EARLY-PLEISTOCENE TIDAL AND FLUVIATILE ENVIRONMENTS IN THE SOUTHERN NETHERLANDS AND NORTHERN BELGIUM

Kees Kasse
4. CHRONOSTRATIGRAPHY

4.1. Introduction

The age of the Early-Pleistocene deposits in Noord-Brabant and northern Belgium has been investigated previously in several studies (Van der Vlerk and Florschütz, 1953; Tavernier, 1954; Van Dorsser, 1956; Dricot, 1961; De Ploey, 1961; Paepe and Vanhoorne, 1970; Van Montfrans, 1971; Geys, 1975; Hus et al., 1976). The conclusions, however, were not very coherent (see §4.2), since a Tigilian up to a Cromerian age has been proposed. Furthermore, equivalent deposits in The Netherlands and Belgium were correlated with different chronostratigraphic stages. Finally, biostratigraphical and paleomagnetic methods were used in combination only sporadically.

The present study therefore aimed at:
1. Accurately establishing the chronostratigraphic position of the various lithostratigraphic units with the highest possible resolution, in order to enable reliable paleogeographic reconstructions.
2. Correlating the chronostratigraphy in The Netherlands and Belgium.
3. Integrating magnetostratigraphic and bio-climatostratigraphic evidence.

In The Netherlands the Pliocene-Pleistocene boundary is commonly placed at the base of the Praetiglacial glacial, 2.5 m.y. ago (Zagwijn, 1975b). The age of this boundary is still a matter for discussion, as it has also been dated at 1.6 m.y., at the top of the Olduvai magnetozone (Haq et al., 1977; Jenkins, 1987). However, in the study area cold periods, older than 1.6 m.y. and characteristic for the Quaternary are present. In accordance with Zagwijn these cold phases are included in the Pleistocene and the Pliocene-Pleistocene boundary is therefore maintained at 2.5 m.y.

As in other parts of The Netherlands and Belgium the Early-Pleistocene deposits in the area cannot be dated by absolute dating techniques. Therefore, the age of the deposits was established by pollen analysis, some guide fossils, the magnetic polarity and to a certain extent the lithostratigraphic position. The results have been correlated with the existing biochronostratigraphic time scale of The Netherlands (Zagwijn, 1986).

The pollen assemblages of Quaternary deposits in The Netherlands reveal an alternation in time of warm-temperate and cold climatic conditions, which define successive interglacials and glacial (Zagwijn, 1986). The pollen analytical investigations show an intricate climatic evolution. Several stages, which were formerly considered as interglacials, later appeared to be complexes of warmer and cooler periods (Zagwijn, 1957, 1960, 1971, 1974; Zagwijn and De Jong, 1984). The Early-Pleistocene warm-temperate phases are all characterized paleobotanically by low percentages of Early-Pleistocene species like Pterocarya, Carya, Tsuga and Eucommia. Tertiary floral elements such as Nyssa and Sciadopitys are absent or reworked from underlying deposits (Zagwijn, 1975b).

The geomagnetic method offers the opportunity to establish a magnetostratigraphic time scale. The latter is based on the recorded reversals of the earth magnetic field and associated magnetozones, which are correlated with the well established polarity time scale of the Quaternary (Mankinen and Dalrymple, 1979). During the Quaternary at least 8 reversals are known with certainty (Hus, 1988). The combination of the pollen record, the magnetostratigraphy and lithostratigraphy, results in a more complete chronological framework for the geological evolution in the investigated area.
4.2 Historical review

Since the start of the geological investigations in the Dutch-Belgian border area in the late 19th century, the age of the deposits has been a matter for discussion (see table 2.1 for the lithostratigraphic nomenclature). An extensive review has been given by Geys (1975). A Pleistocene (Tiglian) age has been proposed for the Campine/Tegelen Formation by Van der Vlerk and Florschütz (1953) and Tavernier (1954), on the basis of paleobotanical similarities with the Tiglian deposits in the Tegelen type area in the Dutch province of Limburg. The underlying Mol Sands (and Merksplas Sands) were finally dated as of Tertiary age (Vanhoorne, 1962). A Tiglian or Taxandrian age ("Kedichem Series") has also been proposed for the Early-Pleistocene deposits close to the surface in Noord-Brabant (Nelson and Van der Hammen, 1950; Doppert and Zonneveld, 1955).

In 1957 Zagwijn introduced a more detailed subdivision of the Early-Pleistocene in The Netherlands, based on pollen analysis. In succession to the Tiglian, he defined the Eburonian, Waalian and Menapian periods, which correspond respectively to a glacial, interglacial and glacial climate.

Paepe and Vanhoorne (1970, 1976) later applied this Dutch chronostratigraphic subdivision in Belgium. The Rijkevorsel Member was connected with the Tiglian period, because of the presence of Azolla tegellensis (Greguss and Vanhoorne, 1961). The overlying Beerse and Turnhout Members were correlated with the Eburonian and Waalian periods respectively, based on the observation of periglacial phenomena in the Beerse Member. A paleomagnetic reversal from reversed to normal in the upper part of the Turnhout Member was interpreted as corresponding to the base of the Jaramillo magnetozone (Van Montfrans, 1971; Paepe and Vanhoorne, 1970). Some discrepancies developed when Zagwijn (1975a, 1979) located the Waalian shoreline west of the recent Dutch coast, whereas Paepe and Vanhoorne (1970) described tidal flat and marsh deposits of Waalian age in Belgium, as far east as Turnhout (Turnhout Member).

On the top of the Campine/Tegelen Formation, sands with a stable heavy mineral composition are predominantly present (§2.5.8: Gilze Member). In Belgium these sands have been dated as Early- and Middle-Weichselian (De Ploey, 1961: St. Lenaarts Formation; Haest, 1985; Haest et al., 1986). The St. Lenaarts Formation has been continued in The Netherlands in the so-called Alphen Sands (§2.6), which have been interpreted as probably Menapian (Vandenberghhe and Krook, 1981; Vandenberghhe et al., 1986).

In 1984 Zagwijn and De Jong defined a new chronostratigraphic stage (Bavelian) in the Early-Pleistocene, which comprises two interglacials and two glacials. Deposits of Bavelian age were identified at Bavel, in the Central Graben, in terrace deposits of the Meuse and in the Central Netherlands.

Based on the review given above the following questions arise:
1. In which phase(s) of the Tiglian was the Rijkevorsel Member formed (Greguss and Vanhoorne, 1961; Paepe and Vanhoorne, 1970)?
2. Is the Beerse Member of Eburonian/Menapian age and the Turnhout Member of Waalian/Cromerian age (Dricot, 1961; De Ploey, 1961; Paepe and Vanhoorne, 1970, 1976)? How to explain in that case the occurrence of perimarine deposits in Belgium (Turnhout Member) and fluvialite deposits in The Netherlands (Kedichem Formation; Zagwijn and Van Staaldhuizen, 1975)?
3. Do both the Hoogerheide and Woensdrecht Members belong to the
Tiglian (Nelson and Van der Hammen, 1950) or are they partly younger (Van Doersele, 1956)? Is the top of the Woensdrecht Member in the west and the Turnhout Member in the east isochronous?

4. Has the Gilze Member been deposited in the Early-Pleistocene or Late-Pleistocene during one or several stages (Menapian) (De Ploey, 1961; Vandenberghhe and Krukk, 1981)?

5. Are deposits of Bavelian age present in western Noord-Brabant?

4.3 Results

4.3.1 Biostratigraphy

In this paragraph the paleobotanical results are presented in a chronological order. The chronostratigraphic interpretations have been summarized in Table 4.1. Only the most relevant pollen diagrams are discussed in the text. The remainder is presented in the appendix.

Table 4.1: Bio(chrono)stratigraphic interpretation of the investigated pollen sections.

<table>
<thead>
<tr>
<th>BIO-CHRONO-STRATIGRAPHY</th>
<th>LOCATIONS</th>
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<tr>
<td>BAELERIE</td>
<td>BEVERBOUT</td>
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<td>BAVELIAN</td>
<td>MENAPIAN</td>
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The pollen samples have been taken from borings and from exposures. In general only clay-, silt- and peat-layers were sampled. Sand-beds are often poor in pollen and the pollen may also be reworked. The vertical sampling distance varied widely, ranging from 1 cm to several meters. Short intervals were used in clay-and peat-beds, occurring in the upper part of several members. It is assumed that sediment accumulation was slow in these fine-grained beds and therefore a comparatively long period may be represented by thin lithological units. Large sampling intervals were applied in more silty sections, which probably reflect...
higher energy conditions and more rapid sedimentation. The pollen samples have been treated according to standard laboratory methods (Faegri and Iversen, 1975). Preparation includes: KOH treatment, sieving, acetolysis (Erdtmann), removal of clastic material by heavy fluids separation and HP treatment. Wherever possible 300 pollen grains have been counted. All trees and herbs (except water plants) have been included in the pollen sum, which can lead to a dominance of local elements, for instance in peat-layers. The zoning in the pollen diagrams is a local one, based on the changes in tree pollen and the AP/NAP ratio.

The Early-Pleistocene age of the deposits is illustrated by the presence of Pterocarya, Carya, Tsuga and Eucommia pollen in low values, which are absent from the Middle-Pleistocene onwards (Zagwijn, 1975b). Tertiary pollen like Nyssa and Sciadopitys are very rare. Occasionally, they are found in fluvialite sediments (Gilze Member; e.g. boring Zwart Goor), where they are probably reworked from Tertiary deposits.

Pliocene - Tiglian A
According to Vanhoorne (1962) sands of Tertiary age are present below the Campine Clay (our Rijkevosel and Turnhout Members). He described a pollen sample at Turnhout at 30 m below the surface (fig. 2.7: boring 17E-154), probably from an in situ peat-layer. It is characterized by Nyssa (1.9%), Sciadopitys (3.8%) and Fagus (3.3%) (sum of all trees is 100%) (Vanhoorne, 1962). According to Vanhoorne this pollen assemblage is similar to the pollen spectra of the Mol Sands at Mol, although the amount of Tertiary pollen is higher in the latter location. The sample was probably taken at the transition from the Merksplas Member to the Rijkevosel Member. The low values of Tertiary pollen and the presence of Fagus in boring 17E-154 points to a Late-Pliocene to Early-Tiglian age for the Merksplas Member, since Fagus is present until the Tiglian A (Zagwijn, 1963a).

Fagus and Tertiary pollen have not been found in the lower part of the Rijkevosel Member in the borings Bolk and Zwart Water (see appendix), although they are situated fairly close to boring 17E-154 of Vanhoorne (1962). The pollen spectra of silt/clay-laminae in these borings are dominated by Alnus and Pinus. It is therefore concluded that no depos-

![Pollen diagram of the Rijkevosel Member at Beerse Dakt](legend in appendix).
its of Late-Tertiary or Tiglian A age have been found in this study.

**Tiglian**
The Rijkevorsel Member (Tegelen Formation-Campine Clay and Sand Formation) overlies the Merksplas Member. It has been investigated in the stratotype at Beersse Dakt (fig. 4.1) and in several other borings and exposures (see app.).

The member is characterized by fairly high values of thermophilous trees (30%) of dry (Quercus) and wet (Alnus) habitats. Alnus, Betula, Pinus and Quercus dominate the tree pollen. The high Chenopodiaceae content (12%) is characteristic for the distal tidal environment of the Rijkevorsel Member. This assemblage distinguishes the Rijkevorsel Member from the underlying Merksplas Member and the overlying Beersse Member, since practically no thermophilous species occur in the latter unit.

Several samples have been analysed on the presence of megasporangia of Azolla. This waterfern has not been found, but according to Greguss and Vanhoorne (1961) *Azolla tegeliensis* is a common constituent in the Rijkevorsel Member. Therefore the Rijkevorsel Member is regarded to be of Tiglian age, since *Azolla tegeliensis* is a guide fossil for the Tiglian period (Zagwijn, 1963a).

The distal tidal flat deposits of the Rijkevorsel Member are over lain by continental (eolian) deposits of the Beersse Member in the southeastern part of the study area (fig. 4.2). The top of the Rijkevorsel Member at Merksplas Strafinrichting has not been eroded and therefore no hiatus occurs between the Rijkevorsel Member and the Beersse Member. Unfortunately the upper part of the Rijkevorsel Member appeared to be sterile in pollen probably because of oxidation and soil-ripening during silting above mean sea level in the tidal litter zone environment as revealed by the well developed crumbliness (§3.3.2). Therefore, the ecological and climatological transition from the Rijkevorsel Member into the Beersse Member could not be reconstructed.

Five soils were found at the base, in and on the top of the Beersse Member in Merksplas Strafinrichting (fig. 4.2: Merksplas(M) 1-5). In contrast to the underlying Rijkevorsel Member (M 5: 10.80 m) and over-
Fig. 4.2: Pollen diagram of the Rijkevorsel Member, Beerse Member and Turnhout Member at Merksplas Strafinrichting (Tiglian C3, C4, C5) (legend in appendix).

lying Turnhout Member (M 0) the thermophilous trees of dry and wet places are almost completely absent. The pollen diagrams (M 2, 3, 4) are dominated by so-called indifferent trees (Pinus), herbs (Gramineae, Cyperaceae) and Ericaceae. The pollen assemblages point to a taiga or tundra vegetation. The associated cryoturbations and small ice-wedge casts in the eolian sands between the soils, indicate a cold climate, probably with local permafrost conditions and a mean annual temperature around -5°C (§3.3.3). The upper soil (M 1) is different from the lower three. Alnus is more important, but the Ericaceae are still dominant. It is uncertain whether the Alnus pollen belong to Alnus viridis or Alnus glutinosa. The size of the pollen grains was measured at 23.7 μm
(N=50). Since the measurements were established in glycerine gel, a conversion factor of 0.8 must be applied to correct for expansion of the pollen grains (Paegri and Iversen, 1975). Pollen size then amounts to 18.9 μm. The size of *Alnus* pollen at Meerle, situated in the overlying warm temperate phase, amounts to 19.6 μm (N=50; conversion factor 0.8). According to Menke (1976) *Alnus glutinosa* and *Alnus viridis* have a diameter of 21.0 ± 1.0 μm and 17.9 ± 0.9 μm respectively. Both our values lie between those mentioned by Menke and therefore no conclusions can be drawn from the size measurements. However, the habitus of the *Alnus* pollen from soil M 1 resembles more the habitus of recent *Alnus glutinosa*. The increase of *Alnus* at the top of the Beerse Member in M 1 possibly represents the climatological change from the glacial phase to the next interglacial phase. Moreover, it cannot be excluded that soil M 1 was formed during the interglacial period itself. Wet and oligotrophic conditions may have been responsible for the presence of *Alnus*, Ericaceae and *Sphagnum* in diagram M 1.

The Turnhout Member overlies the Beerse Member in Merksplas Strafinrichting. The upper soil of the Beerse Member (M 1) was locally eroded. The Turnhout Member is dominated by *Alnus*, *Pinus*, *Quercus* and *Betula* (fig. 4.2: M 0). Thermophilous trees of wet and dry habitats are well represented (max. 30%). *Typha* and *Osmunda* point to a relatively high summer temperature. The Chenopodiaceae content is as high as or higher than in the Rijkevorsel Member (max. 40%). This again indicates a high sea-level and distal tidal flat and tidal litter zone environments (§3.3.4). The high content of Chenopodiaceae pollen suppresses the values of the thermophilous tree pollen. In spite of this occasional dominance of local pollen, the pollen assemblage as a whole is characteristic of a temperate climate, comparable to the Holocene. The upward decrease of Ericaceae in M 0 can be explained by the decreased reworking of pollen from the underlying soils (M 1) of the Beerse Member and by the increasing distance to the mainland in the south during the transgression of the Turnhout Member.

In the Turnhout Member at Merksplas Strafinrichting (fig. 4.2: M 0, 5.2 m below surface) 30 megasporangia of *Azolla tegeliensis* have been found. In Meerle the Turnhout Member contained up to 48 megasporangia of *Azolla tegeliensis* in one small sample. The presence of *Azolla tegeliensis* unmistakenly points to deposition during the Tiglian, since *Azolla tegeliensis* is regarded as a guide fossil for the Tiglian stage (Zagwijn, 1963a). *Azolla filiculoides* has never been found in the Turnhout Member, nor in the Rijkevorsel Member, which confirms the Tiglian date of the members. The Tiglian age of the Turnhout Member is in contradiction to previous ideas of Dricot (1961), De Ploey (1961) and Paepe and Vanhoorne (1970). The latter found *Azolla tegeliensis* in the Rijkevorsel Member, but not in the Turnhout Member (pers. comm. R. Vanhoorne). They therefore interpreted the Rijkevorsel Member as Tiglian and the Turnhout Member as Waalian age. The absence of *Azolla tegeliensis* in the Turnhout Member in previous studies can be explained by the fact that only few samples were investigated, since the Turnhout Member is presently thin or even absent (e.g. in Beerse Dakt) at the southern border of its distributional area. To the north the sedimentary sequence of the Turnhout Member is more complete and *Azolla tegeliensis* is a common constituent in the fining-upward sequences formed by the final silting of the fresh water, tidal environments (see Meerle). The Tiglian age of the Turnhout Member fits well with the finds of deer antlers of *Eucladoceros tegulensis* (Germonpré, 1983; §3.5.4).

Since both the Rijkevorsel and Turnhout Member are of Tiglian age, the
intercalated Beerse Member must be of Tiglian age as well. This result is new, as the cold Beerse Member has been interpreted formerly as Eburonian or even Menapiian (see §4.2). Up to now two cool phases are known within the Tiglian (Zagwijn, 1963a: Tiglian B and Tiglian C4). If the Beerse Member is to be connected with the Tiglian B phase, then the underlying Rijkervorsel Member should have been formed in the warm-temperate Tiglian A. However, the Tiglian A is characterized by the presence of Pagus and low amounts of Tertiary pollen (Sciadopitys, Sequoia, Taxodium) (Zagwijn, 1963a: boring Eindhoven I, II). Since Pagus and Tertiary pollen have never been found (except for a few grains), the Rijkervorsel Member-Tigliand A correlation is rejected. The Beerse Member must be connected then with the cool Tiglian C4 phase (Zagwijn, 1963a). This implies that the Rijkervorsel Member and Turnhout Member were probably formed in the Tiglian C3 and Tiglian C5 respectively. The Tiglian C3 age of the Rijkervorsel Member implies a large hiatus between the Merksplas Member (Pliocene, Praetiglian) and the Rijkervorsel Member, comprising the Tiglian A, Tiglian B and part of the Tiglian C.

The Tiglian C3(b) zone has been described previously as the climatic optimum of the Tiglian. The Tiglian C5 phase reflects another period of warm temperate climatic conditions, almost as warm as the TC3(b) zone (Zagwijn, 1963a). The weak climatic differences between the Tiglian C3 and C5 phases could occasionally be distinguished in the pollen diagrams of respectively the Rijkervorsel and Turnhout Members. The Rijkervorsel Member often contains a somewhat higher content of thermophilous, dry trees than the Turnhout Member (compare fig. 4.1 and fig. 4.2; see also appendix Meerlie Slikgat, Chaam Kapel, Gaalser Meren). Especially Eucamnia, Carpinus, Ulmus, Tilia, Fraxinus and Ilex are often better represented in the Rijkervorsel Member. It is possible to reconstruct the mean summer (and winter) temperatures from the pollen record (Zagwijn, 1963a, 1975b). The pollen of Ilex, Hedera and Castanea in the Rijkervorsel and Turnhout Member indicates mild winter conditions with mean temperatures above 0° C. The presence of (Taxus), Hedera, (Vitis) and Eucamnia point to a mean summer temperature around 20° C. The lower values of the species mentioned above in the Turnhout Member might indicate somewhat lower temperatures in the Tiglian C5 phase.

The correlation of the Beerse Member with the Tiglian C4 implies the introduction of a glacial phase within the Tiglian. The estimated mean annual temperature of -5° C is much lower than described so far by Zagwijn (1963a; TC4c; fig. 6, fig. 15).

As has been stated above, the areal distribution of the Beerse Member is limited because of erosion by the Turnhout Member. Reworked pollen of the Beerse Member, deposited at the base of the Turnhout Member (fig. 4.2: M 0) can give the impression of a cooler phase. In Meerlie Slikgat for instance (see app.) the interval between 7.55 and 19 m below the surface contains less thermophilous, dry trees and more herbaceous and Ericaceae between two pollen zones with a higher content of dry, thermophilous trees. The high values of dry thermophilous trees at the top of the Rijkervorsel Member (19-21 m) and at the top of the Turnhout Member (7-7.5 m) is possibly caused by the increase of pollen from the mainland during the final silting of the distal, tidal environments during the Tiglian C3 and C5 respectively. However, lithologically, sediment-petrographically and environmentally the unit between 7.55 and 19 m is part of the Turnhout Member. Furthermore, the Alnus content (30-35%) is much higher than in the in situ Beerse Member. Therefore, this interval most probably formed in the TC5 phase as well. The higher content of herbs and Ericaceae is probably caused by reworking of
pollen from the Beersse Member and by a basinwards decrease of Alnus (Chowdhury, 1982) (see §3.4). A comparable phenomenon is possibly present more to the north e.g. in boring Rotterdam E55 (Zagwijn, 1963a). The interval between 90 and 115 m below the surface is interpreted as the cool TC4c phase. The pollen assemblage, however, contains up to 10-15% thermophilous trees, which is much higher than in the Beersse Member (fig. 4.2). The pollen may have been reworked from sediments of Tiglian C4 age and deposited in marine sedimentary environments during the beginning of the TC5 phase.

In the upper part of the Turnhout Member very often a strong increase of thermophilous trees (especially Alnus) is found in humic to peaty layers (fig. 4.3 and App.: Meerle, Beersse Blak, Appelenberg, Zwart Water, Meerle Sligat). This increase of thermophilous trees could reflect the climatic optimum of the interglacial Tiglian C5. However, in our opinion this is not the case. The high Alnus content always occurs in a peaty layer at the top of the Turnhout Member, which is interpreted as the final phase of silting of the distal, tidal flat tidal litter zone environments. The increase of thermophilous trees is considered therefore not the result of more optimal climatic conditions, but of local edaphic factors.

The effects of progressive silting and subsequent drowning are well illustrated at Ravels (fig. 4.3). At the base of the diagram (3.41 m) sedimentation occurred in open water conditions (lenticular bedding) and regional pollen dominates the pollen assemblage. Approximately 15 cm below the peat-layer (2.53 m) the pollen spectrum is strongly dominated by local Chenopodiaceae pollen. At 2.39 m below the surface, peat formation started and Chenopodiaceae are replaced by Gramineae. This succession was interrupted at 2.37 m by renewed clay sedimentation with a temporarily increase of the Chenopodiaceae content. At 2.35 m renewed peat formation occurred and Gramineae content declined, followed by a decline of Typha, whereas at the same time Alnus increased (up to 55%). The Alnus Osmdna vegetation points to fresh and eutrophic water supply in an open swamp environment. The subsequent drowning of the peat at 2.28 m led to the disappearance of Alnus and first Gramineae reappeared, followed by Chenopodiaceae.

Fig. 4.3: Pollen diagram of the Turnhout Member at Ravels, illustrating the final silting at the top of the member (Tiglian C5).
Chronostratigraphic position of the Woensdrecht and Hoogerheide Members.

The correlation of the Turnhout Member with the Woensdrecht Member is reliable, since the clayey top of these members continues through the whole area (fig. 2.3 and 2.6). The connection of the Rijkevoorsel Member with the Hoogerheide Member is somewhat uncertain, however. No evidence was found in the pollen record for a cool or cold interval either within the Hoogerheide and Woensdrecht Members or at their transition. The macro remains from the clay-bed in the upper part of the Woensdrecht Member yielded large amounts (37) of megasporangia of Azolla tegeliensis (Huyzer and Van Toor, 1986)(fig. 3.34, 3.35). The presence of this water fern confirms the Tiglian age of the Woensdrecht Member (Nelson and Van der Hammen, 1950: II-0 deposits).

The Hoogerheide Member is characterized by the presence of Alnus, Pinus, Betula and Chenopodiaceae (Armeria)(App. Kalmthoutse Hoek). The Woensdrecht Member contains a comparable pollen assemblage, but the Alnus content can be higher (up to 45%), especially in peaty layers in the upper part of the member (fig. 4.4). The pollen assemblages in the upper part of the Turnhout and Woensdrecht Members resemble each other (fig. 4.3: Ravels and fig 4.4: Kortevenn; be aware of the large differences in vertical scale). Diagram Kortevenn (fig. 4.4) is dominated by Quercus, Alnus, Pinus and Chenopodiaceae. The peat-layer is characterized by Alnus and Osmunda. Below and above the peat-layer the content of Chenopodiaceae is more important, while the Alnus content is lower. The higher values of Gramineae in Ravels just below and above the peat are not found in Kortevenn, probably because of too wide sampling intervals.

As has been stated above, both the Turnhout and Woensdrecht Members are characterized by the presence of Azolla tegeliensis. Florschütz (1938) and Van der Vlerk and Florschütz (1953) described Azolla tegeliensis as well, at Hoogerheide at 3 m below the surface; this is in the Woensdrecht Member. At Wernhout they found this water fern at 2 m below the surface; this is in the Turnhout Member (see fig. 2.6). Because of the comparable pollen associations and the presence of Azolla tegeliensis, the top of the Woensdrecht and Turnhout Members is interpreted as more
Fig. 4.4: Pollen diagram of the Woensdrecht Member in boring Korteven, showing the palynological resemblance to the Turnhout Member in Ravels (Tiglian C5).

or less isochronous (Tiglian C5). In the Hoogerheide Member Tertiary pollen and Fagus are absent, so it must be younger than the Tiglian A (Zagwijn, 1963a). Because of its pollen composition (App. Kalmthoutse Hoek: Alnus, Quercus, Pinus, Betula) and the close similarity to the pollen assemblage of the Woensdrecht Member a Tiglian C age seems the most likely. The Hoogerheide Member then might have been formed in the Tiglian C3.

The clayey top of the Turnhout and Woensdrecht Members has been eroded at many places (fig. 2.6: Kalmthoutse Hoek, Nieuwmoer, Ghil, Zwart Goor); especially in the Mark-Weerijse river basin (Achtermaal, Wernhout Maalbergen). In those situations a hiatus is present between the clay and overlying units (Gilze Member, Eindhoven Formation, Twente Formation). According to De Ploe (1961) and Van Oosten (1967) a humic horizon, which was dated as Eemian, is locally present in the top of the clay. However, deposits of Eemian age have not been found in the investigated sections probably because of erosion during the Early- or Middle-Weichselian. According to Vandenberghhe (1985) Eemian deposits occur only locally on interfluvia and in subsiding areas (Central Graben) where they were protected against Weichselian erosion. In the study area the humic clay at the top of the Turnhout Member is commonly characterized by a cool or cold pollen assemblage (appendix Merksplas Strafinr., Appelberg, Zwart Water). The cold pollen spectrum can date from any glacial between the Tiglian and the Holocene. The "Eemian" peat-layer at Meerle described by De Ploe (1961) was reinvestigated in this study (App. Meerle). The pollen composition and the presence of Anolla tegeliensis point to a Tiglian instead of an Eemian age.
Tiglian - Eburonian transition

In boring Appelenberg (fig. 4.5), Zwart Water and Meerle Slikgat (App.) a gradual lithological transition has been found between the Turnhout Member and the overlying Gilze Member. Here a more or less continuous sedimentary sequence is present, in which climatic changes have been registered.

The pollen assemblage of the Turnhout Member at Appelenberg is very characteristic of the Tiglian C5 period (fig. 4.5). Alnus dominates the pollen spectrum, especially in the humic soil horizon. In the upper 30 cm of the Turnhout Member Alnus decreases and Pinus, Picea, Gramineae and Juniperus increase. This change does not seem to be connected to a change in the sedimentary facies and it is therefore interpreted as a cooling of the climate. This deterioration of the climate is normally situated in the Tiglian C6 zone (Zagwijn, 1963a).

At 12 m below the surface the clay changes upwards into peat, gytta, loam and very fine sand of the Gilze Member. The sediments between 11.23 and 11.55 m have been deposited in very wet, locally lacustrine environments. Gramineae and Cyperaceae dominate the pollen spectrum in this interval, but they may be over represented because of the local, wet sedimentary environment. Thermophilous trees are virtually absent, indicating cold climatic conditions. Because of the more or less continuous vertical sequence of the Turnhout Member into the Gilze Member, the pollen assemblages most probably represent the Eburonian cold stage.

Above 10.95 m fluvialite overbank deposits become more important and local dryer conditions are reflected by a higher Pinus content in the diagram (fig. 4.5). The increase of Artemisia and Thalictrum indicates a change to a more continental climate in the course of the Eburonian period. The increase of Corylus, Quercus and Castanea is explained by an increased reworking of pollen due to higher current velocities during the sedimentation.
Fig. 4.5: Pollen diagram with the transition of the Turnhout Member into the Gilze Member in boring Appelenberg (Tiglian C5, C6, Eburonian).

In diagram Zwart Water (app.) the pollen spectra of the cold Eburonian stage directly overlie at 4.36 m below the surface the Alnus dominated spectra of the warm temperate Tiglian C5 phase, although no clear break is present in the sedimentary sequence. The Eburonian is characterized by fluctuations in the Pinus-Gramineae ratio, which probably represent stadial (low Pinus content) and interstadial phases (higher Pinus content) within the Eburonian period (Eburonian I, II, III: Zagwijn, 1963a: Pit Russel-Tiglia-Egypte, boring Eindhoven I).

**Waalian**

The Gilze Member consists predominantly of sand and continuous clay- or peat-beds are scarce. Therefore, the pollen diagrams from the Gilze Member are often short and difficult to correlate from one place to another.

Following the Eburonian stage, the next phase with a high content of thermophilous trees occurs in the Gilze Member (Gilze Clay) at Gilze (fig. 4.6). Unfortunately this pollen section does not form one continuous, vertical sequence with the Eburonian and Tiglian deposits, because of local erosion of the Turnhout Member at this spot (see fig. 2.8). The lower part of the diagram (fig. 4.6: 5.5 - 14 m below the surface) contains a high content of Pinus, Betula and Gramineae. It is situated stratigraphically above the upper part of diagram Appelenberg (fig. 4.5). Because of the high Pinus values a late Eburonian or early Waalian age is proposed for the base of the Gilze diagram. Above 5.48 m the pollen spectra become dominated by thermophilous dry (Carpinus, Quercus, Ulmus) and wet (Alnus, max. 60%) trees. The pollen assemblage is characteristic for a temperate-warm climate. Above 2.10 m below the surface the thermophilous trees decrease and the pollen spectrum becomes dominated again by Pinus, Betula, Gramineae and Ericaceae (fig. 4.6). The Corylus increase at 1.25 m is probably caused by a higher current velocity (clay changing into loam) and the connected reworking of pollen.
The chronostratigraphic position of this warm phase can be deduced in the following manner. The presence of Tsuga (4%) is an indication for the Early-Pleistocene age of this section (fig. 4.6). Analysis of the macro remains revealed large amounts of megasporangia and massulae of Azolla filiculoides, which were nicely attached to each other. This waterfern is not restricted to the Early-Pleistocene. According to Zagwijn (1963a) it occurs frequently after the Tiglian (and sporadically in Tiglian C4, TC5, TC6), in the Waalian, Bavelian, Cromerian and Holsteinian stages. The pollen spectrum at Gilze does not resemble the Bavel Interglacial pollen assemblages, since Tsuga and Eucommia content is much higher in the Bavel Interglacial (fig. 4.8) (Zagwijn and De Jong, 1984). To conclude, the pollen spectrum at Gilze dates from an Early-Pleistocene interglacial, younger than Tiglian and older than Bavelian, which is the Waalian.

The pollen spectra of Waalian age at Gilze resemble other spectra of Waalian age in the Central Netherlands (e.g. Zagwijn and De Jong, 1984: boring Leerdam). Zagwijn has been able to distinguish a tripartition in the Waalian (Waalian A, B, C) in some pollen diagrams (Zagwijn, 1957: boring Veldhuizen; Zagwijn, 1963a: boring Eindhoven I; Zagwijn and De Jong, 1984: boring Leerdam). The differences in the pollen assemblages of the warm temperate Waalian A and Waalian C are not always evident, especially when the intermediate, cooler Waalian B phase is absent. In Gilze only one warm temperate phase of the Waalian seems to be present (fig. 4.6). Because of the relatively high content of thermophilous dry trees (Carpinus, Quercus) it is probable that only the Waalian A phase has been registered. The strong decline of thermophilous trees above 2.1 m reflects a cooling of the climate, possibly representing the beginning of the Waalian B phase. The relatively high content of Pinus and Betula is more characteristic for the cool Waalian B, than for the cold Menapian phase.

**Menapian**

In the neighbourhood of Alphen, the clay-layers of Waalian age (exposed at Gilze) have been eroded by channels, which have subsequently been filled with medium to coarse so-called "Alphen Sands" (Vandenberghhe and Krook, 1981). The latter unit is incorporated in the Gilze Member.
Fig. 4.6: Pollen diagram of the Gilze Member at Gilze.
(coarse-grained lithofacies), because of its stable heavy mineral content (chapter 2). According to Vandenberghhe and Krook (1981) the pollen diagram of the upper part of the "Alphen Sands" is dominated by Pinus, Betula, Gramineae and Cyperaceae. This association points to a park-tundra vegetation and a cool climate. The authors dated the pollen section at Alphen as "possibly Menapian". This age agrees well with the Waalian age of the underlying clay-bed at Gilze (fig. 4.6).

Fig. 4.7: Pollen diagram of the Gilze Member (Spruitenstroom Clay) at Kinderlaan (Menapian).

Fig. 4.8: Pollen diagram of the Bavel Member at Bavel (Bavelian Bv3b).
In the present study the dating of the coarse upper part of the Gilze Member (Alphen Sands) is generally impeded by the lack of peat- or clay-layers (App.: Ghil, Zwart Goor, Ravels). Reworking of pollen is locally very important. For instance, the presence of 10% pollen of Sciadopitys, Nyssa and Sequoia in the Gilze Member at Zwart Goor (App.) indicates the reworking of pollen from Tertiary deposits. The degree of reworking is in general well demonstrated by the higher content of
Corylus pollen (fig. 4.5: 10.65 m; fig. 4.6: 1.25 m). In the east of the study area a clay-bed is found in the upper part of the Gilze Member (Spruitenstroom Clay). The pollen diagram from this unit at Kinderlaan is completely dominated by Gramineae and Cyperaceae (fig. 4.7). The continuous presence of Thalictrum (and Cruciferae) indicates cold climatic conditions. Because of the lithostratigraphic position in the upper part of the Gilze Member, above the Gilze Clay of Waalian age and below the Bavel clay of Bavelian age, this pollen diagram is interpreted as Menapian. However, it must be remembered that the pollen sections at Kinderlaan (fig. 4.7) and Alphen (Vandenberghhe and Krook, 1981) represent only parts of this cold stage. In any case it is concluded that the Gilze Member as a whole was formed during the Eburonian, Waalian and Menapian stages.

Previously the St. Lenaarts Formation in Belgium has been interpreted as Weichselian, because of the presence of cold pollen spectra and their position under Weichselian eolian sands (De Ploey, 1961; Haest, 1985; Haest et al., 1986). In our opinion these sands overlying the Turnhout Member can be correlated lithostratigraphically with the Gilze Member. Since the Gilze Member in its turn is overlain by the Sterksel Formation (Appelenberg) and contains Early-Pleistocene warm temperate pollen assemblages, it is evident that the St. Lenaarts Formation is of Early-Pleistocene age as well (§2.5.8). Furthermore, the Weichselian date of a peat-layer in the sand (55.300 ± 700 BP; Haest et al., 1986) is calculated on the basis of a very low C-14 concentration, which could as well result from a very slight contamination of dead carbon with younger material.

Bavelian
In the neighbourhood of Bavel clay- and sand-beds of the Bavel Member erosively overlay the Gilze Member (fig. 2.5). The clay (2 to 10 m below the surface) is characterized by very high values of dry, therophilous trees (up to 40%), which point to a warm interglacial climate (fig. 4.8). Especially the high Carpinus (up to 20%), Tsuga (up to 11%) and Eucommia content differentiates the Bavel Member from all underlying Early-Pleistocene members in the area (compare fig. 4.1, 4.3, 4.6, 4.8). In accordance with Zagwijn and De Jong (1984: diagram Bavel Ia) the clay of the Bavel Member is correlated with the Bavel Interglacial (Bv3b) of the Bavelian stage.

The clay of the Bavel Member has been eroded by channels. The pollen assemblage at 1.75 m in the upper part of the channel-fill is comparable with the underlying clay, although Betula content is higher (26%). It is therefore incorporated in the Bavelian Interglacial. This observation contradicts the results of Zagwijn and De Jong (1984, diagram Bavel Ia; 3.55 m: Linge Glacial), who found a cold pollen spectrum in the upper part of the sand in a neighbouring pit.

The upper two spectra in fig. 4.8 have been taken from cryoturbated peat-layers just below a gravel-bed (probably Beuningen gravel-bed). These are interpreted as Weichselian. The high content of thermophilous trees (20-30%) is explained by the reworking of pollen from the underlying Bavel Member.

To conclude, deposits of the Bavel Interglacial are characterized by a high Tsuga and Carpinus content. This pollen assemblage is restricted to the northeastern part of the study area, close to the Central Graben and it has not been found in western Noord-Brabant and adjacent northern Belgium.
4.3.2 Magnetostratigraphy

Magnetostratigraphy is mainly based on changes of the magnetic polarities in rock strata. These so-called reversals of the earth magnetic field are quite well established (Mankinen and Dalrymple, 1979; Lowrie and Alvarez, 1981). They occur in a short time period (1000-10,000 years) and they therefore provide excellent time markers. Furthermore, polarity changes are registered globally in different lithologies. Marine and continental deposits can therefore be correlated by the presence of essentially isochronous polarity changes. With the aid of the well dated reversals, the biostratigraphical units (pollen zones) can be connected with the worldwide magnetostratigraphic time scale. However, it should be remembered that the magnetostratigraphic units are based on time independent physical properties. Magnetostratigraphic units are therefore not chronostratigraphic units, in spite of their worldwide applicability (Hus, 1988).

One of the major problems of geomagnetic dating in continental deposits is the lack of a continuous sedimentary sequence, in comparison to the deep sea record. Therefore, the geomagnetic record on the continent is often fragmentary. Geomagnetic reversals are found occasionally in different lithostratigraphical units of which the mutual relation is not always known. Furthermore, because of the repetitive nature of the reversals, it is difficult to establish which polarity zone is involved. Additional (i.e. biostratigraphic) information is required then to identify the reversals with the transition of specific magnetozones.

Several paleomagnetic investigations have been performed of Early-Pleistocene sediments in The Netherlands and Belgium (Van Montfrans, 1971; Zagwijn et al., 1971; Hus et al., 1976; Prakash Chandra Adhikary, unpubl.; Hus, 1988). Van Montfrans (1971) investigated several exposures in Noord-Brabant and northern Belgium, which are evaluated first, before the new results are presented.

4.3.2.1 Evaluation of former paleomagnetic investigations (Van Montfrans, 1971)

The geomagnetic results of Van Montfrans (1971) have been summarized in table 4.2. The upper part of the table contains data obtained by Van Montfrans from Noord-Brabant and northern Belgium. In the lower part of the table his results from exposures in the neighbourhood of Tegelen in the Dutch province of Limburg (stratotype of the Tegelen Formation) are added for comparison purposes. At the right side of the table litho- and biochronostratigraphic interpretations are given according to the present study.

The Dorst and Bavel locations were formerly interpreted as Waalian C, but were later reinterpreted as Bovelian (Zagwijn and De Jong, 1984). Because of this reinterpretation the Jaramillo magnetozone (normal polarity) shifted from the Waalian to the Bavelian, which illustrates the problems of bio- and magnetostratigraphy.

The clay-bed in location the Chaamse Bossen is correlated in the present study with the Gilze Member (Kedichem Formation) (see fig. 2.8), instead of the Tegelen Formation. The new Waalian B/Menapian date is inferred from the cold pollen spectra in the upper part of the clay-bed in Gilze (fig. 4.6; Gilze pit 1), which is in the neighbourhood of the Chaamse Bossen.

The sediments at the Wouwse Plantage probably date from the Tiglian and the Eburonian (see App.), instead of the Tiglian.

The paleomagnetic results in the upper part of the Tegelen Formation
Table 4.2: Former paleomagnetic investigations in Noord-Brabant and northern Belgium (after Van Montfrans, 1971).

<table>
<thead>
<tr>
<th>Location</th>
<th>Exposure</th>
<th>Biochrono-Stratigraphy</th>
<th>Polarity (Normal)</th>
<th>Member</th>
<th>Biochrono-Stratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorst</td>
<td>—</td>
<td>Upper Waalian C</td>
<td>+</td>
<td>Bavel</td>
<td>Bavelian</td>
</tr>
<tr>
<td>Bavel</td>
<td>—</td>
<td>Upper Waalian C</td>
<td>+</td>
<td>Bavel</td>
<td>Bavelian</td>
</tr>
<tr>
<td>Chaamse Bosken</td>
<td>—</td>
<td>Tiglian 7</td>
<td>+</td>
<td>Gilze</td>
<td>Waalian B?</td>
</tr>
<tr>
<td>Wouwse Plantage</td>
<td>—</td>
<td>Tiglian 7</td>
<td>rejected</td>
<td>Gilze / Turnhout</td>
<td>Eburonian / Tiglian</td>
</tr>
<tr>
<td>Ossendrecht</td>
<td>—</td>
<td>Upper Tiglian</td>
<td>rejected</td>
<td>Woensdrecht</td>
<td>Tiglian C5</td>
</tr>
<tr>
<td>Wernhout</td>
<td>—</td>
<td>Tiglian</td>
<td>rejected</td>
<td>Turnhout</td>
<td>Tiglian C5</td>
</tr>
<tr>
<td>De Toekomst (Beers)</td>
<td>yes upper part</td>
<td>Waalian</td>
<td>+ upper part</td>
<td>Turnhout</td>
<td>Tiglian C5</td>
</tr>
<tr>
<td>Franciscus (Beers)</td>
<td>yes upper part</td>
<td>Waalian</td>
<td>lower part</td>
<td>Turnhout</td>
<td>Tiglian C5</td>
</tr>
<tr>
<td>De Toekomst</td>
<td>—</td>
<td>Eburonian</td>
<td>+ upper part</td>
<td>Beerse</td>
<td>Tiglian C4</td>
</tr>
<tr>
<td>Franciscus</td>
<td>yes upper part</td>
<td>Eburonian</td>
<td>rejected</td>
<td>Beerse</td>
<td>Tiglian C4</td>
</tr>
<tr>
<td>De Toekomst</td>
<td>—</td>
<td>Tiglian</td>
<td>lower part</td>
<td>Rukevorsel</td>
<td>Tiglian C3</td>
</tr>
<tr>
<td>Franciscus</td>
<td>yes upper part</td>
<td>Tiglian</td>
<td>lower part</td>
<td>Rukevorsel</td>
<td>Tiglian C3</td>
</tr>
<tr>
<td>Malbeek</td>
<td>—</td>
<td>Eburonian</td>
<td>rejected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malbeek</td>
<td>—</td>
<td>Lower Eburonian</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kurstjens</td>
<td>—</td>
<td>Tiglian / Eburonian</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wambach</td>
<td>—</td>
<td>Tiglian / Eburonian</td>
<td>+ upper part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laumans</td>
<td>—</td>
<td>Tiglian / Eburonian</td>
<td>+ upper part / lower part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obel</td>
<td>—</td>
<td>Tiglian C</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egypte</td>
<td>—</td>
<td>Tiglian C3-C4ab</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Cleef</td>
<td>—</td>
<td>Tiglian A</td>
<td>+ (middle)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(our Woensdrecht and Turnhout Members) at Ossendrecht, Wouwse Plantage and Wernhout were rejected by Van Montfrans.

The Rijkevorsel, Beers and Turnhout Members in the neighbourhood of Beers (pits De Toekomst and St. Franciscus) have been redated by us as respectively Tiglian C3, Tiglian C4 and Tiglian C5 (§4.3.1), instead of Tiglian, Eburonian and Waalian. The normal (+) polarity obtained by Van Montfrans in the upper part of the Turnhout Member in pit De Toekomst was found in a 0.5-1.0 m thick crypturbated layer (Paepe and Vanhoorne, 1970, fig. 4). The base of the Turnhout Member in pit St. Franciscus was characterized by a reversed polarity. The Beers Member showed a normal polarity for the upper part and a reversed polarity for the lower part of the member. The Rijkevorsel Member revealed a reversed polarity (De Toekomst, St. Franciscus).

The polarity of the Turnhout, Beers and Rijkevorsel Members obtained by Van Montfrans (1971) in pits De Toekomst and St. Franciscus and by Hus et al. (1976) for the latter is different from the results in the Tegelen area. The Turnhout, Beers and Rijkevorsel Members seem to be dominated by a reversed polarity (normal polarity in the crypturbated upper part of the Turnhout Member), whereas time equivalent Tiglian deposits around Tegelen are characterized by normal (+) polarities.

4.3.2.2 Paleomagnetic results from the study area

The paleomagnetic samples have been taken from clay-beds in four exposures and nine borings. Although sand-layers possess a measurable magnetic signal, the results are less reliable due to remagnetization risks. The exposures at Bavel, Ravels and Gilze were sampled continuously and the inclination and azimuth (declination) were measured accurately with standard equipment developed by Prof. Dr. J. Hus at the Centre de Physique du Globe in Douvres (Belgium). Exposure Meerle and the borings have been sampled discontinuously. The azimuth of the samples from borings is not very reliable, since the coring equipment may have rotated during lowering in the borehole.

At first, the natural remanent magnetization (NRM), which is the remanence "in situ", has been measured in all samples. It is assumed that the paleomagnetic directions are impressed in the sediment during the sedimentation or shortly afterwards, when the deposits are still unconsolidated. The remanence measurements were performed with a three-axis SCT superconducting magnetometer. Each sample was measured 4 times (prisms) or 6 times (cubes) and the mean natural remanent magnetization intensity and direction were calculated. After deposition or during storage of the samples in the laboratory the natural remanent magnetization can be influenced by the presence of the geomagnetic field and a viscous remanence may build up spontaneously. This viscous magnetization can be removed by alternating field demagnetization in order to find the original magnetization of the sample (so-called characteristic remanent magnetization). 18 samples were first selected from different members and beds for demagnetization tests. These pilot samples were demagnetized in 13 steps (from 0 to 700 Oersted) in order to establish the stability of the magnetization. The individual members required different demagnetization values ranging from 150 to 300 Oersted to remove the viscous component of the remanent magnetization.

After the demagnetization tests all samples were partially demagnetized according to the values obtained from the tests. The Rijkevorsel and Turnhout Members were demagnetized in alternating fields of 200 to 250 Oersted; the Gilze Member in 300 Oersted and the Bavel Member in 150 Oersted. Then the samples were measured again and the mean values for
the remanent magnetization after alternating field demagnetization were computed. The paleomagnetic measurements were plotted subsequently in a diagram, containing inclination, declination and magnetic intensity of the samples. From each pair (inclination, declination) of each sample the geographic coordinates of the corresponding virtual geomagnetic north pole (VGP) were calculated. When the pole occurs in the northern hemisphere (or southern hemisphere), near to the geographic north pole (south pole), the magnetization is normal (reversed). Allowing for the secular variation, the geomagnetic field is considered as normal (reversed) when the VGP plots within a circle of 40° around true north (south). During a reversal intermediate directions result due to a shift of the geomagnetic pole from one hemisphere to the other. Detailed information concerning the historic outline of paleomagnetic dating, sampling techniques, measurement errors and rejection criteria has previously been given by Van Montfrans (1971).

**Exposure Bavel (fig. 4.9) (Bavel Member)**

A thick (max. 8 m) clay-layer, pollen-analytically equivalent to the Bavel Interglacial of the Bavelian stage (§4.3.1), was investigated. A negative inclination and a southward declination (reversed polarity) was found in the lower part; a positive inclination and northward declination (normal polarity) in the upper part of the clay-layer. The transition zone (5-8 m below the surface) is characterized by an alternation of positive and negative inclinations. The tree roots in the upper part of the clay-layer do not affect the normal polarity. The transition zone is interpreted as a change in polarity from reversed to normal. The magnetic intensity is low with respect to the over- and underlying, normal and reversed units. According to several studies (see Hus, 1988) a reversal of the earth magnetic field lasts between 1000 and 10,000 years and probably near to the lower limit. The magnetic results confirm the results of Van Montfrans (1971: Bavel) and Zagwijn and De Jong (1984: Bavel I and II), who found a reversed magnetozone at the base and a normal magnetozone in the middle and upper part of the Bavel Interglacial deposits.

**Exposure Gilze (fig. 4.10) (Gilze Member)**

The upper 3 m of the Gilze Member at this location have been analysed. The investigated section is lithologically heterogeneous (see App.). The top strata (1.3-2.2 m) are intensively cryptoturbated, probably in the Weichselian. A very fine sand-layer separates the cryptoturbated clay from the underlying compact, crumby clay, which contains humic/peaty soil horizons and becomes coarser grained downwards. The cryptoturbated clay, the sand-layer and 5 samples from the crumby clay reveal a positive inclination and an intermediate polarity. Below 2.0 m positive and negative inclinations both occur. Declination is to the south and a predominantly reversed polarity is inferred for the lower part of the section. The change in polarity occurs approximately 60 cm below the base of the cryptoturbation level at the sampling site.

**Exposure Meerle (fig. 4.11) (top Turnhout Member)**

The investigated clay-layers (3 m thick) belong to the upper part of the Turnhout Member (see appendix). Cryptoturbation of Weichselian age reaches to 1.1 m below the boundary of the Twente Formation and the Turnhout Member (Beuning gravel-bed) at the sampling location. The samples have been taken from 11 boxes (4 samples from one box), approximately 20 cm apart. The section shows a normal polarity in the upper part, an interval with intermediate polarities and a reversed polarity
Fig. 4.9: Inclination and declination of the Bavel Member at Bavel after alternating field (AF) demagnetization (150 Oersted).

in the lower part of the clay-layers. The reversal occurs below the base of the crypturbation level in the 50 cm thick interval with intermediate polarity.

**Exposure Ravels (fig. 4.12) (top Turnhout Member)**
The section has been sampled and analysed by Prof. Dr. J. Hus. He allowed us to present the results in this study. The samples have been taken from the upper part of the Turnhout Member (2 m). The "uncleaned"
Fig. 4.10: Inclination and declination of the Gilze Member at Gilze after alternating field demagnetization (200-300 Oersted).

Fig. 4.11: Inclination and declination of the Turnhout Member at Meerle after alternating field demagnetization (300 Oersted).
Fig. 4.12: NRM of the Turnhout Member at Ravels.

Natural Remanent Magnetization (NRM) of the samples indicate an overall negative inclination and a southward declination, which point to a reversed geomagnetic field. The one sample with a positive inclination might indicate a thin normal polarity zone, but the declination (85°) is still very large. The low magnetic intensity in the upper part and the high intensity in the lower part of the investigated section probably point to the presence of two clay-layers.

It is stressed that Weichselian cryoturbations did not affect the top of the Turnhout Member here, since a 1-1.5 m thick layer of fluvial deposits of the Gilze Member is present between the Turnhout Member and the Weichselian cryoturbations.

Boring Achtmaal (fig. 4.13) (Turnhout and Rijkevorsel Members)

17 samples have been analysed. The azimuth (declination) has not been established in the field. The Turnhout Member shows both positive and negative inclinations. The upper sample of the Turnhout Member is perhaps unreliable, due to remagnetization risks just below the erosional contact of the Eindhoven Formation and the Turnhout Member. The other samples of the Turnhout Member contain predominantly a positive inclination (normal polarity), especially in the lower part of the Turnhout Member (see also Meerle Slikgat). The Rijkevorsel Member is characterized by negative inclinations and doubtless has a reversed polarity.

Fig. 4.13: Inclination of the Rijkevorsel and Turnhout Members in boring Achtmaal after alternating field demagnetization (300 Oersted).
Boring Kalmthoutse Hoek (fig. 4.14) (base Turnhout Member)

The two samples at the base of the Turnhout Member display a positive inclination (declination is unknown), which is interpreted as having a normal polarity.

Fig. 4.14: Inclination of the Turnhout Member in boring Kalmthoutse Hoek after alternating field demagnetization (250 Oersted).

Boring Wernhout Maalbergen (fig. 4.15) (Rijkevorsel Member)

The samples were all derived from the Rijkevorsel Member. Only negative inclinations have been found, which indicate a reversed polarity.

Fig. 4.15: Inclination of the Rijkevorsel Member in boring Wernhout Maalbergen after alternating field demagnetization (200 Oersted).

Fig. 4.16: Inclination and declination of the Rijkevorsel and Turnhout Members in Wortel after AF demagnetization (200 Oersted).
Boring Wortel (fig. 4.16) (Turnhout and Rijkevorsel Members)
Six samples have been investigated. The one sample of the Turnhout Member showed a positive inclination (intermediate polarity). Because of its position close to the Weichselian disconformity this result may be influenced by Weichselian remagnetization. The 5 samples of the Rijkevorsel Member clearly have negative inclinations, i.e. a reversed polarity.

Boring Bolk (fig. 4.17) (Rijkevorsel Member)

![Diagram of inclination and declination](image)

**Fig. 4.17:** Inclination and declination of the Rijkevorsel Member in boring Bolk after alternating field demagnetization (250 Oersted).

The samples are part of the Rijkevorsel Member. The Turnhout Member is missing here because of erosion in the Mark valley (see fig. 2.5). The inclinations are predominantly negative at the base and positive in the upper part of the member. The polarity seems to be intermediate or normal. The upper sample may be influenced by its position directly under the erosional boundary, which separates the Eindhoven Formation or Gilze Member from the Rijkevorsel Member.

Boring Zwart Water (fig. 4.18) (Turnhout Member)
The section has been taken from a thick, clayey facies of the Turnhout Member (comparable to Meerle Slikgat). The upper part of the member is probably equivalent to the Turnhout Member in the nearby clay-
Ravels. The negative inclinations and southward declinations in the upper part of the member point to a reversed polarity. The negative inclinations and northward declinations in the lower part result in an intermediate to normal polarity.

**Fig. 4.18:** Inclination and declination of the Turnhout Member in boring Zwart Water after alternating field demagnetization (250 Gerdsted).

**Boring Meerle Slikcat (fig. 4.19)** (Gilze, Turnhout, Rijkervorcel Members)
The Gilze Member (upper sample) reveals a negative inclination. The Turnhout Member is almost completely fine-grained (clay-silt) at Meerle Slikcat (like in Achtmaal, Zwart Water). Therefore, geomagnetic changes within the Turnhout Member have been registered well. In other places only the clayey upper part of the Turnhout Member could be investigated, because the middle and lower part of the member consists of sand (fig. 2.5: Meerle, Wortel, Chaam Kapel). The upper samples of the Turnhout Member at Meerle Slikcat have a negative inclination (reversed and intermediate polarity). The lower samples show a positive inclination (intermediate polarity). The Rijkervorcel Member (2 samples) is again characterized by a negative inclination (reversed polarity).

**Boring Chaam Kapel (fig. 4.20)** (Gilze, Turnhout, Rijkervorcel Members)
The Gilze Member has a positive inclination, perhaps because of its position 35 cm below the Weichselian unconformity with cryoturbation.
phenomena. The three samples from the upper part of the Turnhout Member clearly have a negative inclination, illustrating the reversed polarity. The sand in the middle and lower part of the Turnhout Member excludes reliable magnetic measurements. The Rijkevorsel Member (2 samples) is characterized by negative inclinations and an intermediate to reversed polarity, as in Meerle Slikgat.

<table>
<thead>
<tr>
<th>INCLINATION (°)</th>
<th>DECLINATION (°)</th>
<th>VGP LATITUDE (°)</th>
<th>MAGNETIC INTENSITY (uT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90</td>
<td>180(E)</td>
<td>90</td>
</tr>
</tbody>
</table>

![Graph showing magnetic measurements](image)

**Fig. 4.19:** Inclination and declination of the Rijkevorsel, Turnhout and Gilze Members in Meerle Slikgat after alternating field demagnetization (200 Oersted).

**Boring Snijders-Chaam (fig. 4.21) (Gilze Member)**
The 5 samples were taken from 3 different clay-layers, which are all included in the Gilze Member. The results are not very consistent. The upper three samples are from one clay-bed: two have a negative and one a positive inclination.

**Fig. 4.20:** Inclination and declination of the Rijkevorsel, Turnhout and Gilze Members in Chaam Kapel after alternating field demagnetization (250 Oersted)(next page, top).

**Fig. 4.21:** Inclination and declination of the Gilze Member in Snijders-Chaam after alternating field demagnetization (300 Oersted)(next page, base).
4.3.2.3 Interpretation of the geomagnetic measurements

The results of the magnetic measurements are summarized in table 4.3. The relation between the Weichselian periglacial structures (frost wedges, ice-wedge casts, convolutions) and magnetic polarity is visualized in fig. 4.22.

<table>
<thead>
<tr>
<th>LITHOSTRATIGRAPHY</th>
<th>TWENTE FORMATION on</th>
<th>GILZE MEMBER on</th>
<th>TURNHOUT MEMBER</th>
<th>TURNHOUT MEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GILZE</td>
<td>BEERSE BLAK (HUS 1987)</td>
<td>MEERLE</td>
<td>RAVELS</td>
</tr>
<tr>
<td>LOCATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GILZE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BERGE-LEONET</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEERLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZWART</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEERLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIKGAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.22: Relation between the Weichselian periglacial structures and the magnetic polarity.

In Meerle and Gilze, where the clays of the Turnhout and Gilze Members are directly overlain by the Twente Formation, the magnetic change coincides with the presence of cryoturbated levels (fig. 4.22) (Van Montfrans, 1971: pit de Toekomst, pit Sint Fransiscus). It is true that the reversal occurs some distance below the base of the macroscopically visible cryoturbation at the sampling site. According to Hus (1988) in exposure Beurse Blak the change in polarity occurs at the top of a humic layer, well below the cryoturbated upper part of the Turnhout clay (see also app.). He warns against the influence of periglacial activity and proposes to apply a field test on deformed strata. Nevertheless, the positive inclinations above the humic bed are interpreted as a normal magnetosubchron in the Matuyama chron (Hus, 1988). However, it is not certain whether the thickness of the melting Weichselian permafrost was equal to the depth of the cryogene structures as seen nowadays in the exposures. Possibly remagnetization and load casting occurred during the melting of the ice-rich topzone of the permafrost, while melting of the underlying ice-poor permafrost zone resulted in (partial) remagnetization without load casting.
In those situations where the Turnhout Member is covered by the Gilze Member and Weichselian cryoturbation phenomena did not influence the clay-beds of the Turnhout Member (e.g. Ravels, Zwart Water, Meerele Slikgat, Chaam Kapel), no polarity changes are registered and the Turnhout Member shows a reversed polarity to the top. Furthermore, it is remarkable that sections influenced by later cryoturbation always reveal a change from a reversed to a normal polarity in different lithostratigraphic units (Gilze as well as Turnhout Members). New magnetozones would be necessary in the existing lithostratigraphic scale, if each reversal in the top of the different lithostratigraphic units is regarded as a primary feature. Although other magnetozones, not given in the polarity time scale of Mankinen and Dalrymple, are certainly present in the Matuyama epoch (Hus, 1988), it does not seem wise to define them in problematic (cryoturbated) layers. The discussion as to whether cryoturbation can effect magnetic polarity depends to a large extent on the plasticity of the clay-beds concerned during the cryoturbation. If the involutions are merely a rigid displacement and overturning of layers, then the original polarity will be partly preserved, giving however a large scatter in the magnetization directions. If cryoturbation involves complete liquefaction of the clay-bed then a reorientation of the magnetic components will occur, according to the then existing magnetic field (remagnetization). In the case of Weichselian remagnetization of a Tiglian clay-bed (Meerele), the reversed polarity of the Matuyama magnetozone will have been replaced by the normal polarity of the Brunhes magnetozone. Laboratory tests by Vandenberghhe and Van den Broek (1982) indicate that oversaturation and excess pore water pressure must have been present during the formation of the Weichselian convolutions. Under such circumstances with a loss of intergranular contacts in the liquefied layer, a complete remagnetization of the sediment is likely to occur. The latter conclusion is adopted in the interpretation of the paleomagnetic results in this study.

The results of the paleomagnetic investigations have been summarized in the following conclusions (table 4.3):
1. The Rijkervorsel Member is almost always characterized by a reversed polarity.
2. The polarity of the Beerse Member could not be investigated because of its sandy nature. Therefore, the lithostratigraphic position of the Beerse glacial is unknown.
3. The polarity of the Turnhout Member is variable. A normal polarity was found locally at the base of the member. The upper part of the Turnhout Member is characterized by a reversed polarity (Ravels). The normal polarity, which is found in the cryoturbated top of the Turnhout Member, can in our opinion be explained by the remagnetization of a liquefied layer, during melting of the permafrost in the Weichselian. However, it cannot be excluded completely, that an "in situ" magnetozone with normal polarity is present in the top of the Turnhout Member, since the reversal is located below the cryoturbated zone and locally coincides with a lithological boundary (Hus, 1988: Beerse Blak).
4. The Gilze Member is characterized by a reversed polarity, but exceptions are regularly found (Chaam Kapel, Snijders-Chaam). The upper part of the Gilze Member at Gilze reveals an intermediate to normal polarity, which is also explained by remagnetization during the Weichselian.
5. The Bavel Member is characterized by a reversed polarity at the base and a normal polarity in the upper part of the member, separated by a well developed transition zone.
4.4 Synthesis of the chronostratigraphy

The combination of the bio- and magnetostratigraphy leads to the following conclusions (Table 4.3):

Table 4.3: Summary of the chronostratigraphical results based on paleobotanical evidence and paleomagnetism (+ is normal polarity, - is reversed polarity, ± is intermediate polarity; signs between brackets are derived from cryoturbated beds).

<table>
<thead>
<tr>
<th>Lithostratigraphy</th>
<th>Chronostratigraphy</th>
<th>Magnetostratigraphy</th>
<th>Polarity Time-Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sterksel Formation</td>
<td>M.P.L. CROMERIAN</td>
<td>BAVEL</td>
<td>+</td>
</tr>
<tr>
<td>Bavel Member</td>
<td></td>
<td>GILZE</td>
<td>(+)</td>
</tr>
<tr>
<td>Gilze Member</td>
<td></td>
<td>MENAPIAN</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WAALIAN</td>
<td>(+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EBURONIAN</td>
<td>(+)</td>
</tr>
<tr>
<td>Turnhout Member</td>
<td></td>
<td>Tiglian C5</td>
<td>(-)</td>
</tr>
<tr>
<td>Beerse Member</td>
<td></td>
<td>Tiglian C4</td>
<td>(+)</td>
</tr>
<tr>
<td>Ruokevorsel Member</td>
<td></td>
<td>Tiglian C3</td>
<td>(-)</td>
</tr>
</tbody>
</table>

1. The Rijkevorsel Member has been formed in the Tiglian C3 phase and is characterized by the reversed polarity of the Matuyama magnetochron.
2. The Beerse and Turnhout Members have been dated respectively as Tiglian C4 and Tiglian C5. The normal polarity at the base of the Turnhout Member and perhaps in the Beerse Member (Van Montfrans, 1971: pit De Toekomst) is correlated with the Olduvai subchron (1.66-1.87 m.y.; Lowrie and Alvarez, 1981) of the Matuyama chron.
3. The Hoogerheide and Woensdrecht Members have been interpreted respectively as possibly Tiglian C3 and probably Tiglian C5.
4. The top of the Turnhout Member dates from the Tiglian C5, Tiglian C6 and the beginning of the Eburonian period and is younger than the Olduvai subchron (reversed polarity).
5. The Gilze Member has been deposited during the Eburonian, Waalian and Menapian bio-chronostratigraphical stages. The predominantly reversed polarity is evidence of deposition during the Matuyama magnetochron.
6. The Bavel Member dates from the Bavel Interglacial of the Bavelian stage. The magnetic reversal from a reversed to a normal polarity is interpreted as the base of the Jaramillo subchron of the Matuyama magnetochron, dated at 0.97 milj. years (Zagwijn and De Jong, 1984).