

## Periglacial environments and climatic development during the Early Pleistocene Tiglian stage (Beerse Glacial) in northern Belgium

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### Abstract

The climatic development of the Early Pleistocene Tiglian stage has been studied in the Tegelen Formation (Rijkevorsel, Beerse and Turnhout Members) in northern Belgium. The sedimentology, paleoecology and periglacial structures of the Beerse Member indicate the presence of a cold period (Beerse Glacial: Tiglian C4) within the warm Tiglian stage. The climatic deterioration led to a drop in sea level, which is reflected by a change in sediment provenance and sedimentary environments. Rhine supply was replaced by a local supply from central Belgium and the interglacial estuarine environment changed into a periglacial eolian sand sheet environment. Gleysols (H-Cg and Ah-Cg profiles) developed in the Beerse Member during phases of land surface stability. During the Beerse cold phase, vegetation was reduced to herbs and pine (tundra and boreal coniferous forest), indicating a mean summer temperature of about 10° C. The periglacial structures (involutions, frost cracks, initial ice-wedge casts) point to a mean annual temperature between –1 and –4° C, which is comparable with the temperature of the Weichselian Pleniglacial.

### Introduction

The climatic reconstruction of the Early Pleistocene in NW Europe has been based mainly on paleobotanical records (Zagwijn 1957, 1963a, 1975). The pollen assemblages revealed an alternation in time of warm-temperate and cold climatic conditions, which define successive interglacials and glacials. In 1957 Zagwijn introduced, in succession to the warm Tiglian stage, the Eburonian (cold), Waalian (warm) and Menapian (cold) stages (Table 1). The Tiglian stage was subdivided later in several warm-temperate (Tiglian A, Tiglian C3, Tiglian C5) and cool phases (Tiglian B, Tiglian C4; Zagwijn 1963b).

The presence of certain botanical species allows to make estimations concerning the minimum summer and winter temperatures, especially of the warmer Tiglian phases. The climatic evolution of

the Tiglian cool phases is more difficult to reconstruct from the pollen record. However, the mean annual temperatures of the colder phases can be estimated from the presence of specific periglacial structures (Maarleveld 1976, Romanovskij 1985, Vandenberghe & Kasse 1989). This article will focus on the climatic development of the Tiglian C4 cold phase as reflected by sedimentary environments and the presence of periglacial structures. Climate-related changes in vegetation will be dealt with as well.

The exposures investigated (Merksplas: 4°49'51"E–51°21'45"N; Beerse Dakt: 4°52'05"E–51°19'55"N; Beerse Blak: 4°49'03"E–51°19'03"N) are situated in northern Belgium (Fig. 1). The exposures Merksplas and Beerse Dakt were described previously in Kasse (1988). Exposure Beerse Blak mentioned in

the text is a newly excavated pit, situated 700 m south of the old exposure Beerse Blak described in Kasse (1988).

In the study area, Lower Pleistocene deposits occur close to the surface. They dip towards the middle of the North Sea basin, where the base of the Quaternary is found up to 900 m below the surface (Zagwijn 1989). To the south, the Lower Pleistocene has been eroded, because of the uplift of the Belgian hinterland. The Lower Pleistocene is covered by a thin layer (1–2 m) of mostly eolian, Weichselian sand. The surface of this layer forms a gently undulating coversand morphology, 25 to 30 m above sea level. Middle Pleistocene deposits are missing because of erosion, which is expressed by a gravel bed on the Lower Pleistocene. Due to the Middle and Late Pleistocene erosion, the so-called Campine microcuesta (De Ploey 1961) developed, which consists of Early Pleistocene estuarine clay beds. The cuesta slope dips gently towards the north. The studied exposures are situated on top of this microcuesta, where the clay beds are exploited by brick-factories.

During the Early Pleistocene, tidal, fluvial and eolian deposition occurred in the area, depending on climate and climate-related sea level changes (Kasse 1990b). The Lower Pleistocene sequence

consists of three members from bottom to top: the Rijkevorsel, Beerse and Turnhout Members, which together form the Campine Clay and Sand Formation (Paepé & Vanhoorne 1976). These Belgian lithostratigraphic units were correlated with the Tegelen Formation in the Netherlands (Zagwijn & Van Staalduinen 1975, Kasse 1988, 1990a).

The 'Beersien' was introduced by Dricot (1961) and defined as a sand unit, which is sandwiched between two clay units. It is a synonym of the Beerse Member. The sand unit is characterized by a stable, so-called B-Limburg, heavy mineral association. Dricot interpreted the 'Beersien' as an eolian sand deposited in an arctic climate during the Eburonian or Menapian glacial stages. Later Paepé & Vanhoorne (1970) correlated this unit with the Eburonian stage. Recently, Kasse (1988, 1990a) provided evidence that the Beerse Member is probably older and formed during an intra-Tiglian cold phase, probably the Tiglian C4 (Table 1). This result sheds new light on the climatic evolution of the Quaternary, since it indicates that periglacial conditions (and permafrost) already occurred during the early Early Pleistocene (Vandenberghe & Kasse 1989).

Table 1. Chronostratigraphy, lithostratigraphy, provenance and climate of the Early Pleistocene in the study area (R = Rhine, M = Meuse, S = Scheldt).

| CHRONOSTRATIGRAPHY |             | LITHOSTRATIGRAPHY  |                   | PROVENANCE         | CLIMATE |      |
|--------------------|-------------|--------------------|-------------------|--------------------|---------|------|
| EARLY-PLEISTOCENE  | Bavelian    | Kedichem Formation | Bavel Member      | R+M                | complex |      |
|                    | Menapian    |                    | Gilze Member      | S+M                | cold    |      |
|                    | Waalian     |                    |                   | S(+R)              | complex |      |
|                    | Eburonian   |                    |                   | S                  | cold    |      |
|                    | Tiglian     | C5                 | Tegelen Formation | Turnhout Member    | R(+S)   | warm |
|                    |             | C4                 |                   | Beerse Member      | S       | cold |
|                    |             | C3                 |                   | Rijkevorsel Member | R(+S)   | warm |
|                    |             | B                  |                   | hiatus             |         |      |
|                    | A           | warm               |                   |                    |         |      |
|                    | Praetiglian |                    |                   |                    |         | cold |

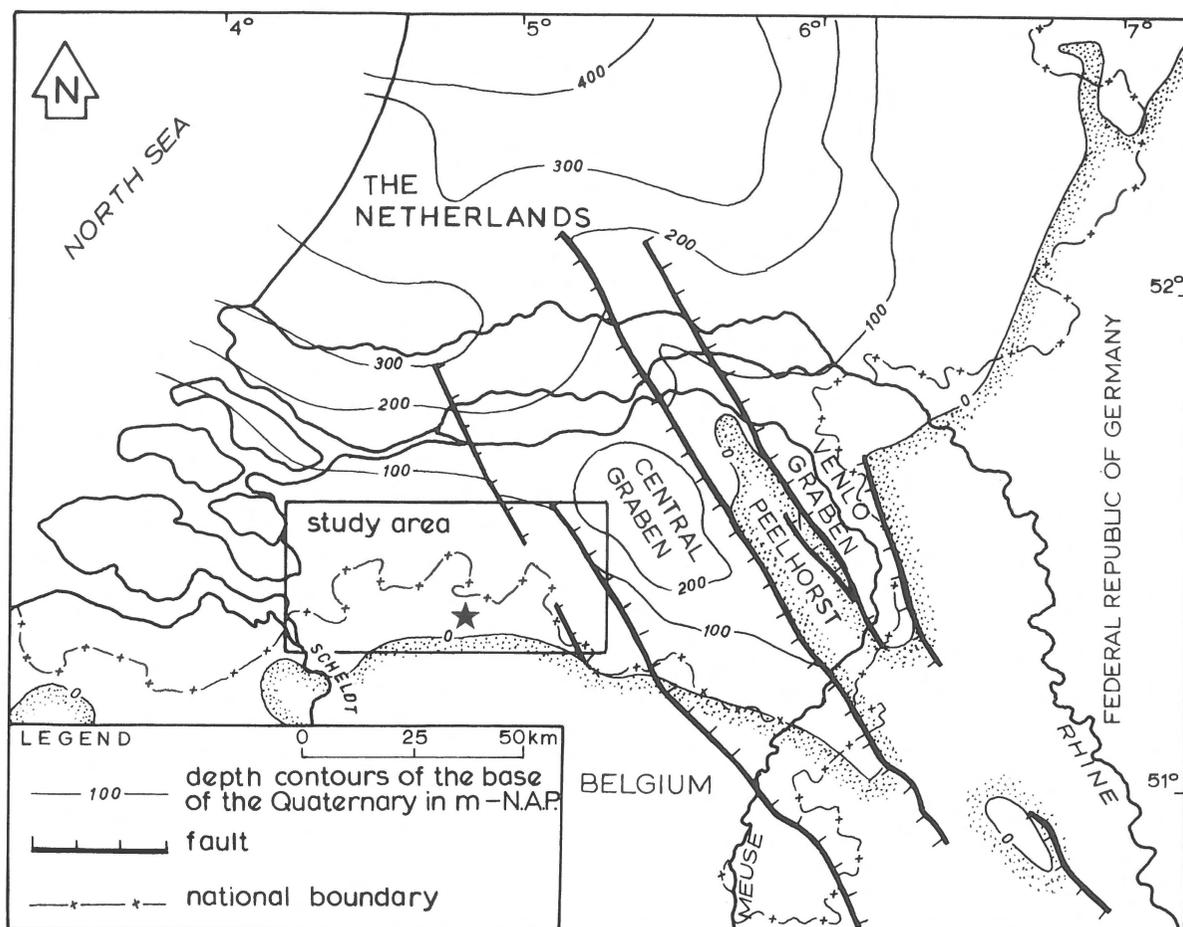


Fig. 1. Location map with depth contours of base Quaternary and major tectonic units of the southern North Sea basin (after Zagwijn & Doppert 1978). Asterisk indicates Merksplas-Beerse area.

### Lithostratigraphy and provenance

The stratigraphy of the area is illustrated in Table 1 and Fig. 2. Exposure Merksplas (Fig. 2) gives a fairly complete view of the Lower Pleistocene sequence. The clay beds at the base of the Merksplas exposure (Fig. 2: beds 1–4) form the upper part of the Rijkvorsel Member. This member is characterized by a fining-upward sequence, which formed in an inshore tidal (estuarine) environment (Dricot 1961, Kasse 1988). The clay (crumbly by soil ripening) and peaty beds in the upper part of the member reflect the final silting and freshening of the estuarine environment.

Garnet, epidote and hornblende are the dominant, unstable heavy minerals in the Rijkvorsel

Member (Fig. 3), which point to a Rhine supply (Zonneveld 1948). South of Merksplas the garnet, epidote and hornblende content decreases and zircon, rutile and tourmaline become more important. This change in heavy mineral composition is attributed to an additional supply from the south by the Scheldt and other Belgian rivers, discharging their sediment at the southern margin of the North Sea basin (Kasse 1988, 1990a).

The Rijkvorsel Member is concordantly overlain by the Beerse Member. The fluvial and eolian, fine sands of the Beerse Member are characterized by the presence of three or four, often strongly deformed humic soils or peat beds (Fig. 2: beds 6, 8 and 10; Fig. 6: soils 1–4). The Beerse Member has been preserved along the southern margin of the

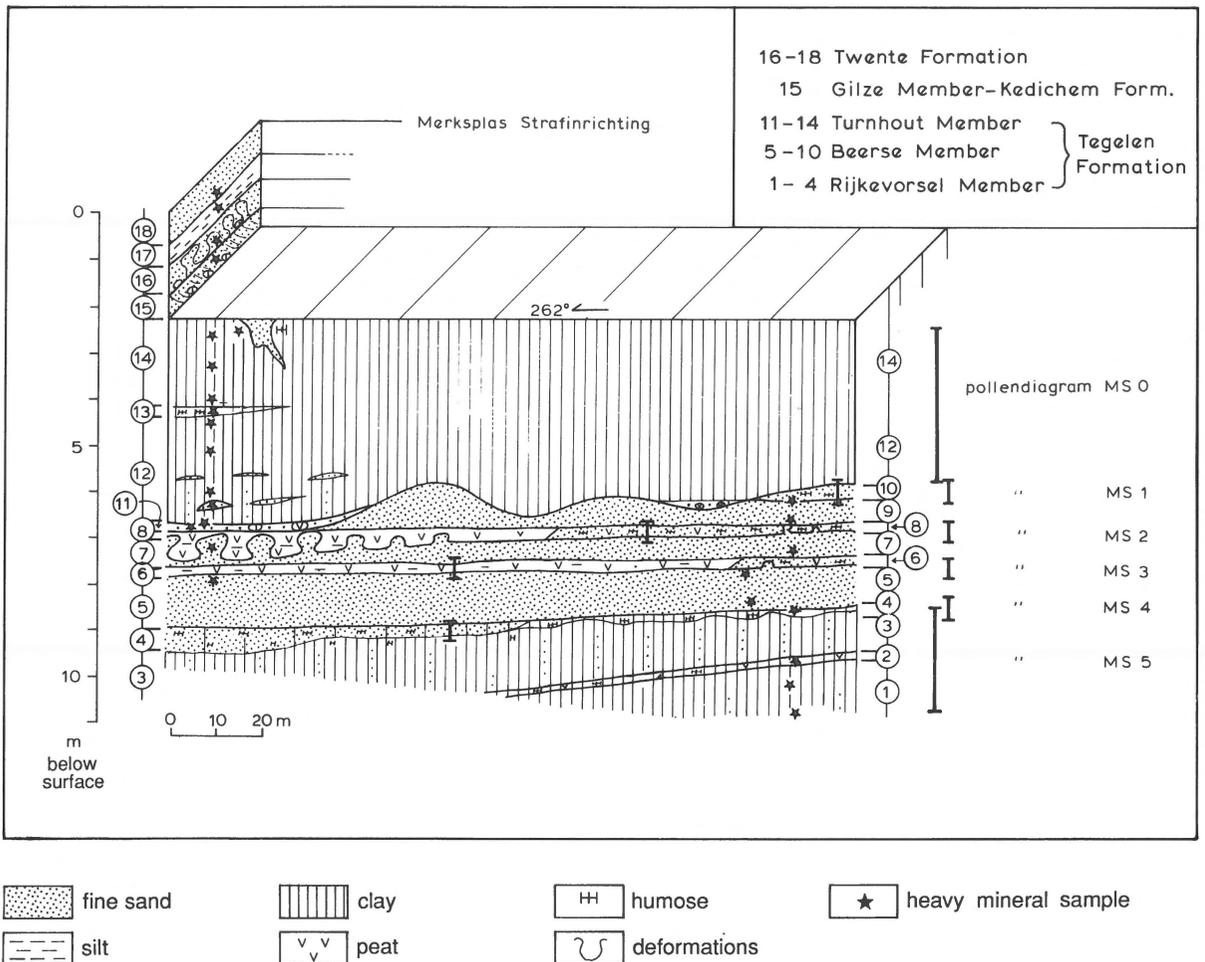


Fig. 2. Generalised geological profile of exposure Merksplas (surface is 25 m above sea level).

North Sea basin only. Basin inwards, this unit was eroded before the deposition of the Turnhout Member.

In contrast to the Rijkvorsel and Turnhout Members, the heavy mineral assemblage in the fine sands of the Beerse Member is dominated by stable species (zircon, rutile, staurolite, andalusite, kyanite and tourmaline; Fig. 3). This association reflects a strong increase of sediment supplied by the rivers from central Belgium (Kasse 1990a). Normally, the expansion of the Belgian river systems to the north, over the previously formed estuarine deposits of the Rijkvorsel Member, would be taken as progradation of the coast, leading to a sequence with fluvial and eolian deposits overlying inshore tidal and marine sediments. However, according to

the palynological results, this vertical facies change is accompanied by a change from temperate-type pollen assemblages in the Rijkvorsel Member to cool or cold-type assemblages in the Beerse Member (see Fig. 12). Therefore, the change in facies from the Rijkvorsel into the Beerse Member was not caused by simple progradation only; the deterioration of the climate probably resulted in a significant sea level drop, which caused a northward expansion of the central Belgian, river-dominated area (Kasse 1988, 1990a).

The Beerse Member is eroded by tidal channels of the marine transgression which led to the deposition of the Turnhout Member. Therefore, the thickness and number of soils of the Beerse Member can vary considerably over a short distance (see Fig. 2:

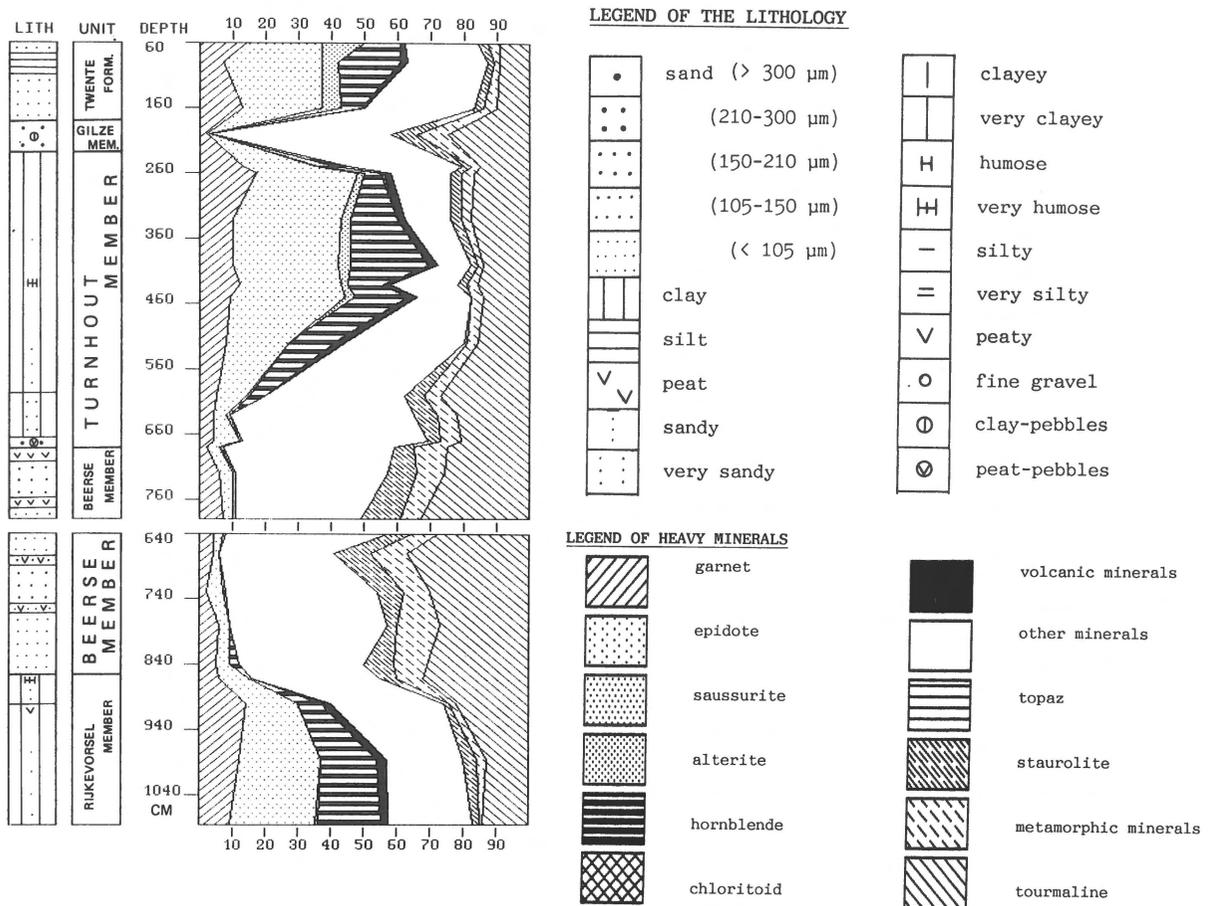


Fig. 3. Heavy mineral diagram of exposure Merksplas (depth in cm below surface; location of samples indicated in Fig. 2). Saussurite and topaz, shown in the legend, do not occur in the samples.

bed 10). The base of the Turnhout Member consists of fine to medium sand, locally with large peat clasts, eroded from peat beds in the Beerse Member (Fig. 4). A thick, crumbly, greenish gray clay bed, locally with an intercalated peaty bed, is found in the upper part of the Turnhout Member (Fig. 2: beds 12–14). The up to 5 m-thick, fining-upward sequence is explained by lateral migration of tidal channels (lateral accretion cross-bedding) and vertical accretion in the inshore tidal (estuarine) environment.

The heavy mineral composition of the Turnhout Member is similar to that of the Rijkevorsel Member (Fig. 3). The mixture of relatively unstable minerals (garnet, epidote, hornblende) and stable min-

erals (zircon, rutile, metamorphic minerals, tourmaline) points to the interfingering of two sediment-petrographical provinces. During the formation of the Turnhout Member, the Rhine flowed through the Central Graben to the northwest (Zagwijn 1989). The Rhine sediments, which are dominated by garnet, epidote and hornblende, were redistributed in the southern North Sea by tides and waves. Along the margin of the basin, an admixture occurred with sediments dominated by stable heavy minerals, which were supplied by the rivers from central Belgium (Kasse 1990a).

The fine-grained lithology, the sediment-petrographical composition and the stratigraphical position of the Rijkevorsel and Turnhout Members in-

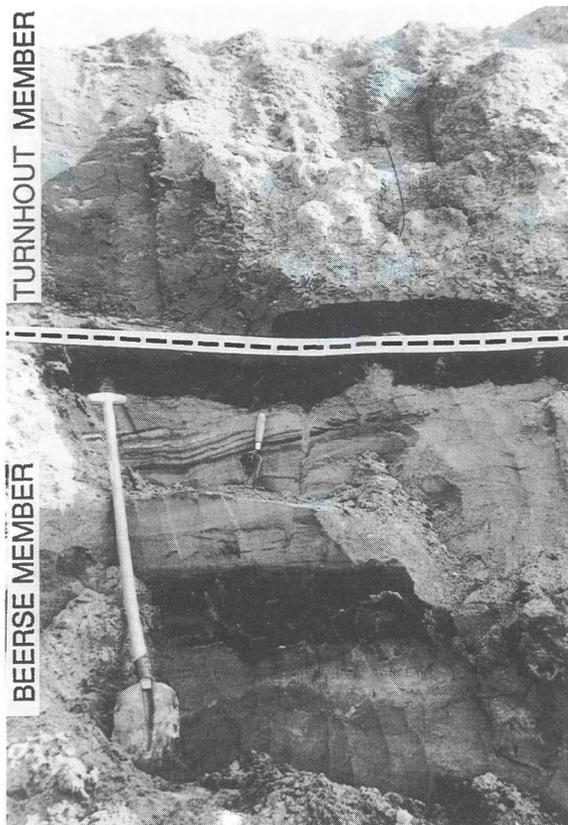


Fig. 4. Erosive base of an estuarine channel of the Turnhout Member with an elongate peat clast eroded from the Beerse Member. Note the frost crack below the peat soil in the Beerse Member (exposure Beerse Blak; spade for scale is 120 cm).

indicate that both units can be correlated with the Tegelen Formation in the Netherlands (Zagwijn & Van Staaldunin 1975, Kasse 1988). The presence of the water fern *Azolla tegeliensis* in both units indicates their Tiglian age (Kasse 1988, p. 118). Therefore, the intercalated Beerse Member is part of the Tegelen Formation and Tiglian as well. This age contrasts with previous results of Paepe & Vanhoorne (1970), who correlated the Rijkvorsel, Beerse and Turnhout Members with the Tiglian, Eburonian and Waalian, respectively.

On top of the Turnhout Member, a thin fluvial sand unit occurs locally; it is dominated by stable heavy minerals (Fig. 2: bed 15; Fig. 3: Gilze Member, Kedichem Formation). This unit is thin on the Campine microcuesta, because of Middle and Late Pleistocene erosion, but it thickens rapidly to the north. Pollenanalytical investigations of peat beds

in the Gilze Member indicate Eburonian, Waalian and Menapian ages (Kasse 1988).

The top of the Turnhout and Gilze Members is heavily deformed by a polygonal pattern of ice-wedge casts and involutions of Weichselian age. A gravel bed separates the Early Pleistocene Gilze and Turnhout Members from the Weichselian Twente Formation. The hiatus reflects the Middle and Late Pleistocene erosion, by which the Campine microcuesta developed. In this erosional phase sand was removed and the gravel was concentrated in a lag deposit.

### Depositional environment

The Beerse Member consists of fine sand (105–210  $\mu\text{m}$ ) with several humic or peaty soils and periglacial structures (Figs 2, 6). The bedding types in the Early Pleistocene Beerse Member resemble those of the Late Pleistocene coversands (Schwan 1988). Discontinuous and continuous wavy bedding are dominant (Fig. 5). Small-scale cross-lamination, low-angle cross-bedding and horizontal parallel lamination occur less frequently. The wavy bedding is explained by adhesion of windblown sand in plane beds or small adhesion ripples on a moist to wet surface. Local reworking of this eolian sediment by surficial runoff formed some small-scale cross-lamination (Fig. 5: between 70–80 cm). The horizontal parallel lamination (top Fig. 5) is interpreted as eolian deposition in plane beds or flat wind ripples on a dry surface. The alternations in the upper part of the lacquer peel of wavy, adhesion ripple bedding and eolian, plane bed lamination indicate subtle changes in soil moisture content. A high groundwater table with saturated conditions at the surface resulted in adhesion ripple formation, while a groundwater table slightly below the surface resulted in plane bed deposition.

The Beerse Member shows a drying-upward sequence with an upward decrease of current flow and soil moisture content (Fig. 6). In the lower part, more small-scale current ripple cross-lamination and shallow channel fill cross-bedding are found (see Fig. 4 and 5). Towards the top, wet eolian adhesion ripple bedding and dry eolian plane bedding

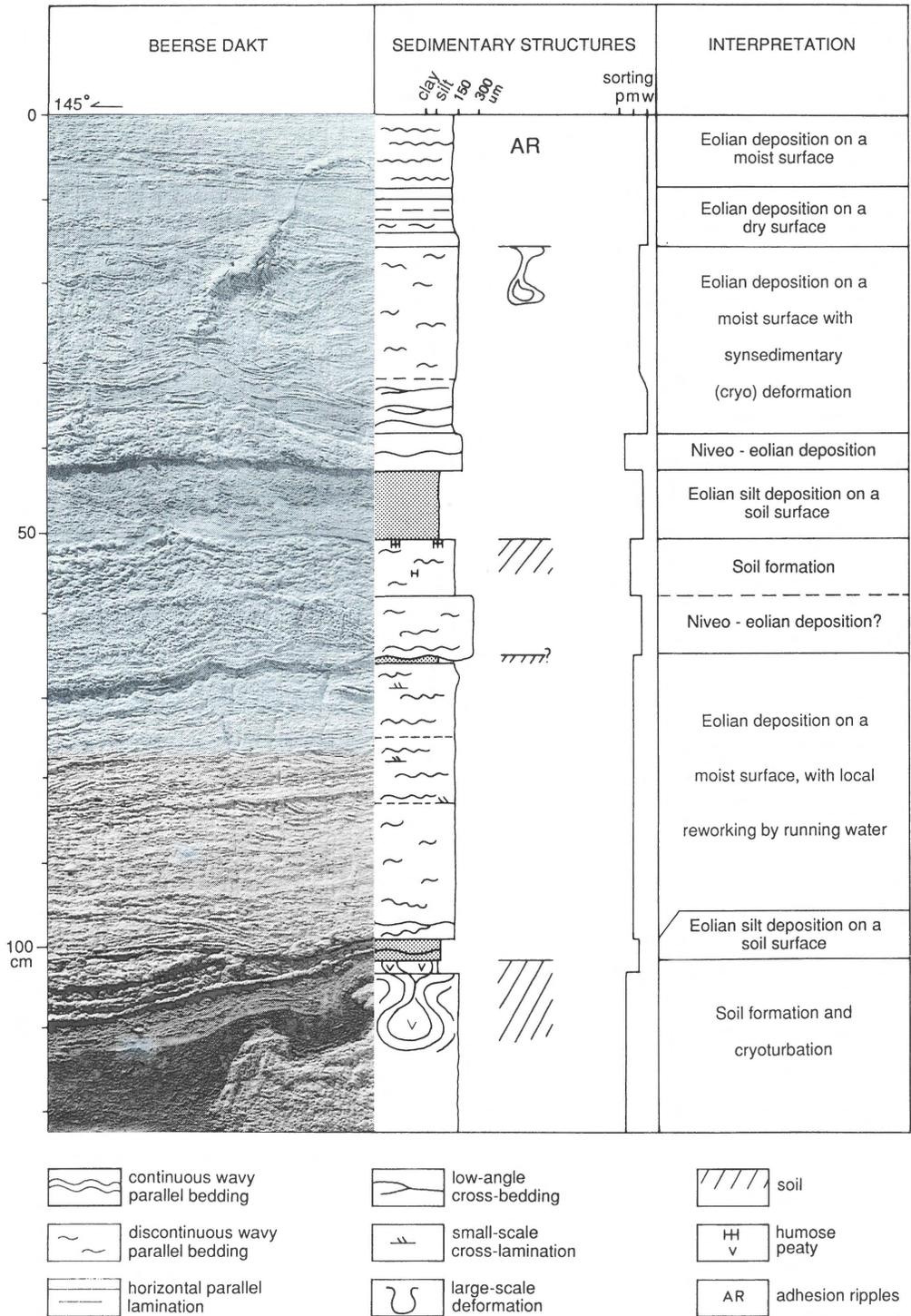


Fig. 5. Lacquer peel of the lower part of the Beerse Member with eolian and shallow fluvial deposits interrupted by soil formation (exposure Beerse Dakt). Sorting: p = poorly, m = moderately, w = well sorted. Fine stippling indicates silt.

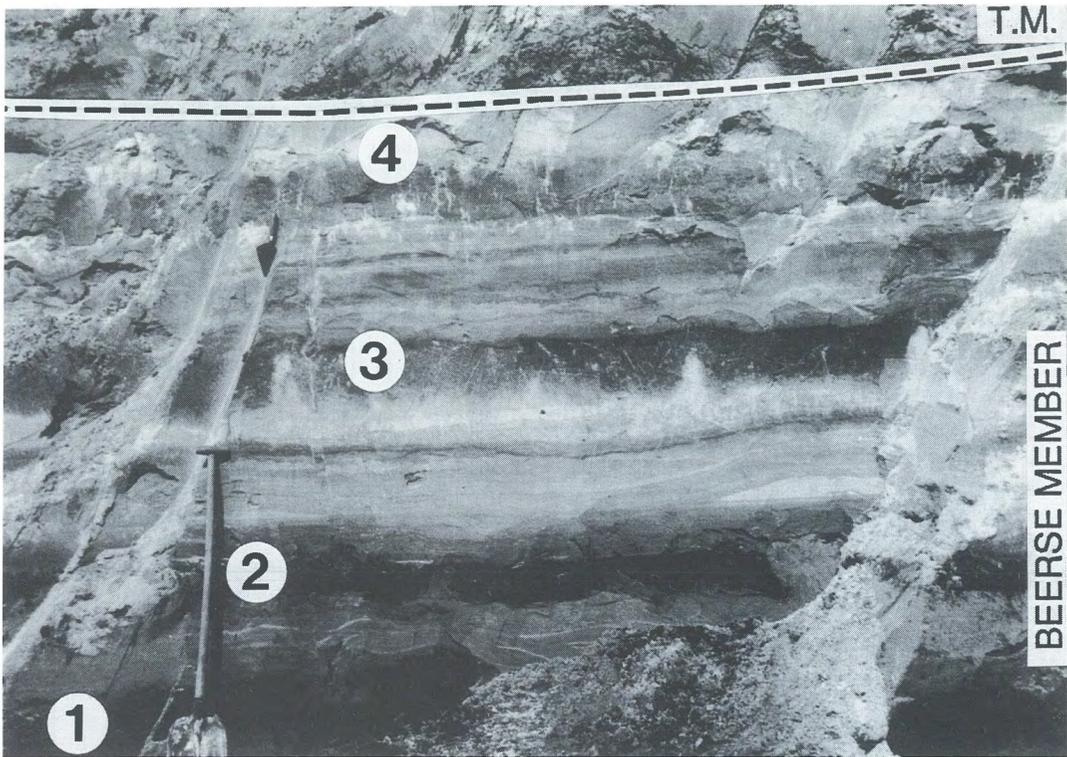


Fig. 6. Paleosols 1 to 4 reflecting the drying-up sequence in the Beerse Member. 1 = clayey peat (H-horizon); 2 = peat (H-horizon); 3 = humic sand (Ah-horizon); 4 = eluviation horizon (E) and illuviation horizon (B) of podzol soil. The Ah horizon of the podzol has been eroded by the Turnhout Member (T.M.) (exposure Beerse Blak; spade for scale is 120 cm).

occur more frequently. A comparable 'drying-up' sequence is locally found, at a smaller scale, within one sand unit between two soils (Kasse 1988: fig. 3.9).

It is unknown whether this upward decrease in humidity is due to sedimentation itself or to climatological changes. The first hypothesis, being the most simple, is favoured here. At first sand deposition occurred on an impermeable clayey subsoil and the sand layer was quickly saturated by snow melt or precipitation, leading to surficial runoff. The increasing thickness of the sandy Beerse Member enlarged the water storing capacity. Surficial water flow diminished and eolian processes became more important, if it is assumed that precipitation and evapotranspiration remained constant.

The eolian origin of the Beerse Member is also indicated by its geomorphological position. The sand units and the peat beds and soils occur in a stacked sequence (Fig. 2: beds 5–10). The humic, sandy soils are present above each other in the east-

ern part of the exposure (Fig. 2). The equivalent peaty beds, formed in low and wet conditions, occur in the western part. The sand units form parallel sheets with uniform thickness between the soils and peaty beds. Such a stacked sequence is explained by deposition in eolian sand sheets (Ruegg 1983, Kocurek & Nielson 1986, Schwan 1988). Eolian sand sheet formation was favoured by three factors: 1) Large-scale topographic barriers that could stop the flow of sand were absent. The deposition of the eolian sands occurred on the former estuarine plain of the Rijkevorsel Member. 2) Sparseness of vegetation. There are no sedimentological features (root-mottling, structureless beds) that point to the presence of vegetation during the deposition of the sand units. The general wavyness of the bedding is attributed to eolian deposition on a moist to wet surface. 3) The high ratio between wind energy and sand availability. The high ratio was caused by the seasonally frozen state of the soil in winter (frost cracks) and the thawed wet state in summer. The

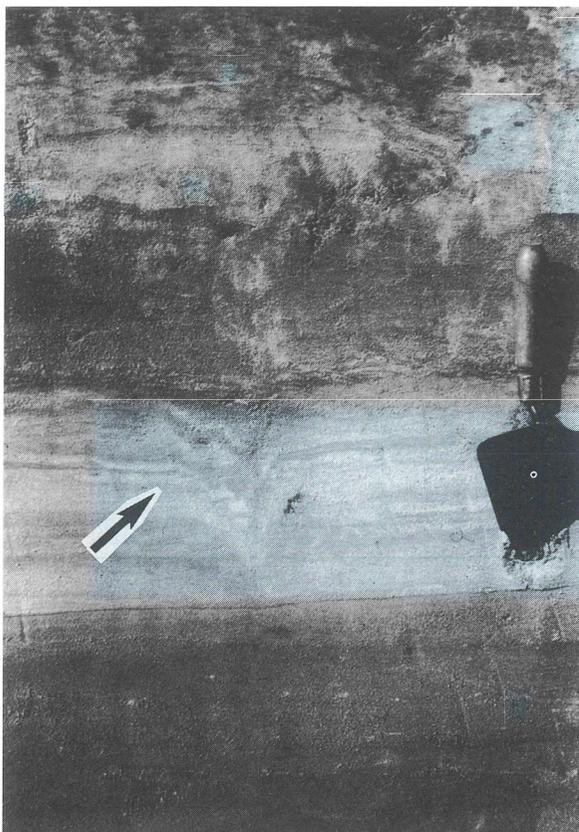


Fig. 7. Initial ice-wedge cast (between soils 2 and 3) in the Beerse Member. Note the normal faulting (arrow) caused by melting of the ice wedge (exposure Beerse Blak; trowel for scale is 25 cm).

high water table is inferred from the presence of adhesion ripple lamination and peat beds. The presence of small-scale, current ripple cross-lamination points to periodic flooding of the depositional surface. The combination of deep seasonal frost, a high water table and periodic flooding suppressed the sand availability for dune formation and favoured the vertical accretion in eolian sand sheets.

The wind direction during deposition of the Beerse Member could not be established in most layers, because of the parallel horizontal nature of the bedding. Only in one lacquer peel (exposure Merksplas: Kasse 1988: fig. 3.9) the direction could be reconstructed from the presence of wind ripples and small-scale, wind ripple cross-lamination. The sedimentary structures indicate an eastern wind blowing westward.

## Paleosols

The paleosols in the Beerse Member represent periods of non-deposition and surface stability in between the sand sheet accumulation phases. Peaty soils developed in the wet depressions and humic soils were formed laterally on the higher locations at Merksplas (see Fig. 2: beds 6, 8, 10). In the Beerse Blak exposure, a vertical soil sequence is present which reflects a decrease in soil moisture content during the successive phases of soil formation (Fig. 6: paleosols 1–4). The lowermost phase of surface stability is characterized by a clayey peat bed, which points to some clastic input by fluvial processes during the peat formation (H-Cg soil profile). The next overlying soil is purely organic, reflecting wet conditions without a clastic influx (H-Cg profile). The peaty soils 1 and 2 have a brown colour.

The third soil consists of a humic Ah horizon with charcoal spots overlying a somewhat bleached E and mottled Cg horizon. The Ah horizon has a brownish gray to purplish gray colour. The soil is somewhat bleached and impoverished in iron. The light gray to pale yellow subsoil is clearly mottled by iron (Cg-horizon). These gley features indicate periodic water saturation of the soil, which resulted in reduction and mobilization of the iron compounds. Subsequent oxidation during the dry season led to the precipitation of these compounds in iron oxides.

These H-Cg and Ah-(E)-Cg soils can be classified as Gleysols or Gelic Gleysol (FAO 1988) if permafrost was present during the soil formation (see below). The present-day Gelic Gleysols have a mean annual temperature below  $-1^{\circ}\text{C}$  (FitzPatrick 1983). Grasses, sedges, lichens and mosses are dominant in most plant communities on these soils. Where these recent soils grade into those of warmer areas, trees become more important and the vegetation becomes characterized by conifers (FitzPatrick 1983). Similar plant communities are also deduced from the pollen diagrams of the soils and peat beds in the Beerse Member, which are dominated by pine, grasses, sedges and heather (see section Vegetation).

The fourth soil (Fig. 6), which formed in the top of the Beerse Member and survived later erosion only locally, reveals an Ah-E-B-Cg soil profile. The



Fig. 8. Large-scale deformations of sand and peat beds in the Beerse Member, erosively overlain by the estuarine sediments of the Turnhout Member (T.M.) (exposure Merksplas; spade is 120 cm).

very white and loose, eluvial E horizon and the underlying illuvial, compact B horizon are characteristic for a Podzol soil (FAO 1988). Since this soil was formed after the deposition of the Beerse Member, it does not give paleoclimatological information concerning the Beerse Member itself. It cannot be excluded that this podzol soil developed during the interglacial following the glacial phase in which the Beerse Member was formed. Podzolization then occurred before the area was covered by estuarine sediments of the Turnhout Member, due to the postglacial eustatic sea level rise.

The paleosols at Beerse are often covered by silt beds (Fig. 5). These silt beds were formed at the start of a new, sand sheet depositional phase, when the receiving site was not yet reached by the saltation sand carpet. Suspension clouds of silt were generated in the source area during strong winds. This silt settled from suspension during fair weather periods on the soils of the receiving site. Later the migrating sand sheet reached the receiving site and eo-

lian sand deposition became dominant over the continued, regional fall out of silt.

### Periglacial structures

The Beerse Member is characterized by the presence of several types of periglacial structures (Kasse 1988, Vandenberghe & Kasse 1989). Frost cracks (up to 100 cm deep) are found below and in association with each soil (Fig. 4). This means that climatic conditions remained rather constant during the successive phases of soil surface stability. The soils do therefore not represent relatively warmer climatic intervals, separating colder phases with sand deposition. Small ice-wedge casts (c. 25 cm wide and 50 cm deep) occur occasionally (Fig. 7). They are restricted to a few levels within the Beerse Member. A correlation with specific soil horizons was not found, since they are located within the sand units enveloped by soil horizons. They

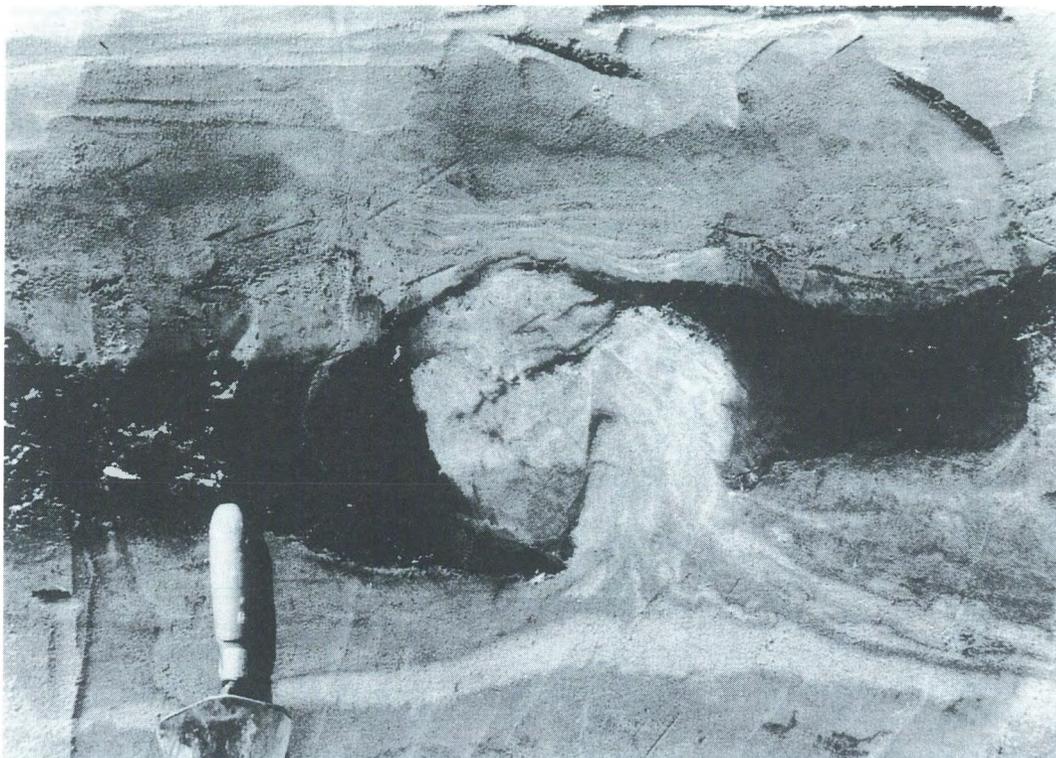


Fig. 9. Cauliflower-like intrusion of sand into peaty soil 2 (Fig. 6) of the Beerse Member at Beerse Blak (trowel for scale is 25 cm).

are regarded as initial ice-wedge casts which survived only a restricted timespan.

Large-scale deformations of the peaty beds are common. The peaty soils are often stronger deformed than the humic soils, probably because of the higher soil moisture content of the peaty soils at the time of disturbance. The involutions are often regularly spaced and reach a maximal depth of 100 cm (Fig. 8). In the weaker deformed parts of the peaty soils, the deformations appear to be intrusions of sand from below, injected in the overlying peat bed, making cauliflower-like structures (Fig. 9). In a horizontal section the sand intrusions form a polygonal pattern with the sand forming the polygon lines, while the peat is found in the polygon centres (Fig. 10). This special type of cryoturbation, caused by sand intrusion from below, will be described in more detail by Vandenberghe (1992). Associated with these sand intrusions, frost cracks were found locally below the injections (Fig. 11). It is concluded that the sand intruded upward into a polygonal frost crack pattern, which was present in the peaty soil. The injection, causing the deforma-

tions, occurred shortly after the start of a new sedimentation phase, as the silty bed on top of the peaty soil is also disturbed by the intrusions, while the overlying sand is undisturbed. The deposition on the peaty soil probably led to an increase in pore water pressure and oversaturation of the sand bed below the peaty soil. Because of the presence of more or less impermeable beds (underlying peaty soil 1 and Rijkvorsel Member clay) in the subsoil, the liquified sand was expelled upward and intruded the peaty soil on its way to the surface. The resulting deformations therefore are not evidence for a climatic amelioration during the formation of the peaty soil, since they were formed by an inversed density gradient caused by the renewed sedimentation. The degradation of local ground ice, caused by the start of the sedimentation, may have strengthened this process, since more ground ice will have been present in the low-lying, more humid depressions.

The frequent occurrence of frost cracks points to a mean annual temperature below  $-1^{\circ}\text{C}$  during the deposition of the Beerse Member. The initial ice-



Fig. 10. Horizontal section of peaty soil 2 (Fig. 6) in the Beerse Member showing a polygon pattern formed by the injection of sand in a preexisting frost crack network (exposure Beerse Blak; spade is 120 cm).

wedge casts testify to the presence of at least episodic permafrost. This means that the mean annual temperature was about  $-4^{\circ}\text{C}$  (Romanovskij 1985). From this estimation it is concluded that the Beerse Member was formed in a cold period within the Tiglian stage.

### Vegetation

The vegetation of the Beerse Member was studied by pollen analysis of the humic soils and peaty beds. The results are presented in Fig. 12.

Diagram Merksplas 5 reveals a change in vegetation in the upper part of the Rijkevorsel clay. At the base of this diagram thermophilous trees of dry (*Quercus*) and wet (*Alnus*) habitats are present. The high Chenopodiaceae content (11%) illustrates the inshore tidal, estuarine depositional environment of the Rijkevorsel Member. The presence of *Azolla tegeliensis* in the member, reported by Greguss & Vanhoorne (1961), points to a Tiglian age

(Zagwijn 1963b). Kasse (1988) dated the member in the warm temperate Tiglian C3 phase.

The upper part of the Rijkevorsel Member (Fig. 12: top diagram Merksplas 5 and Merksplas 4) reveals a completely different vegetation type. Thermophilous trees are absent and the pollen spectrum is dominated by *Pinus*, Gramineae, Cyperaceae and Ericaceae. This pollen assemblage indicates a boreal coniferous forest vegetation.

Unfortunately, the transition of the warm temperate forest vegetation of the Tiglian C3 period into the boreal vegetation of the Tiglian C4 is missing. This interval contains no pollen, probably because of oxidation and soil ripening during the final silting up of the Rijkevorsel Member environment.

Like in the top of the Rijkevorsel Member, the soils within the Beerse Member are characterized by *Pinus*, Gramineae, Cyperaceae and Ericaceae (Fig. 12: Merksplas 3 and 2). The differences in pollen composition in Merksplas 3 and 2 are caused by local factors and local dominance of species. The peat bed of Merksplas 3 formed in a wet environ-

ment and accordingly, the diagram is dominated by species of wet habitats (Gramineae and Cyperaceae). The soil of Merksplas 2 on the other hand developed under dryer conditions, which is reflected by higher values of Ericaceae.

The increase of *Artemisia* in the top of Merksplas 3 and of *Thalictrum* in Merksplas 2 possibly indicate a change to a more continental climate during the formation of the upper part of the Beerse Member.

The soil at the top of this member shows a different pollen composition (Fig. 12: Merksplas 1). It is characterized by *Alnus* and Ericaceae. The *Alnus* increase possibly represents the climatological change from the cold Tiglian C4 into the warm temperate Tiglian C5. The boreal coniferous forest (Merksplas 2, 3, 4) was succeeded by a deciduous forest (Merksplas 1 and 0). It is supposed that soil Merksplas 1 represents an interglacial soil, which was formed before the marine transgression inundated the area in the course of the Tiglian C5. This marine transgression, caused by post-glacial sea level rise, locally eroded soil Merksplas 1, and deposited a 4–5 m-thick clay unit in the area (see Fig. 2: Turnhout Member). Like in the Rijkevorsel Member, the pollen composition of the Turnhout Member is characterized by thermophilous trees of dry and wet habitats (up to 30% in Fig. 12: Merksplas 0), which points to deposition in a warm temperate climate. The estuarine nature of the clay unit is expressed by the abundance of Chenopodiaceae (up to 40%). The presence of macroremains of *Azolla tegeliensis* in Merksplas 0 at 5.2 m below the surface proves the Tiglian age of the Turnhout Member. Kasse (1988) related this member more precisely to the Tiglian C5 phase.

### Climatic evolution during the Late Tiglian

Paleobotanical information and periglacial phenomena have been used to reconstruct the mean annual and mean July temperature curves of the Tiglian stage (Zagwijn 1963b, Vandenberghe & Kasse 1989).

The pollen of *Ilex* and *Hedera* in the Rijkevorsel and Turnhout Members indicate an oceanic climate with mild winter conditions and mean winter tem-

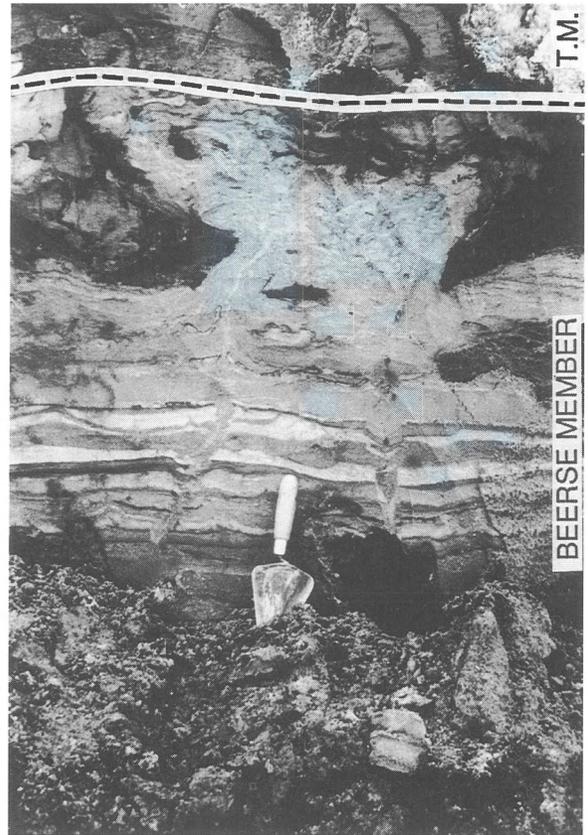


Fig. 11. Frost cracks below an intrusion of sand in peaty soil 2 (Fig. 6) of the Beerse Member (T.M. is Turnhout Member; exposure Beerse Blak; trowel is 25 cm).

peratures above 0° C during the Tiglian C3 and C5 interglacials. *Hedera*, *Vitis* and *Eucommia* are connected to a mean summer temperature between 16 and 20° C (Zagwijn 1963b).

The abundance of *Pinus*, Gramineae, Cyperaceae and Ericaceae in the soils of the Beerse Member points to an open, pine forest vegetation. From this a mean summer temperature can be inferred of about 10° C. This implies a summer temperature drop of almost 10° C at the transition from Tiglian C3 to Tiglian C4.

The frost cracks and initial ice-wedge casts in the Beerse Member allow an estimation of the mean annual temperature between –1 and –4° C. The mean summer temperature (10° C) and the mean annual temperature (–1 to –4° C) point to a mean winter temperature of –12 to –18° C during the Beerse Glacial. These estimations reveal that the mean temperatures of the Early Pleistocene Beerse



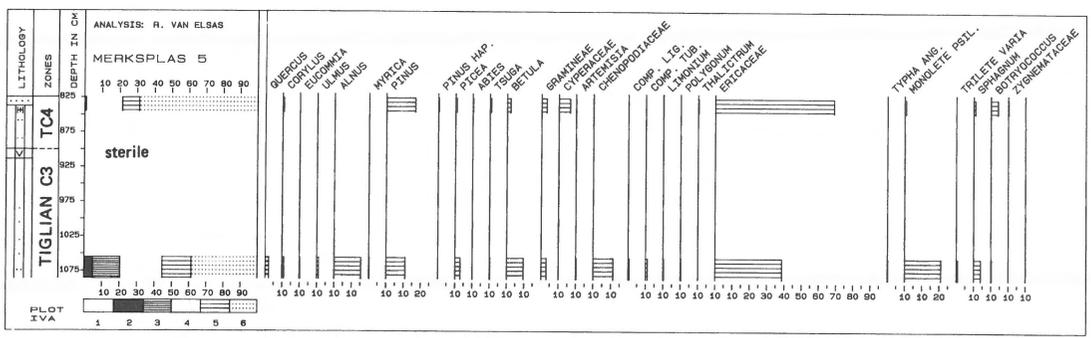
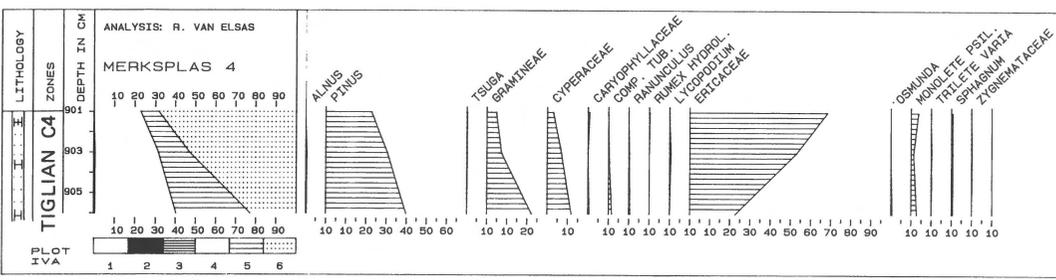
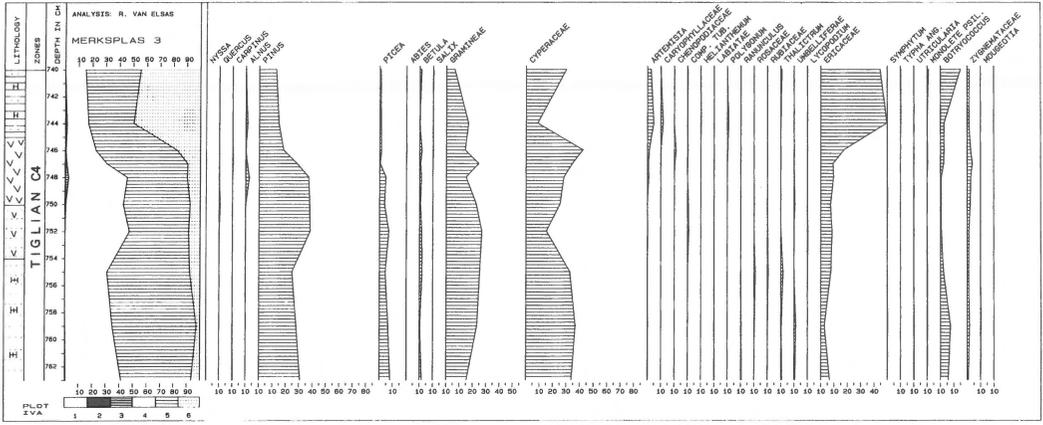


Fig. 12. Pollen diagrams of the Rijkvorsel (Tiglian C3), Beerse (Tiglian C4) and Turnhout Member (Tiglian C5) at Merksplas. Boundary between Beerse and Turnhout Members is at 590 cm depth. Legend of main diagram: 1 = Tertiary trees; 2 = thermophilous trees (dry habitats); 3 = thermophilous trees (wet habitats); 4 = other trees; 5 = terrestrial herbs; 6 = Ericales. Depth in cm below the surface; location of sampled intervals indicated in Fig. 2.

Glacial are comparable to those of the Weichselian Pleniglacial (Ran & Van Huissteden 1990).

**Conclusions**

The study of the Early Pleistocene Tiglian deposits in northern Belgium shows that:

1. The Tiglian stage is characterized by strong climatic fluctuations. The warm temperate climate (mean July = 18° C) of the Tiglian C3 and C5 phases was interrupted by the boreal to tundra climate (mean July = 10° C) of the Tiglian C4 (Beerse Glacial).
2. The interglacial climates of the Tiglian C3 and C5 resulted in two phases with a high sea level.

Deposition of Rhine-derived sediments occurred in an estuarine environment (Rijkevorsel and Turnhout Members). During the intervening Beerse Glacial (Tiglian C4) a eustatic sea level drop took place. Fluvial and eolian deposition of Scheldt provenance (Beerse Member) extended northward over the former estuarine plain of the Rijkevorsel Member.

3. The depositional environments of the Beerse Glacial are characterized by shallow fluvial systems and eolian sand sheets. Sand sheet formation was favoured by the high water table, local surficial runoff, the absence of topographic barriers and the sparseness of vegetation.
4. During the formation of the Beerse Member, phases with sand sheet deposition were interrupted by three phases of land surface stability in which Gleysols developed. The clastic sediments of the depositional phases and the paleosols reveal a gradual drying-upward sequence. The Podzol soil in the top of the Beerse Member was formed during the interglacial Tiglian C5 phase, following the Beerse Glacial. This soil was covered later by the estuarine Turnhout Member as a consequence of the Tiglian C5 eustatic sea level rise.
5. The vegetation of the Beerse Glacial was reduced to a boreal, coniferous or tundra vegetation. The wet habitats were dominated by Gramineae and Cyperaceae; *Pinus* and Ericaceae grew on the higher locations. A mean July temperature around 10° C is inferred from the presence of the boreal coniferous elements in the vegetation of the paleosols.
6. The periglacial phenomena (frost cracks, initial ice-wedge casts and large-scale cryoturbations) in the Beerse Member indicate a mean annual temperature between -1 and -4° C. Together with the palynological data, these estimations indicate that the interglacial (Tiglian C3) – glacial (Tiglian C4) – interglacial (Tiglian C5) cycle was accompanied by fluctuations in the annual temperature of more than 10° C.

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