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Clay fabric as an indicator of cyclic changes in an estuarine palaeo-environment - Lower Pleistocene, northern Campine Area, Belgium

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Abstract

SEM photographs of the Turnhout Member (Lower Pleistocene), reveal a vertical cyclicity of 2 main clay-fabric types: (a) face-to-face domains and (b) edge-to-face domains, each of them indicating the existence of respectively dispersed particles deposited in a fresh-water environment, and flocculated particles deposited in a salt-water environment, the transition being marked by intermediate clay-fabric types. It is suggested that the sequence corresponds to fluctuations in the position of the fluvial-marine equilibrium, related to important changes in river runoff or tidal amplitude. These observations indicate the utility of applying clay-fabric analyses to achieve a higher resolution in palaeoenvironmental interpretations.

Key-words: clay fabric, Quaternary stratigraphy, palaeoenvironment

Résumé

Les photographes du Turnhout Member (Pleistocène inférieur) prises au MEB (microscope électronique à balayage) révèlent une cyclicité verticale comprenant deux types principaux de "clay fabric" (texture argileuse): (a) des zone face-à-face et (b) des zones bord-à-face, chacun deux indiquant, respectivement, la présence de particules dispersées déposées dans un milieu d'eau douce et des particules floculées déposées dans un milieu d'eau saumâtre, la transition étant marquée par des types de "clay-fabric" intermédiaires. Il est suggéré que la séquence correspond aux fluctuations de la position de l'équilibre fluvio-marin, lié aux changements importants qui peuvent se produire dans le débit des rivières ou dans l'amplitude de la marée. Ces observations démontrent l'utilité qu'il y a à recourir aux analyses du "clay-fabric" pour arriver à une plus haute résolution dans les interprétations paléo-environementales.

Mots-clefs: texture argileuse, stratigraphie du Quaternaire, paléo-environement

Introduction

"Clay-fabric" refers to the spatial distribution, orientation and particle to particle relations of sediment particles (generally those less than 4 microns) (BENNETT & HULBERT, 1986). Several physical, chemical, biological and climatological factors define a specific environment of sedimentary deposition within which the primary fabric develops. The aim of the present study was compare the clay-fabric exhibited by Recent marine, estuarine and limnic clays with the clay-fabric exhibited by ancient deposits of an uncertain palaeoenvironment.

Until recently, the primary goals of clay-fabric research had focused on the processes of flocculation, dispersion and domain-formation, on describing the different configurations between the clay-particles and finally, on the understanding of the geotechnical properties of the material (LAMBE, 1958; GRIM, 1962; BARDEN & SIDES, 1970; MOON, 1972; COLLINS MCGOWN, 1974; SMART, 1975; BENNETT, BRYANT & KELLER, 1977, 1979, 1981; BENNETT & HULBERT, 1981; FAAS & CROCKET, 1983; WARTEL , SETHI & FAAS, 1991). Very little work, however, has been done in trying to characterize Quaternary palaeoenvironments through the study of the clay-fabric.

The present study deals with the defining of the palaeoenvironment of the Turnhout Member (Lower Pleistocene) of the Campine Formation (PAEPE & VANHOORNE, 1976), northern Campine Area, Belgium. The northern Campine area has from the 19^{the} century been a subject of contradiction, not only as far as the litho- and chronostratigraphy is concerned but also regarding the palaeontological findings, the depositional environments and last but not least the geographic evolution of the area.

The quaternary sequence, that attains in this part of the country its greatest thickness, shows a succession of clayey and sandy facies. The clayey facies, present at the immediate subsurface, are used as raw material in the coarse ceramic industry. These particular facies consists either of a series of clay layers or of an alternation of clay and sand layers. The whole clayey-sandy sequence is geologically defined as the Campine Clays (TAVERNIER, 1954) or, more recently as the Campine Formation (PAEPE & VANHOORNE, 1976). The latter formation is further subdivided by the same authors into the Rijkevorsel, the Beerse, and the Turnhout Members. Present day data however reveal five distinct sediment-genetic units within the Campine Formation through which five lithostratigraphic units on the level of a Member will be used in the future (F. BOGEMANS, in preparation).

Since 1878, various workers have commented on the

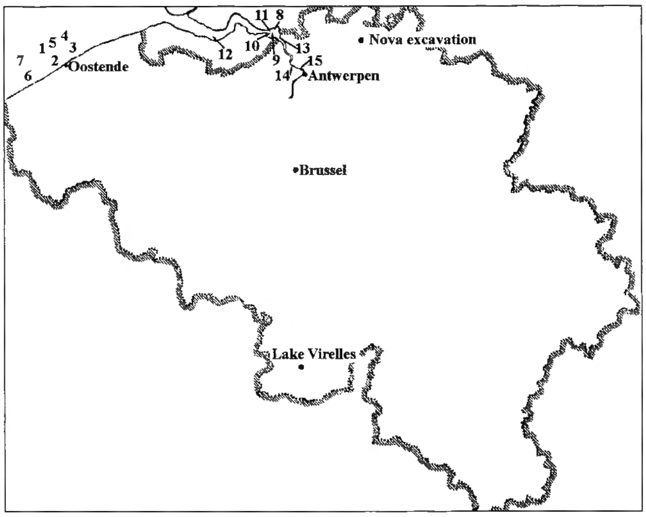

Fig. 1 — Location map of Nova Pit excavation, of Lake Virelles and of Schelde and North Sea samples. Geographic positions of Schelde and North sea samples are listed in Tables 1 & 2.

palaeoenvironment of the Turnhout Member. TAVERNIER (1954) described it as belonging to fluviatile deposits in a meandering river. DRICOT (1961) proposed the deposition of the Campine Sand and Clay Formation in brackish or salt water, probably in an estuary or on tidal flats. An alternation of fresh and brackish water circumstances has been observed in pollen analyses (ADHIKARY, 1987).

In the excavation pit ''Nova'' at Beerse (Figure 1) the Turnhout Member is superimposed by fluvial deposits belonging to the St. Lenaarts Formation (equivalent to the Kedichem Formation in the Netherlands), which in contradiction to DE PLOEY (1961) are not deposited during the Weichselian but still during the Lower-Pleistocene (F. BOGEMANS, in preparation). At the top Weichselian aeolian deposits are present, spread as a blanket over the area.

Table 1 — Geographical co-ordinates of North Sea samples

map #	sample #	latitude	longitude
1	88A22	N51°14.71	E2°53.69
2	88A23	N51°14.07	E2°55.19
3	88A25	N51°16.59	E2°59.22
4	88A26	N51°16.99	E2°57.95
5	88A27	N51°16.27	E2°55.63
6	88A28	N51°13.36	E2°52.00
7	88A29	N51°13.68	E2°51.24

Studied areas

Eight samples from the North Sea were obtained from an area of near-shore mud-deposition on the Belgian continental shelf (Figure 1, Table 1).

Seven samples were also obtained from different mud-deposition areas (tidal flat and main channel) within the turbidity maximum section of the Schelde estuary (WARTEL, 1977) (Figure 1, Table 2).

Table 2 — Geographical co-ordinates of Schelde samples

map #	sample #	latitude	longitude
8	88B23	N51°24.50	E4°11.16
9	88B25	N51°24.90	E4°11.11
10	88B26	N51°24.13	E4°11.80
11	88B27	N51°24.20	E4°12.27
12	88B30	N51°20.87	E3°50.07
13	88B32	N51°20.79	E4°15.70
14	88B33	N51°14.45	E3°23.00
15	88B34	N51°14.10	E4°23.86

One 60 cm long core was obtained from a fresh water lake at Virelles (Southern Belgium, Figure 1), from a depth of 2 m.

Eight samples were obtained from the Turnhout Member (Nova Pit, Beerse, Belgium, Figure 1)). On the sampling site the Turnhout Member consists of an approximately 1.5 m thick clay layer located between 26.5 and 28.25 m T.A.W. (the ''Tweede Algemene Waterpassing'' (Second General Leveling) is the Belgian datum) and overlying a 3 m thick unit of supposedly tidal flat deposits consisting of alternating sand and clay beds.

Methodology and field techniques

SAMPLING TECHNIQUES

Stainless steel boxes (20x16x3.5 cm) were used to obtain oriented and essentially undisturbed samples from the Turnhout Member. A large box-corer was used to obtain unconsolidated, essentially undisturbed and oriented samples from the uppermost 60 cm of the sea bed from the North Sea and the Schelde estuary. From the bulk box-corer sample a smaller, undisturbed and oriented sample was taken using a stainless steel box (20x16x3.5 cm). A PVC-tube (1 m long and 8 cm wide) was used to obtain limnic samples from lake Virelles.

SCANNING ELECTRON MICROSCOPE ANALYSIS

In the laboratory, sub-samples (3x4x2 mm) were taken from the stainless steel boxes and oriented parallel to the bedding plane of the sediment. The samples were split and trimmed into cubes of 2 to 3 mm sides, using a razor blade, and transferred into a porous cup, maintaining their orientation. The ''peeling-technique'' for cleaning (BARDEN & SIDES, 1970) was used and the removal of salt and replacement of water was done by washing with ethanol. The sample was critical-point dried using liquid CO_2 (BENNETT *et al.*, 1979). After the sample was mounted on an aluminium stub and gold-plated, it was studied in a ''Philips-SEM 515'' with magnifications of 10 to 30.000 times. More than 350 SEM Photographs of the oriented samples (with the surface parallel to the bedding plane sediment) were taken and analysed. The terms ''domain'', ''floccule'' or ''floc'', ''chain'' and ''particle'' are used according to the definitions of BENNETT *et al.* (1981). The clay-fabric terminology used is given by VAN OLPHEN (1981).

Observations

LAKE VIRELLES (non-flocculating fresh-water environment)
The fresh water deposits of lake Virelles consist of a bluish-grey to dark blue clay. The radiographs show some burrowing of unidentified organisms; bedding or lamination is not observed. The texture of the sediment is very uniform showing an average clay content of 49% (±7%) and an average silt/clay ratio close to 1. The sediment is free of calcium carbonate. The SEM analyses revealed a loosely compacted micro-structure (Plate 1.1) composed of single particles (S) and few domains (D) in a face-to-face (FF) fabric (SDFF).

SCHELDE (flocculating brackish-water environment)
The estuarine sediments show a layered structure consisting of alternating sand and mud layers. The clay content ranges between a minimum of 2% for the sand layers and a maximum of 45% for the mud layers. The average silt/clay ratio sediments is about 2.4 indicating an important supply of the silt fraction from the river basin. Calcium carbonate content ranges between 6 and 13%, the calcium carbonate being concentrated in the fractions below 125 μm (WARTEL & FAAS, 1986). Total organic matter content is positively correlated with the clay content and ranges between 1% for sand and 10% for mud with a high clay content (>20% clay).

Single particles, along with some domains are randomly oriented in an edge-to-face (EF) configuration (SDEF) (Plate 1.2). The inter-particle space is large as compared to the particle size. Flocs are very common, are formed by particle aggregation in an EF-configuration and range in size from approximately 5 microns to tens of microns. In the flocs the inter-particle space is small as compared to particle size. Some flocs are composed of particles (single or domains) oriented in a FF-configuration which results in a densely packed structure (Plate 1.3). They are called here "closed flocs" in order to distinguish them from the "open flocs" showing a EF-configuration. Flocs, and single particles as well very often aggregate in an edge-to-edge (EE) configuration to form complex chains. Micro gas-voids with diameters from a fraction of a micron to several microns are commonly observed.

NORTH SEA (flocculating salt-water environment)
The marine sediments show a layered structure consisting of alternating sand and mud layers. The clay content ranges between 10 and 33%. The average silt/clay ratio is about 1.2, which is only half of the ratio found for Schelde sediments. The calcium carbonate content is higher than in Schelde sediments and ranges between 16 and 25%. Total organic matter content ranges between 2 and 11% and is positively correlated with the clay content.

The North Sea samples exhibit randomly oriented single particles in a EE- and EF-configuration (Plate 1.4), along with some domains and many "open-flocs" 10 to 20μm in diameter or larger. Single particles and domains, aggregated in a EE-configuration, together with "open-flocs" form complex elongated chains (Plate 1.5).

TURNHOUT CLAY MEMBER
The clay unit of the Turnhout Member has a bluish-grey colour and a compact form. Macroscopically no structures could be observed. Radiographs showed that the upper part of the clay (from 27.9 to 28.25 m, samples 88Q18 and 88Q11) consists of three layered horizons built up by lens-shaped laminae of a few millimetres in thickness. These horizons alternate with non-laminated beds; some beds show a clotted or mottled texture. The clots have a dens nucleus surrounded by less dense material and diameters ranging from a few millimetres to approximately 1cm. From 27 to 27.5m (samples 88Q16 and 88Q12) lamination seems to be lacking and an alternation of beds, several centimetres thick and showing a clotted or mottled structure, with homogeneous beds of comparable thickness, is observed.

The clay contains practically no calcium carbonate (less than 0.5%) and 6 to 9% of organic matter. The clay content ranges between 42 and 77%. The silt content is minimal 24% and maximal 45%, and the sand content is between a fraction of a percent and 15%.

In the lower part of the clay unit (from 26.8 to 27.7m) (Figure 3) two layers with high and rather constant clay content (72 to 77%) occur. The sand content never exceeds a few percent. The two layers are separated at 27.35m by a more silty horizon (45% silt).

In the upper part of the clay unit (from 27.7 to 28.1m) the clay content decreases progressively to 46%, the silt content increases (38 to 40%) and the sand content also increases (6 to 13%).

This grain-size zonation is very well represented by the silt/clay ratio which is around 0.3 in the clay-rich horizons and shows an average around 0.9 (±0.3) in the siltier horizon at 27.35m and the sandier horizons above 27.7m. This indicates that the difference between these two horizons lies essentially in an additional sand supply in the uppermost horizon, the silt-clay counterpart having comparable proportions.

The sand population is clearly seen in the grain-size spectra (Figure 4). It seems to be well sorted with a modal size around 4φ (63μm) or 4.2φ (55μm) and is separated from the silt-clay population by a spectral low located between 4φ (37μm) and 5.5φ (25μm). The sand population dies out towards the 2φ (250μm) fraction, coarser grains being absent. The sand mode located between 63μm and 55μm is observed in all samples, but may be as low as 1% in clay-rich samples (88Q12-S6). A similar type of grain-size distribution is observed in the uniform suspension of the present-day Schelde estuary suggesting that the Turnhout Clay has been deposited from a similar type of uniform suspension. The silt-clay population is mainly concentrated in the fraction smaller than 6φ (16μm).

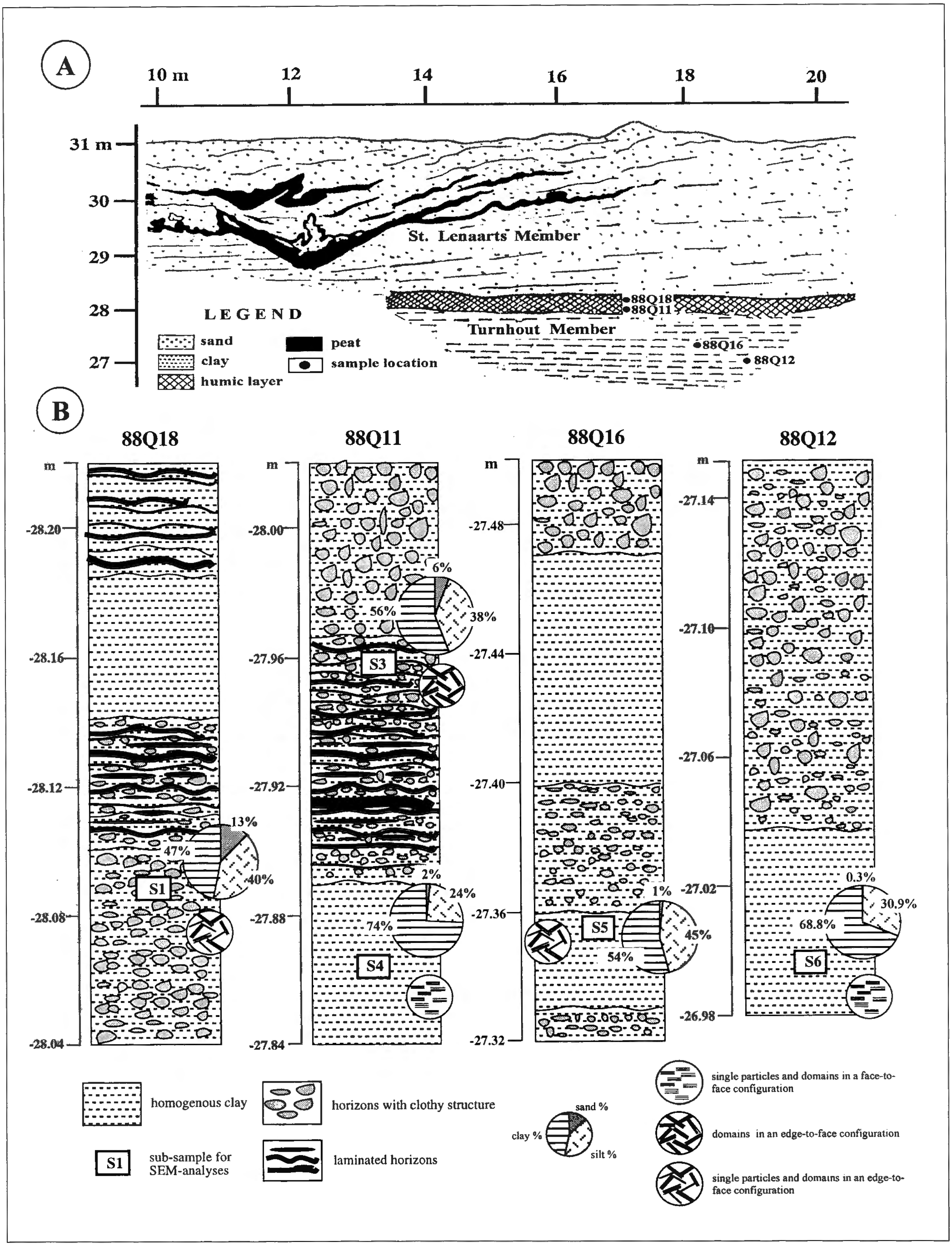

Fig. 2 — A - Geological section of the east-wall in the NOVA excavation, Beerse.
B - Graphic representation of the radiographs from the Turnhout Member with indication of the observed clay-fabric types and sand-silt-clay ratios.

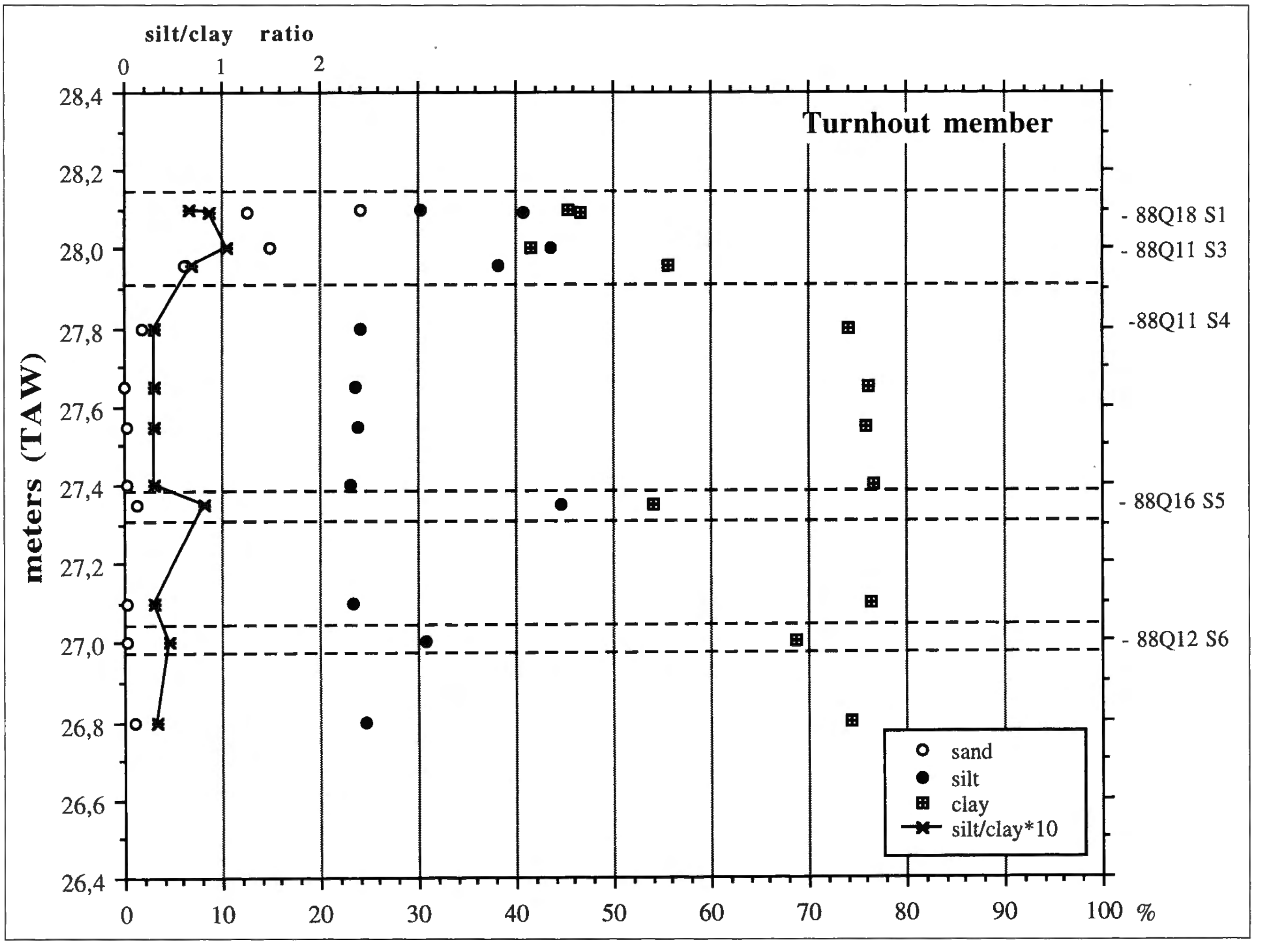

Fig. 3 — Distribution of sand, silt and clay in the clay-unit of the Turnhout Member

The Turnhout Member samples exhibit three primary fabric types. The first type shows single particles and domains with essentially face-to-face (SDFF) contact (Plate 2.1 & 2.2). The fabric indicates that the particles have been deposited in fresh-water under relatively calm conditions.

The second type consists mainly of domains of variable size in a random orientation connected with edge-to-face (SDEF) (Plate 2.3). It is most likely that such a fabric results from erosion of clay showing essentially a SFF- or DFF-fabric followed by deposition after flocculation in a brackish or saline turbulent environment. These observations suggest that deposition and fabric development took place under estuarine or marine conditions.

The third fabric type differs form the second one in that a large number of silt grains occurs. These grains are aggregated with clay particles in a FF-configuration so that the clay particles form a coating on the silt particles (Plate 2.4). Deposition in a brackish or marine environment can be deduced from the numerous clay flocs showing a DEF-fabric.

Discussion and conclusions

The sediments analysed for clay fabric in this study came from modern limnic, brackish and saline environments on the one hand and from a clay layer of the Turnhout Member (Campine Sand and Clay Formation, lower Pleistocene), presumably deposited in a brackish environment on the other hand. The sediments considered here have a relatively high clay content (>20%) in common. Besides they vary considerably in clay-fabric.

The modern limnic sediments (lake Virelles) on the one hand and the estuarine (Schelde) and marine (North Sea) sediments on the other hand exhibit different clay fabrics. Thus far no distinction in clay fabric could be made between the estuarine and the marine environments. In the limnic environment most sedimentary clay particles settle as single particles (SP) from a calm water column. Domains (D) may be formed after deposition or may result from erosion and subsequent deposition as such. The resulting fabric types are 1) single particles aggregated in a face-to-face (FF) fabric

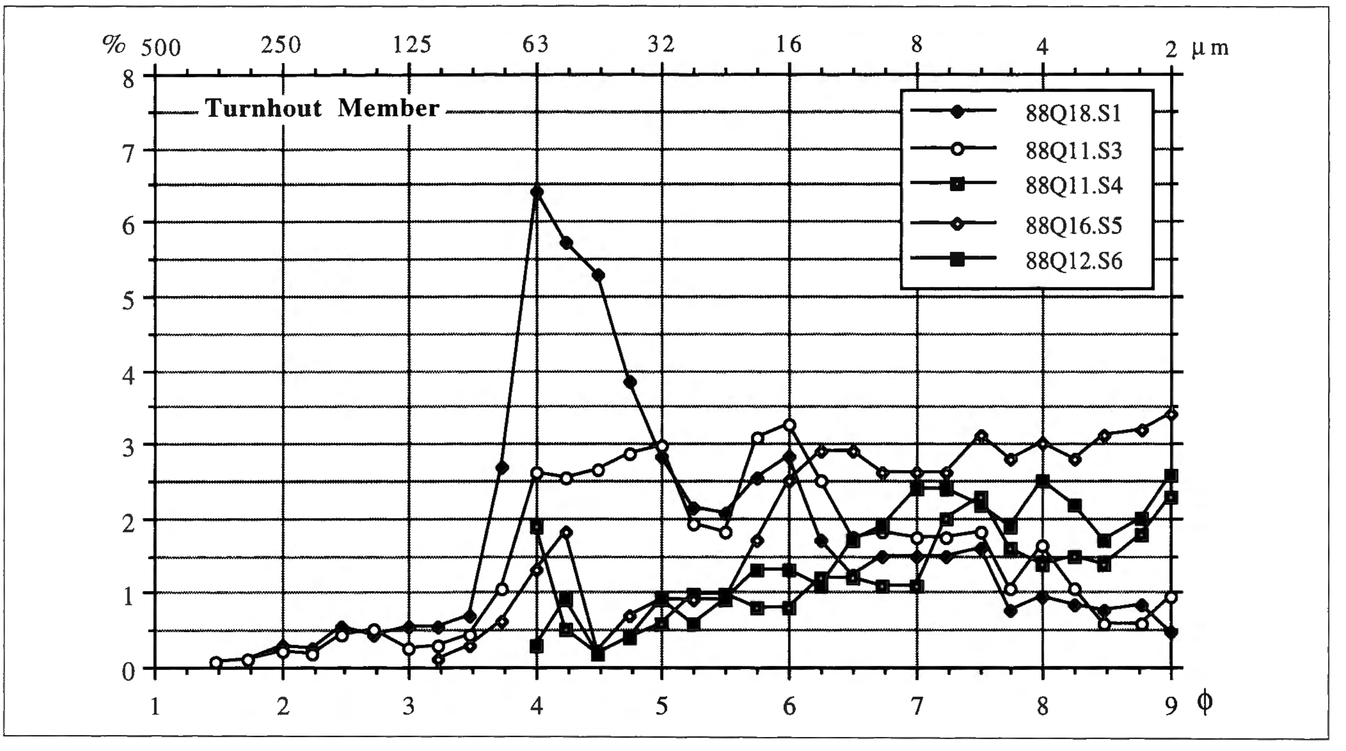

Fig. 4 — Grain-size spectra of samples from the Turnhout Member. Location of the samples is given in Figure 1.

(SP-FF) and 2) domains aggregated in a FF-fabric (D-FF).

In the saline (brackish and salt) environment several modes of deposition and associated clay-fabric can be recognized. Many particles in the water column occur as flocculated aggregates. If the water is only slightly turbulent and the suspended matter concentration not too high, say around 200mg/l, then loose flocs (F) or chained flocs (CF) next to single particles will be deposited. After settling flocs may aggregate to form larger flocs or clots. Domains also occur and seem to be more important in the Schelde than in the North Sea, indicating a nearby source of clay showing a SP-FF or D-FF-fabric. It is assumed that transport in a turbulent environment will rather destroy the suspended domains (EINSTEIN & KRONE, 1962). This, however, is not documented yet. The resulting fabric types are 3) loose flocs or chains composed of SP and/or D in an edge-to-face (EF) fabric (SPD-EF) and 4) loose flocs or chains composed of SP and/or D in an edge-to-edge (EE) fabric (SPD-EE).

When the water current is very turbulent and the suspended matter concentration high larger flocs will form in suspension and settle either as individual flocs or aggregates in single or complex chains.

The resulting fabric types will be 5) densely packed flocs composed of either SP or D or both, aggregated in a EF orientation (SPD-EF) and showing an open structure with no "outer layer" (SPDEF) or 6) densely packed flocs composed of either SP or D or both, aggregated in a EF orientation in a closed structure with an outer layer of flocs showing single particles or domains in a closed FF-orientation (SPDEF-FF).

Several of these fabric types can be recognized in the Turnhout Member. It can also be seen that the limnic and the saline clay-fabric types alternate. At the base (88Q12-S6, 27m) and at 27.86m (88Q11-S4) the sub-samples reveal a D-FF or DS-FF clay-fabric, which suggest that the particles were deposited in a "dispersed" state and assumed a face-to-face orientation during the "domain"-formation stage after sedimentation. During sedimentation no flocculating agents were present which is the case in a dominantly fresh-water environment. At 27.35m (88Q16-S5) and from 27.90m to the top of the clay (88Q18-S1 and 88Q11-S3) the clay-fabric is clearly of an SPD-EF-type. It means that during sedimentation flocculating agents (sea-salt) were active in a similar way as in the present day estuary of the Schelde. This causes aggregation of the clay particles to form small flocs during transportation, and preservation of this flocculated state after deposition and compacting of the clay. It should be noticed that the horizons showing a dominantly SPD-EF clay-fabric also contain numerous micro gas-voids (WARTEL, SETHI & FAAS, 1991), indicating that the environment not only became more saline but also changed to an anoxic one.

The alternation of both limnic and saline fabrics indicates that the sedimentary environment changed several times during the formation of the clay layer. At 27.35m this change involved a change in the grain-size distribution (Figure 3). Thus, not only the salinity of the water changed but also the nature of the deposited sediment.

During the time that the limnic conditions prevailed a silty-clay was deposited. The increase in salinity, as deduced from the clay-fabric, however, was accompanied by an increase in silt supply and a consequent increase in the silt/clay ratio. The sediment changed from a silty-clay to a clayey-silt. From 27.9m to the top of the clay layer a similar change took place. The silt content increased with respect to the clay in the same way as observed at horizon 27.35m and giving rise to a slightly higher silt/clay ratio. In the uppermost horizon, however, also fine-sand was supplied to the deposit (Figure 3: sample 88Q18-S1 and also sample 88Q11-S3).

It can be argued that these episodic changes in the sedimentary environment correspond to a landward progression of the marine influence (increasing salinity) involving, or caused by an increase in tidal energy (increase in tidal range?). A higher tidal energy will produce higher current velocities of the water and consequently winnowing of the finest clay particles so that the silt/clay ratio of the deposit increased. The effect was probably more pronounced in the uppermost horizon as can be deduced from the supply of fine sand. From the foregoing it can be concluded that the clay was deposited near the landward limit, or within the river-marine equilibrium zone and that the saline interface migrated over the clay deposit.

The question now arises whether these changes reflect short term seasonal changes (e.g. a winter-summer cycle) or result from an even minor change in the climate. This problem can be approached by considering the rate of accumulation of modern estuarine sediments. Assuming an accumulation rate of 0.5cm.year^{-1}, based on measurements on the tidal flats of the Schelde (Wartel, unpublished data), gives a time span of approximately 400 years for the deposition of a 2m thick clay layer. Even if the assumed accumulation rate is too low, it seems not very likely that the observed changes in the sedimentation pattern have to be related to seasonal changes. A minor change in the climate may offer a better explanation.

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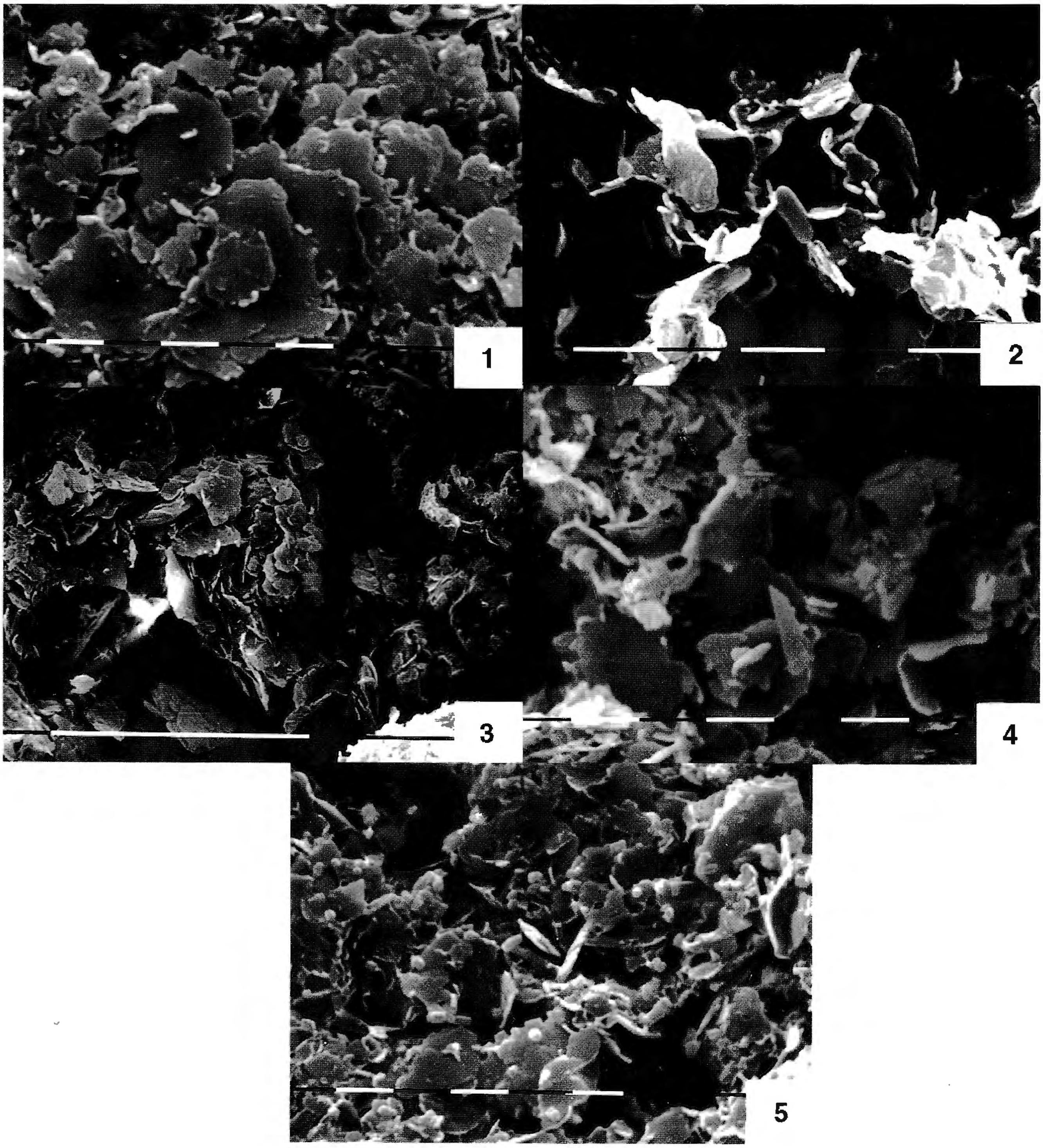

PLATE 1

Fig. 1 — Clay fabric of a limnic sediment (Lake Virelles, sample 88V06). Single particles in a SDFF-configuration, deposited in a non-flocculating calm fresh water environment. White scale-bar is 1 µm SEM 1079-3A.

Fig. 2 — Clay fabric of estuarine mud (Schelde, sample 88B23). Flocs (near the lower right corner of the Photograph) and single particles, in a SEE- and SEF-configuration, forming complex chains. White scale bar is 10 µm (SEM 996-33A).

Fig. 3 — Clay fabric of estuarine mud (Schelde, sample). Closed flocs (near the centre of the Photograph) and open flocs forming complex chains. White scale bar is 1 µm (SEM 996-34A).

Fig. 4 — Clay fabric of marine mud (North Sea, sample 88A27). Chain of single particles, in EE- and EF-configuration, and open flocs. White scale bar is 1 µm (SEM 1017-2A).

Fig. 5 — Clay fabric of marine mud (North Sea, sample 88A25). Open flocs forming chains with single particles and domains. EE- and EF-configurations. White scale bar is 1 µm (SEM 1017-23A).

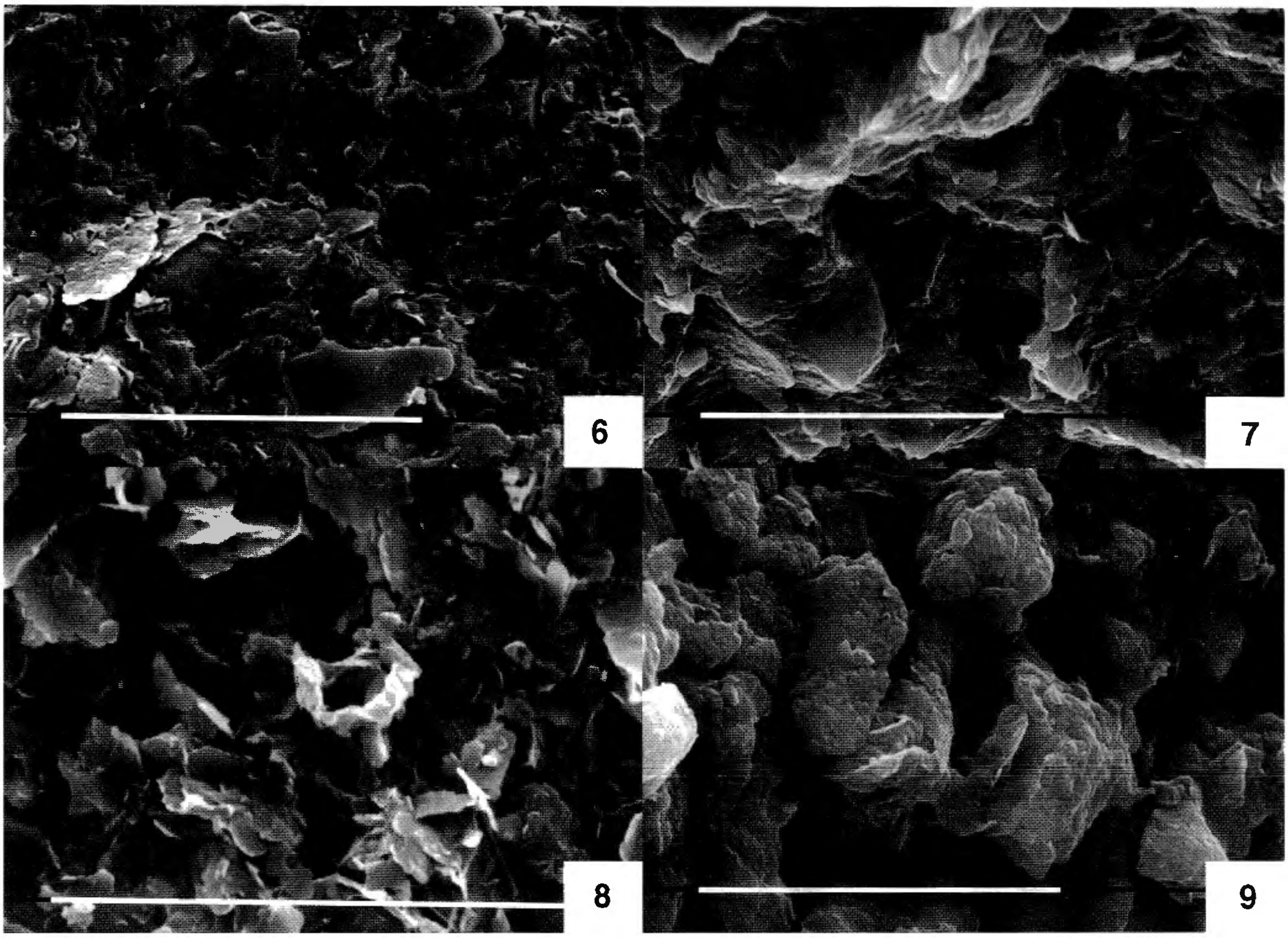

PLATE 2

Fig. 1 — Turnhout Member, sample 88Q12-S6. Clay-fabric shows SDFF-configuration. Clay deposited in a relatively calm, non-flocculating fresh-water environment. White scale is 10 µm (SEM 996-10).

Fig. 2 — Turnhout Member, sample 88Q11-S4. Typical face-to-face configuration of domains seen in side view. Clay deposited in a relatively calm, non-flocculating fresh-water environment. Near the centre of the Photograph a gas-void is seen. White scale-bar is 10 µm (SEM 966-16).

Fig. 3 — Turnhout Member, sample 88Q16-S5. Clay fabric showing SDEF-configuration. Clay deposited in a flocculating salt-water environment. Several gas-void are seen. White scale-bar is 10 mm (SEM 996-9).

Fig. 4 — Turnhout Member, sample 88Q11-S3. Silt grains coated by clay particles and flocs showing DFF-fabric. White scale-bar is 10 µm (SEM 966-4).