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GEOLOGIE UND PALÄONTOLOGIE

Paleobathymetry of Middle Miocene (Badenian) marine deposits at the Weissenegg quarry (Styrian Basin, Austria)

Die Ablagerungstiefen der mittelmiozänen Leithakalk-Sedimentation im Steinbruch Weisenegg (Steirisches Becken, Österreich)

By HANS JØRGEN HANSEN[1]), CARLA MÜLLER[2]) & FRED RÖGL[3])

(With 8 textfigures and 4 tables)
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Abstract

The bathymetric parameters indicative for Recent *Amphistegina* and *Elphidium* have been applied to the Middle Miocene corallinacean („Leithakalk") facies of the Styrian Basin, Austria. This bathymetric application makes use of the light dependence of symbiont-bearing benthic foraminifera: with increasing depth the lamellar thickness in these foraminifera is reduced. A control by isotope ratios of ^{18}O and ^{13}C is given. As the amphisteginas in the section were partly dissolved the method was applied to the better preserved genus *Elphidium*. In the diagenetically altered sediments the relative frequency of both genera and the diameter/thickness ratio of *Elphidium* proved to be a valuable and simple tool for such interpretations. The method has been tested by a parallel investigation of planktonic and smaller benthic foraminifera frequency distributions. Calcareous nannoplankton provided additional paleoecological and biostratigraphical information.

The section of the Weissenegg quarry near Wildon was originally thought to expose a series of three transgressive – regressive cycles in the Middle Badenian part. The application of the indicated methods revealed the presence of only one single transgression – regression cycle in the sedimentary sequence, ending with deltaic sedimentation in the Late Badenian. The water depth in this cycle ranged between a few meters and 30 meters.

The biostratigraphic results are in agreement with former studies, giving an age of Middle Miocene, nannoplankton zone NN 5, corresponding to the Orbulina suturalis zone. In the regional stratigraphy the section comprises the Badenian, the zone with agglutinated foraminifera, and the zone with "Rotalia".

Zusammenfassung

Am Profil des Steinbruches Weissenegg bei Wildon, im Steirischen Becken, wurde versucht, die an rezenten Amphisteginen erzielten Resultate und, in Verbindung damit, vergleichbare Methoden an Elphidien anzuwenden. Es sollte eine Möglichkeit zur genaueren bathymetrischen Einstufung fossiler Seichtwasserablagerungen gefunden werden. Das untersuchte Profil schließt eine mittelmiozäne (Bade-

Adress of the Authors:
1) H. J. HANSEN, Geol. Inst. Univ. of Copenhagen, Øster Voldgade 10, DK 1350 Copenhagen. – Denmark.
2) C. MÜLLER, Paris – Rueil Malmaison. – France.
3) F. RÖGL, Naturhist. Museum Wien, Burgring 7, P. O. Box 417, A-1014 Wien. – Austria.

nien) Abfolge von Lithothamnienkalken und Amphisteginenmergeln auf. Nach den bisherigen Vorstellungen sollte über den liegenden Lithothamnienkalken des unteren Badenien eine in mehreren transgressiven und regressiven Zyklen abgelagerte Schichtfolge des mittleren Badenien auftreten, die in einer fluviatilen Sandfolge endet. Von dieser Voraussetzung ausgehend, lag hier eine ausgezeichnete Kontrollmöglichkeit für die Verwendbarkeit dieser Methoden für paläobathymetrische Aussagen vor.

Die Methodik liegt darin begründet, daß benthonische Foraminiferen mit symbiontischen Algen, z. B. Amphisteginen mit nackten Diatomeen, in ihrer Lebensweise lichtabhängig sind. Dadurch müssen sie in tieferen Wasserschichten aus Gründen der Lichtdurchlässigkeit dünnere Wände aufbauen, d. h. die Lamellen, die bei jeder neuen Kammerbildung auf der Außenwand abgelagert werden, müssen bei zunehmender Wassertiefe dünner sein. Dies bedingt auch, daß die Relation von Gehäusedurchmesser zu Gehäusedicke sich innerhalb einer Art mit der Wassertiefe ändert. Gleichzeitig ändern sich mit der Wassertiefe und Wassertemperatur die Isotopenverhältnisse $^{16}O/^{18}O$ in den Wänden.

Die hier untersuchten Amphisteginen erwiesen sich durch diagnetische Veränderungen als ungeeignet. Die nächste Gruppe größerer Foraminiferen mit guter Erhaltung waren Elphidien. Deren Untersuchung brachte verwertbare Resultate. Statt der komplizierten Messung der Lamellendicke erfolgte eine Berechnung des Verhältnisses von Gehäusedurchmesser zu Gehäusedicke. Zusätzlich wurden die Häufigkeiten des Vorkommens vom *Amphistegina* und *Elphidium* verglichen, da beide Gattungen unterschiedliche Ansprüche an die Umwelt aufweisen und *Amphistegina* in etwas tieferem Wasser häufiger vorkommt. Zur Kontrolle dieser einfachen Methoden der paläobathymetrischen Bestimmung wurde die sonstige Foraminiferenfauna auf ihre Häufigkeitsverhältnisse untersucht. Hinweise brachte auch das kalkige Nannoplankton, sowie eine gesonderte Untersuchung der Bryozoenfauna.

Die Abfolge des mittleren Badenien in Weissenegg erwies sich als ein einziger, einheitlicher Sedimentationszyklus. Beginnend mit sehr seichten Ablagerungen von wenigen Metern Wassertiefe erfolgte mit der Transgression eine Zunahme auf etwa 30 Meter. Nach einem stärker schwankenden Bereich setzte die Regression ein und endete in küstennahen, sandigen Deltaablagerungen. Die Einschaltung eines fossilfreien Sandhorizontes in der Kalk/Mergel-Abfolge beeinflußte die Faunenverhältnisse und die Werte von Amphisteginen und Elphidien nicht. Dies deutet darauf hin, daß es zu keiner zeitweiligen Veränderung des Wasserstandes kam, sondern nur zu Veränderungen in der Sedimentzufuhr. Dies entspricht auch den mikrofaziellen Untersuchungen, die von anderer Seite an den Lithothamnienkalk-Einschaltungen durchgeführt wurden.

In biostatigraphischer Hinsicht konnten die bisherigen Einstufungen im Badenien bestätigt werden. Über der Lagenidenzone folgt der untersuchte Sedimentationszyklus der Sandschalerzone, der in die Sandfazies der Rotalienzone überleitet. Nannoplankton und planktonische Foraminiferen entsprechen dem Mittelmiozän, der Nannoplanktonzone NN 5 und der Orbulina suturalis-Zone.

Introduction

In a series of publications the depth adaptation of different Recent symbiont-bearing foraminifera has been demonstrated (LARSEN 1976; LARSEN & DROOGER 1977; BUCHARDT & HANSEN 1966; HALLOCK 1979, 1981; HALLOCK & HANSEN 1979).

Among the depth-related changes in foraminifera two are of particular interest for paleoecology. Both are linked to the intensity of photo-synthetic activity of symbiontic algae related to the declining amount of light with increasing water depth. This causes a difference in the amount of photosynthetically fractioned oxygen incorporated into the shell carbonate. Thus, with changing water depth it is to be expected that a symbiont-dependent species will show different oxygen isotope ratios (BUCHARDT & HANSEN 1977).

The second phenomenon relates to the different thickness of the secondary lamellae deposited onto the earlier exposed shell portions. This has been demons-

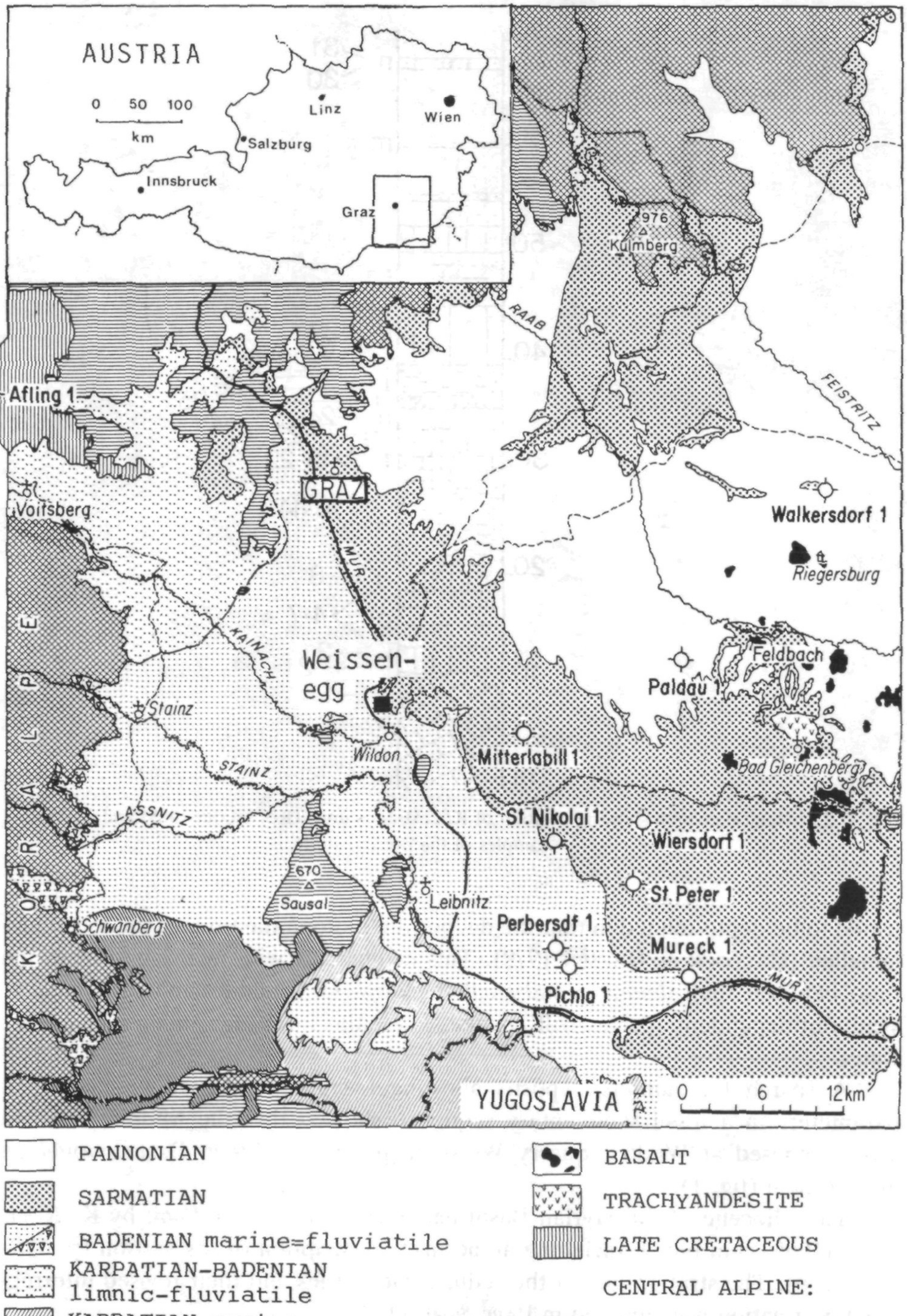

Fig. 1. Geological map of the central and western Styrian Basin with sampling site (K. KOLLMANN in STEININGER & RÖGL 1980).

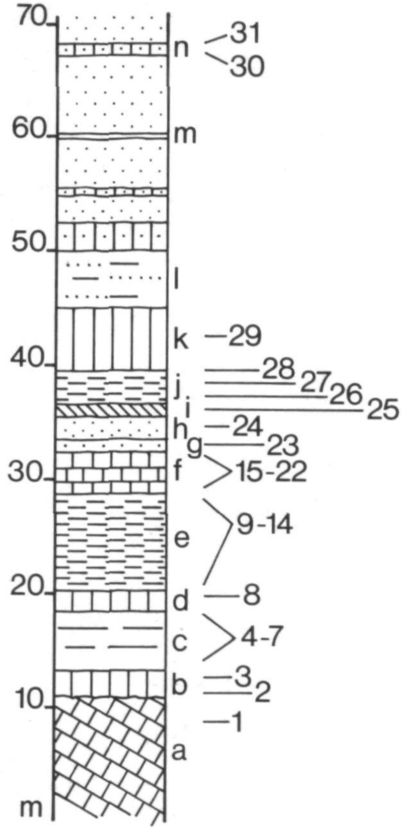

Fig. 2. Lithological column showing position of KOLLMANN's units (KOLLMANN 1965) and position of samples of the present study.

trated to be depth related in that the deeper the biotope the thinner the secondary lamellae (HALLOCK & HANSEN 1979). This means that with increasing depth the ratio between shell diameter and shell thickness in an almost involute lamellar symbiont-dependent species will change, i. e., the form gets thinner in deeper water.

A search for suitable deposits allowing a study of the above-mentioned parameters in a fossil sedimentary sequence showed that the Middle Miocene layers exposed at Wildon, quarry Weissenegg, in the Styrian Basin, would be almost ideal (fig. 1).

The Miocene of the Styrian Basin has been described in detail by K. KOLLMANN (1965, cum bibl.), including an accurate description of the section (p. 535–538, pl. 6). The stratigraphy of the sedimentary cycles and their revised interregional correlation was updated in PAPP & al. (1978).

The region around Wildon is marked by a widespread development of corallinacean limestone ("Leithakalk") facies in the Middle Miocene (Badenian). The old quarry of the cement plant Weissenegg, north of Wildon, is situated at the

SW side of the Kollischberg, which is about 500 m in length and up to 90 m high. The SE part of the quarry was sampled during two visits; the sample levels are shown in fig. 2, corresponding to KOLLMANN's description. DULLO (1983) studied the microfacies of the limestone layers in the same profile. The basal part of the section is formed by detrital algal limestone with a strong foreset bedding and belongs to the Early Badenian (Lagenidae zone). The investigated part belongs to the Middle Badenian (zone with agglutinated foraminifera). The limestones and marly limestones in this section are deposited in a "bioclastic debris facies" (DULLO 1983: 34) formed mainly by corallinacean algae, but also by foraminifera, bryozoan and mollusc debris, and rhodolites. Interbedded are dark gray silty and marly clays with *Amphistegina;* the marly middle part of the section contains larger amounts of rhodolites. In the higher part sand sedimentation is dominant.

Care was taken to sample washable material, which in the nodular limestones often meant that many thin shaly to marly bands between the beds had to be taken as one sample. Often more than one square meter of bedding plane was cleared off to obtain sufficient material (i. e., around 500 g).

The samples were processed without use of chemicals. By drying and moistening the majority of the samples could be washed. A few were disintegrated by repeated freezing and thawing. Samples 1–3 and 8 were too hard to be disintegrated. Smaller un-washed parts of the samples were used for study of calcareous nannoplankton. The sample residues were investigated for the complete foraminifera and bryozoan fauna in order to control the results obtained by the study of *Amphistegina.*

Depth Adaptation of *Amphistegina* and *Elphidium*

The working hypothesis for the Weissenegg section was in accordance with the suggestion by KOLLMANN (1965) that three transgressive cycles are represented. The first cycle should include the layers covered by samples 4–7, the second by samples 9–21 and the third cycle by samples 25 to 29.

This hypothesis leads to testable predictions regarding both isotopic ratios as well as thickness/diameter ratios if redeposition of the relevant forms can be excluded.

The most prominent elements of the foraminifera fauna, i. e., those of large size, are representatives of *Amphistegina mammilla* (FICHTEL & MOLL) and *Elphidium crispum* (LINNE). In general, Recent larger foraminifera are dependent upon symbiontic algae and their large size seems related to help from the algae in the calcification process.

By counting the relative abundances of the two species mentioned above a distinct distributional tendency became evident (fig. 3). In the lower part of the section, i. e., samples 4–7, *Elphidium crispum* dominates. All remaining samples showed dominance of *Amphistegina mammilla* over *E. crispum.* It should be noted, however, that *E. crispum* is present in all samples.

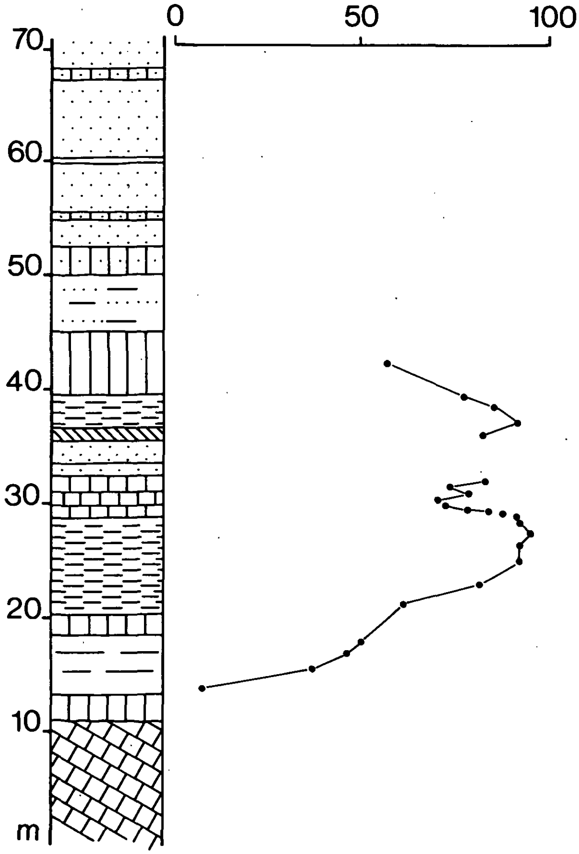

Fig. 3. Lithological column showing relationship between *Amphistegina mammilla* and *Elphidium crispum* expressed as *A. mammilla* × 100 divided by the sum of *A. mammilla* and *E. crispum*.

In the topmost sample (no. 29) *E. crispum* again shows a slight increase after a long period of low representation.

SEM studies of *Amphistegina mammilla* demonstrated that many specimens were affected by diagenesis leading to an exfoliation of secondary lamellae in the umbilical region. This phenomenon is not pronounced in *E. crispum*. However, due to the diagenetic exfoliation observed in *A. mammilla*, only *Elphidium crispum* seemed a good candidate for measurements of the thickness/diameter relation.

Both species were analyzed for carbon and oxygen isotopes. These values are presented in fig. 4 and table 1, where ^{18}O and ^{13}C data are plotted against each other. There is a considerable scatter in ^{18}O. In a stratigraphical plot of the ^{18}O data the most constant values are seen to fall in the sample interval from no. 25 to 28, which represents the non-nodular shaly clay beds (fig. 5).

No conclusions regarding the depositional depths of the strata in question can be drawn from these data. The interval between samples 4 and 7, which according

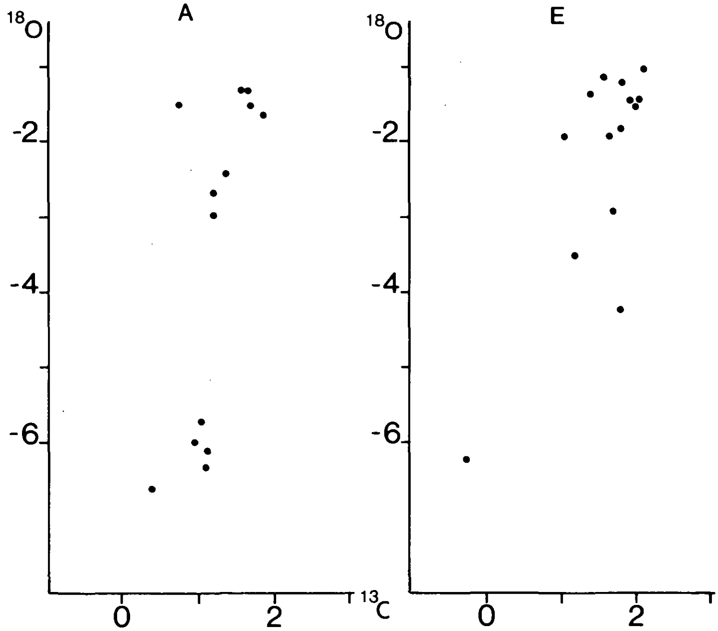

Fig. 4. ^{18}O versus ^{13}C from *Amphistegina mammilla* (A) and *Elphidium crispum* (E).

Table 1. ^{18}O and ^{13}C values from *Amphistegina mammilla* and *Elphidium crispum*. Reproducibility better than 2 permille. All values listed as permille deviations relative to the PDB standard.

Sample no.	*E. crispum*		*A. mamilla*	
	^{18}O	^{13}C	^{18}O	^{13}C
29	–3.51	1.28	–6.76	0.34
28	–1.57	2.08	–1.68	1.92
27	–1.47	2.01	–1.57	1.77
26	–1.24	1.89	–1.35	1.64
25	–1.48	1.92	–1.33	1.68
22	–1.29	1.60	–	–
20	–	–	–2.71	1.22
15	–2.96	1.72	–6.14	1.20
14	–1.34	1.43	–	–
11	–6.26	–0.24	–5.74	1.39
10	–1.95	1.08	–1.56	0.73
9	–	–	–5.94	1.01
7	–1.89	1.62	–2.99	1.21
6	–4.21	1.81	–6.36	1.14
5	–1.85	1.84	–2.39	1.35
4	–1.09	2.15	–	–

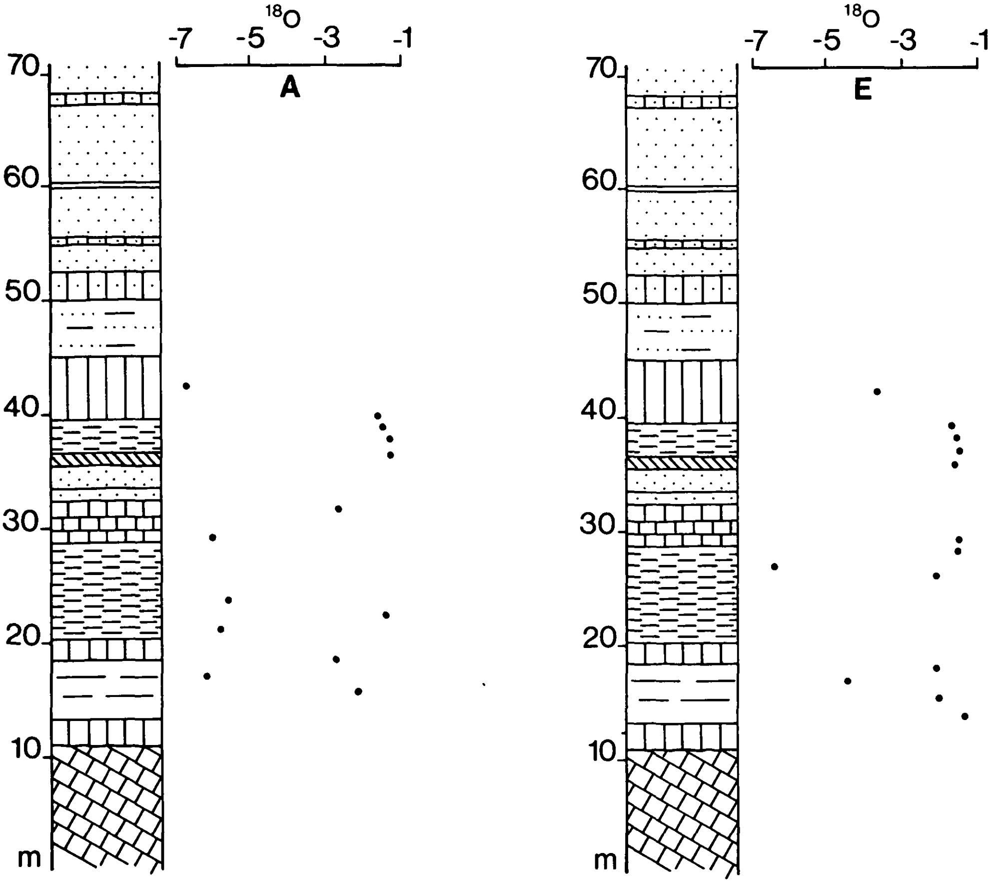

Fig. 5. Stratigraphic plot of ^{18}O from *Amphistegina mamilla* (A) and *Elphidium crispum* (E).

to *Amphistegina* percentages would represent a deepening, show such fluctuations in the ^{18}O values that no explanation other than diagenetic alteration is possible. This completely masks any depth-related isotopic signal.

The possible depth-adaptive diameter/thickness changes expected in *Amphistegina* cannot with any degree of certainty be measured in the present case due to the above-mentioned diagnetic exfoliation of secondary lamellae. This would lead to too low thickness values and exaggeration of the interpreted depth of deposition. Therefore only *Elphidium* remains as an indicator.

If we suppose that the ratio between *Amphistegina* and *Elphidium* reflects the depth of deposition, the possibility exists that the most shallow form, i. e., *Elphidium,* may have become displaced to greater water depth at the time of deposition. This hypothesis can be tested since the shells grown in deeper water will show higher diameter/thickness ratios than those grown at shallower depth.

The majority of *Elphidium crispum* specimens had damaged final chambers, thereby preventing measurement of the largest diameter. Since, however, the umbilical parts of the final chambers are usually preserved it is possible to fix the

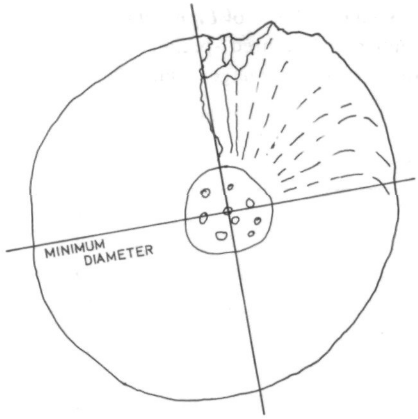

Fig. 6. Line drawing of *Elphidium crispum* with fractured final chamber showing position of minimum diameter as measured in the present study.

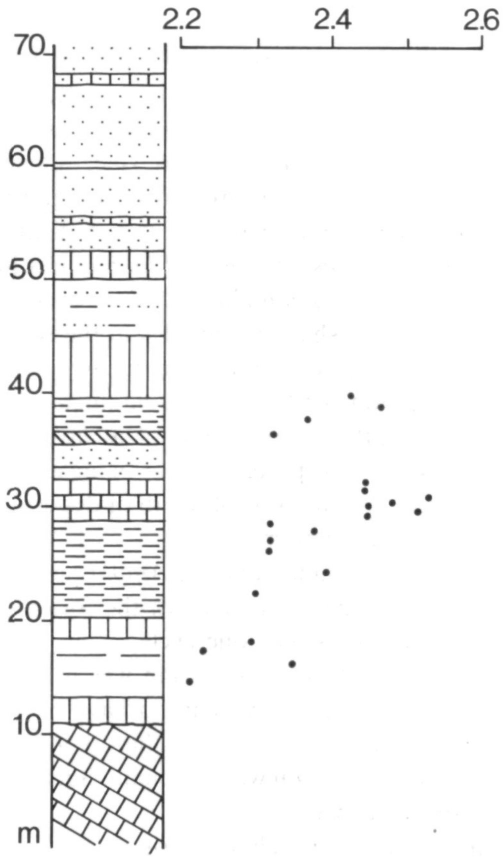

Fig. 7. Stratigraphic plot of relationship between minimum diameter and thickness of *Elphidium crispum*.

Table 2. Values of minimum diameter/thickness of *Elphidium crispum* showing statistical average "x", standard deviation "s" and number of measured specimens "n". Populations 6 and 18 were tested against each other and found to have Pf values larger than 10% and a Pt value of less than 0.001, thus being significantly different.

Sample no.	x	s	n	Sample no.	x	s	n
28	2.42	0.14	21	15	2.44	0.19	15
27	2.46	0.15	19	14	2.31	0.18	15
26	2.36	0.14	14	13	2.37	0.19	18
25	2.32	0.16	16	12	2.31	0.12	20
22	2.44	0.06	8	11	2.31	0.19	16
21	2.44	0.18	15	10	2.39	0.17	18
20	2.47	0.20	14	9	2,29	0.15	16
19	2.47	0.14	12	7	2.29	0.19	8
18	2.44	0.09	12	6	2.22	0.10	16
17	2.52	0.14	14	5	2.34	0.15	14
16	2.52	0.11	11	4	2.20	0.13	16

position of the damaged final chamber and make a diameter measurement at right angles to that direction (fig. 6). In order to obtain the greatest ratio changes, only larger specimens (shell diameter more than 1 mm) were included. This further improves the comparison between populations since identical size classe are compared. The diameter/thickness ratios are shown in fig. 7 and table 2.

Although the values show some scatter there is a distinct tendency towards thinner specimens where the representation of *Elphidium* is low. This means that the presumed deeper water deposits contain *Elphidium* specimens that are thinner than those from the lower (most shallow) samples in the section.

On the basis of earlier published studies and his own observations KOLLMANN (1965) suggested that the section at Weissenegg contained (from the bottom to the top) somewhat changing depth of deposition. The layers "a" (see fig. 2), in agreement with KOLLMANN, are interpreted here as being marine foreset beds. The units "b" to "k" would mean that in terms of depth of deposition three transgressive cycles are represented in the section.

A comparison of the relative abundance of *Amphistegina* and *Elphidium* with the inferred cycles result in strong disagreement: the foraminifera ratio indicates that the whole sequence represents only one cycle.

If a regression with subsequent transgression was present somewhere in the sequence one would expect the regressive part to have been exposed to erosion (leading to loss of the regressive evidence). On the other hand, the transgressive deposits and their content of *Elphidium* would remain. Such phenomena, however, were not registered in the sequence.

The plant-containing layers may well have originated as a slump from a coastal swampy area. There is no evidence at all for adjacent regressive or transgressive phenomena.

This study is of particular interest to those working with rather shallow deposits, since it allows a high-resolution relative depth estimate to be made. In the work carried out on Recent *Amphistegina* in the Gulf of Aqaba (LARSEN 1976) it was possible, using diameter/thickness ratios, to estimate the depth of a sample to within 5 meters. In the Gulf of Aqaba the euphotic zone is very deep; very few ocean regions in the world have such deep euphotic zones.

The water depth at Wildon during the deposition of the Middle Badenian layers probably ranges from 0 to maybe as much as 30 meters. Experience from the shallow water distribution of Recent *Amphistegina* in the Andaman Sea, where the depth of the photic zone is less extreme than in the Red Sea, makes this depth-estimate realistic (HANSEN & SWIDERSKA in prep.). In the Andaman Sea no large *Elphidium* forms occur below ca. 10 meters.

Paleoecology and Biostratigraphy of the Foraminifera Fauna

The sampled section from the foreset bedded marly limestones upwards contains isolated foraminifera only in the marly and sandy parts. The state of preservation is highly variable, being recrystallized in the marly sediments and well preserved in the more clayey layers and sands. Amphisteginas are strongly affected by diagenesis. Larger parts of the assemblages are worn by water movement.

The faunal assemblages and sample residues are described according to the levels of KOLLMANN (1965), demonstrating the continuous changes in the sedimentary cycle. For stratigraphically important species and for faunal frequencies see table 3.

Lithological unit "b": whitish corallinacean limestone; too strongly indurated for washing.

Lithological unit "c": marly limestone with layers of Amphistegina marls.

Sample no. 4 B: brownish gray, silty marls with rich fauna; specimens encrusted by sediment, some crushed and deformed. Planktonic foraminifera scarce and poorly preserved; *Cibicides* and *Asterigerinata* abundant, *Elphidium* common, *Amphistegina* rare (only juvenile specimens). Debris of echinoderms common. – *Asterigerinata planorbis, Bolivina antiqua, B. dilatata, B. hebes, B. plicatella, Caucasina subulata, Cibicides boueanus, C. lobatulus, Cibicides* spp., *Glabratella, Heterolepa dutemplei, Lenticulina inornata, Nonion commune, Reussella spinulosa.*

Sample no. 5 A: light gray calcareous sand and biogenic debris; very abundant rhodophycean algal branches and debris, common debris of echinoderms, molluscs, bryozoans, and sponges; fauna recrystallized. *Cibicides* abundant, *Elphidium* common, *Amphistegina* not rare. Plankton scarce and poorly preserved. – *Ammonia beccarii, Asterigerinata planorbis, Bolivina antiqua, B. dilatata, Cibicides lobatulus, Cibicides* spp., *Cymbalopora granulosa, Eponides repandus, Heterolepa dutemplei, Loxostomum digitale, Nonion commune, Reussella spinulosa, Spirillina, Stilostomella* spp.

Sample no. 5 B: light gray calcareous sand with algal debris. Assemblage similar to 5A but with few, poorly preserved miliolids; *Amphistegina* scarce.

Sample no. 6 B: light gray calcareous sand, biogenic debris of molluscs, echinoderms and less frequently corallinaceans; bryozoans common, some ostracods. Preservation poor due to recrystallization. Plankton rare, *Cibicides* abundant, *Amphistegina* and large elphidiids common. – *Astrononion, Bolivina antiqua, B. dilatata, B. fastigia, B. plicatella, Cibicides boueanus, C. lobatulus, Cibicides* spp., *Discorbis, Eponides repandus, Heterostegina, Loxostomum digitale, Nonion commune, Nonionella* cf. *karaganica, Patellina, Reussella spinulosa, Spaerogypsina globulus, Spirillina.*

Sample no 7 A: gray, silty micaceous clay and whitish calcareous biogenic sand; fauna moderately well preserved, only partially recrystallized. Debris of calcareous algae, molluscs, echinoderms, bryozoans. Plankton poorly preserved and scarce; *Cibicides* abundant, *Amphistegina* and *Elphidium* common. – *Asterigerinata planorbis, Astrononion, Bolivina antiqua, Cibicides lobatulus, Cibicides* spp., *Cymbalopora, Eponides repandus, Glabratella, Heterolepa dutemplei, Loxostomum digitale, Nonion commune, Reussella spinulosa, Sphaerogypsina, Spirillina.*

Sample no. 7 B: whitish-yellowish calcareous sand with an overcrusted, recrystallized fauna.

Lithological unit "d": whitish hard corallinaecean limestone with imprints of megafauna; no isolated foraminifera.

Lithological unit "e": gray marly limestone, layered with nodular bedding and intercalated Amphistegina marls; some thin-shelled molluscs.

Sample no. 9: light gray biogenic sand with mainly calcareous algae, some echinoderms, molluscs, bryozoans, few ostracods. Planktonic foraminifera more common, poorly preserved. Frequency of *Cibicides* strongly reduced. – *Asterigerinata planorbis, Astrononion, Bolivina dilatata, B. fastigia, Cibicides lobatulus, Cibicides* spp., *Loxostomum digitale, Reussella spinulosa, Rosalina, Spirillina, Textularia.*

Sample no. 10: grayish brown silty marls and whitish biogenic sand; fauna fairly well preserved, some specimens pyritized. Plankton more common, poorly preserved. Amphistegina abundant, *Cibicides* still common; nodosariids, *Stilostomella, Bolivina,* and *Reussella* increase in number. – *Asterigerinata planorbis, Bolivina* spp., *Cibicides* spp., *Heterolepa dutemplei, Heterostegina, Lenticulina inornata, Loxostomum digitale, Melonis, Nodosaria* spp., *Nonion commune, Nonionella, Reussella spinulosa, Sagrina, Spirillina, Stilostomella, Trifarina.*

Sample no. 11: light gray calcareous sand, mainly of corallinacean algae, some debris of echinoderms, molluscs; bryozoans common and some ostracods. *Amphistegina* abundant, *Cibicides* common, *Bolivina* not scare. Plankton as above, poorly preserved. – *Bolivina antiqua, B. dilatata, B. fastigia, Cibicides* spp., *Cyclogyra, Eponides repandus, Heterolepa dutemplei, Heterostegina, Loxostomum digitale, Melonis, Nodosaria, Nonion, Nonionella, Patellina, Planorbulina* cf. *mediterranensis, Reussella, Spirillina, Stilostomella, Textularia.*

Sample no. 12: light gray silty marls and whitish calcareous sand, some pyrite and gypsum. Fauna well preserved with the exception of *Amphistegina.* Some debris of echinoderms and molluscs. Rich planktonic fauna, fairly well preserved. *Amphistegina* abundant, elphidiids scarce; *Cibicides* common; *Bolivina, Reussella,* lagenids fairly common. – *Astrononion, Bolivina antiqua, B. dilatata, B. fastigia, B. plicatella, Buliminella, Cancris* cf. *auriculus, Caucasina subulata, Cibicides* spp., *Heterolepa dutemplei, Stilostomella* spp., *Nodosaria* spp., *Melonis, Nonion, Reussella, Trifarina.*

Sample no. 13: light gray calcareous sand with amphisteginas and heterosteginas; debris of echinoderms, molluscs, bryozoans, calcareous algae, some ostracods. Fauna strongly recrystallized. Textulariids fairly common; planktonics common with large specimens. – *Asterigerinata, Bolivina* spp., *Cibicides* spp., *Glabratella, Heterolepa, Loxostomum, Nonion, Nonionella, Patellina, Reussella, Rosalina, Sagrina, Spirillina, Textularia sagitula, T. gramen, T. pala.*

Sample no. 14: brownish gray silty marls with whitish calcareous sands, with amphisteginas. Debris of molluscs, some bryozoans and echinoderms. Fauna fairly well preserved. Planktonic foraminifera large and common, many *Globoquadrina.* – *Astrononion, Bolivina, Cancris* cf. *auriculus, Cibicides, Eponides, Heterolepa, Lenticulina inornata, Loxostomum, Melonis, Nodosaria, Nonion, Reussella, Sagrina, Stilostomella.*

Frequency of counted 160 specimens:

Amphistegina	17.8%	planktonics	25.7%
Elphidium	10.4%	*Reussella*	9.8%
Nodosaria/Stilostomella	1.2%	*Nonion/Melonis*	1.8%
Bolivina	5.5%	*Cibicides/Heterolepa*	27.0%
Asterigerinata	0.6%	others	0.2%

Table 3. Foraminifera distribution and abundance. Presence of stratigraphically important species is indicated on the left. Bar thickness on the right indicates relative frequency of ecologically important groups.

FORAMINIFERA DISTRIBUTION Weissenegg Sample no.	*Gs. quadrilobatus*	*Gg. altispira*	*Gg. tarchanensis*	*Gg. praebulloides*	*Gg. diplostoma*	*Gs. trilobus*	*Gg. concinna*	*Orbulina suturalis*	*Gr. transsylvanica*	*Gg. druryi*	*Gg. cf. falconensis*	*Gg. bulloides*	*Gg. subcretacea*	*Gg. regularis*	*Gr. mayeri*	*Gr. bykovae*	*E. crispum*	*E. macellum*	*E. flex. flexuosum*	*E. flex. reussi*	*E. fichtelianum*	*U. bononiensis compressa*	PLANKTON. FORAMINIFERA	*Asterigerinata planorbis*	*Cibicides/Cibicidoides*	*Bolivina*	*Nodosaria/Stilostomella*	*Textulariidae*
31	•	•		•										•	•	•	•	•	•		•		▌	▏	█	▏	•	
30 A	•			•		•			•								•		•		•		•	▌	▏	•		
29				•		•											•		•				▏	▌	▏	•		
28	•	•		•		•		•		•	•	•		•			•		•		•		▌	▏	█	▏		
27	•	•		•	•	•		•		•							•		•	•	•		▌	▏	█	▏	•	
26	•	•	•	•		•		•									•		•		•		▏	▏	█	▌	•	
25	•	•				•											•		•	•	•	•	▏	▏	█	▏	•	
24																												
23																												
22	•					•										•	•		•	•	•		▏	•	█	•	•	
21	•	•		•		•										•	•		•		•		▌	•	▌	•	•	•
20		•				•									•		•		•		•		▏	•	▌	•	▏	
19	•	•	•	•		•		•						•		•	•		•		•		▌	•	▌	•	▏	
18	•		•			•		•								•	•				•	•	▏	•	▌	•	•	
17	•	•				•	•	•				•		•			•				•	•	▌	•	▌	•	•	•
16	•	•	•			•											•				•		▏	•	▌	•	•	
15	•	•	•			•		•						•			•				•		▌	•	▌	•	•	•
14	•	•										•		•	•	•	•		•		•		▌	•	▌	▏	▏	
13	•	•	•	•		•		•						•	•		•			•			█	•	▌	▏	•	▏
12	•	•	•			•			•							•	•				•		▌	•	▌	▏	▌	
11	•	•		•		•									•	•	•		•	•			▏	•	▌	▏	▏	•
10	•	•	•			•							•	•	•		•		•	•	•		▏	•	▌	▏	▌	
9	•	•		•		•	•										•		•	•			▏	•	▌			•
7 A	•										•	•					•		•	•	•		•	▏	█			
6 B	•		•	•		•			•	•	•						•		•	•	•		•	▏	█	▌		
5 B	•	•	•	•		•	•	•									•		•		•		•	▏	█	▏		•
5 A	•		•	•	•	•											•	•	•	•	•	•	•	▏	█	▏	•	
4 B	•	•	•														•	•	•	•			•	█	█	▏		

Lithological unit "f": yellowish hard corallinacean limestone with thick-shelled molluscs; thin marly layers are interbedded.

Sample no. 15: light gray to whitish sand with calcareous algae and amphisteginas. Debris of bryozoans, echinoderms, molluscs; some ostracods. Fauna recrystallized. Planktonic foraminifera large and common. – *Asterigerinata, Bolivina, Cancris, Cibicides, Eponides, Loxostomum, Melonis, Nonion, Reussella, Rosalina, Spirillina, Stilostomella, Textularia.*

Sample no. 16: light gray to whitish calcareous sand with bryozoans and amphisteginas; some debris of molluscs and echinoderms. Fauna partly recrystallized. Planktonic foraminifera very scarce; *Eponides* common; otherwise scarce assemblage. In coarser fraction *Sphaerogypsina* and *Cymbalopora.*

Sample no. 17: light gray to whitish calcareous sand with bryozoans and amphisteginas. Debris of echinoderms, molluscs, corals, sponge spicules. Fauna only partly recrystallized, Planktonics and elphidiids more common again, *Eponides* fairly common. – *Asterigerinata, Bolivina, Cibicides, Cymbalopora, Eponides, Guttulina, Heterolepa, Lenticulina, Loxostomum, Nodosaria, Patellina, Reussella, Sphaerogypsina, Spirillina, Stilostomella, Textularia.*

Sample no. 18: light gray to whitish calcareous sand with bryozoans and amphisteginas; debris of molluscs, echinoderms, sponge spicules. Fauna well preserved. Planktonic foraminifera rare, small forms predominant. Assemblage similar as above.

Sample no. 19: light gray to whitish calcareous sand with amphisteginas, bryozoans and corallinacean algae. Debris of molluscs and echinoderms. Fauna fairly well preserved, only amphisteginas altered. Plankton common. – *Asterigerinata, Bolivina, Cibicides, Eponides, Lenticulina, Loxostomum, Nodosaria, Nonion, Patellina, Reussella, Spirillina, Stilostomella.*

Sample no. 20: Light gray corallinacean sand with bryozoans and amphisteginas; debris of molluscs, echinoderms, sponge spicules. Fauna recrystallized and encrusted, amphisteginas altered. Fauna rather poor, planktonics scarce.

Sample no. 21: light gray corallinacean sand; some debris of bryozoans and molluscs. Fauna recrystallized. Planktonic foraminifera more common, with large *Globigerinoides.*

Sample no. 22: dark gray silty clay with amphisteginas; some worn calcareous algae and debris of echinoderms and bryozoans. Generally well preserved. Some change in the fauna; specimens smaller. Planktonics small and crushed; *Cibicides* predominant.
Frequency of 110 specimens:

Amphistegina	6.4%	planktonics	21.1%
Elphidium	6.4%	*Cibicides/Heterolepa*	46.8%
Bolivina	5.5%	others	13.8%

Lithological unit "g": dark gray micaceous clayey fine sand with plant matter and precipitation of some mineral salts and sulfur.

Sample no. 23: light-brownish gray, micaceous fine-grained quartz sand. Barren.

Lithological unit "h": light gray, micaceous coarse sand and sandstone, basally with molluscs imprints.

Sample no. 24: light gray micaceous fine-grained quartz sand. Barren.

Lithological unit "i": gray Amphistegina marl with thin-shelled mollusc fauna.

Sample no. 25: light gray micaceous quartz sand. Fauna not recrystallized, well preserved, but partly crushed; some mollusc debris. Planktonic foraminifera scarce. Amphisteginas well preserved, not rare; *Cibicides* predominant, *Elphidium* and *Bolivina* common. – *Ammonia* cf. *beccarii, Asterigerinata planorbis, Bolivina dilatata, B. fastigia, B. plicatella plicatella, B. plicatella mera, B. tortuosa, Cibicides lobatulus, C.* cf. *perlucidus, C. pseudoungerianus, Globulina punctata, G. tuberculata, Heterolepa dutemplei, Loxostomum digitale, Nonion commune, Reussella spinulosa, Uvigerina bononiensis compressa.*

Lithological unit "j": yellowish brown sandy marls and sands with irregular marlstone concretions.

Sample no. 26: micaceous quartz sands with *Amphistegina;* some molluscs debris. Fauna well preserved. Some planktonics, elphidiis common, cibicidids predominant. – *Asterigerinata planorbis, Bolivina dilatata, B. fastigia, Cibicides boueanus, C. lobatulus, C.* cf. *perlucidus, C. pseudoungerianus, Globulina gibba, Heterolepa dutemplei, Loxostomum digitale, Nonion commune, Reussella spinulosa.*

Sample no. 27: quartz sand as above, rich in microfossils; well preserved. Fairly rich planktonic fauna, with many *Globoquadrina.* – *Asterigerinata planorbis, Astrononion, Bolivina alata, B. fastigia, B. plicatella, Cancris auriculus, Cibicides boueanus, C. lobatulus, C.* cf. *perlucidus, C. pseudoungerianus, Discorbis, Dyocibicides, Fissurina, Fursenkoina schreibersiana, Globulina gibba, G. punctata, Guttulina austriaca, Heterolepa dutemplei, Lenticulina inornata, Loxostomum digitale, Nonion commune, Quinqueloculina, Reussella spinulosa, Sagrina.*

Sample no. 28: light gray-brown silty clay with some mollusc debris. Well preserved rich fauna with amphisteginas and common planktonics.

Lithological unit "k": yellowish gray hard corallinacean limestone with some cavities filled by yellowish marls with small molluscs.

Sample no. 29: redish brown carbonate sand with calcite and strongly recrystallized fauna. Some amphisteginas and elphidiids. Another co-occurring fauna type is well preserved. Planctonic foraminifera are scarce.

Lithological unit "l": gray to blue-gray, micaceous sandy clay and sand with coalified plant matter.

Lithological unit "m": yellowish brown micaceous coarse sand with layers of quartz and crystalline pebbles; sandstones.

Lithological unit "n": whitish gray partially marly corallinacean limestone.

Sample no. 30 A: yellowish brown marl with rich fauna; well preserved. Plankton very scarce; amphisteginas missing; elphidiids and *Asterigerinata* very common, some *Ammonia.* – *Ammonia beccarii, Asterigerinata planorbis, Bolivina plicatella, Cancris auriculus, Cibicides lobatulus, C.* cf. *perlucidus, C. pseudoungerianus, Discorbis, Globulina gibba, Guttulina* sp., *Heterolepa dutemplei, Nonion commune, Reussella spinulosa.*

Sample no. 31: yellowish brown calcareous sand with some quartz grains. Debris of molluscs and echinoderms; some ostracods. Foraminifera fauna very rich and well preserved. *Amphistegina* and *Elphidium* very common, *Cibicides* and *Asterigerinata* common, plankton fairly rich. – *Asterigerinata planorbis, Astrononion, Bolivina floridana, B. plicatella plicatella, B. plicatella mera, Buccella granulata, Cibicides boueanus, C. lobatulus, C.* cf. *perlucidus, C. pseudoungerianus, Cibicidoides* spp., *Discorbis, Globulina punctata, Fissurina, Heterolepa dutemplei, Loxostomum digitale, Nonion commune, Quinqueloculina, Reussella spinulosa.*

Sample distances are not continuous but depend on the lithology of the section. The assemblages observed demonstrate similar composition in the lower and upper part of the continuous marine sequence (samples 4–29), with stronger fluctuations of a fairly rich fauna in the middle part. The sandy sedimentation in the higher levels does not contain marine fossils except for a layer near the top of the section (samples 30–31).

Different assemblages exhibiting changing frequencies of characteristic genera, beside *Amphistegina* and *Elphidium,* were observed. The changes are interpreted to be related to alterations of paleoecological conditions.

Litho-unit “c”, sample no. 4, has an *Asterigerinata/Cibicides* community; this is followed by a dominance of *Cibicides* only (samples no 5–7). Litho-unit “e”, samples no. 9–14, have assemblages with an increase of planktonic foraminifera, bolivinas, nodosarias, and stilostomellas. This part of the section is most diversified in genera and species. Litho-unit “f”, samples no. 15–21, have similar faunas, but bolivinas and nodosariids are strongly reduced in numbers. As a new element, *Eponides repandus* is fairly frequent. The planktonic frequency changes in each sample. Sample no. 22 in the same lithological unit shows a change in frequency relations. The *Cibicides/Cibicidoides/Heterolepa* group is predominant again.

The sequence is interrupted by the barren sand levels “g” and “h” (exposed along the entire quarry), but the faunal composition is unchanged in the next litho-unit “i”. The sample no. 25 demonstrates a *Cibicides* dominance like the fauna in the sample below the sands.

In the fauna of litho-unit “j”, samples no. 26–28, the dominance of *Cibicides* continues, but bolivinas and planktonic foraminifera are again fairly frequent. The *Asterigerinata/Cibicides* assemblage of litho-unit “k” (sample 29) resembles the lower part of the section in fauna composition and terminates the Middle Badenian transgressive – regressive cycle. The overlying sands and sandstones of litho-units “l” and “m” do not contain marine fossils. Nevertheless in the higher part of the section, near the top of the outcrop (litho-unit “n”, samples 30–31), a marine intercalation occurs. The assemblage corresponds to that of litho-unit “j”.

In a paleoecological interpretation these different faunas exhibit a dominance of epiphytic and adherent genera. The benthic forms inhabit near-shore and inner shelf areas. Certain genera such as *Heterostegina, Cymbalopora, Sphaerogypsina* are connected to reef environments of tropical/subtropical seas. The planktonic assemblages are rather scare and show some damage by transport into the shallow environment.

The foraminifera assemblages throughout the investigated section have a pattern corresponding to that found in the *Amphistegina/Elphidium* investigation. The ecologically important components of the foraminifera fauna and their relative frequencies are figured on table 3 and figure 8. There is one continuous sedimentary cycle from unit “b” to unit “k”, beginning with an *Asterigerinata/Cibicides* assemblage indicating a very shallow environment. The marine transgression peak with the greatest water depth is encountered in unit “e”. Planktonic foraminifera are relatively common, nodosariids frequent. The shallowing in the upper part starts with smaller fluctuations of frequencies in unit “f”. A new dominance of *Cibicides,* ending with another *Asterigerinata/Cibicides* assemblage, corresponds to new shallow sedimentation. The barren sands (units “g” – “h”) do not affect the faunal composition between “f” and “i”.

The environment is interpreted as a shallow muddy lagoon with fine-grained terrigenous imput, covered by seaweeds. The continuous deepening to a maximum depth of approx. 30–50 m in unit “e” is followed again by a shallowing. The different amount of organic debris, mainly corralinacean branches, as well as the break by the sand sedimentation in the units “g” and “h” may be explained by

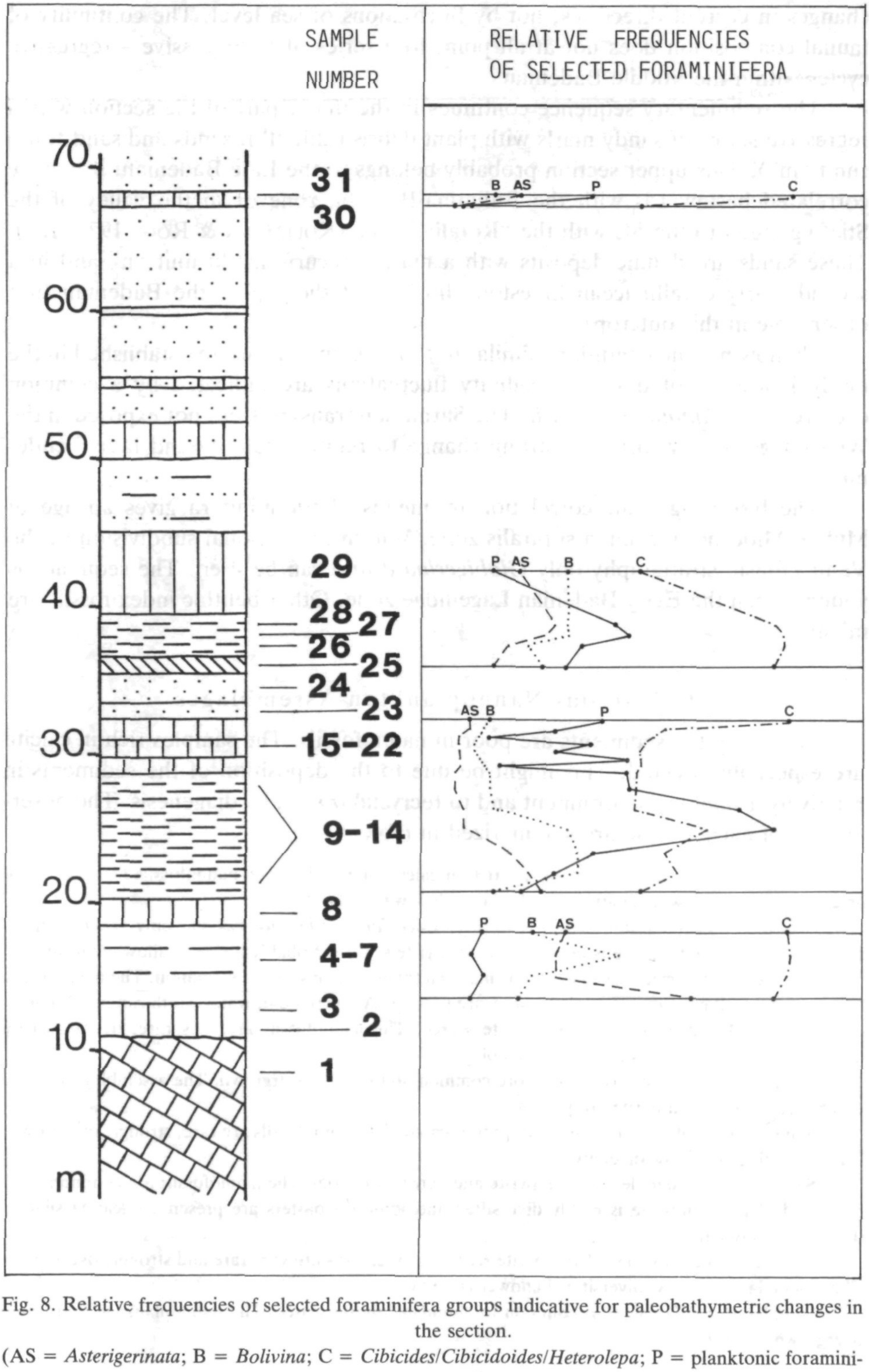

Fig. 8. Relative frequencies of selected foraminifera groups indicative for paleobathymetric changes in the section.
(AS = *Asterigerinata*; B = *Bolivina*; C = *Cibicides*/*Cibicidoides*/*Heterolepa*; P = planktonic foraminifera)

changes in current directions, not by fluctuations of sea level. The continuity of faunal composition does not at all point to a series of transgressive – regressive cycles within the Middle Badenian.

The sedimentary sequence continues in the upper part of the section with a regressive series of sandy marls with plant debris (unit "l"), sands and sandstones (unit "m"). This upper section probably belongs to the Late Badenian; it may be correlated basinwards with the Bulimina-Bolivina zone or in the valley of the Stiefing creek to the SE with the "Rotalia" zone (KOLLMANN & RÖGL 1978: 163). These sands are deltaic deposits with a marine recurrence in unit "n" and in a second marly corallinacean limestone horizon at the top of the Badenian (not observable in this outcrop).

Shallow marine conditions similar to those in unit "j" are re-established in the marly limestone of unit "n". Salinity fluctuations are indicated by a common occurrence of *Ammonia beccarii*. The Sarmatian transgression, not exposed in the Weissenegg quarry, brings a strong change to reduced salinity and faunal endemism.

The biostratigraphic correlation by means of foraminifera gives an age of Middle Miocene, Orbulina suturalis zone. Within the regional subdivision of the Vienna Basin stratigraphy only *Globigerina druryi* can be used. The sequence is younger then the Early Badenian Lagenidae zone. Other benthic index fossils are missing.

Calcareous Nannoplankton Assemblages

Generally the sediments are poor in nannofossils. The samples rich in calcite are especially affected. This might be due to the deposition of the sediments in relatively a shallow environment and to recrystallization by diagenesis. The observations of each sample are summarized in table 4.

Samples 5A, 6B, 7A: sediments are rich in calcite and pyrite. The nannofossils are scarce; the assemblages are of low diversity probably due to low water depth.

Sample 9: the nannofossils are very rare. *Coccolithus pelagicus* was the only species found. Diagenesis is stronger, calcite is more abundant, pyrite scarce. Probably a very shallow environment.

Sample 10: little calcite, some organic material (plant remains), pyrite common. The nannofossils are common, well preserved.Few discoasters are present. An increase of water depth can be assumed.

Sample 11: calcite is abundant, pyrite scarce. The nannofossils are very rare, overgrown by diagenesis. Very low diversity of the assemblage.

Sample 12: the nannofossils are more common and slightly overgrown. The assemblage is more diversified. Calcite and pyrite are present.

Sample 13: calcite is very abundant, pyrite scarce. The nannofossils are rare, strongly overgrown. The assemblage is of low diversity.

Sample 14: The sample is rich in pyrite and detrital material. The nannofossils are common, well preserved. The assemblage is highly diversified and some discoasters are present indicating slightly deeper environment.

Sample 15: Very rich in calcite, pyrite scarce; nannofossils are very rare and strongly overgrown. The assemblage is of low diversity; shallower conditions.

Samples 16 to 20: calcite is common to abundant, pyrite scarce. The nannoplankton is strongly overgrown and rare.

Table 4. Distribution of calcareous nannoplankton. Frequencies are indicated by symbols: x = present; dots = scarce; circle = common (cf. = uncertain determination).

CALCAREOUS NANNOPLANKTON DISTRIBUTION WEISSENEGG Sample no.	*Braarudosphaera bigelowi*	*Coccolithus pelagicus*	*Coronocyclus nitescens*	*Cyclicargolithus abisectus*	*Cyclicargolithus floridanus*	*Cyclococcolithus macintyrei*	*Cyclococcolithus rotula*	*Discoaster exilis*	*Discolithina multipora*	*Helicosphaera carteri*	*Helicosphaera sp.*	*Reticulofenestra pseudoumbilica*	*Sphenolithus abies*	*Sphenolithus heteromorphus*	*Umbilicosphaera jafari*
31	x	○	x	•		x	•	cf.	•	○		○	x	x	
30 A		○					•		•	○		•		•	
28	x	○	•		x	•			•	○	○	○	x		
27		○				•			○	○	•		x		•
26		○	•			•			•	•	•	•	x		•
25		○	•		•	x			x	•		•			
24															
23															
22		•											x	•	
21														•	
20		•					•			•			x	•	
19		○								•		•		•	
18		○								•		•		•	
17		○						•		•		•		•	
16		○								•		•		•	
15		•										•			
14		○	x	•			•	cf.	x	•	•	○		•	
13		•								•		•		•	
12		○					•	•		•	•	•		•	
11		•										•			
10		○					x	•	x			○			
9		•					•								
7 A		○					•		x	•		•	x	•	
6 B		•					x			x				•	
5 A		○		x			x	cf.		•		•		•	

Samples 21–22: very strong diagenesis, neoformation of calcite; nannofossils very rare; the assemblage is of low diversity.

Samples 23–24: no nannofossils; detrital material.

Samples 25–26: calcite is common, probably of organic origin (shell remains), few plant remains. The nannofossils are rare and well preserved. The assemblages are weel diversified.

Sample 27: calcite scarce, some plant remains, pyrite common. The nannofossils are abundant, well preserved.

Sample 28: pyrite is rare, nannofossils are abundant and very well preserved.

Samples 30A and 31: pyrite scarce, calcite common. Nannofossils are common and well preserved.

The scarcity of nannofossils, at least within the lower part of the section (samples 5A to 9), the generally low diversity of the assemblages, the sometimes smaller size of the species, as well as the absence or scarcity of discoasters indicate deposition in a shallow basin with increasing water depth to the upper part, where discoasters are found (samples 10 to 17). *Coccolithus pelagicus* is the most common species in almost all samples. *C. pelagicus* is actually typical for cooler water (8–14° C). The occurrence of plant remains in several samples indicates changing transport from the surrounding landmasses to the basin by rivers.

The complete sequence of the Weissenegg quarry belongs to the Sphenolithus heteromorphus zone (NN 5), which corresponds to the foraminifera zones N 8 (upper part) to N 11 (lower part), comparable to the Langhian stratotype (comp. MARTINI & MÜLLER 1986).

Conclusions

The Middle Miocene shallow water corallinacean limestone facies of the Styrian Basin has been investigated with regard to the application of benthic foraminifera as depth indicators. The sedimentary sequence of the Weissenegg quarry near Wildon has been interpreted by KOLLMANN (1965) to represent repeated changes of transgressions and regressions in the Middle Badenian part of the section. The interbedded corallinacean limestone facies should correspond to the regressive phase of the cycles.

The application of Recent *Amphistegina* results for paleobathymetric interpretations seemed to be useful in this section. Due to poor preservation, the lamellar thickness in *Amphistegina* tests, which increases in shallower environments, as well as the isotope ratios of ^{18}O and ^{13}C did not give the expected results.

The genus *Elphidium* – a second important group of fairly large foraminifera with a better preservation – was also present in the sediments. The living habitats of both genera are different, with *Elphidium* preferring the more near-shore shallow water areas. The relative frequencies of *Amphistegina* against *Elphidium* therefore provided a simple method for paleobathymetric interpretation. A smooth curve was obtained, corresponding to a single transgressive – regressive cycle ending in non-fossiliferous deltaic sands. This was also supported by the results of measurements of the diameter/thickness ratios in *Elphidium*.

To confirm the results of these methods, the assemblages of smaller foraminifera from the Amphistegina marls were studied. The relative frequencies of planktonic foraminifera versus the epiphytic genus *Cibicides* were compared with those of *Asterigerinata*, nodosariids, and bolivinas. The results are in agreement with the *Amphistegina/Elphidium* curve and also demonstrate a single sedimentary cycle. This cycle starts with a transgression of Amphistegina marls on top of the Early Badenian corallinacean limestone, exhibiting a strong foreset bedding. The Middle Badenian transgression has its maximum in the lower third of the sequence and is followed by a slow regression with some fluctuations, probably caused by changing directions of the sediment supplying currents.

The microfacies investigation of the interbedded corallinacean limestones by DULLO (1983: 34) is also in disagreement with an interpretation of different transgression – regression cycles. There are no differencies in the facies of the different horizons, and the form and dimensions of rhodolites in the marls and limestones are similar.

The water depth of the Middle Badenian cycle, based on the *Amphistegina/Elphidium* relations as well as on the smaller benthic foraminifera, ranges from a few meters in the shallowest part at the beginning of the cycle to about 30 m at the time of the maximum transgression. This range is in accordance with the results from bryozoans studied from the same samples (VAVRA in press); the depth is estimated to be between 30 and 40 meters, where the occurrence of *Hornera* gives an upper depth limit of 30 m. The calcareous nannoplankton also points to very shallow deposition.

The biostratigraphic evaluation of calcareous nannoplankton and planktonic foraminifera dates the sequence as Middle Miocene, NN 5, and Orbulina suturalis zone, and in the regional stage system as Middle Badenian, zone of agglutinated foraminifera. The Late Badenian regressive sedimentation can be dated only by regional correlation.

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