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CENTENARY
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FIELD GUIDE TO THE RUPELIAN STRATOTYPE

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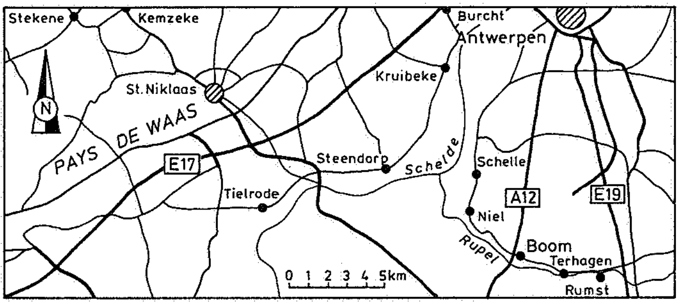

Localization of the outcrops visited.

1. ON THE TERM "RUPELIEN"

The term Rupelien was first introduced in 1849 by M.A. Dumont.
The Rupelian has, ever since its introduction as a stratigraphic unit by Dumont, been subdivided into a lower and an upper part : *"Le système Rupelien a, dans quelques localités, pour base un lit peu épais d'argile sableuse renfermant des nucules ; mais le plus souvent il commence par des sables jaunâtres plus ou moins argileux. La partie supérieure est formée de sables très argileux et d'argiles schistoides auxquelles je rapporte les argiles fossilifères de Rupelmonde, de Boom, de Hasselt, etc..."* (M.A. Dumont, 1849, p. 370).

Particular sections to be used as references were not formally selected. Nevertheless, what is meant by Rupelian, is obvious from the early litterature.

Regarding the upper part of the Rupelian, it is without doubt that the exposure of the clay in the many clay pits of the brick works along the Rupel and Schelde rivers (Boom, Rupelmonde, ...) is meant to be the reference of the Upper Rupelian. Several descriptions of the Boom clay (Upper Rupelian) where given by i.a. E. van den Broeck (1887, 1893), M. Gulinck (1954, D.A.J. Batjes (1958) ; recently a sedimentological study of the Boom Clay was made by N. Vandenberghe (1975, 1978).
A sandy member on top of the Boom Clay was identified by Van den Broeck and classified also in the Upper Rupelian (Van den Broeck, 1884, 1893).
The outcrop zones and the location of the different units of the Rupel group are represented on fig. 1.

2. LITHOSTRATRIGRAPHY OF THE BOOM CLAY

a) *Lithological nature of the clay*

The Boom Clay is composed of clayey silts and silty clays in the terminology of Shepard (1954) (fig. 2a). The water content varies between 25 and 32 %. The clay is stiff, fissured and preconsolidated. The overburden removed was estimated by different methods in the Antwerp area to be about 90 m (J. Schittekat *et al.*, 1983 ; N. Vandenberghe & P. Laga, 1986). Reflectivity measurements, carried out on resinites and rafted wood fragments in the clay show the diagenetic rank of the Boom clay to be still lignitic (fig. 3).
The clay mineralogy is dominated by illite and contains also smectite and illite-smectite random interlayers, kaolinite and some minor chlorite or degraded chlorite. Feldspar can make up 25 % of the sand sized grains.
Authigenic glauconite occurs, especially in the most silty beds. Pyrite, and occasionally marcasite, occurs in different forms ; there are nodular and tubular sulphide concretions of different sizes ranging from a few mm to more than 10 cm and some layered sulphides as well. The shape of the sulphides often suggests a close relationship with organic forms, such as the internal filling of molluscs, and the sulphidation of plant remains and burrow tracks. The remobilisation of the carbonates resulted in the formation of carbonate concretions which evolved into septaria.

b) *The rhythmic nature of the clay*

The Boom Clay consists of a detrital

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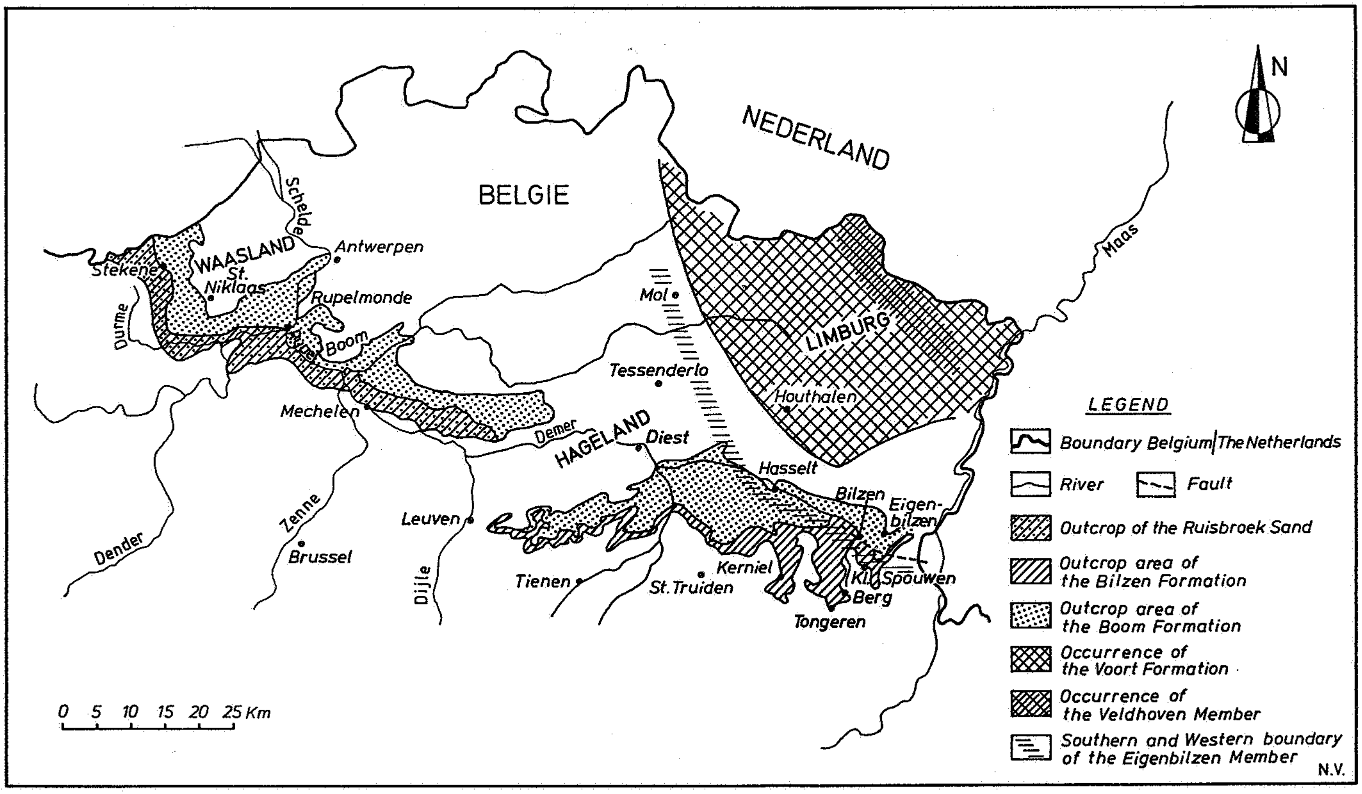


Figure 1. Occurrence of outcrop zones of Rupel group units.

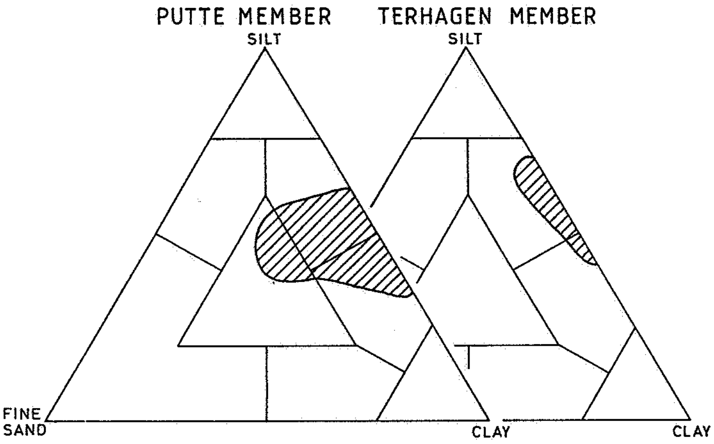


Figure 2a. Sand-silt-clay diagrams of the Boom Clay at Terhagen.

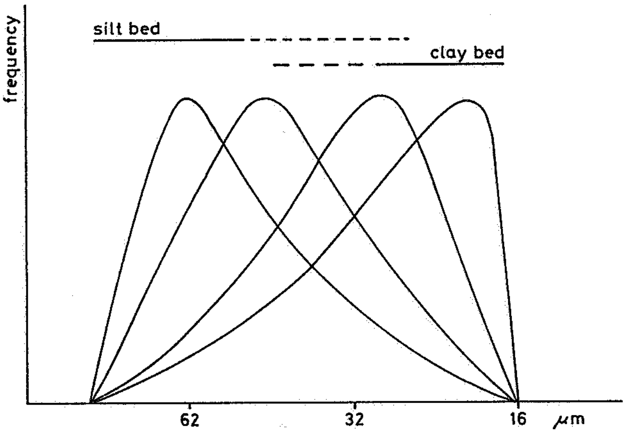


Figure 2b. Frequency distribution types in the coarser subpopulation.

silty clay or clayey silt with rather constant chemical and mineralogical properties throughout the whole deposit.
The variable characteristics are grain-size, carbonate and organic matter content ; they vary rhythmically through the approximately 70 m of clay studied.
The grain-size rhythmicity is the most striking feature of the clay in the field ; about every 40 cm a clay-rich bed changes into a silty bed. The grain-size properties vary gradually through the beds and into adjacent beds no grading occurs.
The middle of the silty layers contains most coarse silt and fine sand and the middle of the clayey layers has the highest clay content.
The grain-size variations are believed to be the result of intensity changes of the bottom turbulence.
Besides the grain-size rhythmicity alternation of black bituminous beds occurs in the Boom Clay. The organic matter content consists for the largest part of land derived detrital plant remains (phytoclasts). In contrast to the grain-size rhythmicity, the organic matter distribution is graded with a maximum content immediately at the bottom of a black bed. All bituminous beds occur just above a silty bed. All but two bituminous beds occur grouped together in the upper part of the clay studied and hence a lower grey clay and an upper black clay can be distinguished.
Several horizons of original marly sedimentation occur. These horizons, a few tens of cm thick, are now mostly represented as septaria layers, a result of diagenetic phenomena. The position of these originally marly beds is not related whatever neither to the grain-size rhythmicity nor the position of the black organic matter rich beds.

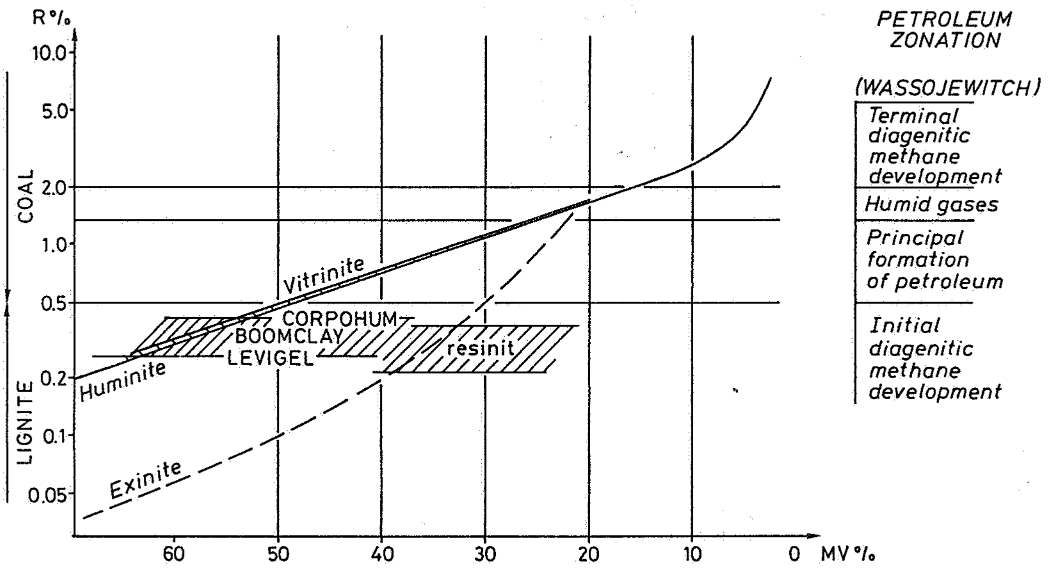


Figure 3. Diagenetic zonation (partly after Alpern) and the position of the Boom Clay.

c) *The microstratigraphical value of the rhythmicity*

A striking feature of the rhythms when comparing clay pits is the similarity of the rhythm sequence. Indeed all pits can be correlated layer by layer (fig. 4) and therefore a unique clay sequence can be established at least for the whole type area (fig. 5, 6).
In practice one is looking for one or more of the typical key horizons and starting from a key horizon then further works out the rhythm sequence one by one.
At the end one can verify that the number of layers and their type and thickness exactly corresponds to the type sequence given in fig. 5 and 6.

Key horizons are :

- a pinkish to reddish brown layer in the lower part of the clay mostly visible with a very thin white lining at the base ;
- the limit between an upper clay with regular repetition of black organic rich horizons and a lower clay without such repetition is visible as a sharp boundary between upper dark grey and lower pale grey clay ;
- the occurrence in the lower part of the dark clay of two relatively coarse layers (39, 41) separated by a thin clay layer can be recognised as their water content at the clay face of a pit generally contrasts with the finer clay above and below.

In addition septaria horizons can help to establish the microstratigraphic position of a clay section in the general Boom Clay sequence (fig. 6). Each horizon has its specific characteristics such as size, shape, frequence and vein filling minerals of the septaria in the horizon, the geometric position of the horizon itself versus a clay or a silt layer, and in some cases the relationship of the position of the rest-carbonate distribution in the surrounding clay versus the position of the septaria (e.g. in septaria thickness and positioned at a level corresponding to the middle of the septaria).

For correlation purposes S50 and S60 are of special value. S50 occurs in a thin silt layer and has septaria with typically very flat almost plate like septaria which have the well known iridescent octahedral pyrite crystal coating in the septae. S60 contains typically many large brownish septaria made up of siderite and with a network of bioturbations made visible around the loaf shaped septaria. Because of its siderite composition this horizon is particularly usefull for correlation in well sections (fig. 7). The different septaria horizons outcropping in the type area are briefly described below.

- S80 small septaria, numerous, calcareous layer
- S70 small septaria, few, calcareous layer
- S61 small septaria, few, calcareous layer
- S60 brown to reddish large septaria, numerous, siderite containing, massive with thin septae sometimes covered with irridescent pyrite, with typical bioturbations especially visible around the septaria
- S50 flat, platy, large septaria, numerous, septae typically covered by irridescent pyrite
- S41 flat, small septaria, few, calcareous layer
- S40 large septaria, numerous, ferroan calcite filling of septae, sometimes covered by iridescent pyrite, contain water in the septae
- S30 small septaria, few, ferroan calcite filling of septae
- S20 very large septaria (up to 1 m diameter), numerous, connected by a thin (cms) calcareous layer, ferroan calcite filling of septae
- S10 large septaria, few, in the Waasland area only a white layer, ferroan calcite filling of the septae.

Above the outcropping part of the clay, about 17 m of clay was further studied in boreholes in which 8 additional septaria levels were identified.

d) *Formal lithostratigraphy*

It is proposed to give the Boom Clay unit the formation status and subdivide it into three members : the Belsele-Waas

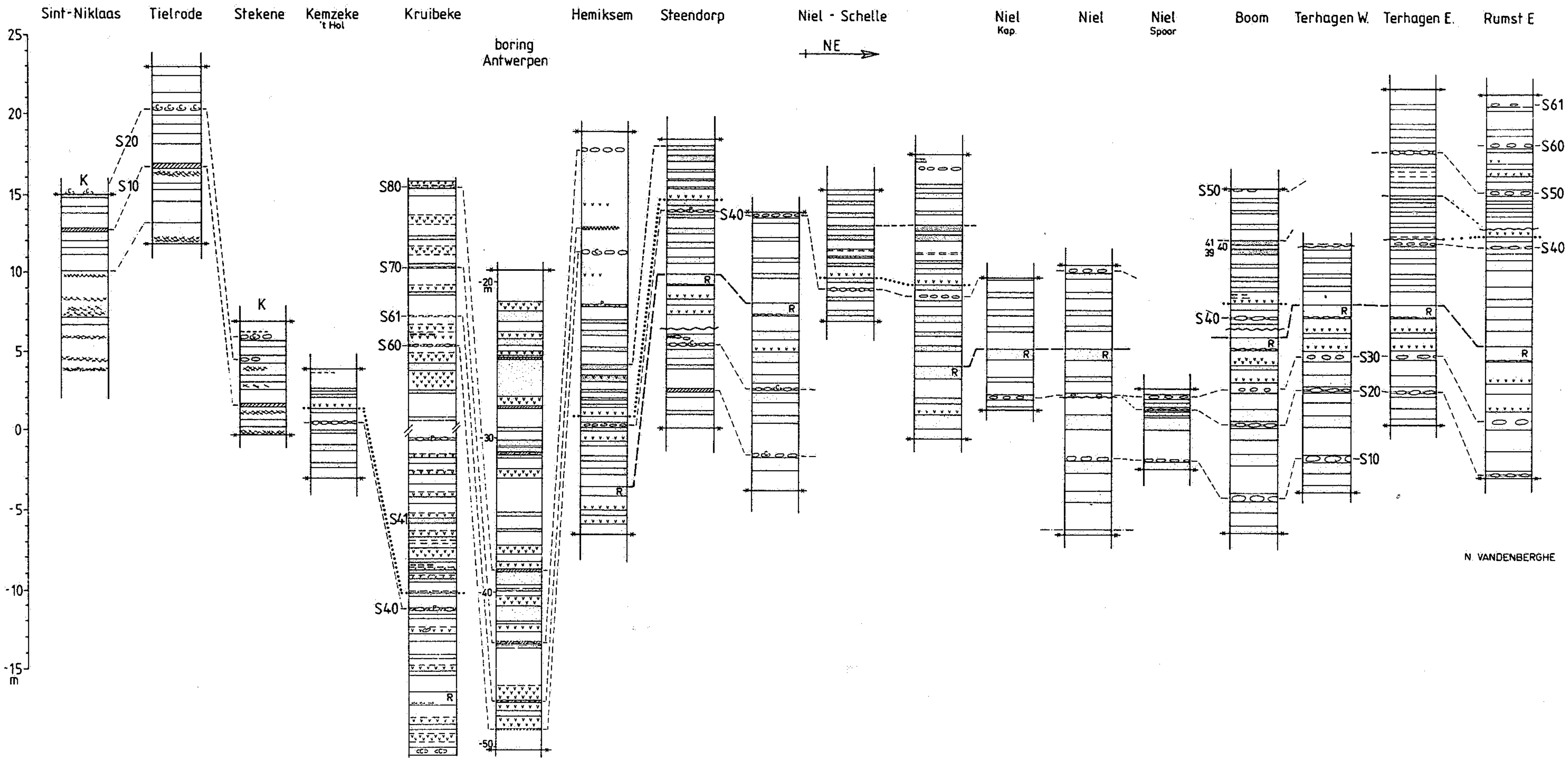


Figure 4. The lithostratigraphic correlation of the different profiles in the Land van Waas Antwerp and the Boom area.

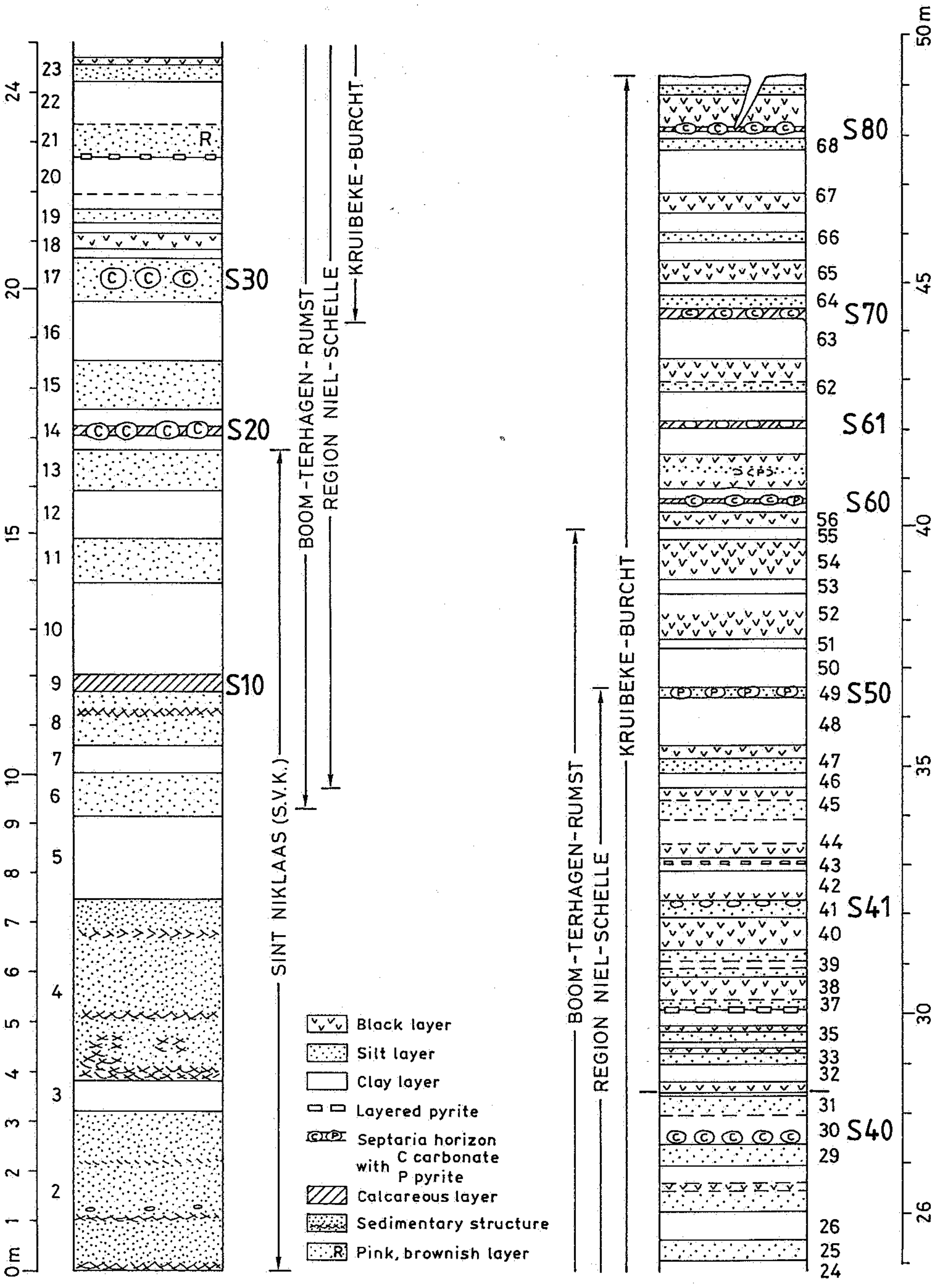
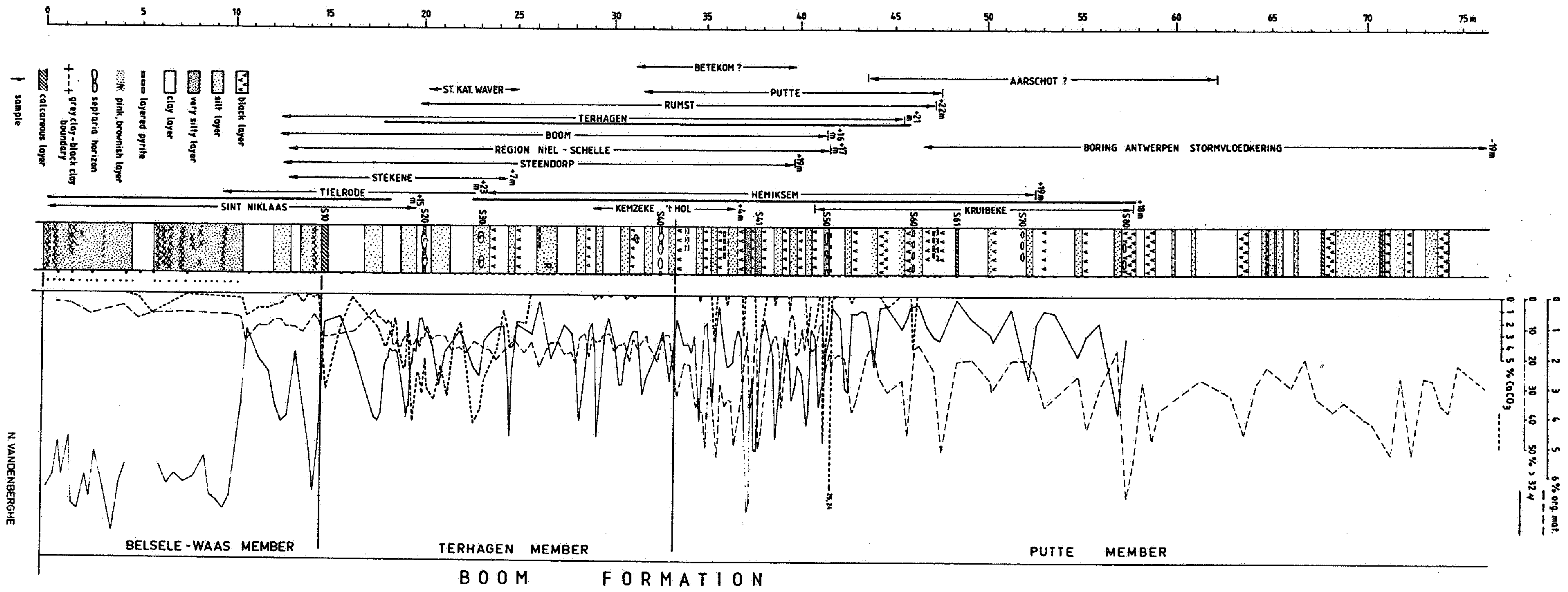


Figure 5. Boom Clay profile based on the outcrops in the clay pits

member at the base, the Terhagen member and the Putte member, the latter corresponding to the dark grey clays (fig. 6).

3. SEDIMENTOLOGICAL MODEL

a) The marine nature of the clay is demonstrated by the fossil content, mineralogy and chemistry and has never been questioned.
Several marine environments were proposed however. Based on a sedimentological study (N. Vandenberghe, 1974, 1975a, 1978) it was concluded that the Boom Clay was deposited in an open marine environment, some 50 m or slightly deeper, with muddy bottom sediments containing enough oxygen to permit the presence of a benthonic micro- and macrofaune. Based on grain-size analysis alone, and including CM - Passega diagrams, S. Geets and P. Jacobs (1975) consider the Boom Clay as a wadden-deposit : Passega himself however interpreted a CM-diagram of the Boom Clay, published by N. Vandenberghe (1975b), as a deposit comparable to recent Adriatic sediments deposited at a depth of 25-30 m (R. Passega, 1977).
A coastal mud flat depositional environment was also favoured earlier by J. de Heinzelin and M. Glibert (1956, p. 36, 168) in a short comment on the faunal composition of the Boom Clay. These authors also point out that the ecological interpretation of the Pleurotomariacea by M. Gulinck (1954) as a bathyal fauna is erroneous.
Based on a study of the mollusca G.J. Boekschoten (1963, 1966) derives a depositional depth of 150 to 200 m for the Boom Clay in the Waasland area ; however the lower limit of the euphotic zone - a key factor in his interpretation - is said by Boekschoten to be 150 m ; this is too deep as a reasonable percent of the sunlight pentrates natural seawater only for at maximum some tens of meters - (B. Ziegler, 1972, p. 159). Besides it is not so improbable that the water contained plenty of suspended matter, seen the muddy nature of the deposit ; such a lower seawater transparency would even reduce the penetration depth of the natural light. According to D.A. Batjes (1958), the foraminifera are comparable to those on a mudshelf north of Trinidad and the Paria peninsula ; the deepest part


0
5
10
15
20
25
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45
50
55
60
65
70
75 m
BETEKOM ?
AARSCHOT ?
ST. KAT. WAVER
PUTTE
+22m
RUMST
+21 m
TERHAGEN
BOOM
+16 m
+17 m
REGION NIEL - SCHELLE
BORING ANTWERPEN STORMVLOEDKERING
-19m
STEENDORP
+19m
STEKENE
+7m
+23 m
TIELRODE
HEMIKSEM
+19m
+15 m
SINT NIKLAAS
KEMZEKE 't HOL
+4m
KRUIBEKE
+18m
S10
S20
S30
S40
S41
S50
S60
S61
S70
S80
black layer
silt layer
very silty layer
clay layer
layered pyrite
pink, brownish layer
septaria horizon
grey clay - black clay boundary
calcareous layer
sample
0 1 2 3 4 5 6 % org. mat.
0 10 20 30 40 50 % > 32 μ
0 1 2 3 4 5 % CaCO3
25,24
BELSELE - WAAS MEMBER
TERHAGEN MEMBER
PUTTE MEMBER
BOOM FORMATION
N. VANDENBERGHE

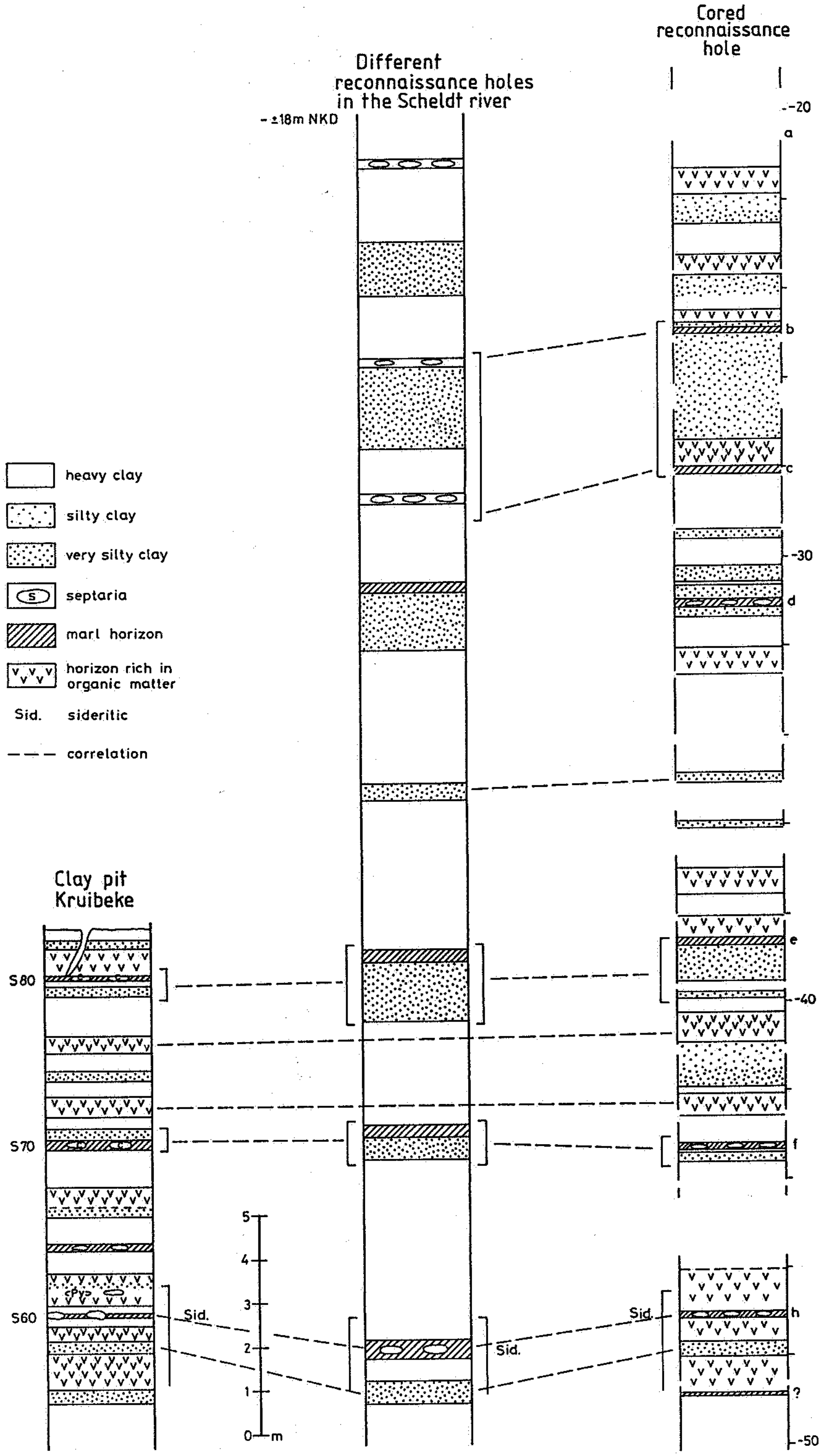


Figure 7. Microstratigraphic correlation in the Boom Clay between the cored and other reconnaissance holes in the Schelde river and the clay pit at Kruibeke.

is about 155 m below sea level. According to T. Vercauteren (1975) the most important foraminifera species represent genera which live actually in open-shelf seas at depths between 20 and 120 m. Fish remnants indicate deposition at a rather deep part of the shelf, at least 50 m deep, in a subtropical climate (M. Leriche, 1910, E. Steurbaut and J. Herman, 1978).

In conclusion the deposition environment of the Boom Clay can be considered to have been an open shelf sea in a subtropical climate with an oxydative mud bottom about 50 m deep or even some tens of meters deeper.

The presence of terrestrial mammal fossils and the common presence of drifted wood suggest that the coast was not too far away.

b) Analysis of the grain-size distribution of silt and clay horizons shows that the maximum grain-size in both types of horizons is almost the same and that the grain size difference between both horizons is due to a larger or lesser proportion of the same coarse silt-very fine sand size fraction (fig. 2b). Besides the variations in grain-size are gradual and maximum coarse and fine fractions are located in the center of respectively silt and clay layers (fig. 6, 8). As in the source area coarser grains were present than the coarse particles now found in the Boom Clay, the grain-size properties of the Boom Clay are determined by the conditions prevailing solely in the sedimentation area and the succession of clay-rich

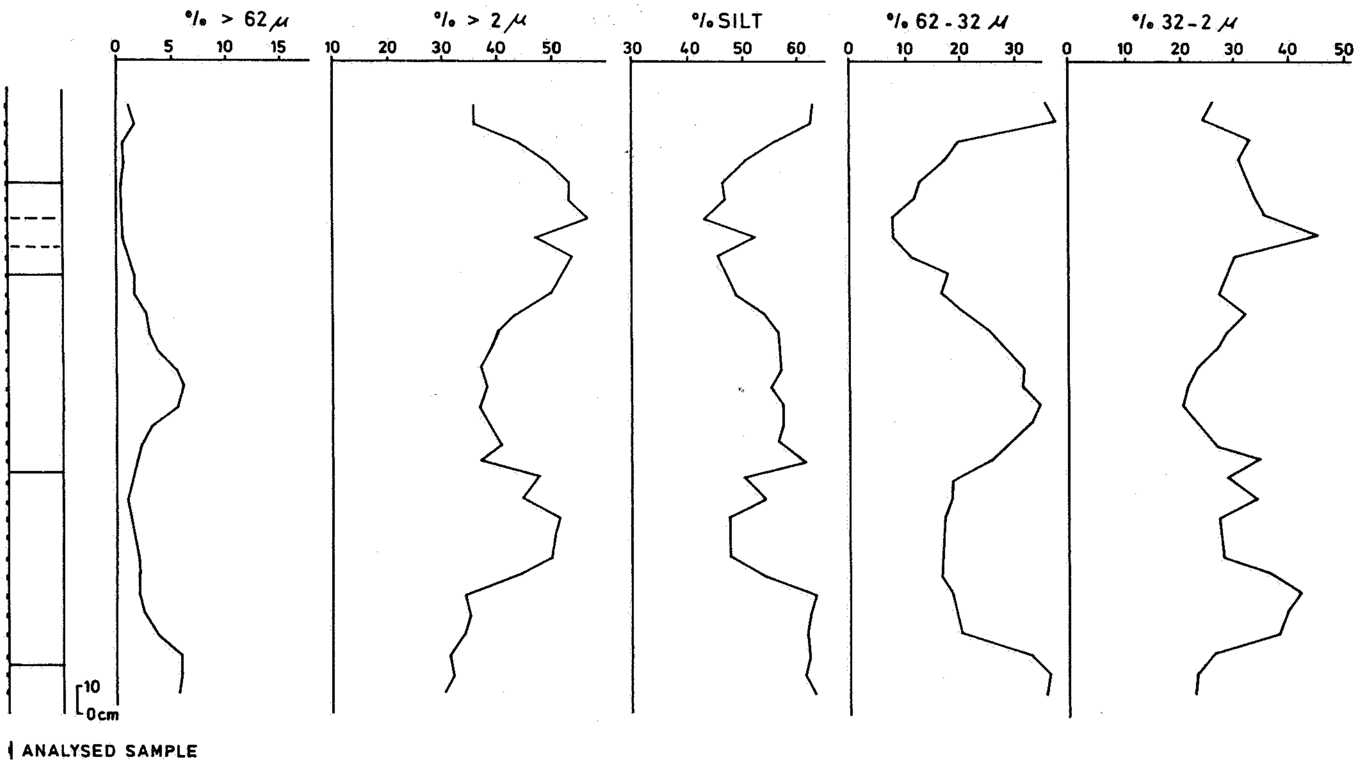


Figure 8. Detailed grain-size analysis of a section at Terhagen.

and silty beds is interpreted in terms of alternating periods of more and less important turbulence. As the rhythmicity is so uniformely developed over a large area it is assumed that the turbulence variations are due to changing wave activity ; the bottom of the sea was periodically within and outside the reach of the wave activity. This was the consequence of either changing wave properties (climate, basin geometry) or changing water depth (sea level).

As the effect of the turbulence increase is the winnowing out or the preventing from settling of the finer particles, it will take a longer time to built up a silty bed of the same thickness as a clay-rich bed. Consequently the silty beds correspond to periods with a slower rate of sedimentation in comparison with the clay-rich beds. Silty beds are indeed systematically thinner than the adjacent clay beds (fig. 11).

c) The bituminous black beds

The black layers are concentrations of land derived plant remains (phytoclasts) of which at least 75 % are primary allochtonous.

The black horizons occur always on top of a silty bed, often already in the top of a silty bed. Black horizons show a high fissility.

The constant relationship between the occurrence of bituminous beds and the grain-size rhythmicity (fig. 6) indicates that both rhythmicities have the same cause (climate, sea level, ...) but the mechanism which translated the effect of this phenomenon into sediment patterns for the grain-size of the clastic particles and for the phytoclasts was different.

It is suggested that the lower density of the phytoclasts prevented their sedimentation until turbulence decreased below a critical value.

d) The septaria horizons and the carbonate content

The carbonate rich layers represent an originally carbonate rich sedimentation, and are not generated by diagenetic precipitation horizons. Several observations plead for this. There is the abundance of carbonate : in the septaria more than 80 percent $CaCO_3$ can be present. There is the occurrence of the mollusc Leda deshayesiana, both valves together, in carbonate horizon S50, in contrast to the rest of the clay where mostly only one valve is found. This points to particular conditions at horizon S50 during sedimentation. Finally the position of the carbonate rich layers, independent of the grain-size-organic matter layering argues against diagenetic control for their location, as diagenesis would normally favour their occurrence in one specific lithology rather than in the clay, silt or organic rich lithology.

It can be concluded that the septaria represent orginally marly sedimentation horizons, which are modified by later diagenesis.

After some mm burial depth in a clayey sediment reducing conditions are initiated.

The upper few meter of such a buried sediment are chemically and biochemically very active. In most anaerobic sediments the result of the different reactions is a slight decrease of the pH as compared with the sea water pH and this may induce a carbonate mobility (Berner, 1971). However in the overal slightly acid sediment, micro environments do exist with a higher pH as e.g. some decaying marine organisms can release ammonia. This might be sites of preferential calcium carbonate precipitation.

Hence the originally sedimented carbonate can be remobilized and redistributed into nodules. Indeed once precipitation started in a basic micro environment it will continue to grow because of the created chemical activity gradients. Ultimately a large nodule can be formed. In the centre of the septaria in the Boom Clay it is rare to find a fossil nucleus. This suggests indeed a purely chemical, initial nucleation.

Several authors have expressed the view that carbonate nodules in shaly sediments started a few meter under the sediment-water interface (Strakhov *et al.*, 1953 ; Müller, 1967 ; Sass and Kolodny, 1972).

Taking into account the inclusion of pyrite concretions inside the septaria and the ferroan calcite nature of the septaria carbonate, it is logic to have the nodules starting to form below the bacterial sulphate reduction zone which might be up to 10 m thick (Curtis, 1978).

This thickness is determinated by the possibility for sulphates to diffuse easily from the sea water down into the sediment.

As the carbonate content, corrected for the septae space, is a measure for the porosity at the thime of formation, the carbonate contents between 65 and 87 % (Van Tassel, 1966) indeed point to a formation in the upper meters.

More, as the carbonate content difference between the core and the outer crust of the septaria is only a few percent (Van Tassel, 1966), the nodule formation probably took place in a narrow porosity interval.

Comparing the present water content about 25-30 % to the carbonate content of the septaria crust, representing in the model the porosity at the end of the nodule formation, the nodule formation was completed quite long before the clay reached its present compaction.

The growth of the nodules continued during the several tens of meter further burial history of the Boom Clay. The final loaf or more platy shape of the nodules is defined by the original thickness of the marly sedimentation horizons and by the amount of carbonate available in the horizon during the remobilization determining the horizontal diameter. The latter factor probably determines also the number of septaria in a horizon. During the further growth of the nodules an additional features developed in the carbonate concretions : the development of septae.

Carbonate nodules have a very different diagenetic evolution compared to the surrounding clay, with respect to dehydration.

It is a well known phenomenon that during diagenesis carbonates lithify more quickly than shales dehydrate. At a certain burial depth the porewater from the carbonate nodule will be expelled at a much higher rater than the porewater from the enclosing clay. The result is that the water expelled from the nodule carbonate is trapped within the original volume of the carbonate nodule.

The dehydrating and lithifying of the carbonate nodule leads to a classic hexagonal septae pattern visible in horizontal sections through the septaria. Expelling water, the carbonates get a mechanical strength, the orientation of the septae being determined by the stress state in the clay. The almost invariable near vertical septae show that the maximal stress direction was vertical, determined by the overburden.

As the nodule grows outwards it is logic to suppose that the inside part, which is the oldest, lithifies and therefore cracks first, whilst the septae gradually grow outwards following the lithification evolution of the progressively younger parts of the nodule, ending in a narrow crack near the rim of the nodule.

At the same time the cracks in the central part grow wider. The uncracked thin outer rim, in direct contact with the surrounding shale, probably contained always enough water to prevent cracking.

This model assumes dehydration to start from the inside outwards in contrast to models which believe an outer crust hardened first and the inside dehydrated later. No deformation of the clay around the earlier formed septaria was observed although the compaction of the clay continued till 25-30 % water content.

It means that the septaria were still soft enough to be deformed together with the clay. This idea is supported by the occurrence of small sometimes soft septaria in the upper part of the clay (S61, S70, S80). This further compaction resulted in the outward curvature of the originally vertical septae.

A few measurements lead us to believe that the interval over which the septae were curved can be estimated in the order of a few percent compaction only.

In our opinion, the pressure decrease resulting from erosion of the clay led to the precipitation of minerals on the septae walls.

The most common and typical mineral film consists of a yellowish to brownish ferroan calcite rim of a few mm thickness ; the crystals are elongated and perpendicular to the septae walls and contain $MgCO_3$ in the order of 2.7 to 4.7 moL %. This description fits the early vein filling calcite in septaria as described by R.C. Lindholm (1974).

In septaria S50, the mineral film consists of a mm thick octahedral pyrite layer, with typical iridescent colours. Similar but less well developed pyrite films are found in the overlying horizon S60 and in the underlying horizon S40.

It is thought that the pyrite coating is related to the clay section with high organic matter and sulphides content.

In horizon S50 ferroan calcite crystals have grown above the pyrite film, whilst in S40 pyrite octahedra have precipitated on top of the ferroan calcite. These relationships indicate that the precipitation of both types of mineral films in the septae occurred in almost the same time interval.

In some cases a very thin film of ferroan calcite powder covers the mineral film in the septae. It contains less Mg than the first thicker ferroan calcite rim. Maybe it is re-

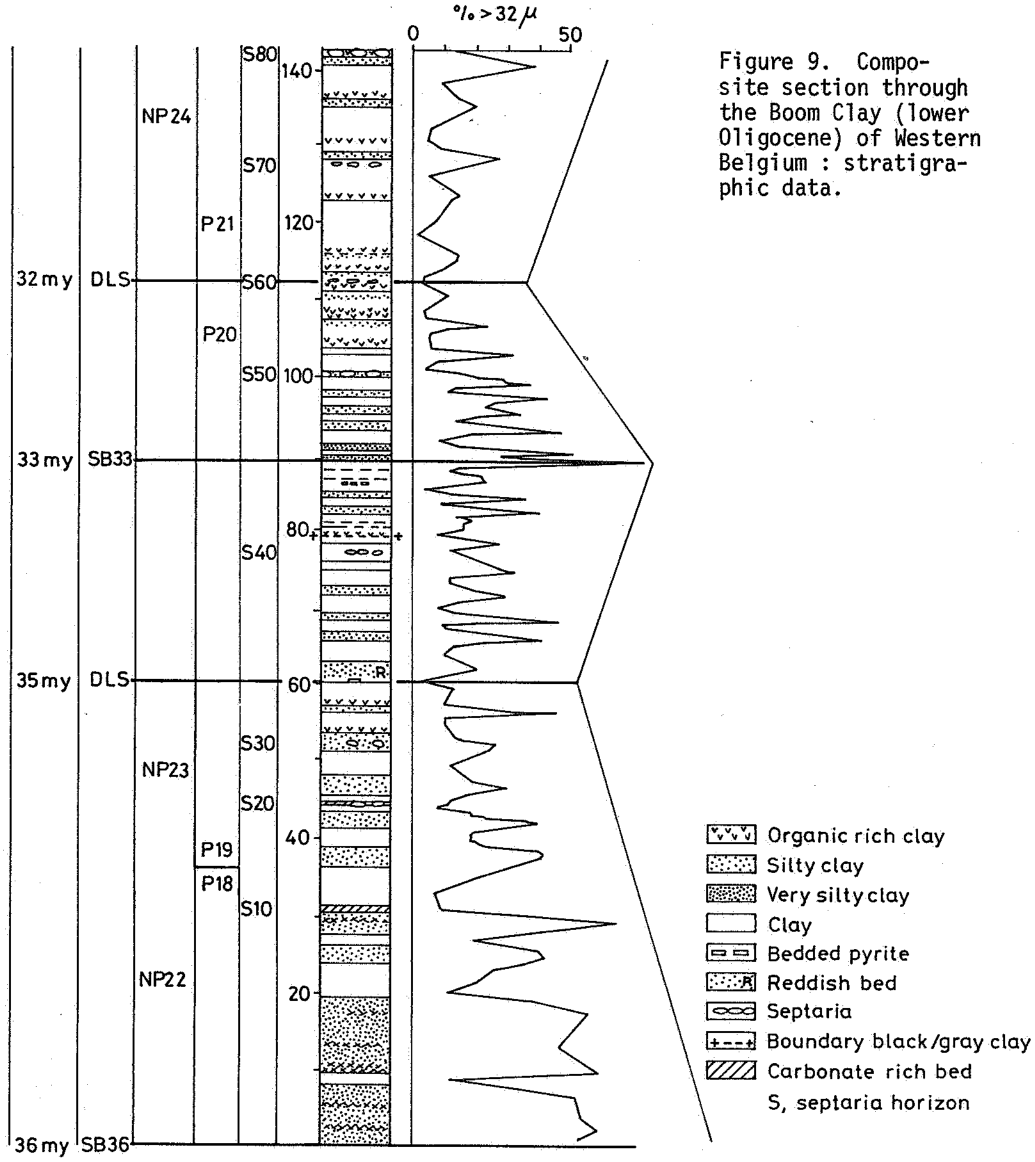


Figure 9. Composite section through the Boom Clay (lower Oligocene) of Western Belgium : stratigraphic data.

(Based on J. HARDENBOL, N. VANDENBERGHE)

lated to the erosion of Neogene sand formations.
The influence of the meteoric water infiltration in the clay is a general carbonate dissolution, most pronounced in the clay section rich in organic matter, an expression of continuing organic matter maturation even in regressive diagenetic conditions.
The general carbonate dissolution led to spurious carbonate content values and to septaria occurring in otherwise decalcified clay.

4. BIOSTRATIGRAPHIC DATA

Planktonic foraminifera data show P18, P19, P20 and P21 to be present (Hooyberghs, 1983).

Nannoplankton in the basal part of the Boom Clay member is indicative of NP22, most of the clay section may be assigned to the NP23 and its top to the lower part of NP24. The boundaries between the zones can not be exactly located (J.W. Verbeek, IGCP-124 reports). The biostratigraphic division is given in fig. 9.

5. RHYTMICITY AND SEQUENCE STRATIGRAPHY

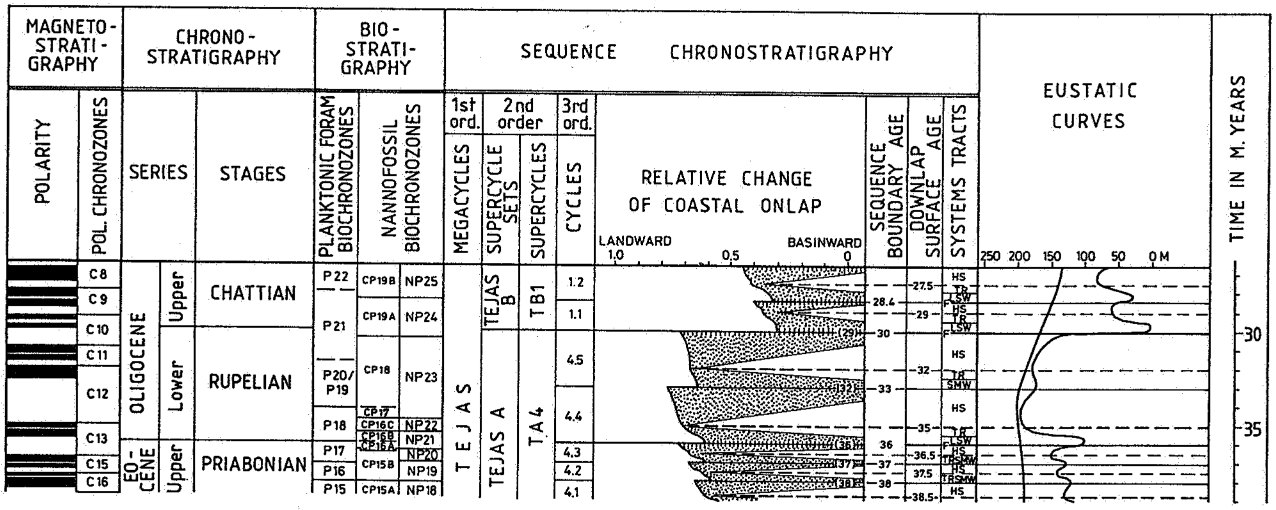
The banded layering of the Boom Clay has a grain-size cyclic variation of about 1 m wavelength.

Although cycles are missing at the top of the clay due to erosion an estimate is made of the time duration of one cycle. At least 45 cycles cover the biozones PP18, 19, 20, 21 and NP22, 23, NP24 found in the clay. The biozone information combined with the chronostratigraphic dating (Odin, 1982) leads to an estimate of a maximum time duration of 6 million years. The cycle duration obtained in this way is a maximum figure as the time span considered covers the whole Rupelian whilst the number of cycles considered is a minimum. Hence an order of magnitude of about 100.000 years for each silt-clay layer pair is a reasonable estimate.

On top of this short term cycles a longer term trend of several tens of meters is visible on the analytic data but also on the bed thickness data (fig. 11).

In the global sea level change model, these larger term trends are significant in defining the sequence boundaries.

In the clay section exposed two 3rd order cycles were determined. Assuming



(Based on B.U. HAQ, J. HARDENBOL, P.R. VAIL)

Figure 10. Stratigraphy of the Oligocene.

chronostratigraphic significance for the sequence boundaries and the downlap surfaces, ages can be attributed to different horizons in the clay (fig. 9, 10).

6. THE THICK SILT LAYERS AT THE BASE OF THE BOOM CLAY (SVK CLAYPIT, BELSELE SINT-NIKLAAS)

At the base of the clay occurs a phosphatic pebble horizon. The phosphate lithified organic structures such as bioturbations and also the top of the underlying sands. Just before the Boom Clay deposition started, the phosphate bed was ripped up and slightly transported forming now the pebble bed.

In an older clay pit, across the road, beds of large Pycnodonta callifera have been observed (A. W. Janssen, 1981). It should be mentionned here that such oysters were also found in the underlying Ruisbroek sands (at Ruisbroek, Rupel tunnel excavations).

The coarse layers contain several levels of flat gully like structures, interpreted as due to wave turbulence on a muddy sea floor.

Within the thick silt layers several grain-size rythms can be observed after analysis (fig. 12) confirming the subdivisions slightly visible on the clay face.

Note also the coarse grains at the base quickly disappear upwards to give grain-size ranges all below about 90 µm.

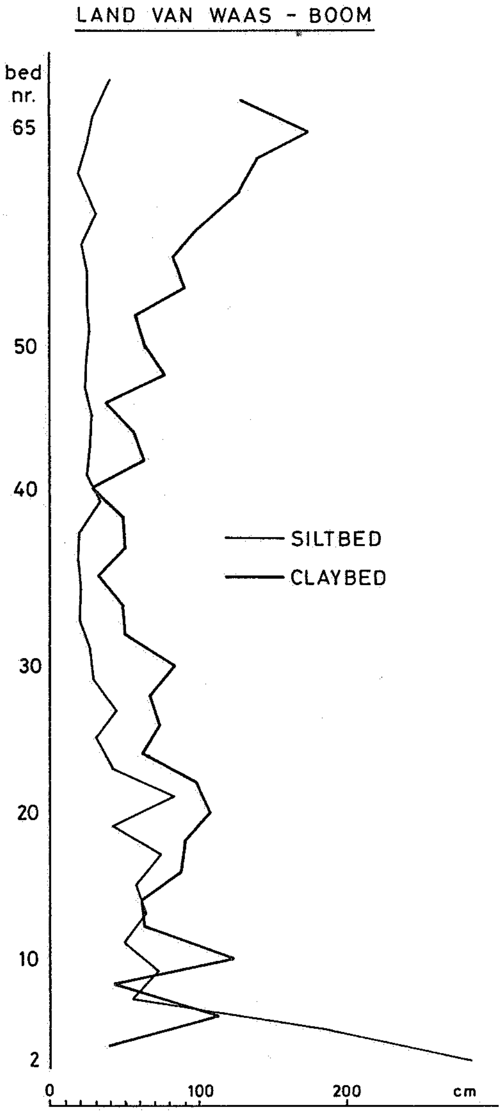


Figure 11. Thickness distribution of the grain-size beds.

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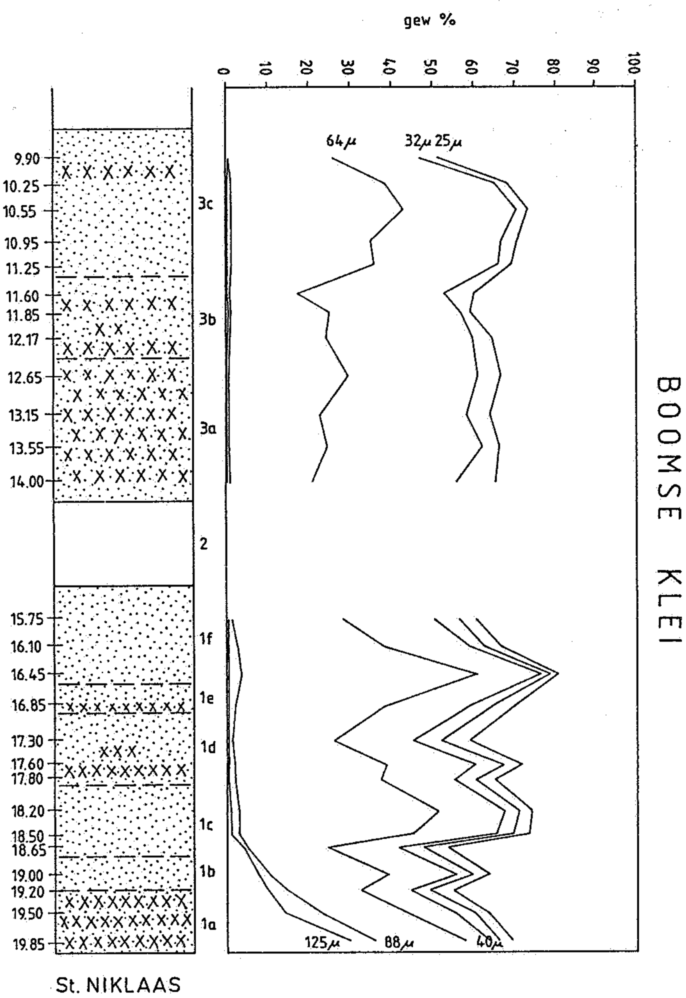

Figure 12. Grain-size analysis of the lower silt horizons (Sint-Niklaas SVK pit)

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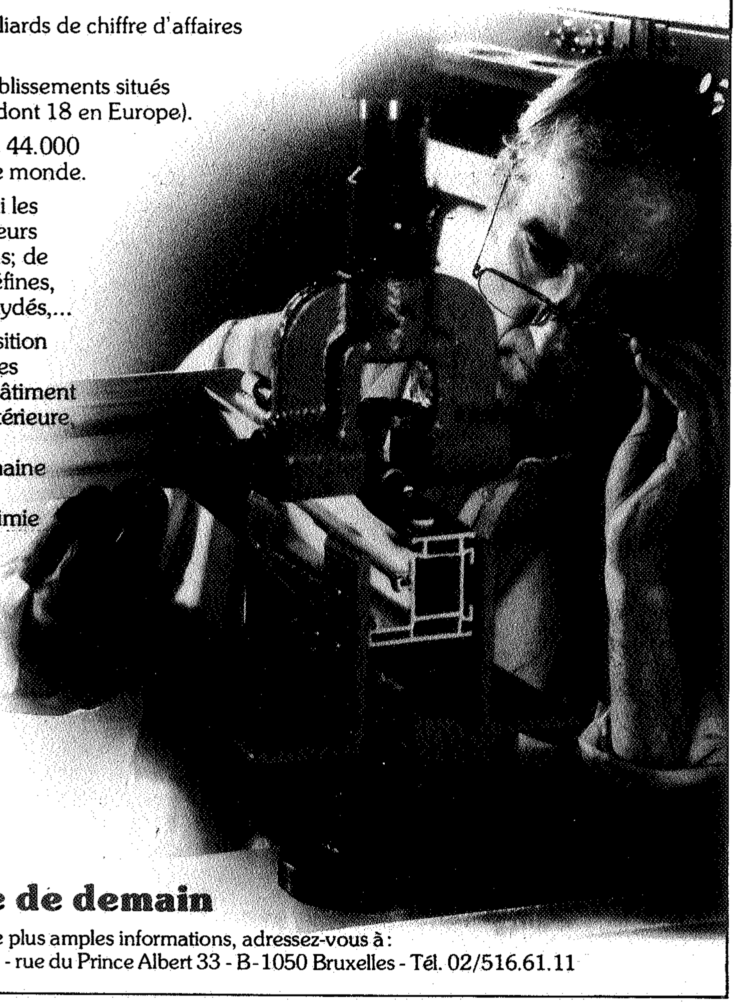

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