Annales de la Société Géologique de Belgique. T. 110 - 1987, pp. 9-38 Mai 1987

STRATIGRAPHIC INTERPRETATION OF THE THERMAE BOREHOLES (VALKENBURG A/D GEUL, THE NETHERLANDS)

by

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(16 figures, 2 tables, 5 plates)

1. INTRODUCTION

The stratigraphic interpretation of the Thermae boreholes is based on lithostratigraphic, biostratigraphic, ecostratigraphic and petrophysical parameters.

The experience of the present study shows that cuttings - if carefully sampled by the driller - may yield sufficient data for a very detailed correlation with wells and outcrops at several kilometers distance.

2. CENOZOIC

Cenozoic deposits consist of Pleistocene loess (only recognized in Thermae 2002, 0-5.5 m), fine sands of Oligocene Tongeren Formation (0.8-30.25 m in Thermae 2000, 1.0-31.5 m in Thermae 2001, and 5.5-17.0 m in Thermae 2002), and a basal conglomerate with reworked (?) fragments of Paleocene chalk of the Houthem Formation (30.25-30.35 m in Thermae 2000, and 31.5-33.5 m in Thermae 2001).

The Houthem chalk has been dated by foraminifer assemblages indicating Hofker's (1966) foram zone P. The chalk contains echinoid spines with a flattened, oar-shaped tip.

The contact between the Oligocene and Paleocene sediments in Thermae 2000 and Thermae 2001 slightly dips to the south. The same holds for the contact between the Paleocene and Upper Cretaceous chalk. Between Thermae 2000 and Thermae 2002 the base of the Oligocene sand slightly dips to the north (fig. 1).

3. UPPER CRETACEOUS

The Upper Cretaceous sediments consist in descending order of tufaceous chalk (biocalcarenites), flint-bearing chalk with frequent intercalations of hard well-cemented layers, glauconitic somewhat sandy clay, and kaolinic mud-sand with fytoclasts. Their subdivision is based on biostratigraphic arguments (foraminifera and microflora), lithostratigraphic comparison (notably with ENCI, Halembaye and Kastanjelaan-2), bioclasts and ostracodes (ecostratigraphic comparison with a.o. ENCI, Halembaye and Kastanjelaan-2) and petrophysical borehole logs (notably GR log compared with that of Kastanjelaan-2). These different parameters are briefly discussed below.

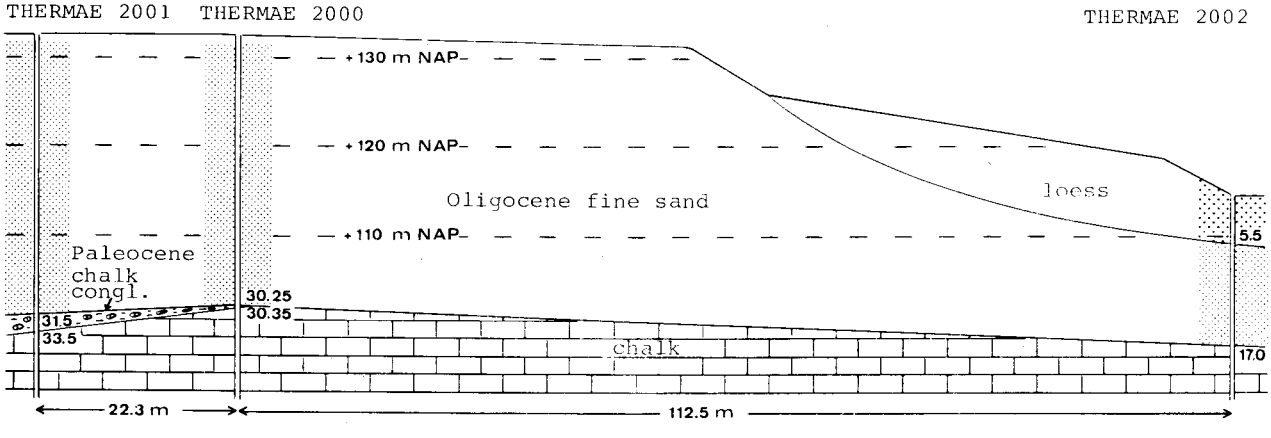

Figure 1 - Cenozoic deposits in in the Thermae boreholes and the top of the underlying Upper Cretaceous chalk.

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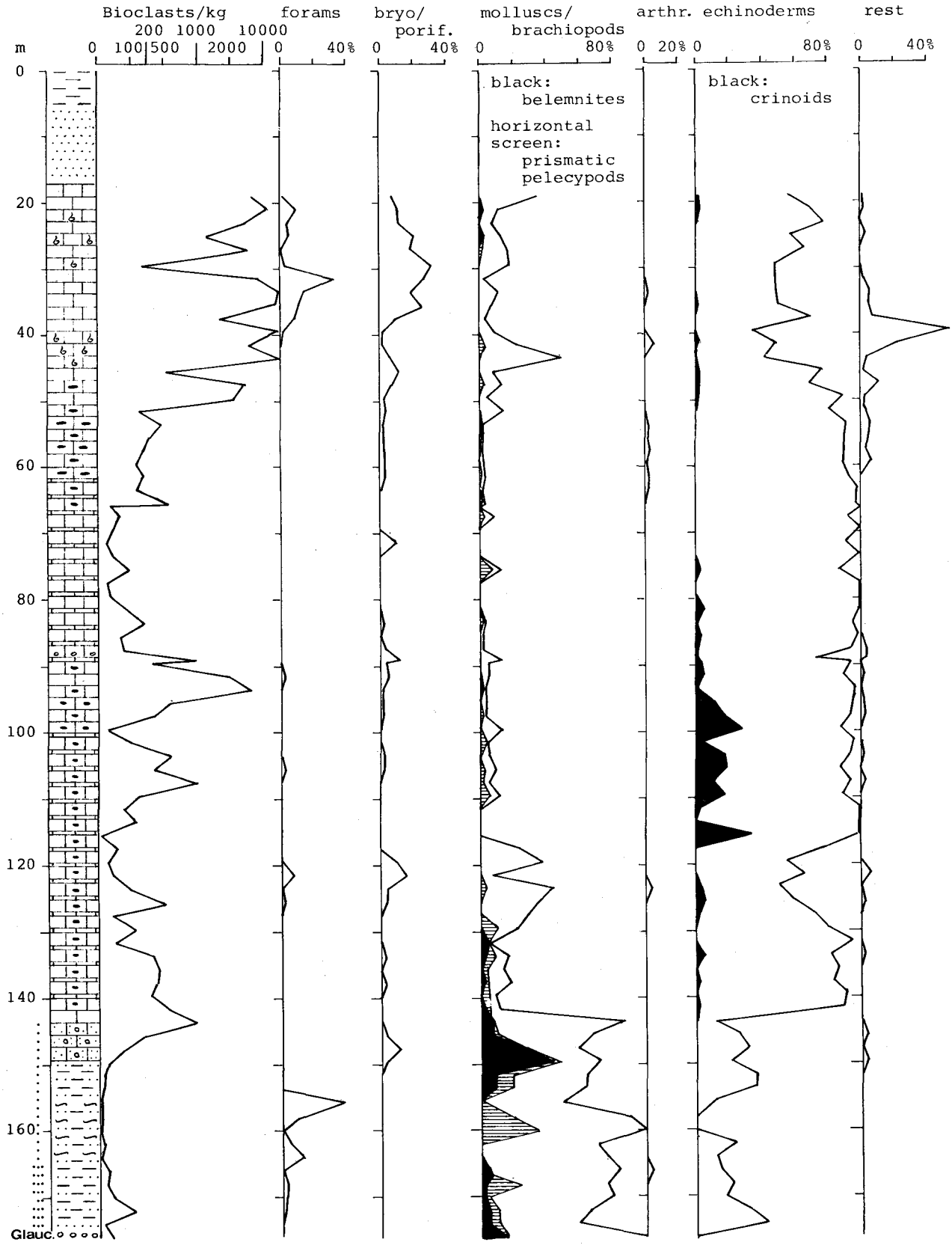

Figure 2 - Distribution of bioclasts in the marine Upper Cretaceous of Thermae 2002. The graphs in this figure are based on the sieve fraction 1.0-2.4 mm. Compare the results with those of figure 3 !

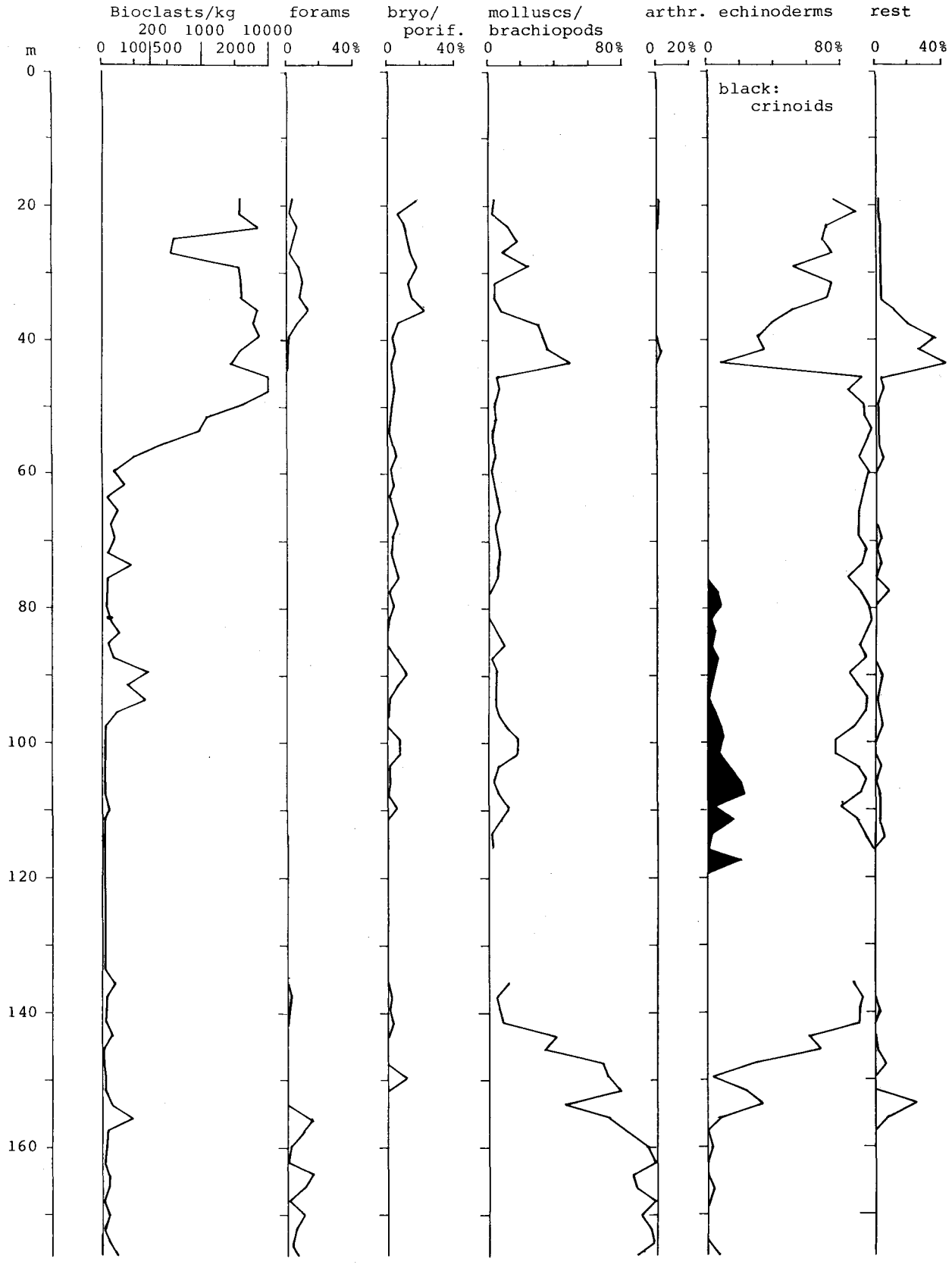

Figure 3 - Distribution of bioclasts in the marine Upper Cretaceous of Thermae 2002.
The graphs in this figure are based on the sieve fraction 0.5-2.0 mm. Compare the results with those of figure 2 !
Note that belemnites and prismatic pelecypods have not been distinguished. Moreover, the low number of bioclasts between 115 and 135 m made that no percentages have been calculated for that interval.

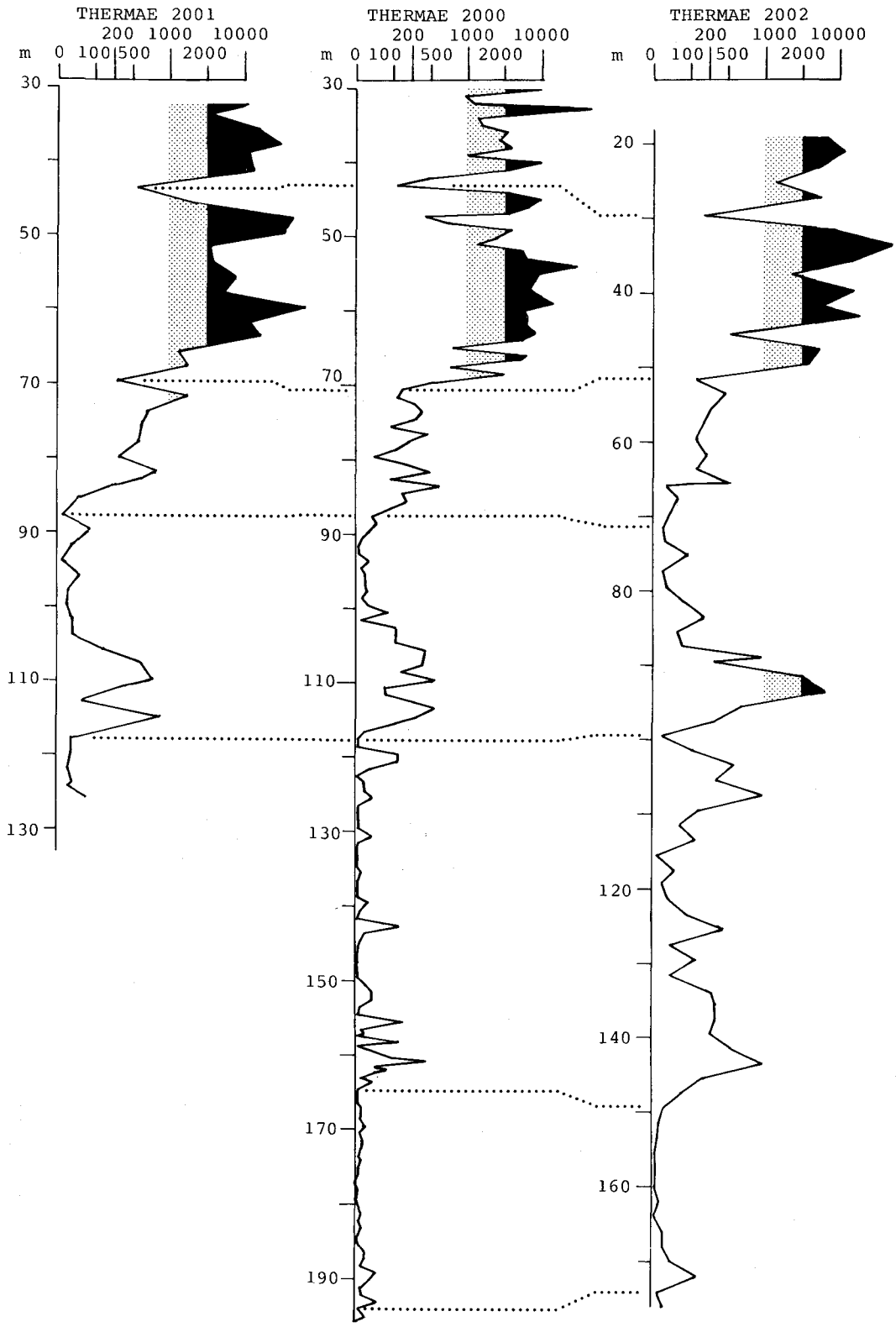

Figure 4 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of the number of bioclasts (1.0-2.4 mm) per kilogram.

3.1. BIOSTRATIGRAPHY

The biostratigraphic subdivision of the marine Upper Cretaceous sediments is based on foraminifer assemblages which are indicative for Hofker's (1966) foram zones. Analysis of the foraminifer assemblages has been restricted to Thermae 2000 and Thermae 2002. The results are summarized in table I. The assemblages consists of benthic foraminifera and are briefly discussed here in descending order.

Table I - Distribution of Hofker's (1966) foram zones in Thermae 2000 and Thermae 2002 (depths in m).

foram zone	Thermae 2000	Thermae 2002
M	32.0 - 37.0	19.0 - 27.0
L	37.0 - 46.7	27.0 - 31.5
K	47.0 - 58.0	31.5 - 43.5
J	58.0 -109.5	43.5 - 89.0
F	113.5 -126.5	101.5 -111.5
E	?	?
C	164.5 -167.0	?
A'-lower	167.0 -195.5	149.5 -174.0

3.1.1. Foram zone M

Characteristic species are *Tremastegina roestae* (large specimens), *Daviesina labanae ornamentata* and *Siderolites laevigata*. The same assemblage occurs in Kastanjelaan-2 between 17.5 and 28.8 m.

3.1.2. Foram zone L

Characteristic species are *Tremastegina roestae* (small specimens), *Rotalia trochidiformis, Nummofallotia cretacea* and *Daviesina fleuriausi*. In Kastanjelaan-2 this assemblage is found between 28.8 and 33.8 m. In the ENCI the base of foram zone L coincides with the Caster Horizon.

3.1.3. Foram zone K

Characteristic species are *Daviesina fleuriausi, Pseudoparrella alata, Lituola senoniensis* and *Pararotalia tuberculifera*. This zone is also marked by the frequent occurrence of *Siderolites calcitrapoides*. The upper portion of zone K and notably the contact between zones K and L is marked by relatively high numbers of large foraminifer specimens (> 1 mm). In Kastanjelaan-2 this foram zone is recognized between 33.8 and 46.8 m. In the ENCI the base of this zone roughly coincides with the Lava/Laumont Horizons.

3.1.4. Foram zone J

The following characteristic species have been recognized : *Gavelinopsis involuta, Nonionella troostae, Allomorphina halli* and *Sigmomorphina soluta*. This assemblage also occurs in Kastanjelaan-2 between 46.8 and 67.8 m.

Foram zone J is absent in the ENCI where it is replaced by foraminifer assemblages indicating foram zones H and I. Zones H and I mark there the interval between the Lichtenberg Horizon and Lava/Laumont Horizons. Remarkable is the occurrence of a few specimens of *Bolivinoides australis* slightly above the base of zone J in Thermae 2000 (106.5-107.5 m). The highest occurrence of this species in the ENCI is a few meters above the Lichtenberg Horizon. Rare specimens of *B. australis* also occur in the basal portion of the Kunrade Chalk («Bouwput RW76» near Benzenrade, Heerlen ; Romein et al. 1977) which is correlated with the lower part of foram zone J in Thermae 2000 (Bless et al. 1987).

3.1.5. Foram zone F

This zone is only marked here by the occurrence of *Eponides frankei*. Other foraminifer species are virtually absent. Much more diverse assemblages occur in Kastanjelaan-2 (67.8-79.8 m) and in the ENCI (between the Lichtenberg Horizon and Nivelle Horizon).

3.1.6. Foram zone E

This interval does not contain any characteristic foraminifera in the Thermae boreholes. But flint-bearing chalk lithologically correlated with the Lixhe Chalk of Halembaye (there characterized by foraminifera of zone E) has been recognized in these wells.

3.1.7. Foram zone C

The lower portion of this zone has been recognized in Thermae 2000, where it is marked by the presence of *Bolivinoides australis* with a mean number of pustulae on the last chamber of 5.3. This can be correlated with a value of 5.4 observed for the same species in Kastanjelaan-2 between 113.8 and 115.8 m. Sediments of the lower half of zone C also occur in Thermae 2002. But these are slightly more sandy and have not yielded any characteristic species.

3.1.8. Foram zone A'-lower

The characteristic species are *Gavelinella clementiana* and *Lenticulina multinodosa* (pl. 2, fig. 3). This zone has also been recognized in Kastanjelaan-2 (166.2-198.2 m) and in Halembaye (Vaals Formation below Zeven Wegen Horizon). Large specimens (> 1 mm) of *Nodosaria* and *Lenticulina* are common in this zone, where a pronounced maximum in the bioclast assemblages marks the base of the upper third of this zone in Thermae 2000 and Thermae 2002 (fig. 5).

Foram zones C to M characterize the Upper Maastrichtian, zone A'-lower the Lower Campanian. Sediments containing foram zones A (Upper Campanian) or B (Lower Maastrichtian) are absent in Thermae 2000 and Thermae 2002. The non-marine mud-sand between 195.5 and 201.8 m in Thermae 2000 and between 176.0 and 184.5 m in Thermae 2002 has yielded a microflora indicating a Santonian age (Batten et al. 1987).

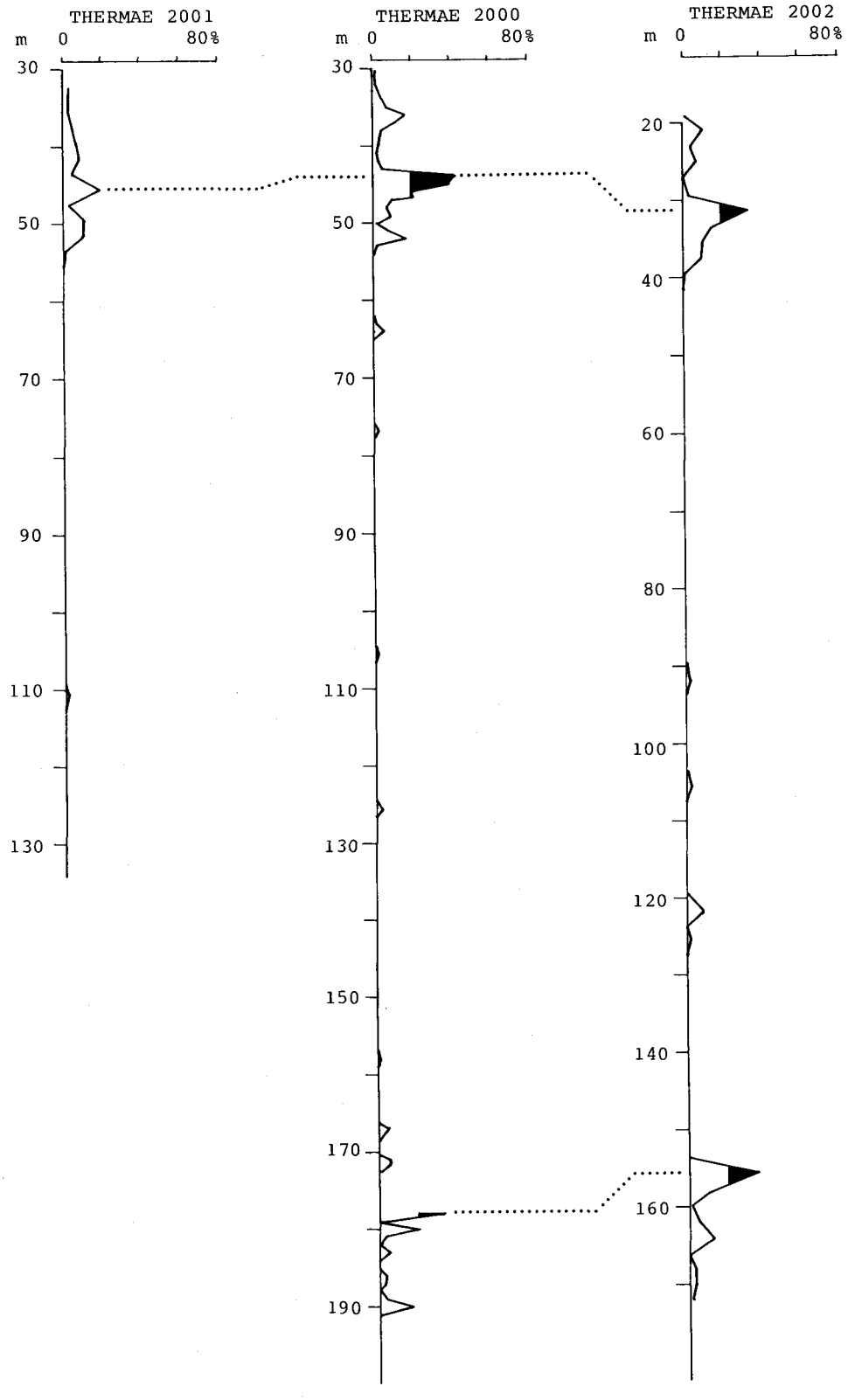

Figure 5 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of foraminifer percentages in the bioclast (1.0-2.4 mm) assemblages.

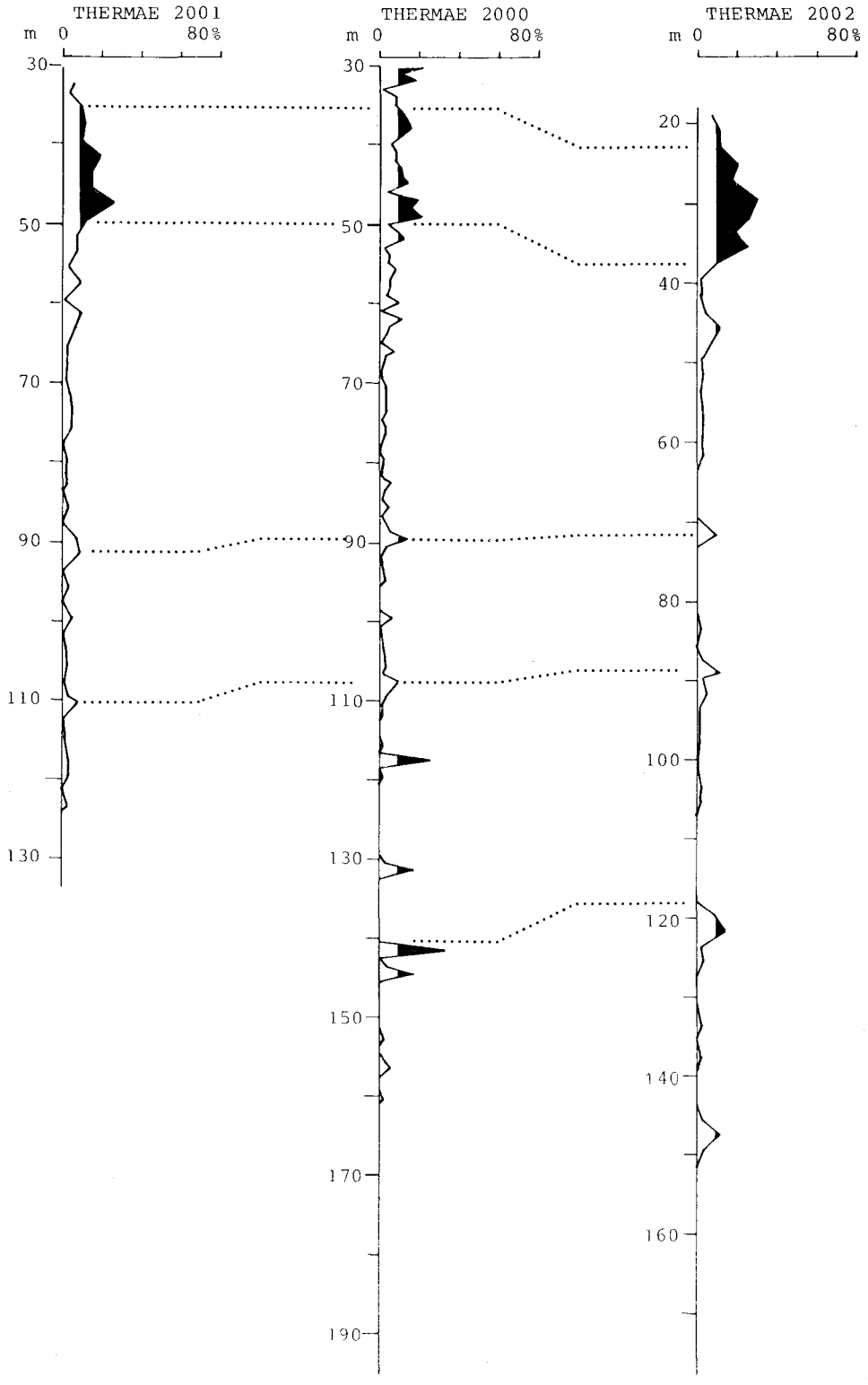

Figure 6 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of bryozoan/sponge percentages in the bioclast (1.0-2.4 mm) assemblages.

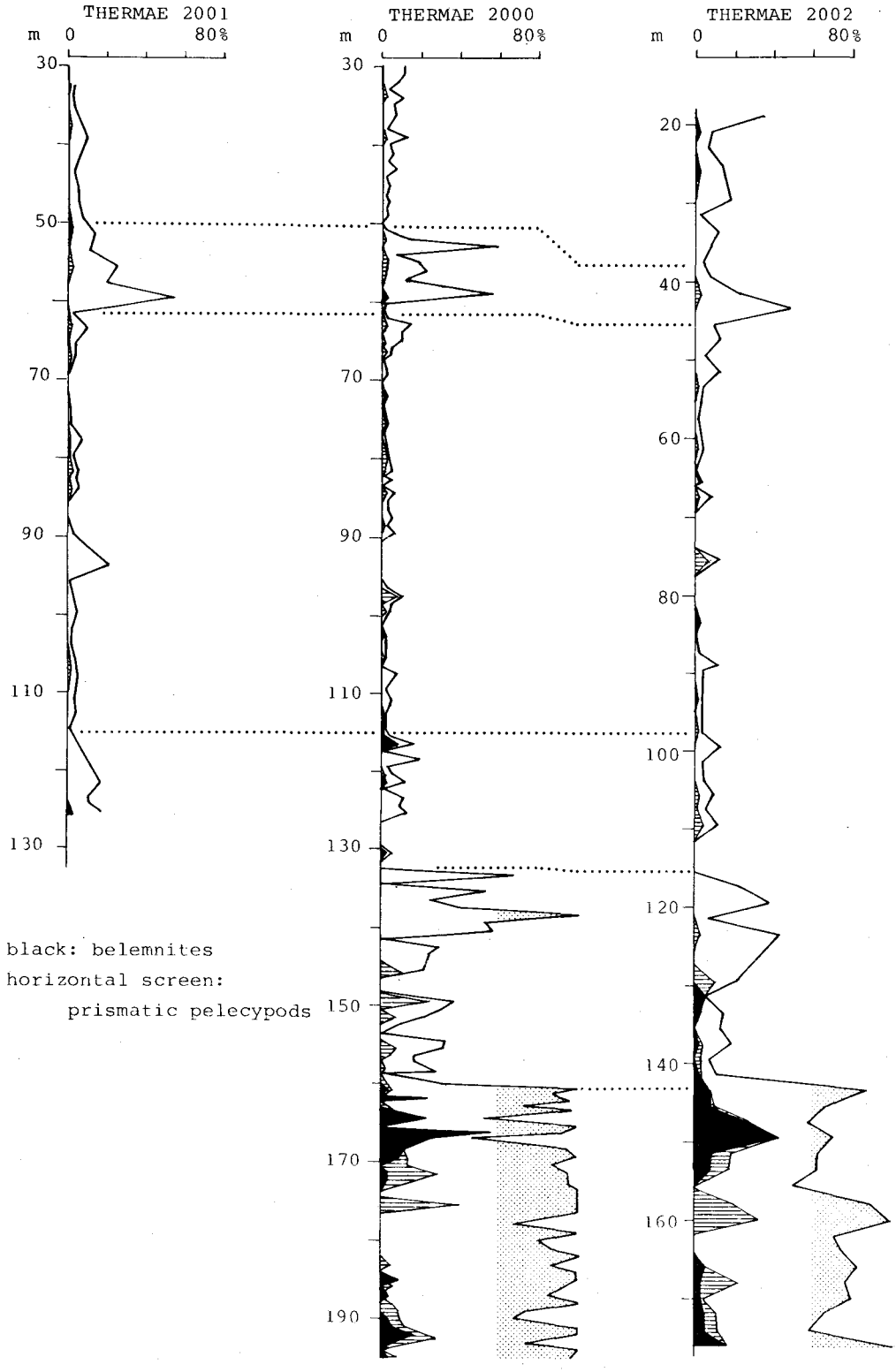

Figure 7 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of mollusc/brachiopod percentages in the bioclast (1.0-2.4 mm) assemblages.

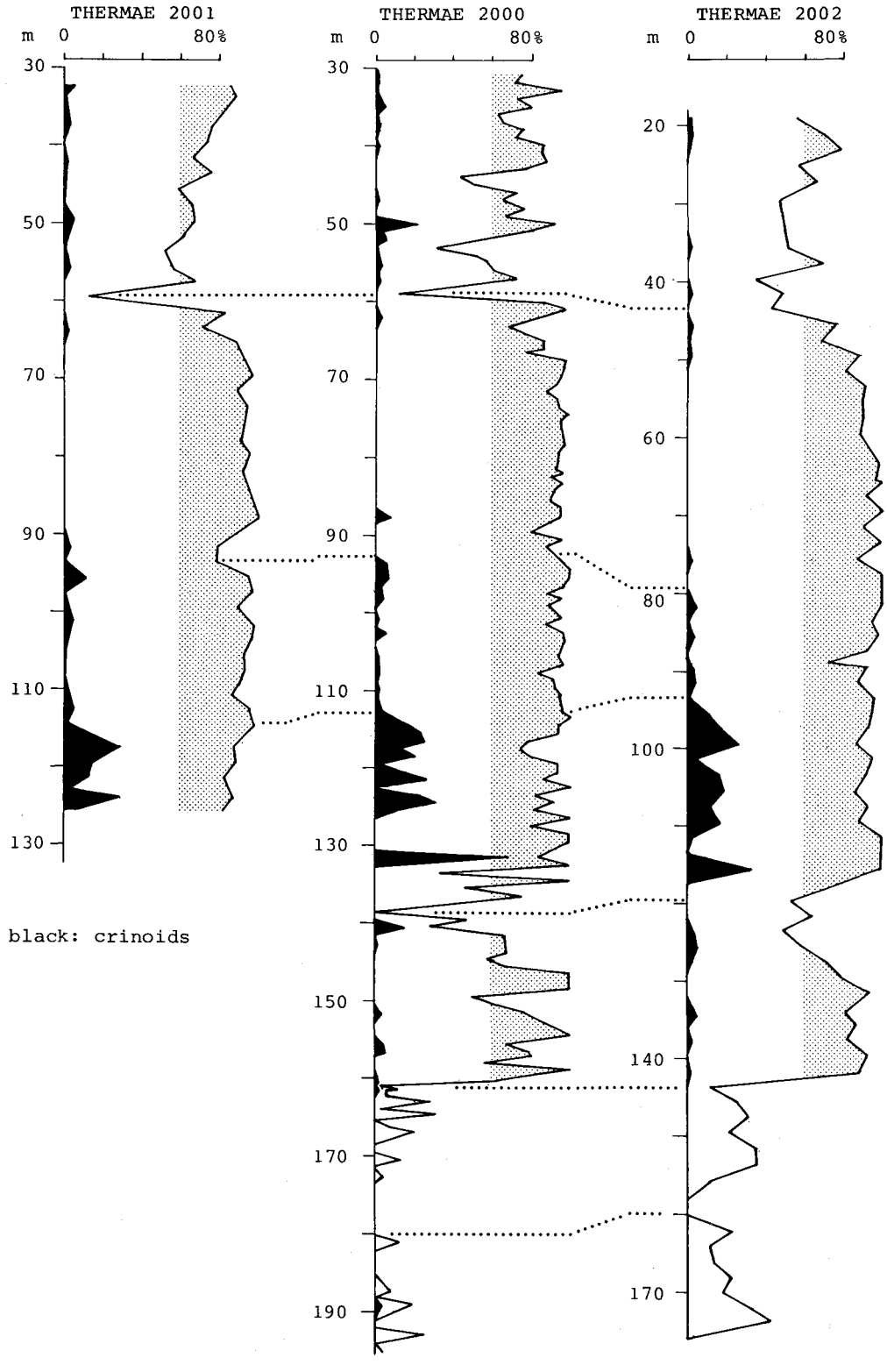

Figure 8 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of echinoderm percentages in the bioclast (1.0-2.4 mm) assemblages.

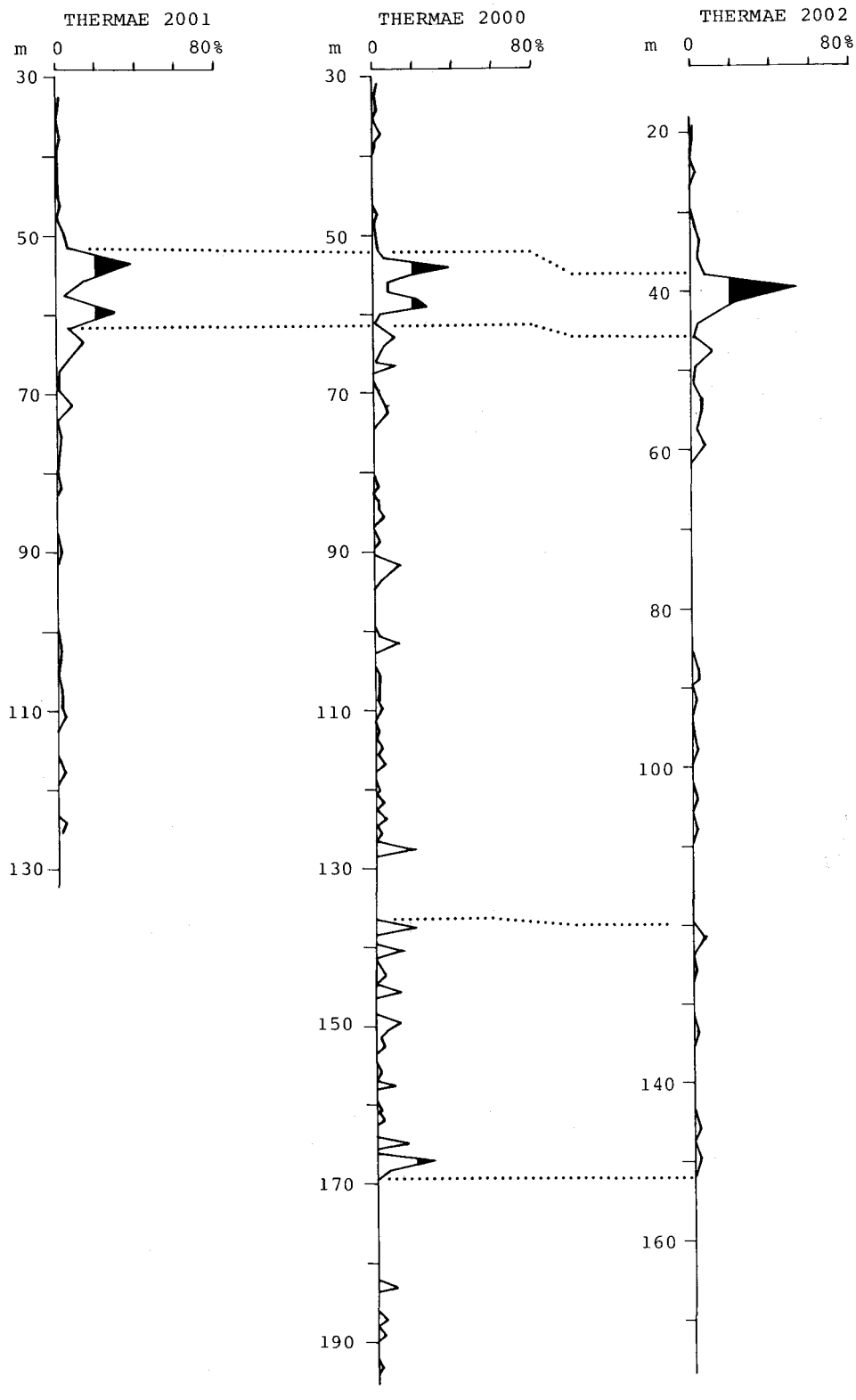

Figure 9 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of the percentages of the rest group (mainly serpulids and fish remains) in the bioclast (1.0-2.4 mm) assemblages.

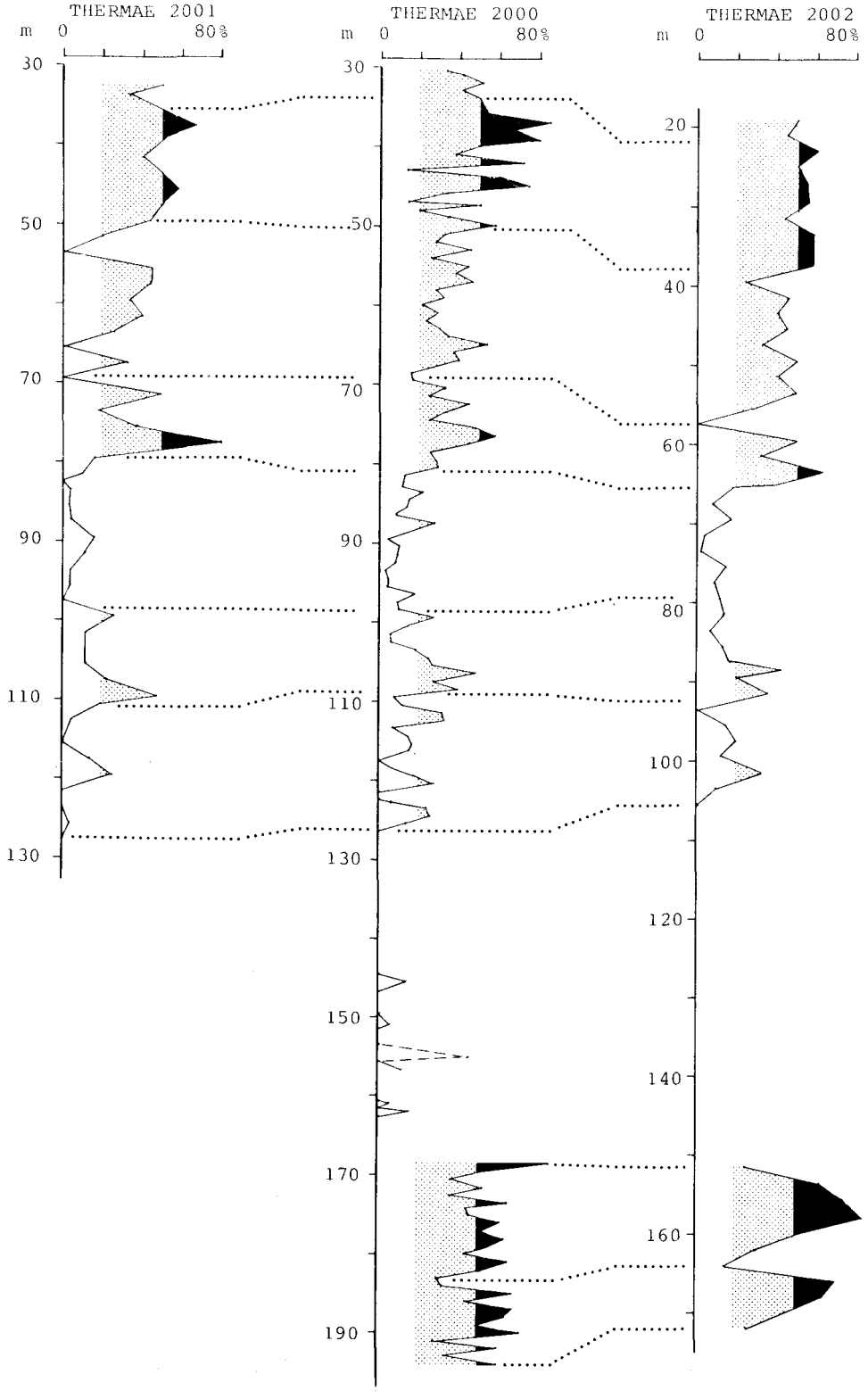

Figure 10 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes by means of the percentage of ornamented ostracode specimens in the ostracode (0.125-1.0 mm) assemblages.

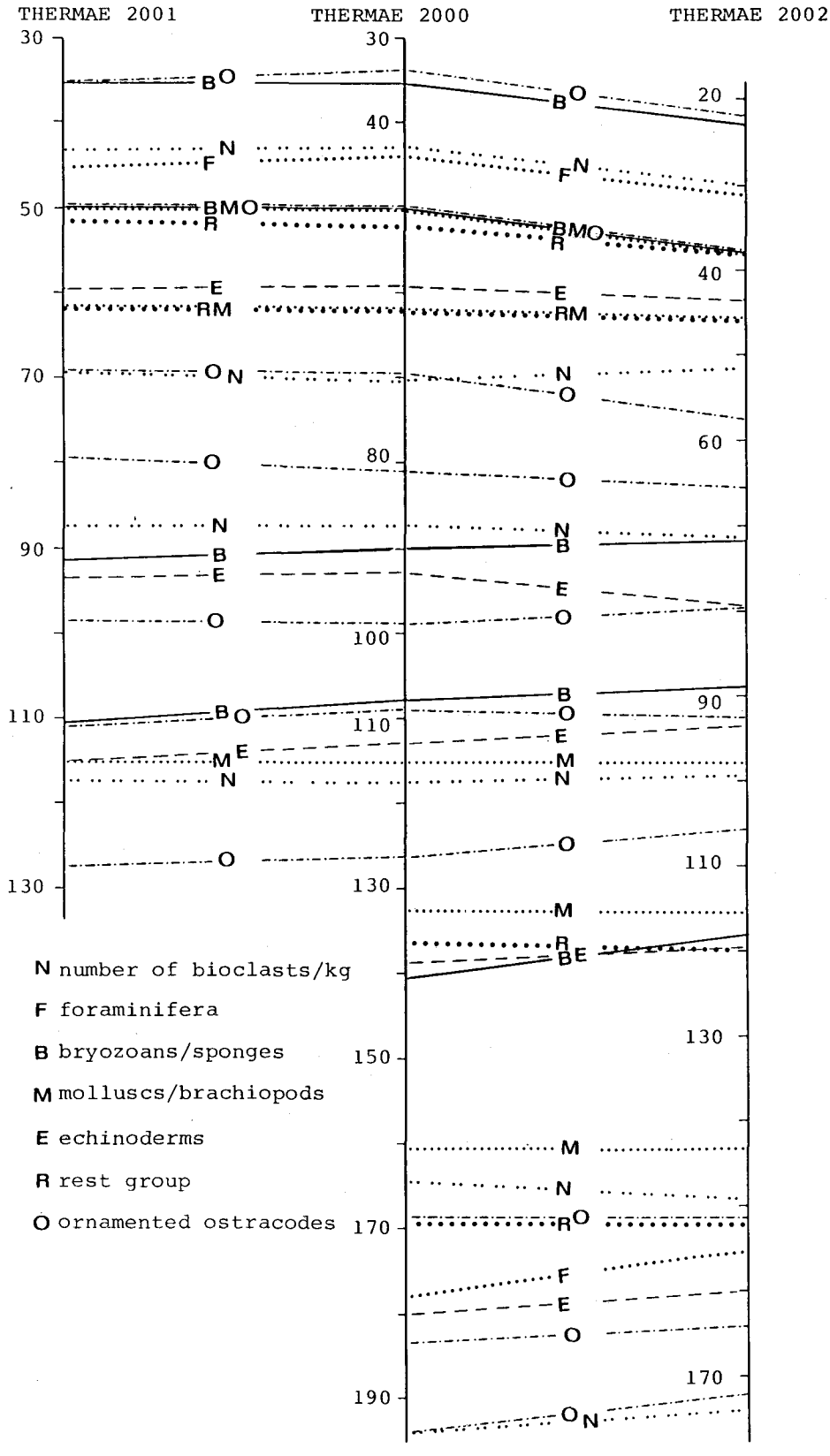

Figure 11 - Correlation of marine Upper Cretaceous and Paleocene strata in the Thermae boreholes using all date presented in figures 4 to 10.

3.2. LITHOSTRATIGRAPHY

The lithology of the Upper Cretaceous strata is very similar in the Thermae boreholes. As an example of the lithostratigraphic subdivision of the Upper Cretaceous Thermae 2002 has been choosen here. Insofar as relevant also data from Thermae 2001 and Thermae 2000 are presented.

The upper portion between 17 and 47 m consists of yellowish, medium- to coarse-grained biocalcarenites with rare hardgrounds. Large bioclasts (> 1 mm) abound. Near the base of this interval numerous pelecypod fragments occur around 43 m. These are interpreted as an oyster layer. The interval is correlated with comparable strata above the Lava Horizon in the ENCI which are characterized by the same foraminifer assemblages (foram zones K, L and M). The oyster layer is marked by a pronounced GR peak which also occurs in Kastanjelaan-2 just above the base of foram zone K around 43 m. This peak can be traced throughout northeastern Belgium and was originally considered to represent the Lava Horizon (P. J. Felder et al. 1985a). Comparison with the ENCI suggests however that the oyster layer represents the Laumont Horizon. Transitory circulation losses at some 47 m in Thermae 2000 and Thermae 2001 indicate the presence of open fissures (above the present water table) in presumably the Caster Horizon at the base of foram zone L. This hardground or circulation losses were not observed in Thermae 2002.

Flint-bearing fine- to medium-grained calcarenites with near the base a few hard, well-cemented chalk layers occur between 47 and 65 m. This interval is correlated with the flint-bearing chalk of the lower portion of the Emael Chalk, the Schiepersberg Chalk and the upper part of the Gronsveld Chalk in the ENCI.

Alternating hard and soft layers of coarse-grained calcisiltites to fine-grained calcarenites have been observed between 65 and 89 m. At the base of this interval some chalk pebbles occur, presumably indicating a reworking horizon. The cemented hard chalk may be partly siliceous. The virtual absence of real flint suggests a correlation with the lower half of the Gronsveld Chalk and with the Valkenburg Chalk in the ENCI. The reworking horizon roughly matches the base of foram zone J and may be correlated with the Lichtenberg Horizon in the ENCI. Remarkable is the fact that circulation losses occurred at or near this Horizon in Thermae 2001 and Thermae 2002. Maybe, this horizon is underlain by a hardground with sometimes open fissures. In the ENCI the Lichtenberg Horizon is an erosion level without underlying hardground.

Flint-bearing coarse-grained calcisiltites are present between 89 and 141 m. Below 100 m these include numerous hard layers. This interval may be compared with the flint-bearing strata of the Lanaye and Lixhe Chalk as observed in the ENCI and in Halembaye. The presence of the numerous well-cemented hard layers may be indicative for a lateral transition into a Kunrade-type chalk.

Glauconitic chalk with some sand and pebbles of white chalk, quartz and quartzite in its lower portion is found between 141 and 149.5 m. This interval is marked by downward strongly increasing GR values. It is correlated with a comparable interval in Kastanjelaan-2 between 118 and 128 m, there interpreted as the «lower Vijlen Chalk». In Thermae 2000 this interval yielded foraminifera indicating the lower half of foram zone C, thus confirming the lithostratigraphic interpretation.

Greyish-green, sometimes marly, clay with some sand is present between 149.5 and 166 m. The sand consists of well-rounded quartz grains. The greenish shades are caused by glauconite. Between 166 and 176 m the sediment consists of a green clay with some sand but without marls. Glauconite is abundant. At the base a basal conglomerate occurs with some pyrite. The pebbles consist of bleached, light-grey, well-rounded fragments of silicified shales and limestones presumably derived from Dinantian rocks. Many pebbles show small holes caused by boring sponges.

This interval is correlated with the Vaals Formation as recognized in Kastanjelaan-2. As in Kastanjelaan-2 it is marked by relatively high GR values. A basal conglomerate at the base of the Vaals Formation has been observed at many outcrops in South-Limburg and the neighbouring areas around Aachen and in the Herve region.

A whitish mud-sand with sometimes abundant lignite fragments and megaspores between 176 and 184.5 m is here correlated with the Hergenrath Clay of the lower Aachen Formation. The clay is mainly kaolonite. The quartz grains are frequenty poorly rounded or only broken quartz crystals. This suggests a local origin for this deposit. Near the base pyrite/marcasite concretions are abundant. Lithologically the sediment strongly resembles the underlying paleosol on top of the Dinantian strata. This paleosol largely consists of kaolinite, authigenic quartz crystals and weathered, whitish-grey fragments of silicified shales and limestones. However no lignite or megaspores occur.

3.3. BIOCLAST ASSEMBLAGES

Bioclasts are fossils or fossil fragments in a sediment. Their nature and relative abundance yield information on the depositional environment and can be used to characterize the sediment. In a basin with relatively widespread uniform environmental conditions any changes in the overall environment are reflected by vertical changes in the composition of bioclast assemblages which may be traced over long distances and therefore serve as ecostratigraphic markers. Apparently, the Upper Cretaceous marine sediments of northeastern Belgium and South-Limburg have been deposited under such widespread uniform conditions (P.J. Felder et al. 1985a, 1985b). And thus vertical variations in the bioclast profiles may be used for correlations within that area.

For practical reasons the sediments are characterized

PLATE 1

1-2 *Limburgina* cf. *ornata* (BOSQUET 1847)
Thermae 2002, 17-19 m, Upper Maastrichtian.

3 *Mauritsina* cf. *hieroglyphica* (BOSQUET 1847)
Thermae 2002, 17-19 m, Upper Maastrichtian.

4-5 *Spongicythere koninckiana* (BOSQUET 1847)
Thermae 2002, 17-19 m, Upper Maastrichtian.

6 *Imhotepia interruptoidea* (VAN VEEN 1936) sensu DEROO 1966
Thermae 2002, 87.5-89.0 m, Upper Maastrichtian.

7 *Cytherella* ex. gr. *ovata* (ROEMER 1841)
Thermae 2002, 87.5-89.0 m, Upper Maastrichtian.

8 *Mosaeleberis* cf. *interrupta* (BOSQUET 1847)
Thermae 2002, 87.5-89.0 m, Upper Maastrichtian.

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by the bioclast assemblages picked from a special sieve fraction. In our case the sieve fraction 1.0-2.4 mm has been choosen. But tests have shown that slightly different sieve meshes (e.g. 0.5-2.0 mm) do not considerably alter the results (fig. 2-3). Howevern the constant usage of the same sieve mesh will certainly improve the quality of the data which are to be compared.

Six different parameters have been selected for correlation of the Upper Cretaceous sediments in the Thermae boreholes. These are :
- the number of bioclasts (1.0-2.4 mm) per kilogram,
- percentage foraminifera in that bioclast assemblage,
- percentage bryozoans/sponges/corals,
- percentage molluscs/brachiopods,
- percentage echinoderms, and
- percentage of a rest group, largely consisting of serpulids and fish remains.

3.3.1. Number of bioclasts/kg

The graphs in figure 4 only refer to the number of bioclasts in the sieve fraction 1.0-2.4 mm which are found in one kilogram of chalk. The overall variations observed in these graphs are rather similar in the three boreholes. The highest values occur in the upper 30 to 40 m of the chalk where the number of bioclasts/kg usually exceeds 1000 specimens. This interval corresponds to the upper portion of foram zone J and to foram zones K, L and M. Similar high values have been recognized for foram zones K, L and M of Kastanjelaan-2 (Maastricht) and for the upper portion of foram zone I and foram zones K, L and M of the ENCI.

Below this interval the number of bioclasts/kg is usually well below 1000 specimens. A less pronounced maximum characterizes the basal portion of foram zone J and foram zone F. Similar observations have been made for Kastanjelaan-2 and the ENCI. A small increase in the number of specimens around 160 m in Thermae 2000 and around 145 m in Thermae 2002 corresponds to the basal portion of foram zone C. This matches a similar increase in the number of bioclasts near the base of foram zone C in Kastanjelaan-2.

3.3.2. Foraminifera

The graphs in figure 5 only show the occurrence of large benthic foraminifera (> 1 mm) in the sieve fraction 1.0-2.4 mm. Smaller foraminifera have been recognized in practically all samples. There is no relationship between the number of small and large specimens. Two maxima are distinguished. The upper one covers the medium- to coarse-grained biocalcarenites of foram zones K, L and M, showing a distinct peak near the boundary between zones K and L. The genera *Siderolites* and *Orbitoides* abound here. A similar maximum with a peak near the contact between zones K and L has been recognized in Kastanjelaan-2.

Siderolites and *Orbitoides* presumably preferred very shallow environments with relatively high water energy (above wave base). They characterize the acme of Mediterranean influence in this area.

The lower maximum occurs within the glauconitic, slightly marly and sandy clay of foram zone A'-lower.

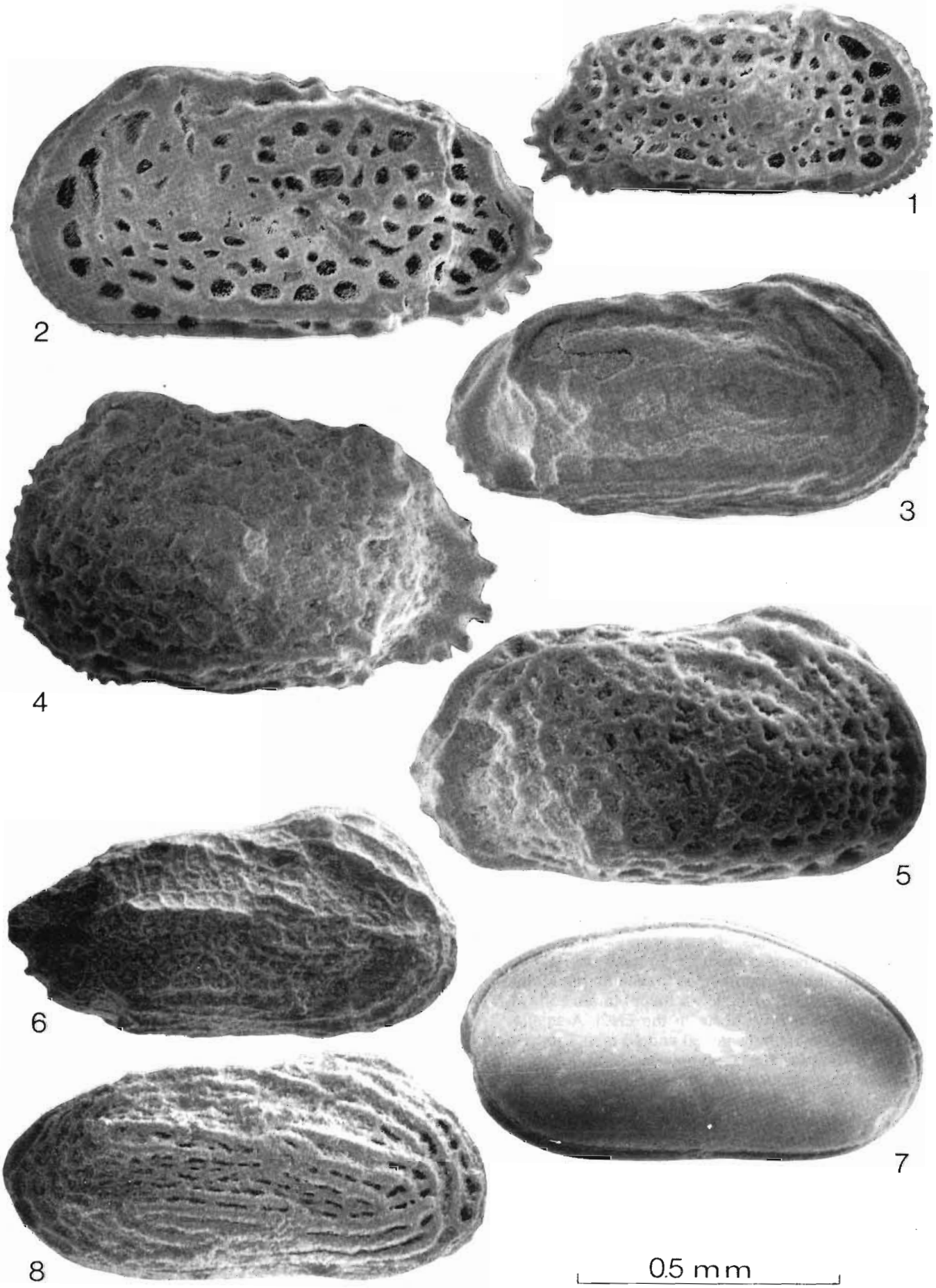
1
2
3
4
5
6
7
8
0.5 mm

PLATE 2

Bar = 0.5 mm : figures 1-4, 6
Bar = 1.0 mm : figure 5

1 *Cythereis hallembayensis* DEROO 1966
Thermae 2002, 164-166 m, Lower Campanian.

2 *Veenia foersteriana* (BOSQUET 1847)
Thermae 2002, 164-166 m, Lower Campanian.

3 *Lenticulina multinodosa*
Thermae 2002, 164-166 m, Lower Campanian.

4 *Pterygocythere laticristata* (BOSQUET 1854)
Thermae 2002, 164-166 m, Lower Campanian.

5 Algae?
Thermae 2002, 182.5-184.0 m, Santonian.

6 *Spermatites* cf. *orbicularis* MINER 1935
Thermae 2002, 182.5-184.0 m, Santonian.

It is characterized by boreal representatives such as *Lenticulina* and *Nodosaria*. Comparison with other boreholes in northeastern Belgium and South-Limburg reveals that foraminifer maxima in zone A'-lower may have only some value for local correlation.

3.3.3. Bryozoans/sponges

The graphs in figure 6 show a complex maximum consisting of three smaller peaks in the upper 20 m of the Upper Cretaceous. These roughly match the upper foraminifer maximum of figure 5. In Kastanjelaan-2 an equally pronounced maximum marks the top of foram zone K to the lower half of foram zone M. The same is known to occur in the ENCI. A smaller complex maximum between 50 and 65 m in Thermae 2000 and Thermae 2001, and between 40 and 50 m in Thermae 2002 characterizes the upper portion of foram zone J. A similar maximum occurs in Kastanjelaan-2 between 50 and 65 m, there corresponding as well to foram zone J. This maximum is also known in the ENCI between the Lava Horizon and Romontbos Horizon.

The small peaks between 140 and 145 m in Thermae 2000 and between 118 and 125 m in Thermae 2002 possibly correspond to a small peak below the Boirs Horizon in the ENCI.

3.3.4. Molluscs/brachiopods

Three maxima are distinguished in figure 7. The upper one between 50 and 60 m in Thermae 2000 and Thermae 2001, and between 40 and 45 m in Thermae 2002, is predominated by oyster fragments. This «oyster layer» matches the GR peak of the Laumont Horizon. This GR peak and «oyster layer» have been also observed in Kastanjelaan-2 between 40 and 50 m.

The second, complex maximum occurs between 132 and 160 m in Thermae 2000 and between 116 and 141 m in Thermae 2002. Fragments of belemnites and prismatic pelecypods are usually rare. This might be compared with a similar, but slightly more regular, maximum in the upper two thirds of foram zone E (80-95 m) in Kastanjelaan-2.

The third and lower maximum is the most important one. The percentages are usually well above 60 % of the bioclast assemblage in this sieve fraction. Fragments of belemnites and prismatic pelecypods are common. Analysis of foram assemblages and ostracodes reveals that this maximum partly corresponds to the lower half of foram zone C («Lower Vijlen Chalk» of Halembaye) and partly to the foram zone A'-lower. The contact between these zones is here marked by a pronounced peak in the belemnite percentages (167 m in Thermae 2000, 149.5 m in Thermae 2002). Whether this peak marks a reworking horizon or a condensed sequence is not clear. It should be noticed that equally pronounced maxima for the lower portion of foram zone C and for foram

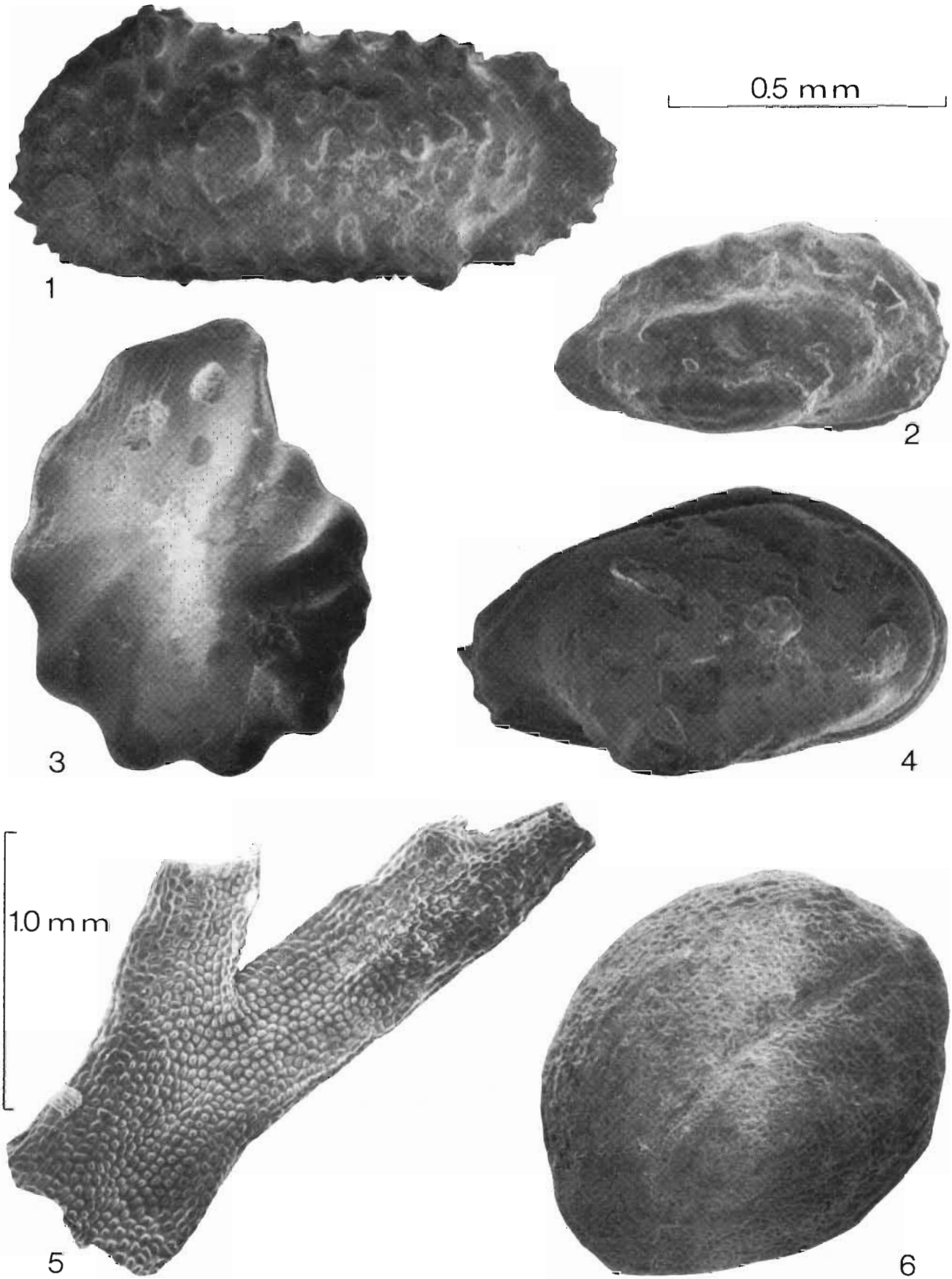
0.5 mm
1
2
3
4
1.0 mm
5
6

PLATE 3

1 *Costatheca diskoensis* (MINER) HALL 1967
Thermae 2002, 182.5-184.0 m, Santonian, X38.

2 Broken, but hardly rounded quartz crystal
Thermae 2002, 182.5-184.0 m, Santonian, X50.
Authigenic quartz crystals of the same size are common in the underlying paleosol between 184.5 and 195.3 m.

3-5 «*Triletes*» cf. *pubescens* DIJKSTRA 1949
Thermae 2002, 182.5-184.0 m, Santonian, X100.

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zone A'-lower have been noticed in Kastanjelaan-2 and in Halembaye.

3.3.5. Echinoderms

Echinoderm fragments usually predominate in this sieve fraction above 160 m in Thermae 2000 and above 143 m in Thermae 2002 (figure 8). A small minimum around 60 m in Thermae 2000 and Thermae 2001, and between 40 and 45 m in Thermae 2002, marks the position of the «oyster layer» (Laumont Horizon), just above the base of foram zone K.

A second minimum around 138 m in Thermae 2000 and around 120 m in Thermae 2002 roughly marks the highest position of the interval where molluscs regularly are important or predominant. This minimum forms the base of the interval where the Mediterranean influence is noticed in the Upper Cretaceous of South Limburg.

Of special interest is the distribution of crinoid ossicles. Extremely low values are regularly observed in the upper 30 to 35 m of the Cretaceous strata. These correspond to free-living «planktonic» species. Below say 90 m in Thermae 2000 and Thermae 2001 and below 80 m in Thermae 2002 the ossicles are from benthonic species. The complex maximum between 112 and 125 m in Thermae 2000 and between 95 and 112 m in Thermae 2002 - in both cases followed by a narrow peak some 5 m lower - is also recognized in Kastanjelaan-2 between 68 and 80 m (foram zones F and upper E) and in the ENCI (starting slightly below the Nivelle Horizon to slightly below the Lichtenberg Horizon ; foram zones F and upper E). The low values between 90 and 112 m in Thermae 2000 and Thermae 2001 and between 80 and 95 m in Thermae 2002 match similar low values in the ENCI between the Lichtenberg Horizon and a position slightly below the Schiepersberg Horizon.

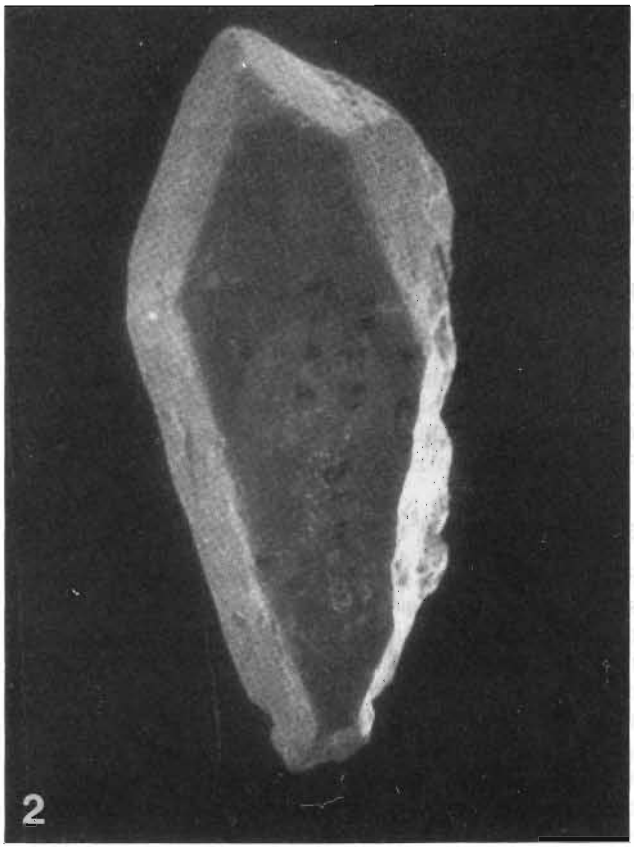
3.3.6. Rest group

Statistically this group is only important in a narrow interval some 20 m below the top of the Upper Cretaceous (figure 9). This maximum has also been observed in Kastanjelaan-2 at about 45 m (halfway foram zone K) and corresponds to the «*Dentalium* layer» slightly above the Laumont Horizon in the ENCI.

3.4. OSTRACODES

Ostracodes have only been found in the sieve fraction 0.125-1.0 mm. These have been subdivided arbitrarily into so-called smooth-shelled and ornamented forms. The philosophy behind this procedure was that ostracodes with an ornamented carapace may have tolerated a relatively higher water energy level than smooth-shelled ones. In order to get a repeatable method a list was made of all genera which «per definition» are considered as smooth-shelled and those which are not. Of course this method has its shortcomings since within a genus a species may be smooth and the others ornamented. Practice has revealed however that this subdivision at the generic level works well. Smooth-shelled genera are notably *Aequacytheridea, Asciocythere, Bairdia, Clithrocytheridea, Cypridina, Cytherella, Globoleberis, Kalyptovalva, Krithe, Macrocypris, «Paracypris», Parataxodonta, Physocythere, Sphaeroleberis, Tumidoleberis, Veenidea, Xestoleberis* and *«Semicytheretta» furcifera*. All other genera, among which notably *Cytherelloidea* and genera belonging to the subfamilies Trachyleberidinae and Bythocytherinae (both sensu Van Morkhoven 1962) are considered as ornamented. The ostracode specimens are picked out and separated into smooth-shelled and ornamented ones. Subsequently the percentage of ornamented ostracode specimens within the total ostracode assemblage is calculated and plotted in a graph as on figure 10.

1



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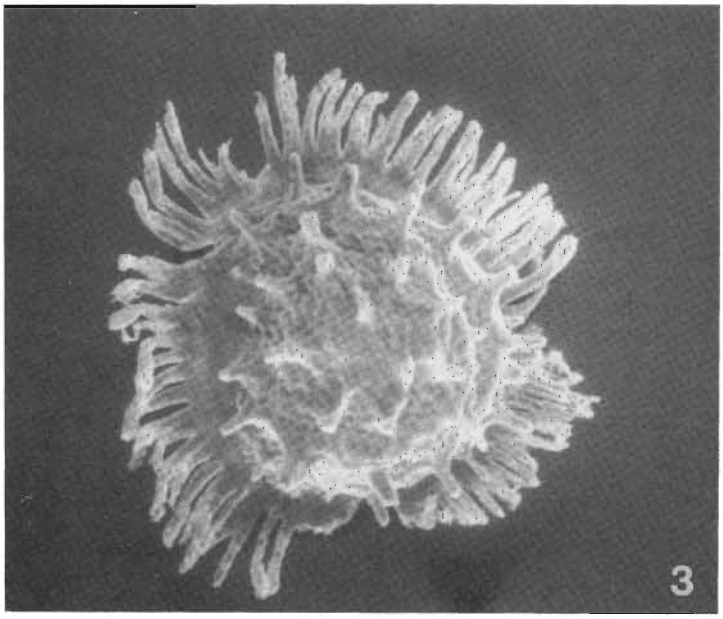

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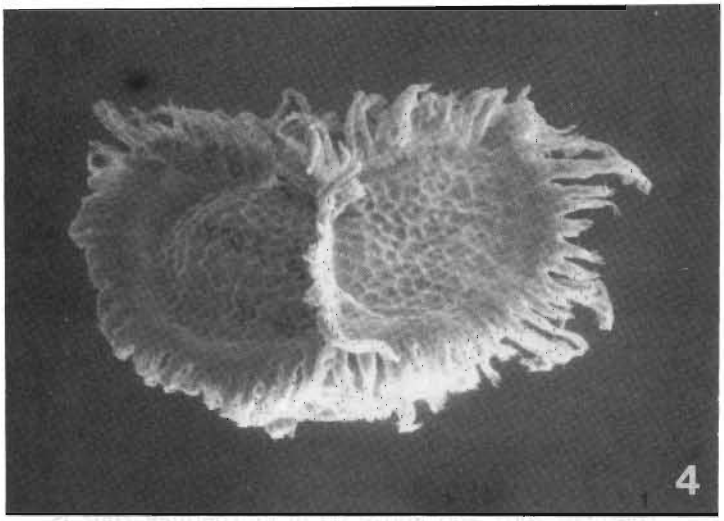

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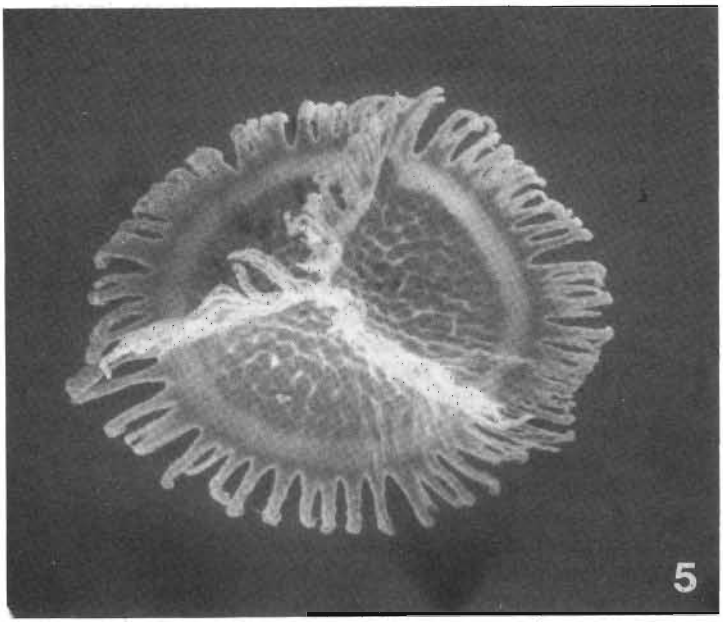

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PLATE 4

Bar = 1.0 mm : figures 1-6
Bar = 0.5 mm : figures 7-9

1 Silicified gastropod
Thermae 2002, 200-202 m, uppermost Visean ?

2-3 Silicified arm plates of ophiuroids
Thermae 2002, 200-202 m, uppermost Visean ?

4-5 Silicified crinoid ossicles
Thermae 2002, 200-202 m, uppermost Visean ?

6 *Shemonaella* sp. (inner mould)
Thermae 2002, 252-254 m, V3bγ

7 *Bairdia* sp. (inner mould)
Thermae 2002, 252-254 m, V3bγ

8-9 *Shishaella* sp. (inner moulds)
Thermae 2002, 252-254 m, V3bγ

Four main intervals may be distinguished in figure 10 which can be correlated between these three wells.

The upper interval above 80 m in Thermae 2000 and Thermae 2001 and above 65 m in Thermae 2002 is characterized by relatively high percentages (more than 20 %) of ornamented ostracodes. Two complex maxima within this interval (values frequently above 50 %) correspond respectively to the medium- to coarse-grained biocalcarenites above the Laumont Horizon of the ENCI, and to a pronounced peak immediately below the Schiepersberg Horizon in the ENCI.

The second interval below 80 m in Thermae 2001, between 80 and 125 m in Thermae 2000 and between 65 and 105 m in Thermae 2002 includes several small peaks. The most obvious one (near 110 m in Thermae 2000 and Thermae 2001, near 90 m in Thermae 2002) has also been observed in the ENCI just above the Lichtenberg Horizon. The same peak can be traced in the outcrop «Bouwput RW76» near Benzenrade (Heerlen). The base of this interval matches with the first income of Mediterranean species in the area. This base occurs in Kastanjelaan-2 at about 80 m (base of foram zone F) and in the ENCI just below the Nivelle Horizon (top of foram zone E). In the Thermae boreholes this base is situated just below the base of foram zone F.

The third interval is characterized by low numbers of ostracodes among which only rarely ornamented specimens. Extremely low numbers of ornamented ostracodes are found in Kastanjelaan-2 between 80 and 153 m (foram zones A to E) and in Halembaye in foram zones A to E.

The fourth interval shows frequently very high numbers of ornamented ostracode specimens among which *«Cythereis», Veenia* and *Pterygocythere* predominate. Similar assemblages and high values occur in Kastanjelaan-2 in foram zone A'-lower to A'-middle (153-198 m) and in Halembaye in the Vaals Formation (foram zone A'-lower).

3.5. SUMMARY OF ECOSTRATIGRAPHIC DATA

Both bioclasts and ostracodes have provided a closely spaced succession of correlation lines between the Thermae boreholes (fig. 11). With few exceptions these lines run parallel. This proves the quality of the driller's sampling of the cuttings and indicates that little or none contamination from higher levels (sloughing) occurred. Remarkable is the observation that the correlation lines just above the contact between the chalk and the glauconitic clay slightly dip northward between Thermae 2000 (160-170 m) and Thermae 2002 (142-153 m), whereas those within

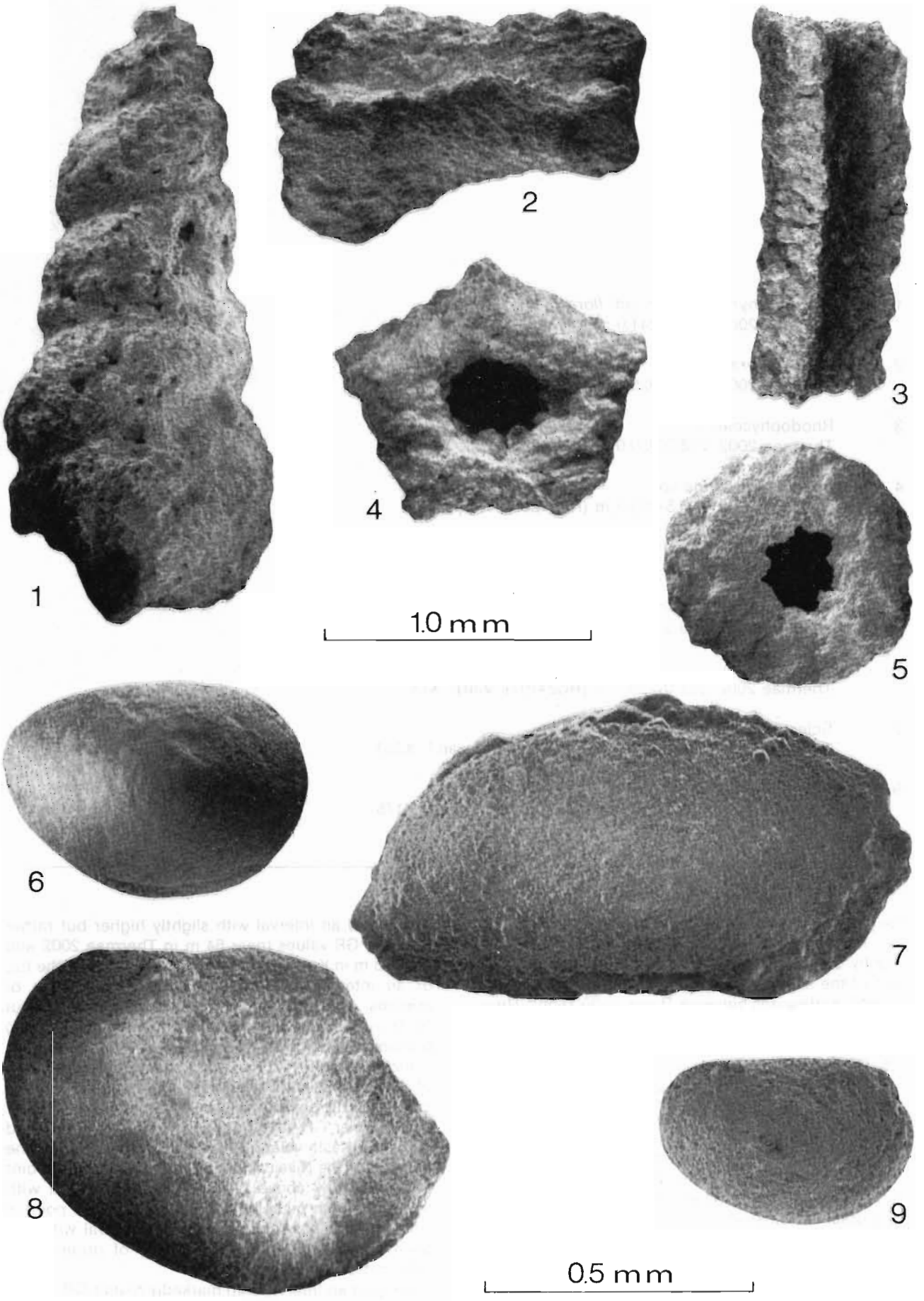
1
2
3
4
5
1.0 mm
6
7
8
9
0.5 mm

PLATE 5

1 *Latiendothyranopsis* sp. aff. *floraviae* CONIL 1982
Thermae 2002, 240.0-241.0 m (RC24195), V3bγ, X75

2 *Eoendothyranopsis* sp.
Thermae 2002, 323.5-325.5 m (RC24198), V3bγ, X75

3 Rhodophycean ?
Thermae 2002, 248.0-250.0 m (RC24202), V3bγ, X50

4 *Koskinobigenerina* sp.
Thermae 2002, 323.5-325.5 m (RC24200), V3bγ, X75

5 *Koskinotextularia* sp. cf. *obliqua* (CONYL & LYS 1964)
Thermae 2002, 257.0-258.0 m (RC24201), V3bγ, X75

6 *Plectogyranopsis convexa* (RAUSER 1948)
Thermae 2002, 323.5-325.5 m (RC24199), V3bγ, X75

7 *Eostaffella* sp.
Thermae 2002, 257.0-258.0 m (RC24197), V3bγ, X75

8 Sclerotioid grain
Thermae 2002, 200.0-202.0 m, uppermost Visean?, X350

9 Sclerotioid grain
Thermae 2000, 223.0-224.0 m, uppermost Visean?, X175

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the glauconitic clay (175-195 m in Thermae 2000 and 155-175 m in Thermae 2002) show a systematic slightly southward dip. This suggests that the upper part of the slightly marly, glauconitic clay somewhat wedges northwards between Thermae 2000 and Thermae 2002.

3.6. GR LOG

Several GR logs of the Upper Cretaceous of Thermae 2002 are available. These have been measured by TNO-Delft. One of these logs has been used in figure 12. The GR log provides supplementary data for correlation with other wells. To that purpose variations in the GR curve have been calibrated by lithostratigraphic, biostratigraphic and ecostratigraphic parameters. Subsequently the GR log has been compared with that of Kastanjelaan-2, also calibrated by the same parameters.

The Laumont peak in the GR curve is matched by a maximum percentage of molluscs (oyster layer) immediately succeeded by a serpulid maximum.

The top of an interval with slightly higher but rather irregular GR values (near 64 m in Thermae 2002 and near 63 m in Kastanjelaan-2) roughly matches the top of an interval with frequently low percentages of crinoids. A small peak within this GR interval (about 90 m in Thermae 2002 and 70 m in Kastanjelaan-2) presumably indicates the position of the Lichtenberg Horizon of the ENCI. This point coincides with the top of an interval with frequently high percentages of crinoids. The base of this interval of slightly higher but irregular GR values (103 m in Thermae 2002 and 80 m in Kastanjelaan-2) presumably indicates the position of the Nivelle Horizon in the ENCI. This point occurs slightly above the base of the interval with frequently high percentages of crinoids. This point is also slightly above the base of the interval with frequently high percentages (> 20 %) of ornamented ostracodes.

The top of an interval with markedly higher GR values at 141 m in Thermae 2002 and at 118 m in Kastanjelaan-2 roughly matches the top of a pronounced maximum in the molluscs. Biostratigraphically this

1

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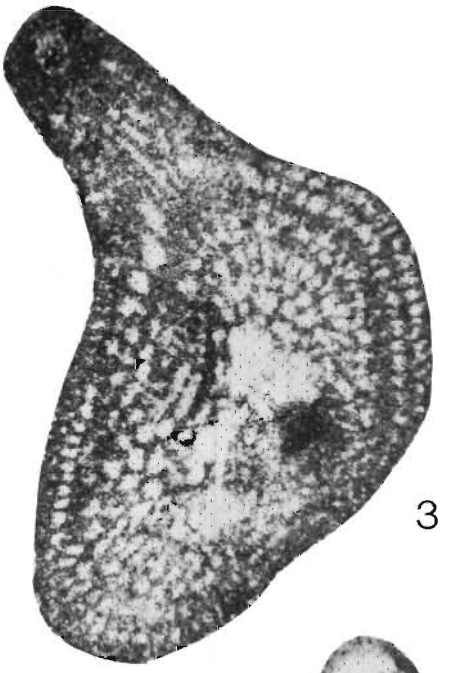

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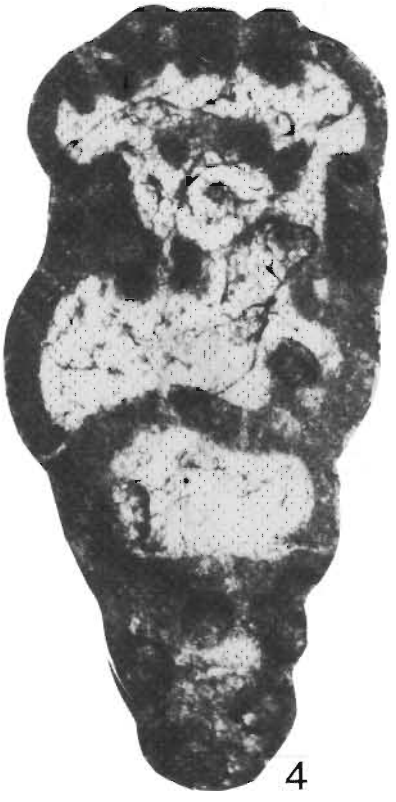

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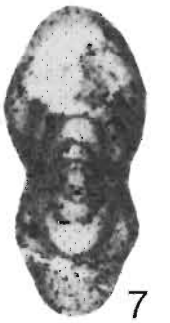

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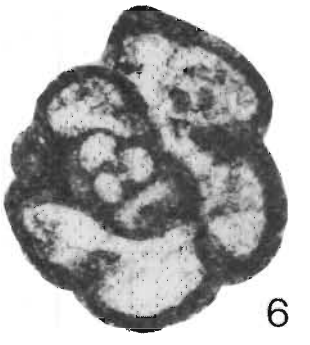

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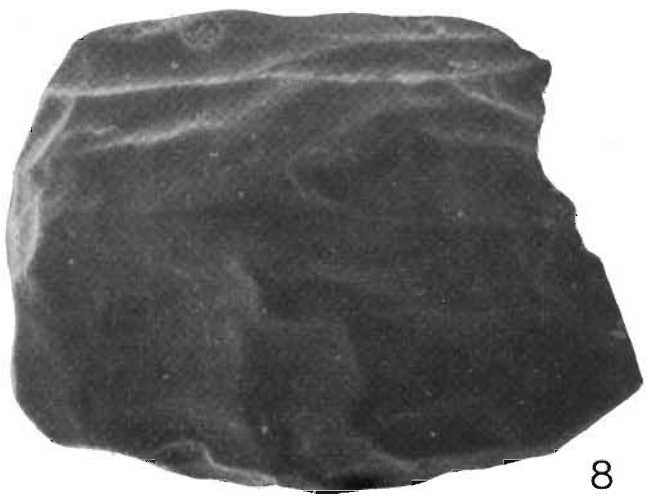

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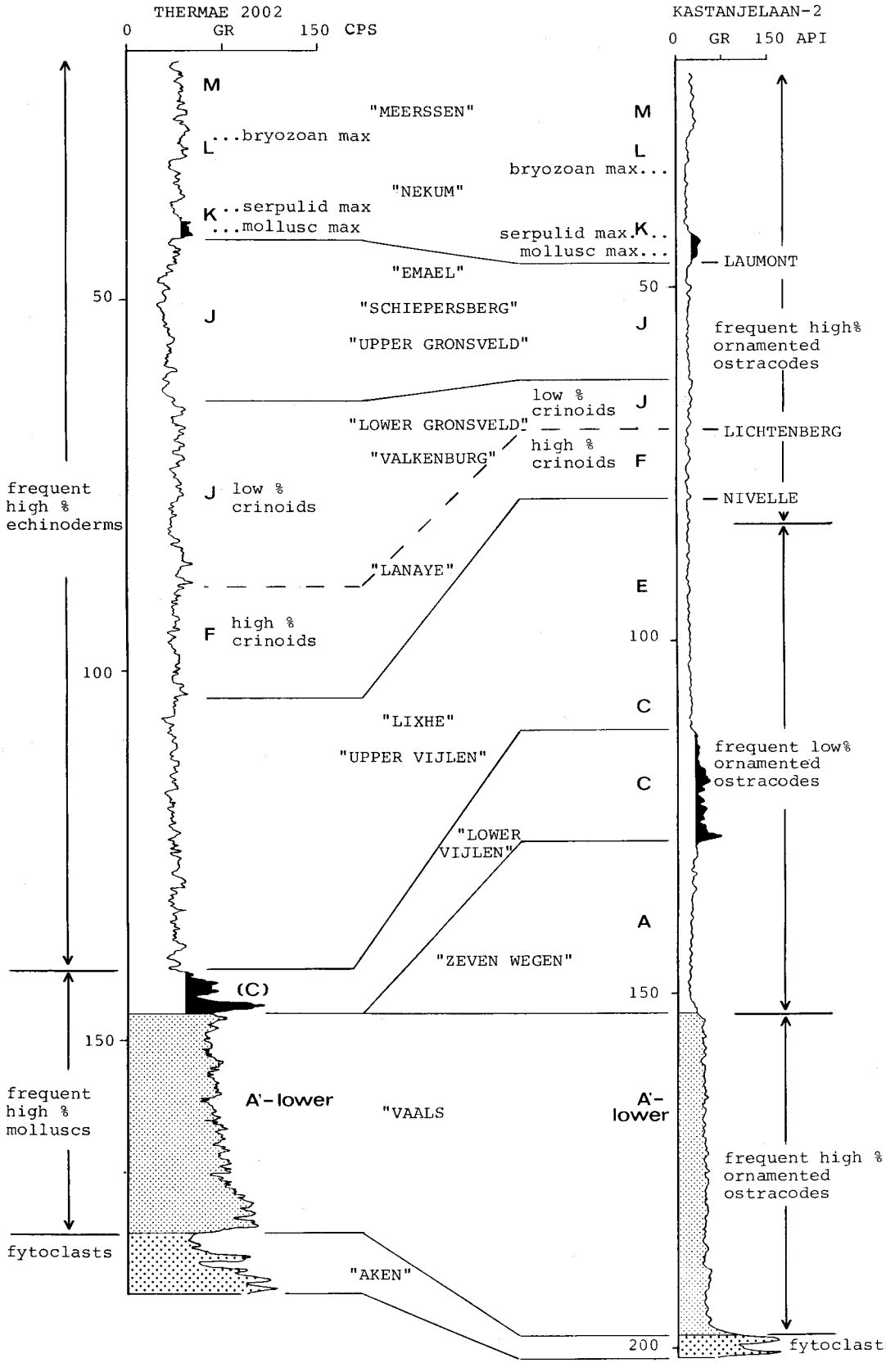

Figure 12 - Correlation of Upper Cretaceous strata in Thermae 2002 with those in Kastanjelaan-2 by means of GR log, foraminifer assemblages, fytoclasts, bioclast (1.0-2.4 mm) assemblages and ostracode (0.125-1.0 mm) assemblages, as well as lithological properties of sediments.

interval is attributed to the lower part of foram zone C. Lithostratigraphically this interval is compared with the slightly more glauconitic lower half of the Vijlen Chalk. The base of this interval is marked by a pronounced GR peak.

Relatively low GR values mark the equivalent of the Zeven Wegen Chalk of Halembaye in Kastanjelaan-2. This interval, characterized by foram zone A, is missing in the Thermae boreholes.

The glauconitic clays of the foram zone A'-lower are marked in both boreholes by relatively high GR values. The top of this interval is marked by the top of frequently high to very high percentages (up to 80 %) of ornamented ostracodes.

Very high GR values mark the kaolinic mud-sand with fytoclasts in both boreholes.

Noteworthy is the fact that the total thickness of the Upper Cretaceous is roughly comparable in both boreholes although important variations in the thickness of individual intervals may occur. The absence of the Zeven Wegen Chalk and the reduced thickness of the Lower Vijlen Chalk in Thermae 2002 is compensated by an increased thickness of foram zone J. This phenomenon is frequently noticed in the Upper Cretaceous of South-Limburg and northeastern Belgium.

4. DINANTIAN

The Dinantian rocks consist in descending order of a kaolinic paleosol with authigenic quartz crystals and silicified foraminifera, black partly silicified shales, completely silicified limestones, and partly silicified limestones. Karst horizons filled with downward decreasing amounts of sulfide minerals, and karst horizons yielding downward increasing amounts of mineral water have been recognized at various depths.

The subdivision of the Dinantian rocks is based on biostratigraphic arguments (foraminifera and sclerotioid grains), lithostratigraphic comparison with Houthem, bioclasts and ostracodes (ecostratigraphic comparison with Houthem) and petrophysical borehole logs (notably GR log). These different parameters are briefly discussed below.

4.1. BIOSTRATIGRAPHY

Two parameters are considered here : foraminifera and sclerotioid grains. These have been used as well for datation of the Dinantian in the nearby Houthem (DB 105) borehole (Bless et al. 1976).

4.1.1. Foraminifera

Foraminifera mainly occur in the bioclastic grainstones which predominate between 251 and 310 m in Thermae 2000 and between 236 and 300 m in Thermae 2002. Specific identification is usually difficult since these limestones are often partly or entirely silicified. Silicified foraminifera (including large, thick-walled Archaediscidae) are also found in the lateritic paleosol (201.8-218.5 m in Thermae 2000, 184.5-195.3 m in Thermae 2002). But these are usually poorly preserved. With few exceptions foraminifera are rare in the bituminous wackestones/packstones which predominate below 310 m in Thermae 2000 and below 300 m in Thermae 2002.

For the biostratigraphic interpretation seven samples from Thermae 2002 have been selected (table II). The overall asemblages are characteristic for the Livian to Warnantian (V2b-V3c). However some genera suggest that the age of the same is Warnantian. The bilaminar Palaeotextularidae appear in the Cf6α (V3bα), whereas *Koskinobigenerina* and *Cribrostomum* only start in the Cf6γ (V3bγ ; M. Laloux, pers. comm.). In contrast to the Houthem borehole, the Archaediscidae do not permit a more detailed biostratigraphic interpretation.

The paleosol between 184.5 and 195.3 m has yielded very large Palaeotextularidae, *Endothyranopsis* ex gr. *crassa, Tetrataxis* and *Archaediscus (Neoarchaediscus)*.The same assemblage occurs in Thermae 2000 between 202 and 218 m (Bless et al. 1986). This may indicate very high V3b or V3c, although a basal Namurian age cannot be excluded (M. Laloux, pers. comm.).

Remarkable is the occurrence of Moliniacian-type foraminifera in several samples. Specimens of *Latiendothyranopsis* and *Eoendothyranopsis* may have been reworked from Moliniacian (V1a-V2a) rocks. Also in Houthem several samples in the V3b yielded reworked Moliniacian foraminifera (Bless et al. 1976).

The lower interval only yielded few foraminifera with the exception of sample 323.5-325.5 m. This sample also contains a Cf6γ (V3bγ) assemblage. It should be noticed that also the lower portion of the dark limestones in the Houthem borehole only yielded a very poor foraminifer assemblage.

4.1.2. Sclerotioid grains

A detailed discussion on the possible nature of sclerotioid grains was presented by M. Wolf in Bless et al. (1976). In the Thermae boreholes these have been observed between 218 and 321 m in Thermae 2000 and between 195.3 and 313 m in Thermae 2002. In Houthem these occur between 206.5 and 307.0 m, which has been dated by foraminifera as Cf6γ (V3bγ). As explained in Bless et al. (1976) these grains appear in the late Visean (V3b) of Czechoslovakia, Federal Republic of Germany and in the Houthem borehole. These occur in shales, limestones and coal. In the Netherlands and in northeastern Belgium these have not been found in older strata although numerous samples have been explicitely examined to that purpose.

The richest sclerotioid assemblages yielding the largest grains have been found in the black shales of Thermae 2000 and Thermae 2002, and in Houthem in the 206-267 m interval of argillaceous limestones with shale intercalations. These do not occur in the Middle Visean black shales of Heugem and Kastanjelaan (Bless en al. 1981), although the shales of these

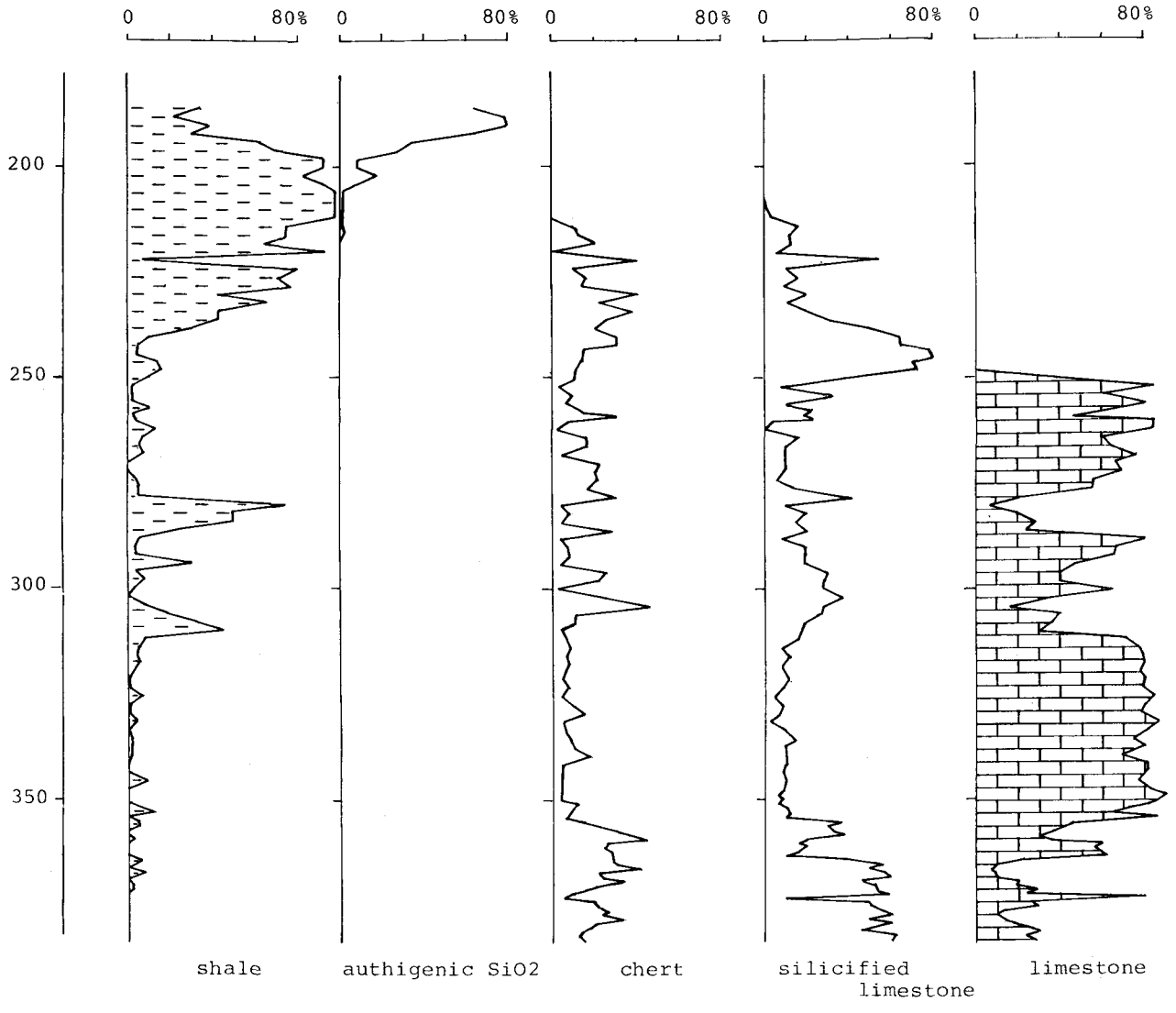

Figure 13 - Quantitative lithological composition of cutting samples (sieve fraction 1.0-2.4 mm) in the Dinantian sequence of Thermae 2002. Compare results with those of figure 14 !

boreholes also contain high amounts of organic matter (up to 6 % against up to 3 % in Thermae 2000 and Thermae 2002).

Since the 206-267 m interval of Houthem yields comparably rich sclerotioid grain assemblages as the black shales in Thermae 2000 and 2002, and since the lithologies may be roughly comparable as well, it is suggested here that the black shales of Thermae 2000 and 2002 have been deposited during the same time as the 206-267 m interval of Houthem dated by foraminifera as V3bγ. The same is accepted for the sediments of the paleosol in the Thermae boreholes since these yielded the same foraminifer assemblages as the silicified upper part of the grainstones.

Eventually it should be noticed that the relatively large sclerotioid grains (0.2-0.5 mm) preferably occur in the uppermost Visean. Distinctly smaller grains have been described from Upper Carboniferous strata.

4.2. LITHOSTRATIGRAPHY

The lithological interpretation of the Dinantian sequence is based on a quantitative analysis of lithoclasts. From each sample from Thermae 2000 and Thermae 2002 some 150 rock chips were counted from the sieve fraction 1.0-2.4 mm. The information was complemented with data from the fraction $>$ 2.4 mm and the fraction 0.125-1.0 mm. As a test also an analysis was made from a slightly different sieve fraction (0.5-2.0 mm). The results are comparable as shown by the example of Thermae 2002 (fig. 13-14).

4.2.1. Kaolinic paleosol

This interval is slightly thicker in Thermae 2000 (201.8-218.5 m) than in Thermae 2002 (184.5-195.3 m). The material consists of kaolinite and microcrystalline

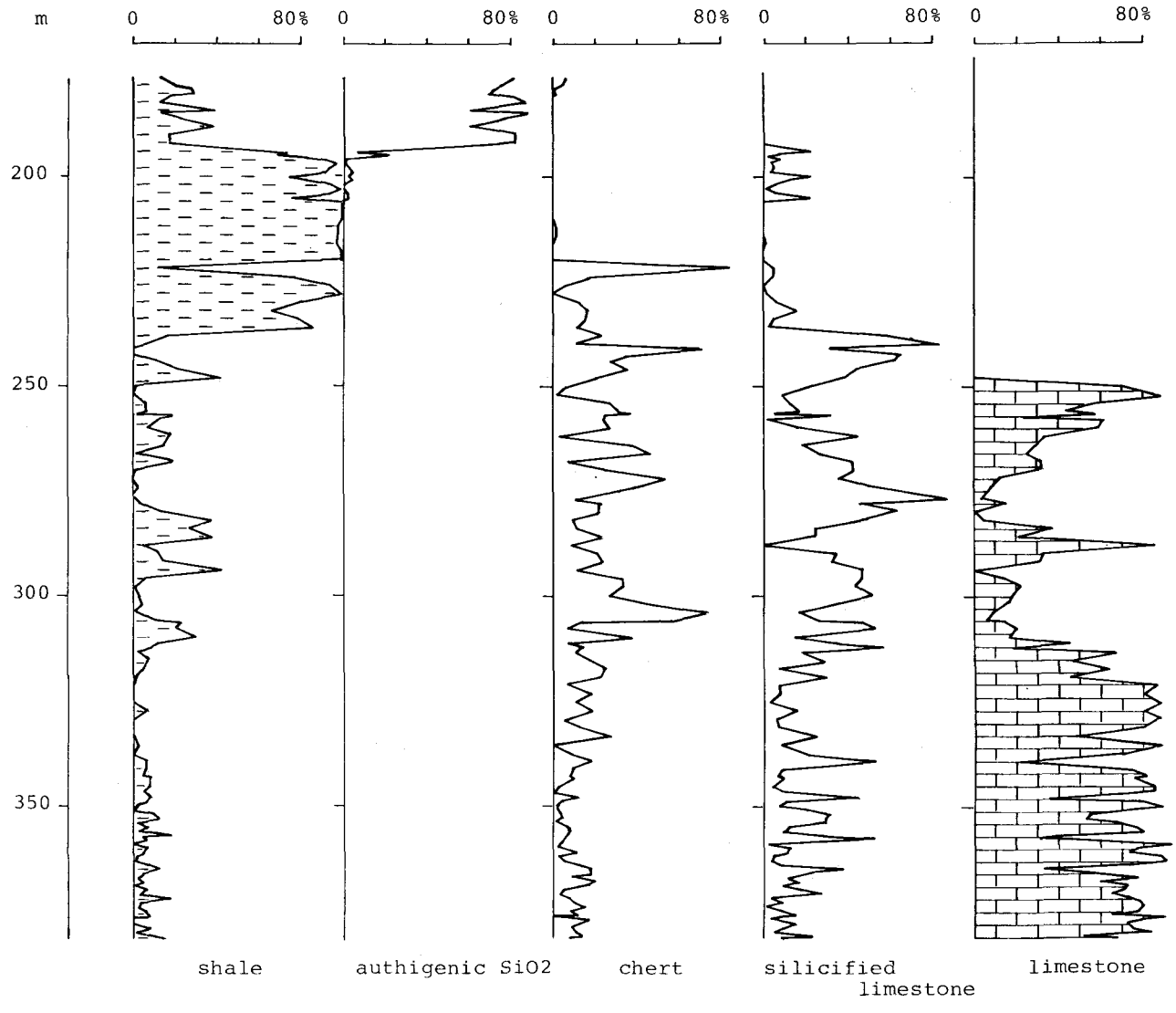

Figure 14 - Quantitative lithological composition of cutting samples (sieve fraction 0.5-2.0 mm) in the Dinantian sequence of Thermae 2002. Compare results with those in figure 13 !

quartz (more than 75 weight-%), authigenic quartz crystals and some silicified fossils (mainly foraminifera ; some sponge spicules, bryozoans, echinoderms and small gastropods). The colour of the clay varies from whitish-grey at the top to dark-grey in the lower portion. Near the contact between the whitish-grey and dark-grey colours the clay was brownish-red and contained small pyrite concretions. The brownish-red colour disappeared a few hours after it came in contact with the air. A similar paleosol has also been described from Heugem-1 (Bless et al. 1981).

Frequently the authigenic quartz crystals display a pronounced zonation and contain a nucleus of presumably carbonate material. In several samples also authigenic crystals of smoky quartz have been observed.

4.2.2. Black shales

This interval occurs between 218.5 and 251 m in Thermae 2000 and between 195.3 and 236 m in Thermae 2002. It consists of black, sometimes silicified shales with apparently high contents of organic carbon. These are intercalated by some thin silicified, fossiliferous limestones and black cherts.

4.2.3. Silicified limestones

Almost completely silicified limestones occur below the shale interval. These contain some chert and thin shale intercalations. The interval is situated between 251 and 268 m in Thermae 2000 and between 236 and 248 m in Thermae 2002. The limestones are bioclastic grainstones with a rich and diverse fossil assemblage (foraminifera, algae, ostracodes, brachiopods and echinoderms).

4.2.4. Bioclastic grainstones

Very fossiliferous bioclastic grainstones, partly silicified and with intercalations of chert and black shale occur between 268 and 310 m in Thermae 2000 and between 248 and 300 m in Thermae 2002. Lithologi-

cally the interval of very fossiliferous limestones (in the Thermae boreholes completely silicified at their top and partly silicified downwards) may be compared with the very fossiliferous limestones between 261 and 310 m in Houthem (fig. 16).

4.2.5. Bituminous wackestones/packstones

Black, bituminous wackestones/packstones which may be partly silicified and with frequent intercalations of chert and black shale predominate below 310 m in Thermae 2000 and below 300 m in Thermae 2002. Grainstones only occur in lenses. Sponge spicules and radiolarians may be common. Other fossils are usually rare. Lithologically this poorly fossiliferous interval bears some resemblance with the black limestones below 310 m in Houthem (fig. 16).

4.3. ECOSTRATIGRAPHY

Several, mostly silicified, fossil assemblages have been recognized in the Dinantian sequence. These allow ecostratigraphic correlation between the two Thermae boreholes and an overall comparison with Houthem. The top of the kaolinic paleosol in Thermae 2000 and Thermae 2002 yielded a rich foraminifer assemblage also including some sponge spicules. Between 213 and 218 m in Thermae 2000 (within the paleosol) and between 192 and 204 m in Thermae 2002 (within the shales) a rather diverse assemblage of bryozoans, small gastropods, crinoid ossicles and ophiuroid plates occurs.

Between 267 and 304 m in Thermae 2000 and between 248 and 304 m in Thermae 2002 the fossil assemblages include large foraminifera (mainly Endothyridae, Palaeotextulariidae and *Tetrataxis*), brachiopod fragments, ostracodes (Bairdiidae, Paraparchitacea) and echinoderms (crinoids, ophiuroids and echinoids). Remarkable is the frequent occurrence of coated crinoid ossicles which suggest very shallow depositional environment. The relative abundance of foraminifera in this rather diverse fossil assemblage suggests a correlation of this interval with that between 265 and 310 m in Houthem where also very rich and diverse fossil assemblages have been observed.

Table II - Dinantian foraminifera from seven spot samples of Thermae 2002. The genera Endothyra, Earlandia, Pachysphaerina and Diplosphaerina which occur in practically all samples have not been mentioned separately.

DEPTH in m / FORAMINIFERA	240 – 241	241 – 242.5	248 – 250	257 – 258	286 – 288	323 – 325	333.5 – 335.5
Caulerpales			x				
Koninckopora (double wall)			x	x		x	
Rhodophycean?			x			x	
Pseudoammodiscus	cf.						
Brunsia			x	x		x	
Pseudolituotuba gravata (Conil & Lys 1965)			x			x	
Palaeotextulariidae	x	cf.	cf.	x		x	
monolaminar Palaeotextulariidae				x		x	
bilaminar Palaeotextulariidae			cf.	x		cf.	
Cribrostomum			cf.			cf.	
Koskinotextularia				x			
Koskinobigenerina						x	
Archaediscus	x	x		x		x	x
Lituotubellinae			x				
Forschiella						x	
Tetrataxis			x	x		x	cf.
Valvulinella						cf.	
Latiendothyranopsis	x					x	
Eoendothyranopsis				cf.			
Plectogyranopsis convexa (Rauser 1948)						x	
Omphalotis minima Rauser & Reitlinger 1936						x	
Endothyranopsis						cf.	
Endospiroplectammina syzranica (Lipina 1948)	cf.						
Pojarkovella nibelis (Durkina 1959)				cf.			
Eostaffella	cf.			x		x	
Fasciella						cf.	
Luteotubulus						cf.	
Kamaenidae	x		x			x	
Issinellidae	x		x		x	x	

4.4. PETROPHYSICAL BOREHOLE LOG

Several GR logs have been prepared by TNO-Delft. The example of Thermae 2002 shows that the kaolinic paleosol is marked by relatively low GR values (fig. 16). The top of the black shales is marked by extremely high (up to 250 CPS) GR values which gradually decrease downwards. The carbonates show very low GR values which are interrupted by narrow peaks possibly corresponding to more clayey intervals. At least two of these peaks (302-303 m and

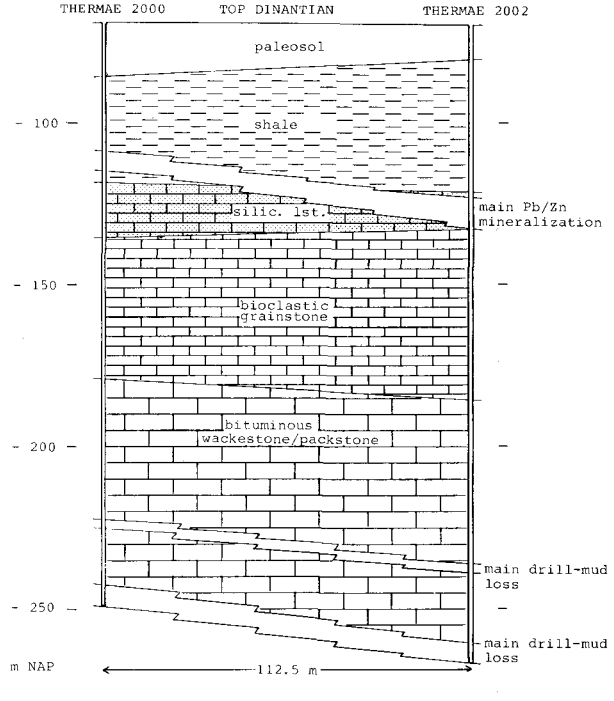

Figure 15 - Schematic section of Dinantian sequence through Thermae 2000 and Thermae 2002. Predominant lithologies determined from quantitative lithological composition of cutting samples.

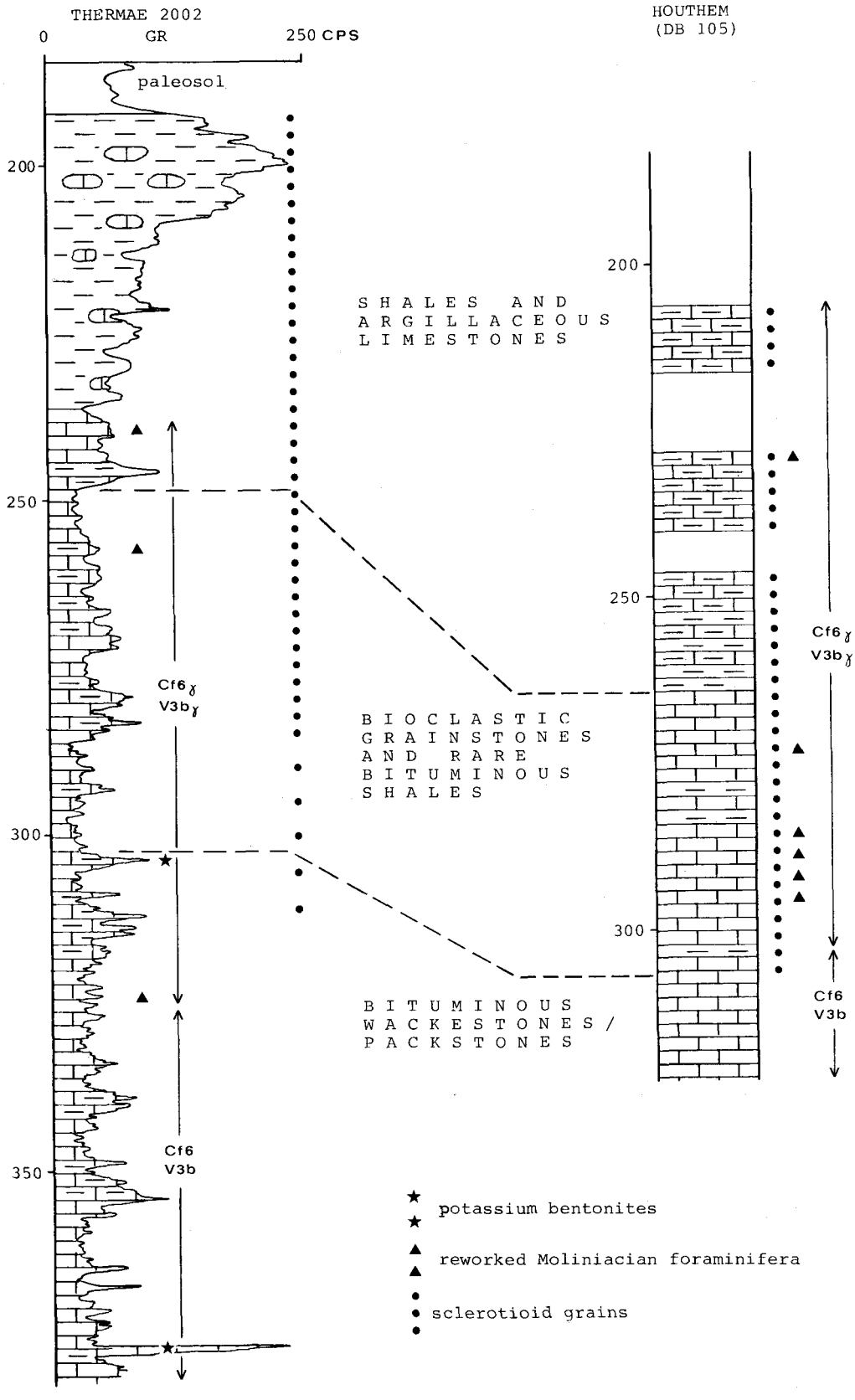

Figure 16 - Tentative correlation of Dinantian sequence of Thermae 2002 with that of Houthem (DB 105).

375-376 m) turned out to represent potassium-bentonites of volcanic origin (Thorez 1987). It seems likely that several more peaks mark volcanic potassium bentonites. In the V3b of Belgium also several bentonites have been recognized (cf. Paproth et al. 1983).

4.5. SUMMARY OF RESULTS

The rocks below the kaolinic paleosol in Thermae 2000 and Thermae 2002 present a rather similar succession of lithologies and fossil assemblages indicating a slight northward dip of the sediments between Thermae 2000 and Thermae 2002. This is remarkable since the top of the paleosol is subhorizontal between these boreholes and its base slightly dips to the south.

Biostratigraphically the carbonates are of V3b(γ) age because of the foraminifera. The black shales below the paleosol may be of V3b-c age because these contain the same rich assemblages of relatively large sclerotioid grains as the 206-267 m interval in Houthem. As long as no better date are available we refer to the black shales interval as «uppermost Visean?», since revision of several sections in Belgium has revealed that some strata including shale intercalations on top of the Dinantian may be of E2 rather than V3b-c age.

A broad-brush correlation between Houthem and Thermae suggests a very slight dip for the top of the Dinantian and the Dinantian strata towards the northwest. This would fit in the regional geological pattern.

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