites* borings). This horizon contains scarce fossil debris and (macro-)fossils (e.g. oysters, sea urchins). Coarse gravel accumulated on top of the bed. Farther to the west (= landward) lignite was deposited (Weber and Weiss, 1983). During the Lower Badenian the high terrigenous input inhibited the development of a carbonate platform in that area. Instead massive, medium to coarse-grained sand was deposited. Primary sedimentary structures were destroyed by bioturbation. This sand contains distinct layers with well cemented nodules (Fig. 5). It is overlain by massive to laminated silt with authigenic glauconite and an abundant foraminiferal fauna.

Areas of low terrigenous input (Retznei, Gamlitz, Sausal) show a very different development. In the Retznei area pebbly siltstone was deposited during the latest Karpatian. Clasts of Palaeozoic and metamorphic rocks originating from gravelly layers within the Karpatian basement are arranged as a pavement of poorly defined small channels. Cobbles are also concentrated at the top of this horizon.

At the beginning of the Badenian Leithakalk sedimentation started. At Retznei (Fig. 6) and at the eastern flanks of the Sausal Mountains patch reefs developed both as fringing reefs and on abandoned fan delta lobes. In the Retznei build-up (Piller et al., 1991) the cobbles on top of the pebbly siltstone acted as a stable substrate for the initiation of the patch reef. The basal part of the reef shows a distinct facies zonation controlled by the inhereted relief (Fig. 7). Coral growth occurred in slightly deeper water, whereas in the centre of the shoal moderately sorted, massive, bioturbated sand with bivalves, epiphytic serpulids and foraminifera and abundant crustacean debris was deposited. These two facies were separated by a rhodolith/corallith belt (Fig. 7). Massive colonies of *Porites* sp., *Tarbellastraea* sp. and *Montastraea* sp. were the main reef builders. Other corals were of minor importance. They are intensively bored by *Lithophaga* sp. Other bivalves, mainly pectinidae, barnacles, rhodoliths, and algal debris are common. The younger part of the patch reef (unit 3 in Fig. 6) shows no distinct facies zonation. Owing to the volcanic activity in the Eastern Styrian Basin (Flügel, 1988) reef growth was frequently interrupted and at last terminated by ash falls as indicated by marly layers with abundant euhedral biotite, zircon and apatite.

The patch reef is covered by algal debris limestone (rudstone – packstone and grainstone; foraminiferal algal/rhodolite debris facies; Dullo, 1983; unit 4 in

Fig. 4. The 'Styrian Unconformity', a tectonically enhanced sequence boundary (arrows). B = basement (Karpatian offshore sediments); L = conglomerates consisting of reworked basement – lowstand systems tract (uppermost Karpatian); T = massive upper shoreface sands – transgressive systems tract (Early Badenian); Katzengraben near Spielfeld

Fig. 5. Massive upper shoreface sands comprising the siliciclastic transgressive systems tract of the first depositional sequence. Note distinct layers of well cemented nodules. Katzengraben near Spielfeld

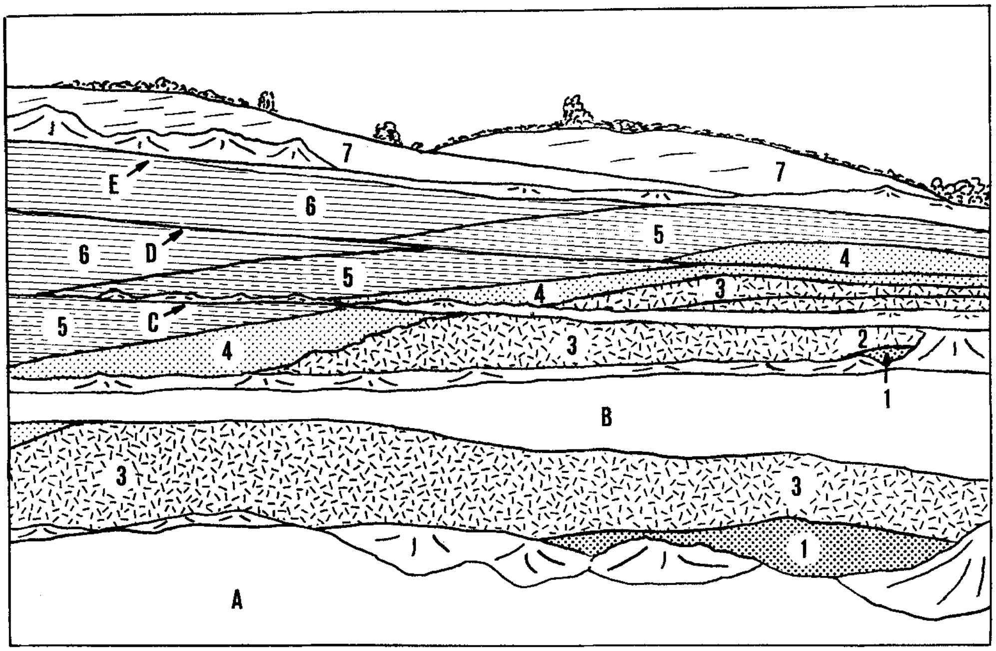


Fig. 6. Sketch of the Retznei quarry (first depositional sequence): 1 = Pebbly marl (lowstand systems tract); 2 = basal facies zonation (early transgressive systems tract, see Fig. 7 and text); 3 = patch reef; 4 = algal debris grainstone (reduced tectonic subsidence); 5 and 6 = marly rhodolith limestone ('catch-up' during late transgressive systems tract); 7 = siliciclastics (marl and fine sand; early highstand systems tract); A to E = working floors. View to the west; height of quarry walls approximately 8 m; Friebe (1988)

Fig. 6). The deposits of deeper water contain frequently undamaged branching to columnar rhodoliths and small colonies of *Porites* sp. (partly coralliths) whereas the shallow water deposits of this unit consist of very fine-grained algal debris grainstone. The grain size does not exceed 1 mm. Macrofossils are rare. The foraminifera show the typical shallow water Leithakalk association with *Amphistegina hauerina* d'Orbigny, *Elphidium crispum* (Linne), *Cibicides lobatulus* (Walker and Jacob), *Heterolepa dutemplei* (d'Orbigny), *Asterigerinata planorbis* (d'Orbigny), *Loxostomum digitale* (d'Orbigny), *Borelis melo* (Fichtel and Moll), and abundant Miliolidae. The crab *Daira speciosa* (Reuss) and bivalves (mainly oysters and Pectinidae) are common in deposits of slightly deeper water. A large portion of detritus was transported beyond the reef into a lagoon between the patch reef of Retznei and a shoal approximately 1.5 km farther north west.

Fig. 7. Lowstand and transgressive systems tracts in the Retznei build-up. 1 = Pebbly marl (lowstand systems tract); arrows = transgressive lag; 2 = massive sand, seagrass meadow; 3 = rhodolith/corallith belt; 4 = patch reef. To the south-east in a more basinward position the pebbly marl (1) is directly succeeded by the patch reef (4)

The top of the build-up consists of marly rhodolith limestone (bioclastic rhodolite debris facies, Dullo, 1983; units 5 and 6 in Fig. 6). Layers with boxwork rhodoliths alternate with beds of branching rhodoliths up to 10 cm in diameter. *Porites* sp. formed flat incrusting and small massive colonies (the latter probably representing coralliths). Within unit 6 two coral carpets with large colonies of *Montastraea* sp. (up to 1 m in diameter) developed. Algal and coral growth was restricted to the southern flank of the build-up whereas in the centre of the shoal sedimentation was reduced (indicated by the formation of authigenic glauconite and a compensation of the relief). This resulted in a pronounced offlapping sedimentation pattern. Thin marly layers containing apatite, titanite, euhedral zircon and biotite are of volcaniclastic origin. Terrigenous input was relatively high.

Similar to the Retznei build-up at the beginning of the Badenian, a widespread rhodolith platform (wackestones to floatstones; bioclastic algal/rhodolite debris facies of Dullo, 1983) developed in the Gamlitz area. It is underlain by massive to trough cross-bedded conglomerates of latest Karpatian age. Coralline algal growth was interrupted by an oyster bed. Local intercalations of coral carpets are restricted to the lower part of the build-up beneath the oyster bed.

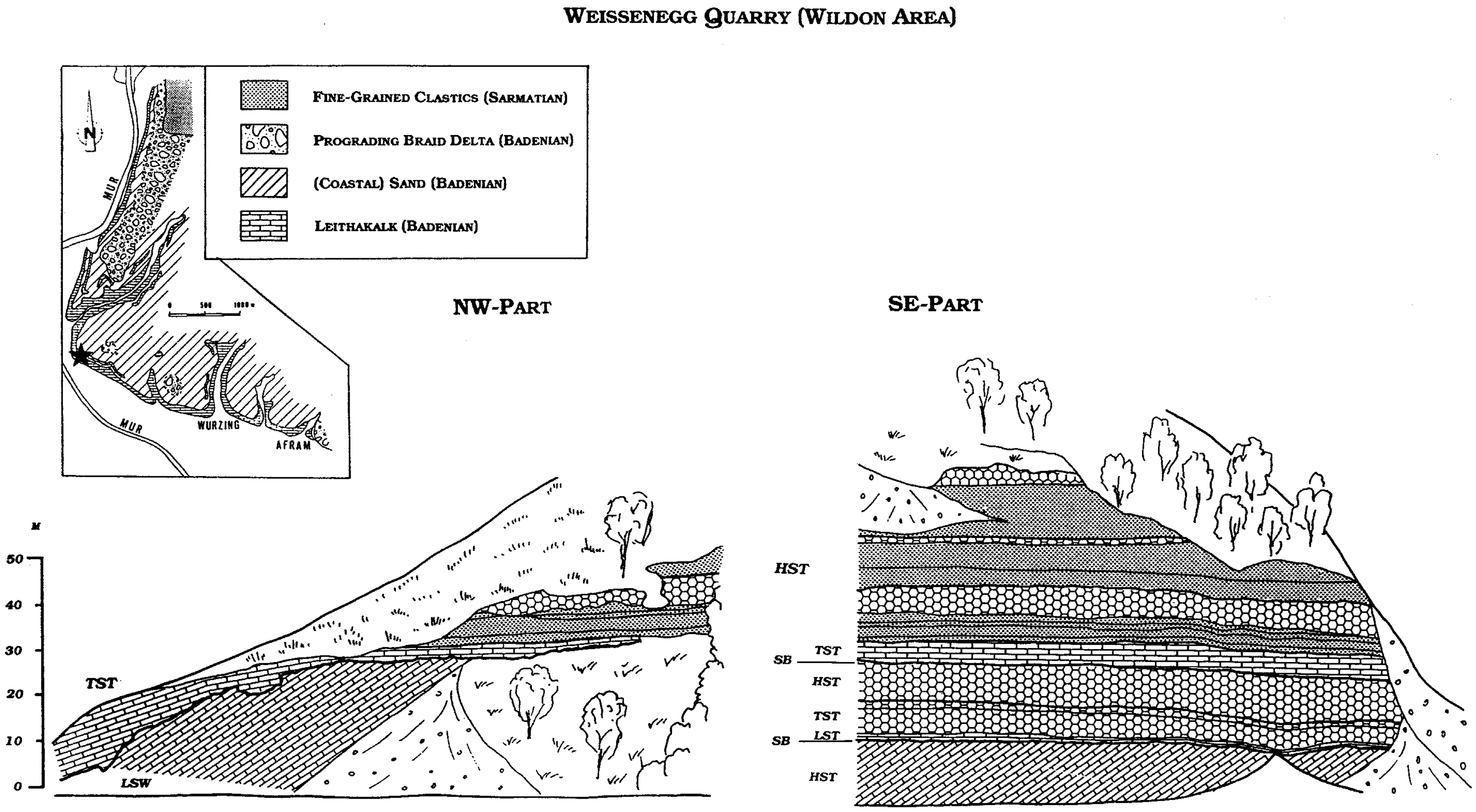


Fig. 8. Sketch of the Weißenegg quarry: highstand carbonate prograding complex of sequence 1, sequences 2 and 3; redrawn after Kollmann (1965) and Friebe (1990)

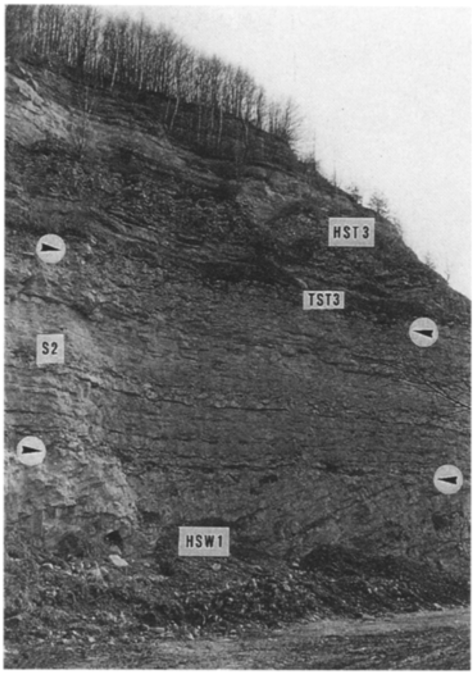


Fig. 9. South-eastern part of the Weißenegg quarry showing the top of depositional sequence 1 (HSW1; carbonate highstand wedge, foraminiferal algal debris facies), sequence 2 (continuous transition from foraminiferal algal debris facies to marly bioclastic rhodolite debris facies) and the transgressive (TST3) and early highstand (HST3) systems tracts of sequence 3; arrows = sequence boundaries

The eastern flanks of the Sausal islands were fringed by patch reefs. Corals colonized a fining-upwards horizon of reworked Palaeozoic basement rocks and abandoned fan delta lobes. Within the reefs the portion of encrusting coralline algae and rhodoliths gradually increases towards the top.

All these carbonate build-ups were suffocated by siliciclastics (Sausal, Retznei) or drowned (Gamlitz). They are overlain by silt and fine sand with occasionally turbiditic layers (Retznei). The rich foraminiferal fauna with *Cibicidoides ungerianus* (d'Orbigny), *Dentalina* spp. (various species), *Gyroidinoides soldanii* (d'Orbigny), *Lenticulina* spp. (various species), *Melonis pompilioides* (Fichtel and Moll), *Nodosaria* spp. (various species), *Pullenia bulloides* (d'Orbigny), *Sphaeroidina bulloides* d'Orbigny, *Spiroplectammina carinata* (d'Orbigny), *Stilostomella* spp. (various species), *Uvigerina* spp. (various species), and others indicates a water depth of approximately 100 m.

Latest Lower to Middle Badenian = Spiroplectammina Zone

Gamlitz – Graßnitzberg area. At the end of the Upper Lagenid Zone (Lower Badenian) a significant basinwards shift of facies occurred in the Gamlitz – Graßnitzberg area. Massive to laminated silt is intercalated by layers of normal graded coarse sand (mass flow deposits). The frequency of these sandy interlayers increases upwards. Inverse to normal graded conglomerates (gravelly high density turbidity currents) occur at the top of the succession, which records a continous shallowing. It is overlain by massive sand (Graßnitzberg). Primary sedimentary structures were destroyed by bioturbation. Occasionally gravel occurs on its top. At the beginning of the Spiroplectammina Zone these shallow water sand bodies were selectively colonized by coralline algae. Within the Graßnitzberg platform a transition from wackestones (foraminiferal algal debris facies) to floatstones (bioclastic rhodolite debris facies) records a successive increase in water depth during the Spiroplectammina Zone.

Wildon area. In the Upper Lagenid Zone first algal platforms (bioclastic algal/rhodolite debris facies) and occasionally coral carpets alternating with coarsening-/shallowing-upwards siliciclastic successions were deposited north of the Sausal islands in the Wildon area. At least three cycles can be distinguished. A typical cycle consists of massive to laminated offshore silt, ripple-bedded silt-sand alternations, massive coastal sand, occasionally lagoonal *Amphistegina* marl, and Leithakalk. During the latest Upper Lagenid Zone the youngest platform prograded to the north. The progradational wedge (grainstone; foraminiferal algal debris facies) was subsequently truncated (Figs 8 and 9). It is overlain by a thin layer of algal debris grainstone (foraminiferal algal/rhodolite debris facies).

During the Spiroplectammina Zone the Wildon platform shows a continous transition from grainstones (foraminiferal algal debris facies) via wackestones – floatstones (bioclastic algal debris facies) to a predominance of floatstones and rudstones (bioclastic rhodolite debris facies and bioclastic algal mollusk facies with abundant massive bryozoan colonies, Fig. 11). This general trend is accompanied by an increase in rhodolith size, a change in rhodolith growth forms from branched columnar to columnar laminar, a change in the composition of foraminiferal and bryozoan faunas, and an increase in terrigenous influx (Dullo, 1983; Hansen et al., 1987; Vavra, 1989; Friebe, 1990). A maximum water depth of approximately 30 – 50 m was estimated by Hansen et al. (1987). Terrigenous siliciclastics reduced the growth potential of the coralline algae and thus sedimentation rates. However, the platform was not suffocated. Net sedimentation rates were still significantly higher than in the surrounding siliciclastics, resulting in an elevation of the platform of approximately 30 m above the muddy Western Styrian Basin.

Upper Badenian = Bulimina – Bolivina Zone (Wildon)

At the end of the Spiroplectammina Zone a younger progradational wedge (foraminiferal algal debris facies; Fig. 12) developed at the northern margin of the Wildon platform (Figs 8 and 10). Its upper surface shows a considerable relief. It is succeeded by a thin blanket of algal debris grainstone (foraminiferal algal debris facies).

Fig. 10. North-western part of the Weißenegg quarry showing the carbonate lowstand wedge of sequence 3 (LSW; foraminiferal algal debris facies), the transgressive surface (arrow) and transgressive systems tract (TST; foraminiferal algal debris facies) and the first mixed siliciclastic–carbonate parasequence of the highstand systems tract of sequence 3 (PS1)

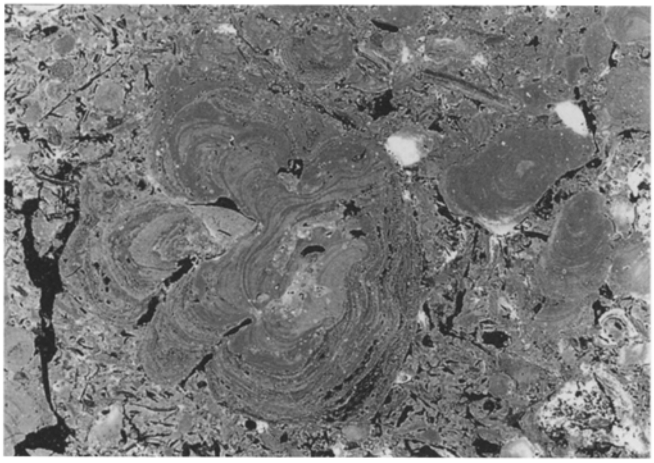


Fig. 11. Leithakalk: bioclastic rhodolite debris facies (Dullo, 1983); highstand systems tract of sequence 2, Weißenegg quarry (16 × 24 mm).

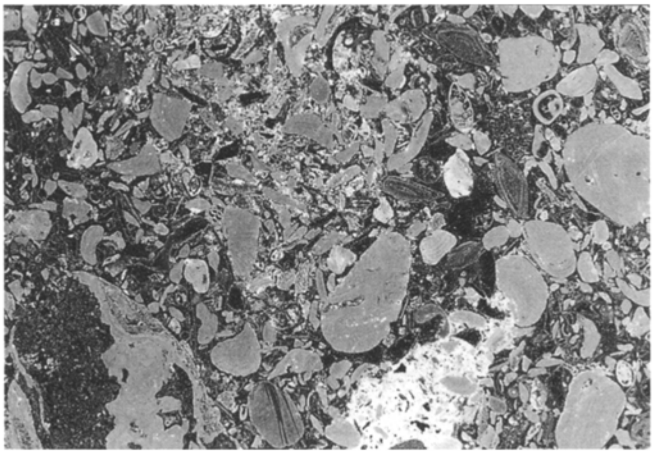
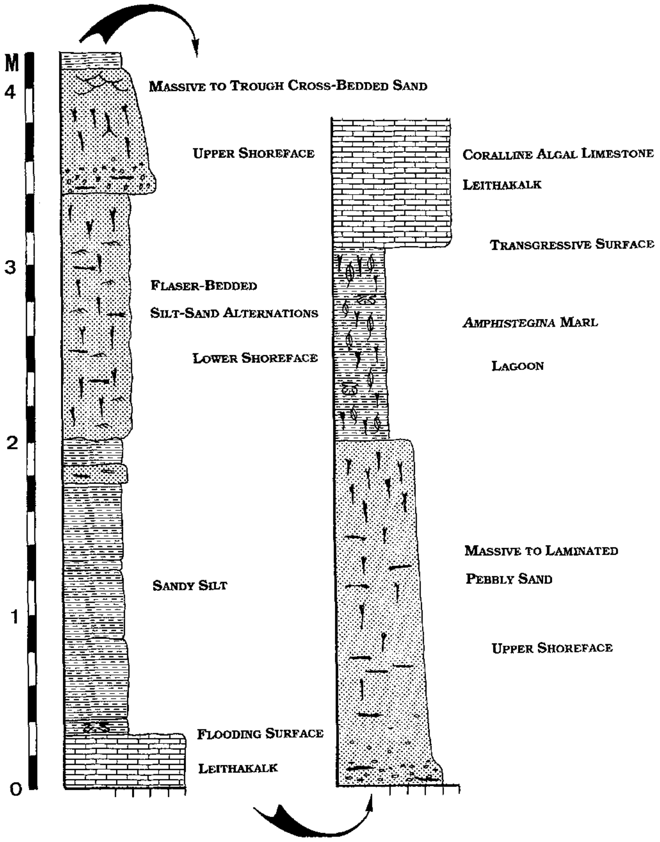


Fig. 12. Leithakalk: foraminiferal algal debris facies (Dullo, 1983); carbonate lowstand wedge (sequence 3); Weißenegg quarry (13 × 19 mm)

Mainly siliciclastics were deposited on top of this platform during the Bulimina–Bolivina Zone. They form three coarsening-/shallowing-upwards cycles (Fig. 13), each terminated by a Leithakalk bed (wackestones to floatstones; bioclastic algal/rhodolite debris facies). Each cycle starts with massive to laminated silt conformably overlying the Leithakalk of the previous cycle. It occasionally contains scattered bivalves in live position or as open but still articulated shells. Fine-grained plant debris is common; foraminifera and ostracods are scarce. The silt grades upwards into sandy silt – sand alternations with draped ripples and locally bioturbation, followed by fine- to medium-grained, ripple bedded sand. With the increase in grain size two-dimensional wave ripples become the predominant sedimentary structure. This ripple bedded sand is succeeded by massive, coarse-grained sand with occasionally pebbly beds and layers with coarse plant debris. Physical sedi-

Fig. 13 Stratal characteristics of a mixed siliciclastic–carbonate parasequence, Weißenegg quarry



mentary structures have been completely destroyed by bioturbation. *Ophiomorpha*sp. is common at the top of this lithofacies. A cycle is terminated by a bed of rhodolith and/or coralline algal debris wackestone to floatstone (bioclastic algal/rhodolite debris facies). In the first cycle the massive, bioturbated sand and the Leithakalk are separated by *Amphistegina* marl (Fig. 13), which is missing in the subsequent cycles.

At the end of the Badenian ('Zone with an impoverished fauna') a coarse-grained delta prograded from the north-west into the Western Styrian Basin causing a decrease of foraminiferal diversity and abundance (Kollmann and Rögl, 1978). Early Sarmatian deposits contain coal seams. They are overlain by fine-grained marine siliciclastics (Weber and Weiss, 1983).

Badenian Sea-Level Changes and Sequence Stratigraphy

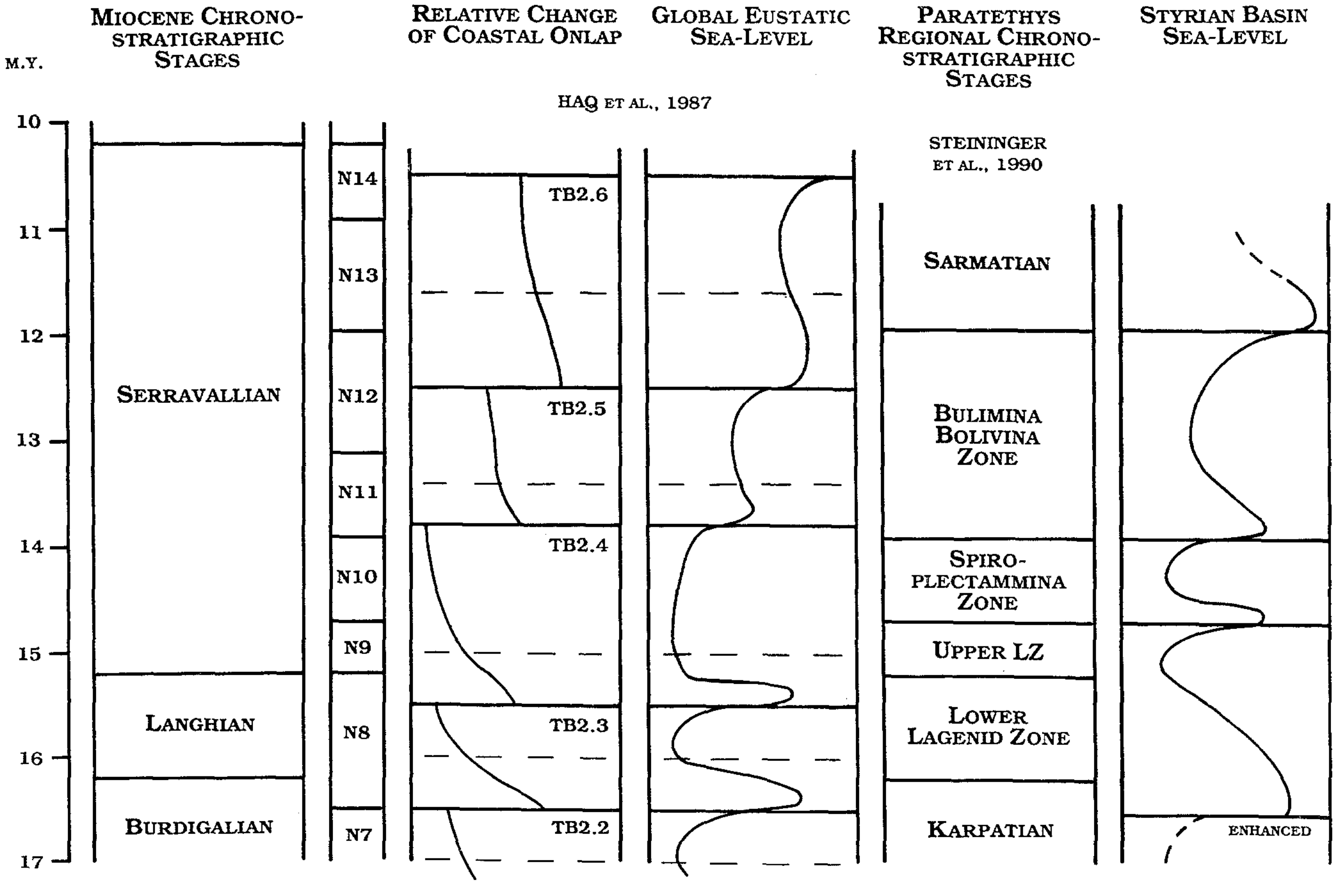
In the study area three depositional sequences resulting from eustatic sea-level changes, but modified by local tectonics as well as autocyclic processes, can be distinguished (Figs 3 and 14).

Sequence 1 (Lower Badenian)

During the Middle Miocene the continuing convergence of the Adriatic (= Apulian) plate and Europe caused the eastwards extrusion of a crustal wedge in the eastern Alps east of the Tauern Window (Neubauer and Genser, 1990; Ratschbacher et al. 1991). In the latest Karpatian block tilting within the wedge initiated by this 'continental escape' caused uplift, tilting and subsequent subaerial erosion of the Karpatian offshore sediments. This coincided with a rapid sea-level fall resulting in a tectonically enhanced sequence boundary (Vail et al., 1991; 'Styrian Unconformity', Fig. 4; Friebe, 1991b; 1991c). Lowstand systems tract sediments include lignite deposits (Weber and Weiss, 1983), conglomerates consisting of reworked Karpatian basement and sub- to intertidal pebbly siltstone.

Transgression started at the beginning of the Badenian. Gravel derived from the reworking of coarse-grained layers within the Karpatian basement was concentrated at the top of the lowstand deposits forming a transgressive lag. At Retznei it provided a relatively stable substrate for the colonization by corals. Patch reefs (Sausal islands, Retznei; unit 3 in Fig. 6) and rhodolith platforms (Gamlitz) were able to keep up with the slowly rising sea level. The location of carbonate sedimentation

Fig. 14. Comparision of the sea-level changes in the Styrian Basin with the global eustatic sea-level curve (Haq et al., 1987). Absoltute ages according to Haq et al. (1987), correlation of the regional bio-chronostratigraphic zones and stages of the (Central) Paratethys with international Miocene stages according to Steininger et al., 1990, using standard planktic foraminiferal zones (Blow, 1969)



was controlled by an inherited relief and the amount of terrigenous influx. A superimposed decrease of the rate of relative sea level rise in the Lower Lagenid Zone, recorded by algal debris limestone in Retznei (unit 4 in Fig. 6) and an oyster bed in Gamlitz, is thought to be the consequence of a local short-term decrease of subsidence rates or a superimposed short-term sea level fall. In the siliciclastics the early transgressive systems tract is composed of coastal sand bodies. Layers of well cemented nodules record reduced sedimentation during short-term transgressive pulses.

The 'late' transgressive systems tract is characterized by a catch-up of the Retznei build-up. In this area the relative sea level rose only slowly, resulting in a compensation of the pre-existing relief and a pronounced offlapping geometry (units 5 and 6 in Fig. 6). This peculiar situation may be explained by local tectonics (decreased subsidence rates or even a slight uplift). The marly rhodolith limestone of units 5 and 6 indicates relatively high environmental stress due to siltation. This build-up, as well as the patch reefs fringing the Sausal islands, were subsequently suffocated by siliciclastics (unit 7 in Fig. 6). In the Gamlitz area carbonate sedimentation could not keep pace with rising sea level. There the platform was drowned. Drowning was facilitated by the influx of terrigenous material. A continuous increase in water depth inhibited the removal of the fine-grained siliciclastics by fair weather waves. Additional silt could have been brought to the site of carbonate deposition by the shifting of delta lobes in the Western Styrian Basin. In the siliciclastics maximum flooding is indicated by an abrupt deepening (massive silt with foraminifera of deeper water overlying coastal sand) and the occurrence of glauconite. The foraminiferal fauna indicates a water depth of approximately 100 m.

The early highstand systems tract of sequence 1 (Upper Lagenid Zone), which comprises progradational silt and sand with an overall coarsening upwards trend, does not contain any carbonate platforms. In the south (Graßnitzberg area) the late highstand systems tract is characterized by the progradation of a braid delta from the west, which is indicated by an upwards increase of the frequency of mass flow beds intercalated into massive to laminated silt and the deposits of gravelly high density turbidity currents on top of the succession. In the north (Wildon area) late highstand parasequences comprise siliciclastic shallowing upward cycles terminated by rhodolith limestone and a flooding surface.

Sequence 2 (Middle Badenian)

In the Graßnitzberg and the Wildon areas the boundary between the first and second sequence is very different. In Graßnitzberg braid delta gravel is overlain by relatively coarse-grained sand bars (shelf margin systems tract) with no apparent unconformity (type 2 sequence boundary). In the Wildon area the uppermost carbonate platform prograded to the north forming a latest highstand progradational wedge (Figs 8 and 9; cf. Schlager, 1991). The platform was truncated during subsequent sea-level lowstand, when it was probably exposed. However, no karst features can be observed. The type 1 sequence boundary of the Wildon area corresponds to sea-level lowstand rather than to a maximum rate of sea-level fall. As a consequence the subsequent late lowstand systems tract (foraminiferal algal debris facies) of this platform is thin and indistinct.

The transgressive systems tract of the second depositional cycle (Spiroplectammina Zone) reflects a continous increase in water depth both in the Graßnitzberg and the Wildon areas, indicated by a rapid transition from grainstone (foraminiferal algal debris facies) to wackestone – floatstone (bioclastic algal debris facies) and (on the Wildon platform) to a predominance of floatstone and rudstone (bioclastic rhodolite debris facies and bioclastic algal mollusc facies with abundant massive bryozoan colonies). There algal growth was not able to keep up with rising sea level. However, algal growth exceeded sedimentation rates in the siliciclastics resulting in an elevation of the Wildon platform of approximately 30 m above its surroundings. Although the Graßnitzberg platform was either drowned or suffocated by siliciclastics (younger siliciclastic sediments are not preserved in that area), incipient drowning (Kendall and Schlager, 1981) characterizes the highstand systems tract in the Wildon platform. The boundary between transgressive and highstand systems tracts is indistinct. A very marly rhodolith floatstone to rudstone indicates maximum flooding. Although the marl content decreases again towards the top of this unit, a distinction between early and late highstand systems tracts is not possible.

Sequence 3 (Upper Badenian)

The second depositional cycle was terminated by a rapid sea-level fall. During lowstand the top of the Wildon platform, which suffered incipient drowning during the previous highstand, was at a position between sea level and fair weather wave base again and re-attained its maximum growth potential. However, the platform shows no evidence of exposure. This peculiar situation lead to the formation of a type 2 sequence boundary on the platform, although sea-level fall was rather rapid. A younger progradational wedge (grainstone, foraminiferal algal debris facies) developed during sea-level lowstand (Figs 8 and 10). The lowstand/shelf margin systems tract of the third depositional sequence (Bulimina – Bolivina Zone), which is only preserved in the Wildon area, is a rare example of lowstand carbonate shedding. Its upper, partly erosional boundary is interpreted as a transgressive surface. The transgressive systems tract consists of a thin layer of fine-grained algal debris grainstone (foraminiferal algal debris facies) (Fig. 12).

The highstand systems tract is composed of three shallowing-upwards punctuated aggradational cycles (Goodwin and Anderson, 1985) or parasequences (Mitchum and Van Wagoner, 1991) each starting with massive to laminated silt and ending with a bank of Leithakalk (bioclastic algal/rhodolite debris facies) and a flooding surface (Fig. 13). They record fourth-order sea-level fluctuations. Fine-grained offshore sediments were deposited during (fourth-order) early sea-level highstand; ripple bedded silt – sand alternations correspond to late sea-level highstand. During the lowstand of the next fourth-order cycle massive to bioturbated coastal sand bodies developed. Coralline algae colonized these sand bodies during the next transgressive pulse when terrigenous siliciclastics were stored in a coastal plain farther landward. The *Amphistegina* marl, which contains abundant epiphytic foraminifera between massive sand and Leithakalk in the first parasequence (Fig. 13) is interpreted as a lagoonal deposit. Its formation is related to autocyclic processes rather than to sea-level changes.

The late highstand systems tract of the third depositional cycle contains successions of trough-cross-bedded conglomerates succeeded by ripple bedded medium to coarse sand and laminated silt. At that time a braid delta prograded from the north west ('Zone with an impoverished fauna', Kollmann and Rögl, 1978). Fine-grained siliciclastic sediments of the Sarmatian with minor coal seams (Weber and Weiss, 1983) belong to the lowstand/shelf margin and/or transgressive systems tract of the following depositional sequence. The exact position of the sequence boundary cannot be determined because of the lack of good quality outcrops.

Discussion

The sedimentary record of the Badenian in the Styrian Basin (Weißenegg Formation) can be subdivided into three depositional sequences bounded by unconformities (Fig. 3). Sequence 1 ranges from the latest Karpatian to the Lagenid Zone/Spiroplectammina Zone boundary (latest NN4 to late NN5 and N7/N8 to N9/N10 boundaries, respectively; Neogene standard biozones of Martini, 1971 and Blow, 1969; correlations according to Steininger et al., 1990). A local, short-term decrease in subsidence rates is superimposed. Sequence 2 comprises the Spiroplectammina Zone (late NN5 and N10, respectively). Sequence 3 ranges approximately from the Spiroplectammina Zone/Bulimina – Bolivina Zone boundary to the Badenian – Sarmatian boundary (NN6 and N11 to N12, respectively). The facies distribution suggests that sequences 2 and 3 are superimposed on the highstand systems tract of a second-order eustatic cycle. Owing to the relatively poor outcrop density a strict distinction between type 1 and type 2 sequence boundaries is not always possible. Furthermore, seismic data from the Eastern Styrian Basin have not yet been released by the petroleum companies.

In spite of the fact that the basal boundary of sequence 1 was modified by local tectonics ('Styrian phase', latest Karpatian, Friebe 1991 b), the overall tectonic activity during the Badenian in the vicinity of the swell under consideration ('Mittelsteirische Schwelle') is estimated to be low. In this area changes in tectonic subsidence only slightly modified the sedimentary sequences generated by sea-level changes (e.g. decreased subsidence within sequence 1 in the Retznei/Gamlitz area). Sedimentation largely kept pace with subsidence. However, in a more distal setting (Eastern Styrian Basin) the influence of tectonics should not be underestimated. For the entire Badenian Ebner and Sachsenhofer (1991) estimated subsidence rates of up to 3 cm/100 years for basinal settings.

The special situation at the end of sequence 2 allows an estimation of the magnitude of sea-level changes. For the almost drowned Wildon platform a maximum water depth of approximately 30 – 50 m is indicated both by foraminifera (Hansen et al., 1987) and bryozoa (Vavra, 1989). During the following lowstand water depth did not exceed a few metres (Friebe, 1990). Thus without taking into account local subsidence, sea-level fall must have been at least of the order of 30 – 50 m.

A sequence stratigraphic analysis of the Badenian mixed carbonate – siliciclastic Weissenegg (Allo-) Formation reveals the following general trends.

(1) The site of carbonate sedimentation was not only determined by sea-level fluctuations, but mainly controlled by basin configuration (position of morphological highs) and autocyclic processes (shifting locations of terrigenous influx due to delta lobe abandonment).

(2) Carbonate sedimentation occurred predominately during transgressive phases when terrigenous siliciclastics were stored in a coastal plain farther landwards.

(3) Transgressive lag sediments acted as a relatively stable substrate for the colonization by corals and other sessile organisms and thus faciliated the development of patch reefs.

(4) The carbonate build-ups were usually drowned or suffocated by siliciclastics during continuing transgression. Drowning was faciliated by strong environmental stress because of siltation.

(5) (Late) highstand deposits predominantely consist of mixed siliciclastic – carbonate shallowing-upwards parasequences. Each parasequence is terminated by a limestone bed deposited during fourth-order transgressive pulses and a flooding surface.

(6) A lowstand carbonate progradational wedge developed on one platform which suffered incipient drowning during a highstand. During the following lowstand, the platform top was near sea level again, thus re-attaining its maximum growth potential. Although sea-level drop was rather rapid, the result was a type 2 sequence boundary as the platform was not exposed.

Badenian sea-level changes in the Central Paratethys

A similar pattern of depositional sequences is recorded from the Vienna basin (Dullo, 1983; Piller et al., 1991). There marine sediments of Lower Badenian age overlie fluvial gravel of the Karpatian. Lower Badenian sediments were in part eroded during the early Spiroplectammina Zone. In the late Spiroplectammina Zone a widespread transgression caused a differentiation into patch reefs and siliciclastic lagoons. These reefs were partly exposed at the end of the Spiroplectammina Zone. Lowstand deposits comprise oyster beds and algal debris limestone. A minor transgression occurred at the beginning of the Bulimina – Bolivina Zone. Patch reefs were common. Reef growth was terminated by shallow marine siliciclastics and/or delta progradation. Differences in the timing of the unconformities between the Styrian and Vienna Basins may be explained by local tectonics.

Steininger et al. (1978) compiled palaeogeographical data for the Central Paratethys. They also clearly recognized two main phases of transgression at the base of the Lagenid Zone and the Bulimina – Bolivina Zone respectively. At the base of the Badenian 'basal conglomerates' (siliciclastic lowstand wedges?) were widespread [various contributions in Papp et al. (1978) and Steininger et al. (1985)]. A third transgressive phase at the beginning of the Spiroplectammina Zone is only present in the western part of the Central Paratethys. In eastern and north-eastern Hungary as well as in the Carpathian foredeep this transgression was subdued, probably by local tectonics. In these areas evaporites were deposited. Delta progradation was widespread during the Upper Badenian. In south-western Slovacia a sea-level lowstand at the Badenian – Sarmatian boundary caused erosion of large portions of the Upper Badenian sediments (Jiricek in Papp et al., 1978). Steininger et al. (1978) correlated these transgressive-regressive cycles with the opening and interruption of marine seaways between the Central Paratethys and the Indo-Pacific and Mediterranean/Atlantic, respectively.

Based on these data Rögl and Steininger (1983; 1984) compiled a sea-level curve of the (Central) Paratethys, which was modified by Steininger et al., (1989). Unfortunately, this curve contains data derived from various basins, each having its own tectonic history. It records both the transgressions of the Lagenid Zone and the Bulimina – Bolivina Zone. However, it does not contain a sea-level lowstand at the Lagenid Zone – Spiroplectammina Zone boundary. The evaporites of the Spiroplectammina Zone were interpreted to have been deposited during a period of slowly falling sea level (late highstand) resulting in an isolation of these areas. Again these local sea-level changes have been explained by the opening and interruption of marine seaways due to major tectonic events and not in terms of global sea-level changes modified by local tectonics.

The sequence boundaries observed in the Weißenegg (Allo-) Formation correspond fairly well to biozone boundaries of Central Paratethys. As Rögl and Steininger (1984) pointed out, the local stratigraphy of the Central Paratethys is to a large degree based on ecological changes rather than on evolutionary trends (eco-stratigraphy). In fact, within the Badenian stage only two biozone boundaries are defined by the evolutionary first occurrence of planktonic foraminfera: (1) the Karpatian – Badenian boundary is defined by the first occurrence of *Praeorbulina glomerosa* (Blow) (= Burdigalian – Langhian boundary); (2) the boundary between the Lower and Upper Lagenid Zone corresponds to the worldwide *Orbulina* datum (= base of N9). Neither correspond to sequence boundaries. All other biozones are defined by major changes in fossil assemblages. Rögl and Steininger (1983; 1984) attributed them to the opening and closing of marine seaways due to tectonic processes. As an alternative model a close relationship between the eco-stratigraphic boundaries of the Central Paratethys and third-order sequence boundaries is suggested.

World-wide Middle Miocene sea-level

A comparision with the global sea-level curve of Haq et al. (1987) yields fairly good correspondence between global and local sea-level tendencies (Fig. 14). For correlation of the local (Central) Paratethys bio-chronostratigraphic zones and stages with the global Miocene stages the correlation table of Steininger et al. (1990) was used (see Fig. 2). The boundary Upper Lagenid Zone – Spiroplectammina Zone corresponds to the N9/N10 boundary (Rögl and Steininger, 1983). Local sea-level changes were correlated with the global curve using the foraminiferal standard biozones of Blow (1969). Using nannoplankton standard zones (Martini, 1971) for correlation yields less satisfying results.

The lower tectonically enhanced boundary of sequence 1 coincides approximately with the N7/N8 boundary, thus corresponding to the base of the Tejas TB 2.3 cycle. Its upper boundary is dated as uppermost N9 to N9/N10 whereas the TB 2.3 cycle is terminated approximately at the N8/N9 boundary. The sequence boundary separating sequences 2 and 3 is dated as uppermost N10 near the N10/N11 boundary. The TB 2.4/TB 2.5 boundary lies within N11. The top of sequence 3 corresponds approximately to the N12/N13 boundary. TB 2.5 is terminated within N12; the following lowstand corresponds to the N12/N13 boundary.

Thus the sea-level fluctuations observed in the Styrian Basin approximately correspond to the Tejas TB 2.3, TB 2.4 and TB 2.5 cycles of Haq et al. (1987). Differences between the dating of the sequence boundaries in the Styrian Basin and the global sea-level curve (especially the sequence 1/2 boundary versus TB 2.3/TB 2.4 boundary) may be interpreted as the results of local tectonics or inadequate biostratigraphic correlation.

Conclusions

(1) In the Badenian (Middle Miocene) mixed carbonate – siliciclastic Weißenegg (Allo-) Formation of the Styrian Basin (Austria) three depositional sequences corresponding approximately to the TB 2.3, TB 2.4 and TB 2.5 cycles of the global

sea-level chart (Haq et al., 1987) can be distinguished. Sea-level fluctuations were of the order of at least 30 m. Similar transgressive – regressive patterns have been recorded throughout the Central Paratethys.

(2) Siliciclastic lowstand systems tracts comprise lignite deposits, reworked basement and tidal siltstones (overlying a tectonically enhanced sequence boundary) as well as coastal sand bodies.

(3) The transgressive lag gravel provided a relatively stable substrate for colonization by corals.

(4) Coral patch reefs and rhodolith platforms developed predominantly during transgressive phases.

(5) Carbonate platforms and patch reefs were commonly drowned and/or suffocated by siliciclastics during continuing transgression.

(6) Carbonate lowstand progradation is possible when a platform, which suffered incipient drowning during highstand, is near sea level again during the subsequent lowstand and re-attains its maximum growth potential. The result is a type 2 sequence boundary, even if the sea-level drop is rather rapid.

(7) Maximum flooding is indicated by an abundance of planktic foraminifera and the occurrence of glauconite.

(8) The (late) highstand systems tract consists of shallowing-upwards siliciclastic – carbonate parasequences, each starting with fine-grained offshore siliciclastics and ending with a bank of rhodolith/algal debris limestone and a flooding surface. They record fourth-order sea-level fluctuations. Coastal sand bodies are deposited during lowstand. The limestone beds record transgressive pulses, offshore massive to laminated silt was deposited during highstand.

(9) Late highstand (braid) delta progradation is common.

(10) A close relationship between the eco-stratigraphic biozone boundaries of the Central Paratethys and major eustatic sea-level falls is suggested.

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