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Early Pleistocene Tiglian sites in the Netherlands: A revised view on the significance for quaternary stratigraphy

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A R T I C L E I N F O

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A B S T R A C T

The Tiglian-A, B and C form the main subdivision of the Early Pleistocene Tiglian Stage in Northwest European chronostratigraphy since the 1960's. We re-evaluated the sedimentary context and new and legacy pollen assemblages of the classic type localities of these Tiglian pollen zones in the Dutch-German border area and Roer-Valley-Graben. Following recalculation of new upland pollen sums, we found that the three-fold subdivision of the Tiglian Stage is too simplistic and lacks a sound stratigraphic basis. The Tiglian-A is only found locally and cannot be positively identified in the RVG. The Tiglian-B in the Tegelen-Maalbeek area is not unique since similar occurrences are present at other depths in the RVG. Sedimentary and pollen analysis suggests Tiglian-C as defined in the Tegelen-Maalbeek type area could have been deposited in a very short amount of time, although this does contradict mammal data. The T-B/C cycle preserved in the type area likely represent a single example of multiple similar Early Pleistocene climate cycles. The sediments of the so-called cool or cold phase of pollen zone T-C 4^c in the stratotype of the Tiglian C substage are interpreted as having formed during the onset of crevassing and therefore its significance as a regional climate indicator is discussed. We conclude that the extrapolation of the Tiglian pollen zones into chronostratigraphical substages is questioned and it is concluded that the chronostratigraphical subdivision of the Early Pleistocene, based on palynological characteristics and palaeobotanical analyses, requires reconsideration based on independent dating and land-sea record integration.

1. Introduction

Geological research on the Early Pleistocene Tiglian Stage sites of the Dutch-German border area, near Venlo and Tegelen, has formed the framework of the Early Pleistocene stratigraphy in The Netherlands (Reid and Reid, 1915; Van der Vlerk and Florschütz, 1953; Zagwijn, 1960, 1963a). It has been developed by compilation of evidence derived from palaeobotanical (i.e. pollen and plant macro remains), sediment petrological (heavy-minerals), lithostratigraphical and palaeontological (small and large mammal) investigations. However, palynology played the central role in the development of Early Pleistocene stratigraphy in these sequences (Fig. 1).

The Early Pleistocene pollen record of The Netherlands is mainly derived from fluvial deposits and was generally interpreted through a straightforward equation between vegetation development and climate change. All of the sites investigated are part of the Plio-Pleistocene Rhine-Meuse river system and have provided a wealth of data (filed at the Geological Survey of the Netherlands). Some of the sites are situated on the Peel Block, where Lower Pleistocene deposits are situated at or near the surface. Complementary data were derived from boreholes situated in the adjacent subsiding Roer Valley Graben (RVG).

During the Pliocene the vegetation in the area was dominated by the so-called 'Tertiary elements' (e.g. Zagwijn, 1960), dominated by e.g. *Taxodium*-type, *Sequoia*-type, *Sciadopitys* (dominant in Pliocene but some early Pleistocene occurrence; Donders et al., 2018), *Nyssa*, and *Liquidambar.* Their extinction at the end of that epoch took place more or less simultaneously with changes in the mammal and mollusc fauna, and forms one of the striking features that characterise the onset of the Quaternary in this area (Donders et al., 2007). The classic Tiglian stratigraphy is primarily based on pollen analytical investigations of fluvial clay deposits at the

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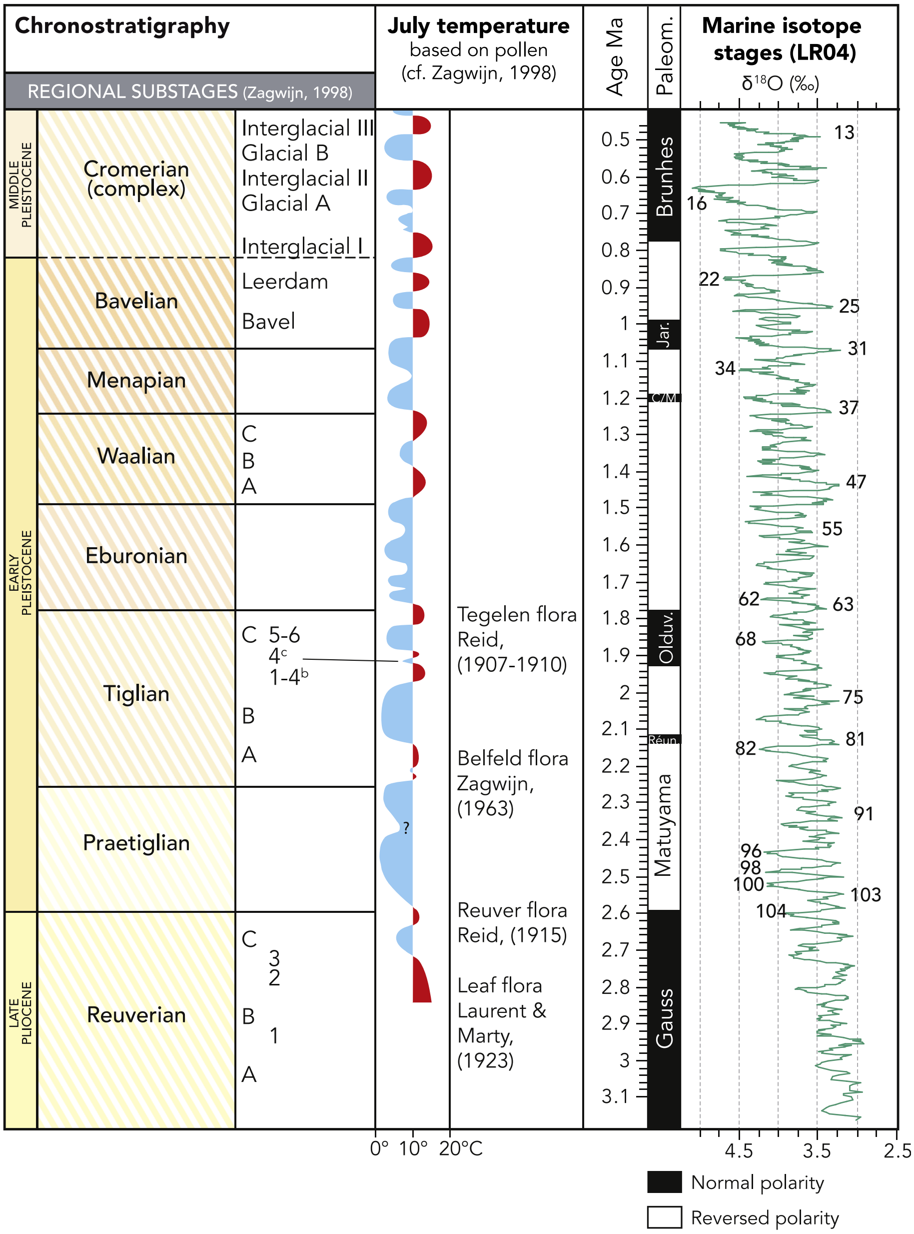

Fig. 1. Chronostratigraphical subdivision of the Early Pleistocene with pollen-defined stages and subdivisions, and a pollen-based temperature curve (Zagwijn, 1998), compared with the Marine Isotope Stages (global benthic stack; Lisiecki and Raymo, 2005) and the paleomagnetic record.

Russel-Tiglia-Egypte pit, near Tegelen, and borehole data in the vicinity of Eindhoven (Zagwijn, 1963a). Three pollen zones,[2] respectively T-A, T-B, and T-C form the main subdivision of the Tiglian Stage. Pollen zone T-A is defined by the presence of *Fagus* and absence of the 'Tertiary' elements. *Fagus* is a genus that lacks in younger pollen zones for a very long time and only re-enters The Netherlands during the Holocene (Van der Hammen et al., 1971). It was first described from a clay deposit in the Jansen-Dings excavation near Belfeld (Van der Vlerk and Florschütz, 1953; Zagwijn, 1963a). The T-B pollen zone is dominated by high values of Ericaceae accompanied by some *Artemisia* pollen and a general low content of tree pollen. This pollen zone was first described from borehole B51G0218, near Eindhoven in the RVG (Zagwijn, 1963a). However, it was realised that this zone showed an incomplete picture (Zagwijn, 1975). *Pterocarya* is a characteristic and often dominant taxon in the T-C pollen zone. This zone with its detailed subdivisions was first defined in the clay deposits of the Russel-Tiglia-Egypte pit near Tegelen (Zagwijn, 1963a).

Absolute ages are not known but correlation with the paleomagnetic timescale has provided some constraints (Van Montfrans, 1971; Kasse, 1996) that should be considered as indicative at best. In these early paleomagnetic studies the presence of the mineral greigite (Fe_3S_4) was not considered and the acquisition mechanism of the natural remanent magnetization (NRM) was taken as detrital (deposition of clastic magnetic mineral particles), the classic NRM acquisition mechanism in sediments. This has been shown since to be problematic in the case of greigite, which is typified by much

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[2] The term pollen zone is used here in its original sense as defined by Zagwijn (1963a) as a division of a pollen sequence typified by specific pollen content. In contrast the terms Tiglian A, Tiglian B and Tiglian C are strictly used as chronostratigraphical substages.

more complex, protracted NRM acquisition (e.g. Vasiliev et al., 2008; Roberts et al., 2011; Aben et al., 2014; Chang et al., 2014; Van Baak et al., 2016; Kelder et al., 2018). This realisation essentially invalidates simple magnetostratigraphic labelling as adopted in those early studies. Based on the early paleomagnetic data the whole of the Tiglian Stage probably lasted from c. 2.2 until c. 1.7 Ma (Zagwijn, 1998). However, in successive publications these boundaries vary between 2.4 and 1.8 or 1.6 Ma (compare Zagwijn, 1975, 1992).

Two main questions arise from a closer examination of the Tiglian pollen zones. The first problem concerns the up-scaling of the relatively thin (15—25 m) fluvial sequences in the Tegelen exposures to the thick (≥100 m) Early Pleistocene sequences in the RVG. This major difference in accommodation space makes it unlikely that the sequences of both areas reflect a similar amount of time. Extrapolation of the Tiglian pollen zones to a regional scale, based on their original definition, and their chronostratigraphical significance needs to be reconsidered. The second question deals with the general problem of interpreting the pollen record from discontinuous fluvial sequences. The main issue is how to distinguish autochthonous and allochthonous signals. Sedimentological interpretations of the sequences in the key-reference area demonstrate a correlation of facies changes and pollen content due to the dominance of wetland forest taxa in the data. This problem has previously also been recognised for the Pliocene terrestrial stages in the Dutch-German border area (Reuverian and Brunssumian) (Donders et al., 2007), although this mostly considered hydrological biases on wetland tree abundance that were the basis of Pliocene pollen zonations, which is less relevant in the Tiglian zonation. However, time control is poor and the fluvial record likely contains many hiatuses. Therefore, reconstruction of a pollen and climate-based stratigraphy can only be achieved when it is based on a firm lithostratigraphical and sediment-architectural framework. Here we assess the validity of the original Tiglian (sub)stage definition against a series of new borehole and outcrop pollen and sedimentary data and review the effect of revising the ecological grouping and pollen sum definition to exclude hydrological bias on the correlations.

2. Tectonic framework and lithostratigraphic setting

The south-eastern Netherlands are part of the Lower Rhine Embayment (LRE) a tectonically subsiding area on the south-eastern margin of the North Sea Basin. To the southeast it is bounded by the Palaeozoic rocks of the Rhenish Massif (Fig. 2). The area is part of the Roer Valley Rift System (Klostermann, 1983; Geluk et al., 1994; Ziegler, 1994; Michon et al., 2003; Van Balen et al., 2005). Regarding the Tiglian key-reference sites, the subsiding RVG and the adjacent Peel Block form two main tectonic elements. Especially the Peel Block is a complicated structure which is strongly dissected by SE-NW running faults.

Fluvial sedimentation in the LRE began at the end of the Miocene and extended gradually westwards through the Pliocene (Schäfer et al., 2005). These Pliocene fluvial deposits are assigned to the Kieseloölite Formation that reaches a thickness over 200 m in the RVG. It consists of thick sand bodies repeatedly interrupted by clay deposits of up to ten or more metres thick with characteristic intercalations of peat or brown coal layers. The uppermost clay deposit has been described as the Reuver Clay and was initially studied in several pits on the Peel Block, southeast of Tegelen, near Reuver (Reid and Reid, 1915). The Kieseloölite Formation is typified by stable heavy-mineral associations due to the strongly weathered sediment derived from its source area: the overburden of the Rhenish Massif (Boenigk, 1978; Kemna, 2005).

The overlying fluvial deposits are assigned to the Waalre Formation (Westerhoff et al., 2003).[3] They consist of mixed Rhine-Meuse deposits, with an unstable (garnet, epidote, green hornblende dominated) heavy-mineral content resulting from the extension of the Rhine catchment into the Alpine region (Zonneveld, 1947[b]; Van Andel, 1950; Boenigk, 1970, 2002; Hagedorn, 2004; Kemna, 2005; Westerhoff et al., 2008). In the RVG the deposits of the Waalre Formation reach a thickness up to 100 m, while the preserved remnants of the formation on the Peel Block show an average thickness of 15—25 m. The Waalre Formation was deposited during the Late Pliocene and Early Pleistocene (Boenigk, 2002; Westerhoff, 2009). Formerly the larger part of the Waalre Formation was assigned to the Tegelen Formation (cf. Doppert et al., 1975; Zagwijn, 1963a).

3. Late Pliocene and Early Pleistocene sedimentary architecture, palynology and paleo-environmental interpretations of the Tegelen - Maalbeek area

3.1. Sedimentary architecture

Many clay pits along the Netherlands-German border area east of Tegelen, have been subject to geological research over the last century and include classic Late Pliocene and Early Pleistocene key-reference sites (Fig. 3; see references in Zagwijn, 1998 and Meijer, 1998). Key pits that we discuss in this paper are the Maalbeek, Laumans and Russel-Tiglia-Egypte (RTE) pits, the latter being the main key-reference site for the Tiglian stage (Zagwijn, 1963a, 1998). Due to its position on the Peel Block a discontinuous record of Late Pliocene and Early Pleistocene fluvial deposits has been preserved in the border area. The general stratigraphy is shown in the N-S orientated cross-section that parallels the state boundary (Figs. 3 and 4). The section clearly demonstrates the NE-orientated tilting of the tectonic blocks. The main lithostratigraphical units are listed in Table 1.

The upper part of the Late Pliocene sequence in the study area is characterised by a distinct zone of clay and overlying brown coal layer(s). These sediments overly Pliocene channel belt deposits and Miocene sands of the Breda Formation. In the southernmost part of the study area, the Late Pliocene sequence is assigned to the Oebel Bed of the Waalre Formation.

A 15—25 m thick Early Pleistocene sequence, assigned to the Waalre Formation, occurs on top (Fig. 4). These sediments occur within clear fining-upward sequences. The basal part of these sequences consist of coarse-grained gravel-bearing channel-belt deposits. These sediments thicken in north-eastern direction, which corresponds with the general trend of the tectonic tilt. The zone of maximum thickness of these coarse-grained sediments may indicate the position of the main channel belt systems that supplied fine-grained material to the adjacent flood basins. The flood basins are filled-in with up to 10 m thick floodplain fines (Fig. 4). Within these floodplain fines, four distinct facies types can be distinguished: fine-grained infillings of oxbow lakes typified by bedded clay with siderite enrichments, massive flood-basin clay deposits with local accumulation of peat, and irregular alternating sand-clay

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[3] In this paper all Rhine sediments with an unstable mineral association are assigned to the Waalre Formation. The first sediments with an unstable mineral association that overly the stable sediments of the Kieseloölite Formation are referred to as the Oebel Beds or WA-1 unit (Figs. 4 and 12; Westerhoff et al., 2003). TNO-GDN (www.dinoloket.nl) now assigns the Oebel Beds or WA-1 unit to the *Kieseloölite Formation* since without heavy mineral data and/or very good cores, these sediments cannot be differentiated from other (stable) sediments of the Kieseloölite Formation. However, in order to prevent confusion in this paper, we decided not to change the stratigraphic terminology as originally applied by Wim Westerhoff.

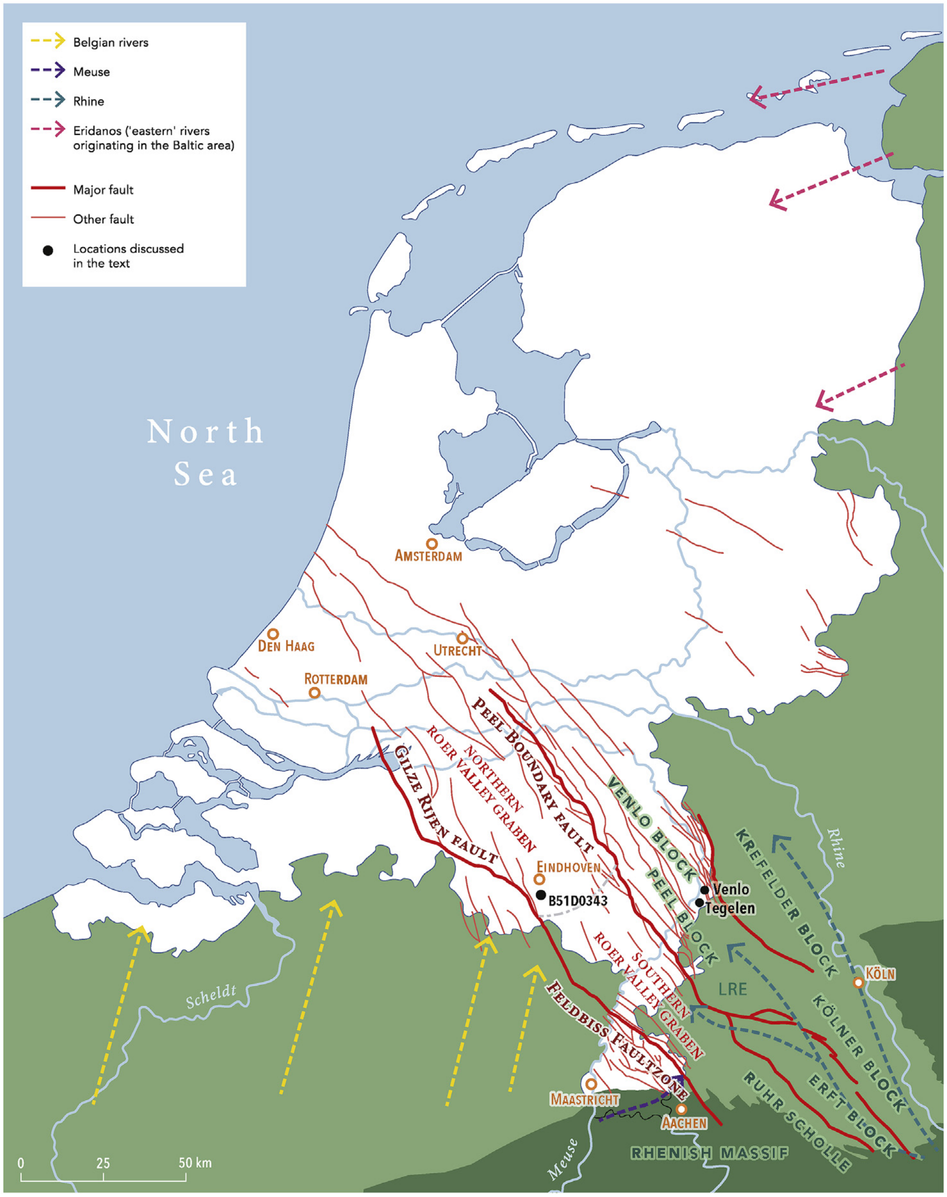

Fig. 2. Tectonic setting of the Lower Rhine Embayment and adjacent areas in the Netherlands. Indicated are the main depositional direction of the Pliocene and Early Pleistocene fluvial systems at the southern margins of the North Sea Basin.

deposits formed as overbank or crevasse splays. This assemblage of facies types characterises the fluvial sequence of Tegelen-Maalbeek area as part of a fine-grained meandering or anastomosing river system (Miall, 1996). Comparable facies types occur in the Russel-Tiglia-Egypte pit while in between the Russel-Tiglia-Egypte and Laumans pits only the clay of the flood-basin facies type has been observed. Detailed sedimentary descriptions for three key localities for Late Pliocene - Late Pleistocene research, the Maalbeek, Laumans and Russel-Tiglia-Egypte pits are given below.

3.1.1. *Maalbeek pit*

The Maalbeek pit is known from several earlier publications (Nota, 1956; Kortenbout van der Sluis, 1960; Zagwijn, 1963a; Boenigk, 1970; Urban, 1978; Westerhoff et al., 1998). The general stratigraphical sequence is presented in Fig. 4. Details, showing the relationship of the facies assemblages within the Waalre formation are given in Fig. 5. Two logs showing facies unit details are given in Figs. 7 and 8.

On top of c. 5 m thick basal channel belt deposits four facies units are recognised within the clay deposits of the Waalre Formation (Fig. 5):

- MLBK-1A: A flood-basin clay with laminae of fine sand in its lowermost part and more massive clay towards the top (Fig. 7). Enrichment by siderite is notable by light grey to white colors when the clay is freshly exposed. The clay is covered by a peat layer up to 50 cm thick. The unit is 4–5 m thick.
- MLBK-1B: A massive structureless flood-basin clay (Fig. 6A; Fig. 7). The lower part contains some thin lenses of fine sand or sandy laminae. Within the unit two weakly developed, crumbly soil horizons with tiny rootlets and a slightly higher content of organic matter indicates ripening during initial stages of soil formation. Siderite occurs in diffuse patterns or as irregular distributed small nodules. The upper boundary is always formed

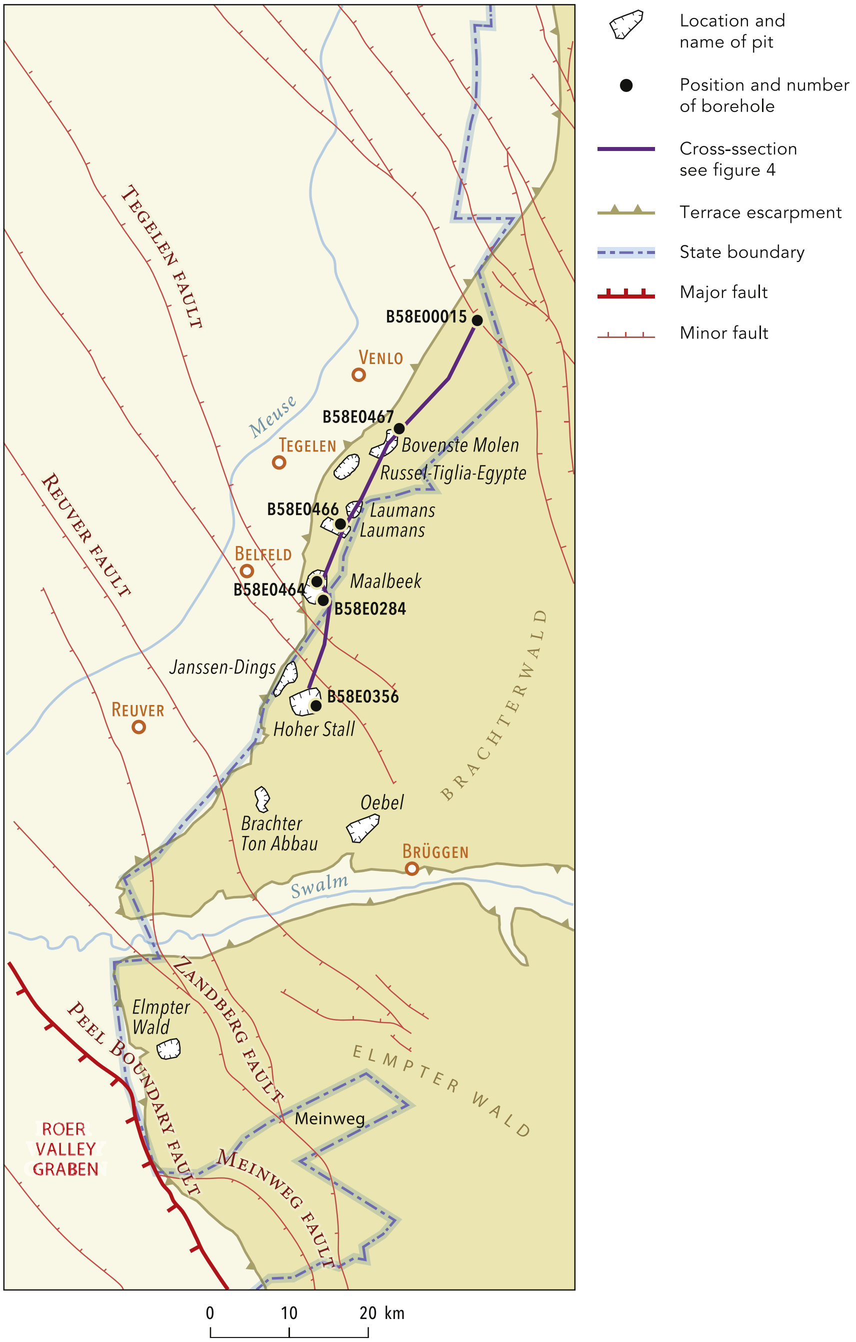

Fig. 3. Detailed location map of the Tegelen-Maalbeek area near the Dutch-German borderline. The position of the faults is derived from the recently updated version of the Digital Geological Model (DGM at www.dinoloket.nl). The pits of interest for present and former geological investigations are indicated (Zagwijn, 1960; Boenigk, 1970; Westerhoff, 2009).

by an erosional contact and often marked by rounded nodules of siderite (pebble and boulder size). The thickness of the unit varies from 3 to 4 m.

- MLBK-2: A strongly bedded clay that represents the infill of an abandoned channel (Fig. 6B; Fig. 8). The thickness of individual clay beds varies between 10 cm (lower part) to about 30 cm (upper part), which probably indicates that sedimentation rates in the upper part were considerably higher. Due to the enrichment of siderite a remarkable light grey to nearly white colour characterises the uppermost part of the individual beds. Between the clay beds thin layers of sand, millimetres to decimetres in thickness, may occur. The thicker sand beds often show climbing ripple lamination indicating rapid sedimentation during waning flow conditions. The intercalated sand beds can be rich in fossil remains of small and large mammals, molluscs and plants. Throughout the pit the thickness of the unit increases towards the northeast to a maximum observed thickness of about 9 m (Fig. 5). The channel scour that preceded the infilling eroded large parts of facies type MLBK-1.
- MLBK-3: Alternating sand and clay layers formed by extensive crevasse splays on top of the laminated channel-fill (Figs. 5 and 6C; 7; 8). Two cone penetration tests situated very close to boreholes B58E464 and B58E0465 show the characteristic

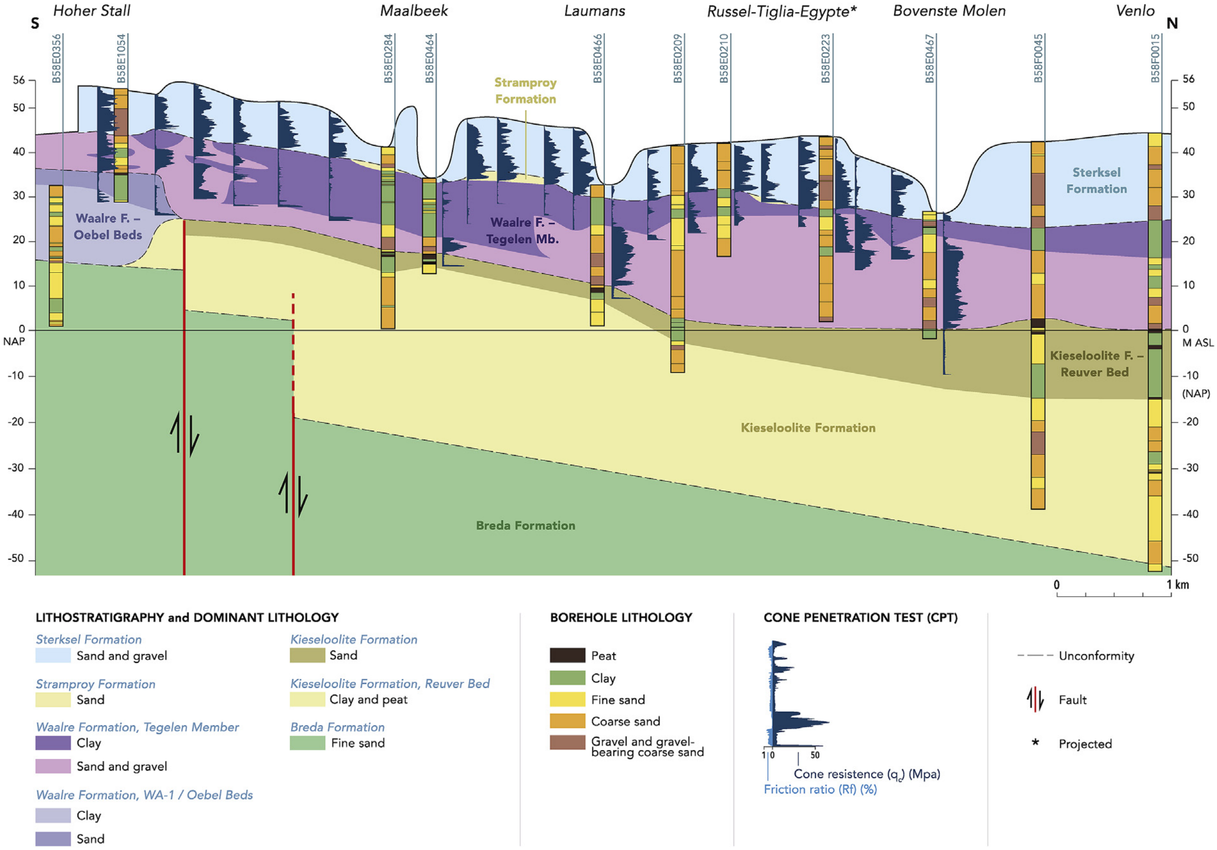

Fig. 4. Cross-section along the Dutch-German border in the Tegelen-Maalbeek area (location indicated in Fig. 3). The position of the lithostratigraphical units is based on field observations, borehole data and cone penetration tests. The northward dipping of the main lithostratigraphical units results from the generally NE orientated tilting of the main tectonic blocks in the area.

Table 1
Lithostratigraphical units in the Tegelen-Maalbeek area.

Lithostratigraphy	General characteristics
Sterksel Formation (ST)	Coarse-grained gravel-bearing fluvial deposits. The lower boundary forms an erosional marker horizon that can be traced throughout the large part of the LRE (Boenigk, 2002) contact with the underlying deposits. The heavy-mineral content is characterised by unstable (Rhine) associations in which epidote dominates. The unit is of Mid-Pleistocene age
Stramproy Formation (SY)	Typical relics of discontinuous preserved fluvial sediment. Mainly medium-grained sand only a few metres thick. The heavy-mineral content is dominant stable due to its provenance in central and northern Belgium (Westerhoff et al., 2008). The deposits regular show periglacial phenomena (Van Straaten, 1956; Zagwijn, 1963a; Kasse and Bohncke, 2001). The unit is of Early Pleistocene age.
Waalre Formation (WA)	Fluvial deposits up to 25 m thick. The basal part consists of coarse-grained channel deposits (gravel and sand) that grade upwards into fine-grained floodplain deposits. The erosional lower boundary marks the transition to the Kieseloölite Formation. The sand is typified by unstable heavy mineral assemblages. A lower subunit is preserved near the Hoher Stall pit (southern part of the section, Fig. 4) and positively correlated with the so-called Oebel Beds (Boenigk, 1970; Zagwijn, 1974; Kemna, 2005, 2008; Boenigk and Frechen, 2006; Heumann and Litt, 2002). The upper subunit is assigned as Tegelen Member of the Waalre Formation and shows thick accumulations of floodplain fines. The unit is Late Pliocene to Early Pleistocene in age.
Kieseloölite Formation (KI)	Unconformable overlying the marine deposits. Up to 30 m thick medium to coarse-grained fluvial deposits grading into a several metre thick clay deposit towards the top. The latter is assigned to the Reuver Bed. (Zagwijn, 1960; Boenigk, 1970; Westerhoff, 2004) and contains two characteristic peat or brown coal strata in its uppermost part. The sand is typified by dominant stable heavy-mineral content. The unit is of Pliocene (Piazencian) age.
Breda Formation (BR)	Fine-grained and glauconite-bearing marine deposits of Miocene age (Westerhoff et al., 2003).

alternating sand-clay bedding and the increase of the sand content of this facies type (Fig. 5).

The section (Fig. 5) shows the position of the borehole (B58E0254) investigated by Nota (1956). At about the same site Zagwijn (1963a) investigated the then exposed clay deposit which, according to his description, resembles facies type MLBK-1A. Borehole B58E0269 is situated in front of the excavation face described by Westerhoff et al. (1998) and is used to sample the non-exposed part of the sequence below the clay pit (Fig. 7). Borehole B58E0284 is situated just outside the Maalbeek pit (Fig. 5) and comprises a nearly complete sequence of the laminated channel fill (facies unit MLBK-2) Fig. 8). The upper part of the fine-grained sequence shows an increase of laminae of intercalated fine sand and can be correlated to the crevasse splay facies of the exposure (facies unit MLBK-3). The deposits of the Waalre Formation are underlain by the Reuver Bed (Figs. 4, 5, 7 and 8). This is interpreted as a flood-basin deposit with extensive swamps where peat

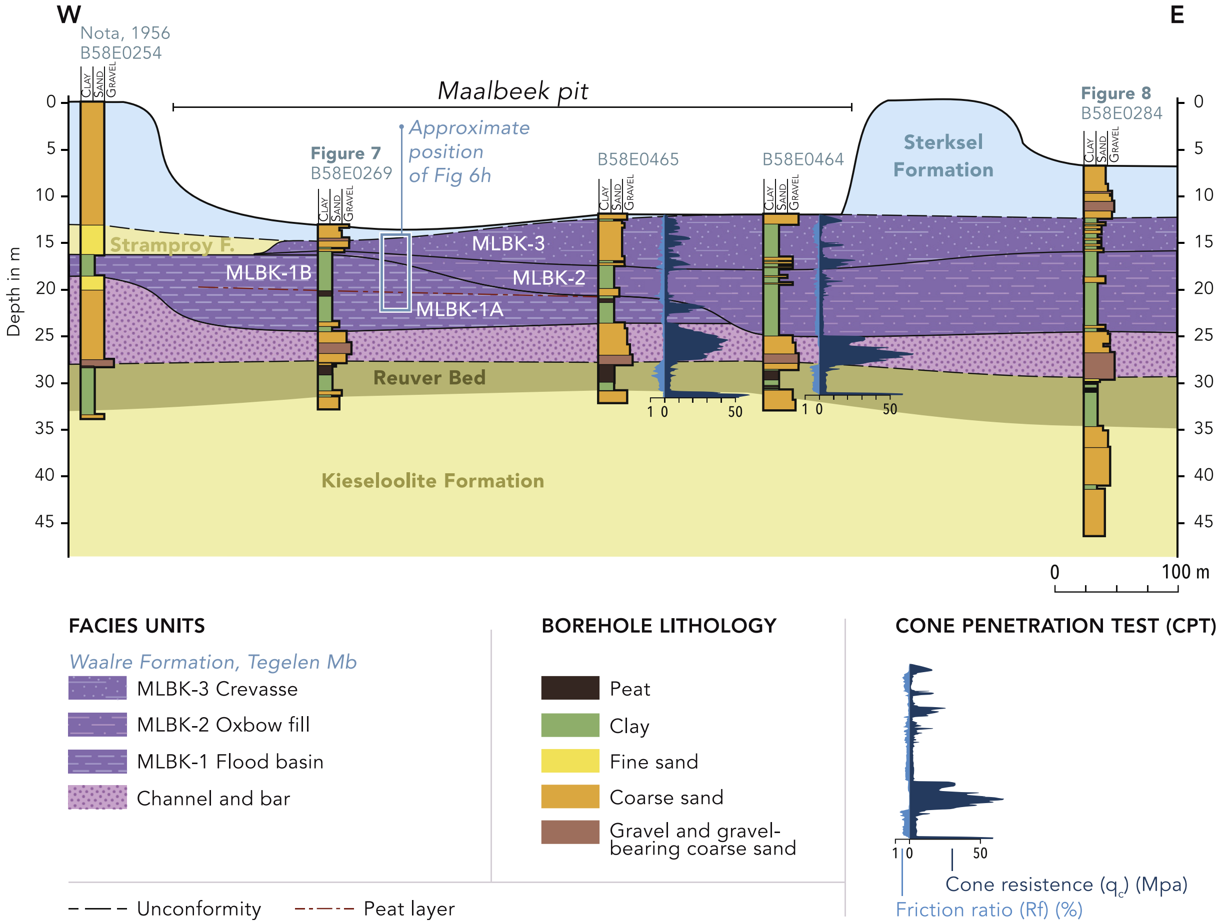

Fig. 5. Detailed W-E cross-section in the excavated area of the Maalbeek site (for location see Fig. 3). Of main interest is the interrelationship of the facies assemblages that occur within the Waalre Formation. Note that the floodbasin facies (MLBK-1) is subdivided in part by a thin layer of peat. The channel-fill facies of unit MLBK-2 thickens to the east and can be well-recognised by the low resistance and high friction values in the graph of the cone penetration test. The upper facies unit (MLBK-3) consist of complex and irregular alternations of sand and clay. In the western part of the section deposits of the Stramproy Formation (stable heavy-mineral assemblages) intercalate the Waalre and Sterksel Formation.

accumulated.

3.1.2. Laumans pit

The Laumans pit (LM), situated 1.5 km north of Maalbeek (Fig. 3), so far has few published good pollen data and is known from a few scarce founds of fossil remains (Zagwijn, 1963a; Kasse and Bohncke, 2001; Vandenberghe, 2001). Van Straaten (1956) described cryoturbation phenomena and frost wedges in the neighbouring and long-abandoned pit Wambach. These indicators for cold climatic conditions were observed in deposits that are presently assigned to the Stramproy Formation.

The general stratigraphy resembles that of the Maalbeek pit (Fig. 9). A key difference is however the greater thickness of the coarse-grained basal part (channel belt) of the Waalre Formation (Fig. 4). Floodplain fines which may reach a thickness of c. 9 m overly the channel belt deposits of the Waalre Formation and represent a massive and nearly structureless flood basin deposit. Only the upper c. 4 m of the clay is regularly exposed (Fig. 6D). The top few metres of the deposits are heavily affected by (post-depositional) enrichment of siderite and formation of siderite nodules (Fig. 6E and F, 10). They occur in irregular patterns and largely mask the original structure of the deposits. Another marked feature is the occurrence of a large-scale polygonal network of wedges in the upper part of the floodplain fines indicating cold climate conditions after deposition of the clay (Fig. 9). The non-exposed part of the flood basin clay, is only known from cored boreholes and CPTs (Figs. 4 and 9).

From the base to top three main facies types are recognised within the flood plain fines at the top of the Waalre Formation (Fig. 9):

- LM-1: A 2–3 m thick laminated flood basin clay with siderite enrichments and an increasing number of cm-to dm-thick sand beds. This part is interpreted as the transitional facies from the underlying channel belt to flood basin fines.
- LM-2: A 6 m thick massive flood basin clay without sedimentary structures. The upper meter of the exposed clay shows crumbly and prismatic structures that may be the result of initial soil formation (Kasse and Bohncke, 2001) in a floodplain with fluctuating groundwater tables. Locally thin lenses of sand occur.
- LM-3: A $\leq$ 1 m thick flood basin facies with fine cm-thick sand laminations (section I and II, Figs. 9 and 10) indicating the regular influx of clastic material in a back-swamp environment.

The underlying channel belt deposits contain up to 14 m thick coarse-grained sand and gravel. Like in the Maalbeek pit, the deposits of the Waalre Formation are underlain by the Reuver Bed (Figs. 4, 9 and 10).

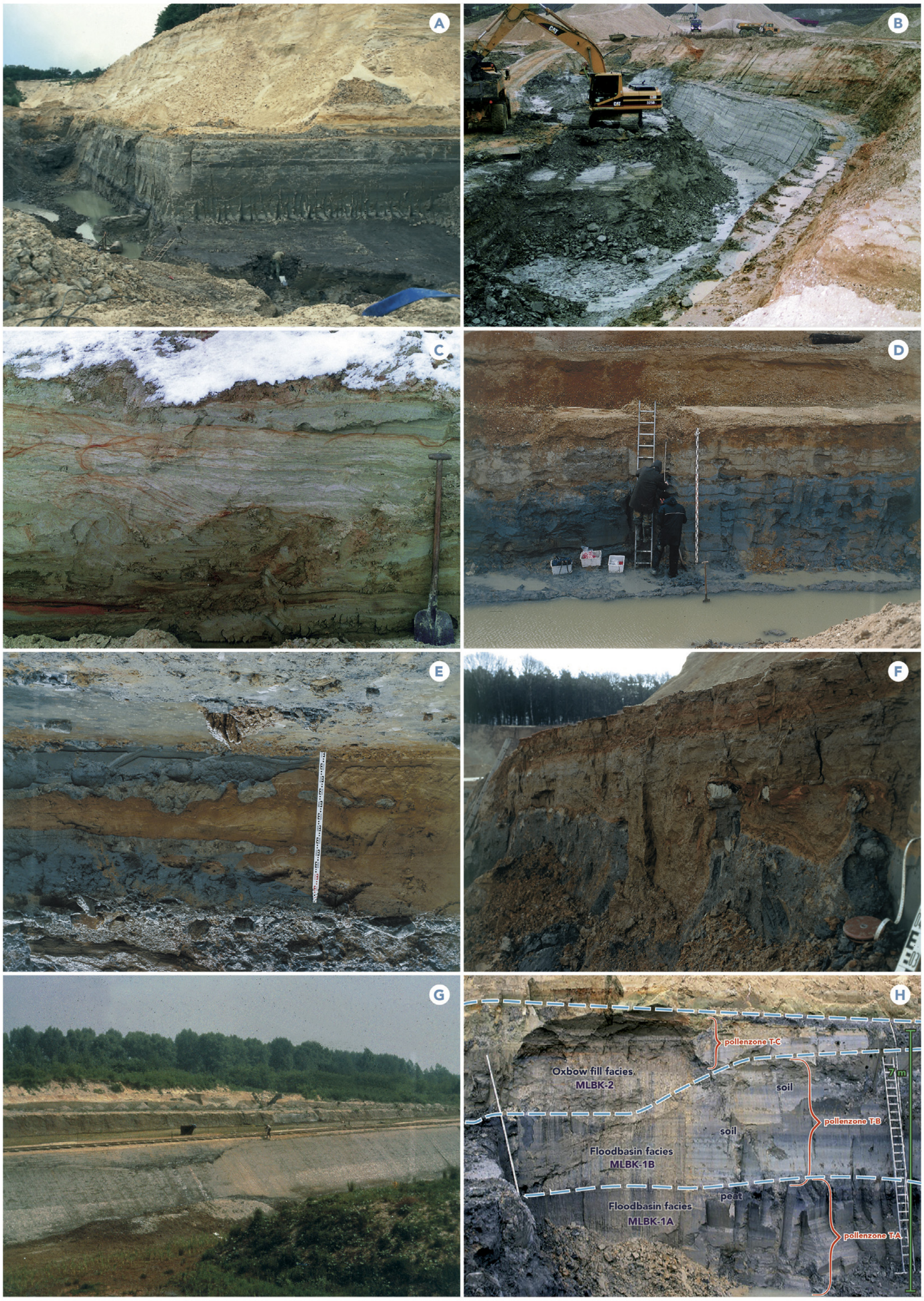

Fig. 6. A: Flood-basins clay exposed in the Maalbeek pit, the dark layer at the left is the peat layer that divides facies units MLBK-1A and MLBK-1B. B: Oxbow fill with bedded clay from the Maalbeek pit (Unit MLBK-2), white colors represent siderite enrichments. C: Crevasse splay deposits (Unit MLBK-3) overlying the oxbow fill (Unit MLBK-2) in the Maalbeek pit. D: Floodbasin deposits (Units LM-2 & 3) of the Laumans pit at section I (Fig. 9). Note the by oxidation of siderite light colored upper part of the clay. The overlying gravel-bearing deposits belong to the Sterksel Formation. E: Floodbasin deposit of the Laumans pit (Unit LM-2 & 3). The red-brown colors result from siderite oxidation. Lithologically it is the same clay as the surrounding blue colored deposits. F: Floodbasin deposit of the Laumans pit (Units LM-2 & 3). Note the large concretions of siderite with light colored inner part. G: The Russel-Tiglia-Egypte pit in 1961. The lower part is formed by an oxbow fill consisting of bedded clay (Unit RTE-1). The small channel in the central part belongs to the overlying crevasse-overbank complex (Units RTE-2 & 3). H. Detail of flood-basins facies, overlying oxbow fill facies and classical T-pollen zonation of Zagwijn (1960, 1963a) in the south-western part of the Maalbeek pit (see Fig. 5 for position). Lower floodbasin clays and peat layer represent Unit MLBK-1A (pollen zone T-A), overlying floodbasin clays represent Unit MLBK-1B. Oxbow fill sediments of Unit MLBK-2 (pollen zone T-C) form the top of the sequence. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

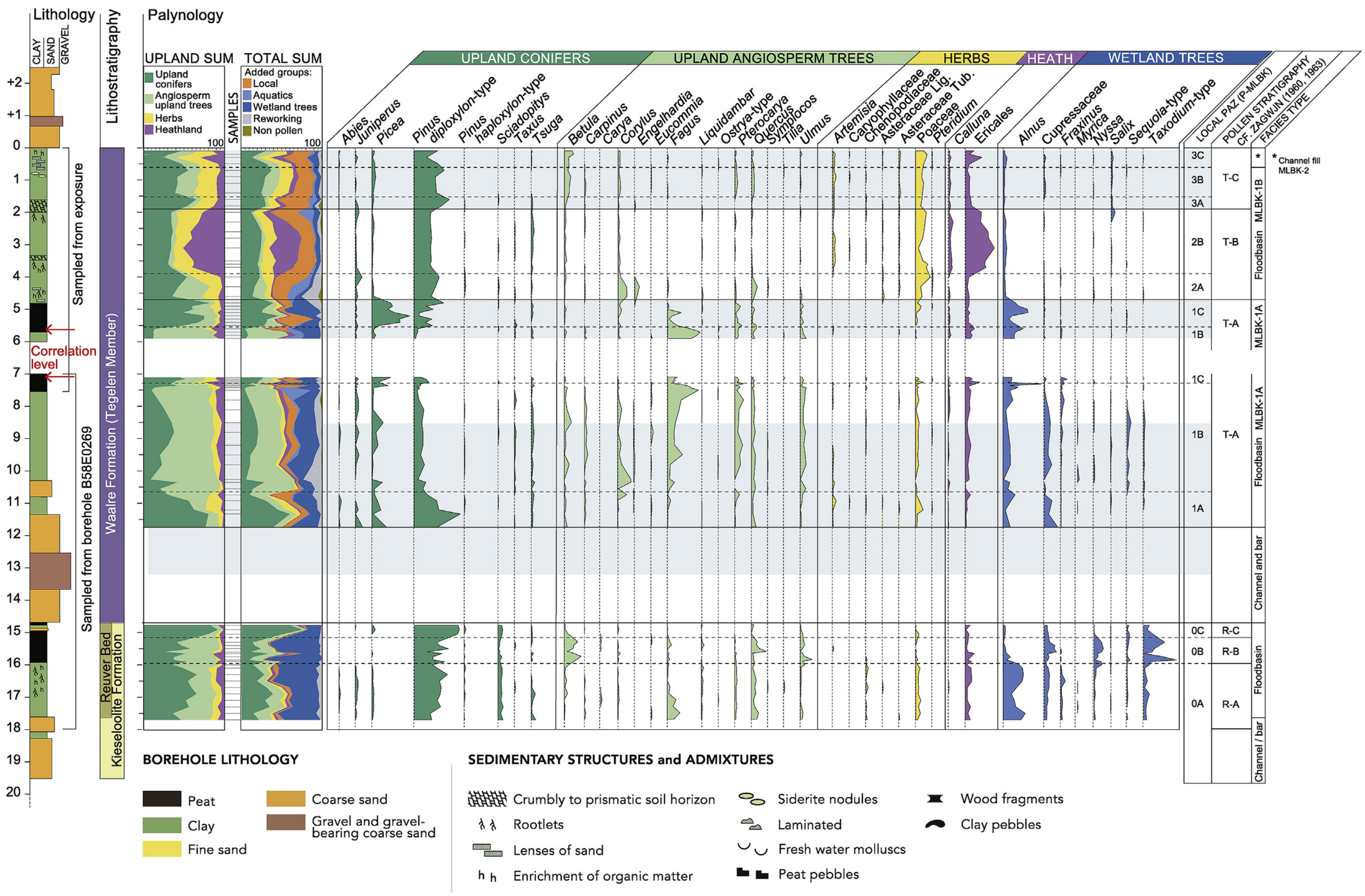

Fig. 7. Lithology, lithostratigraphy, pollen diagram and facies units from the Maalbeek pit (for location see Figs. 3 and 5). The lower two pollen diagrams are derived from borehole B58E0269. The upper diagram is sampled from the excavation in 1993 (Westerhoff et al., 1998). Local pollen assemblage zones (PAZ) are delineated by black lines, subzones by dashed lines (NOTE: zone numbers are updated low to high from base to top with respect to Westerhoff et al., 1998). Alternate grey highlighted zones for visibility.

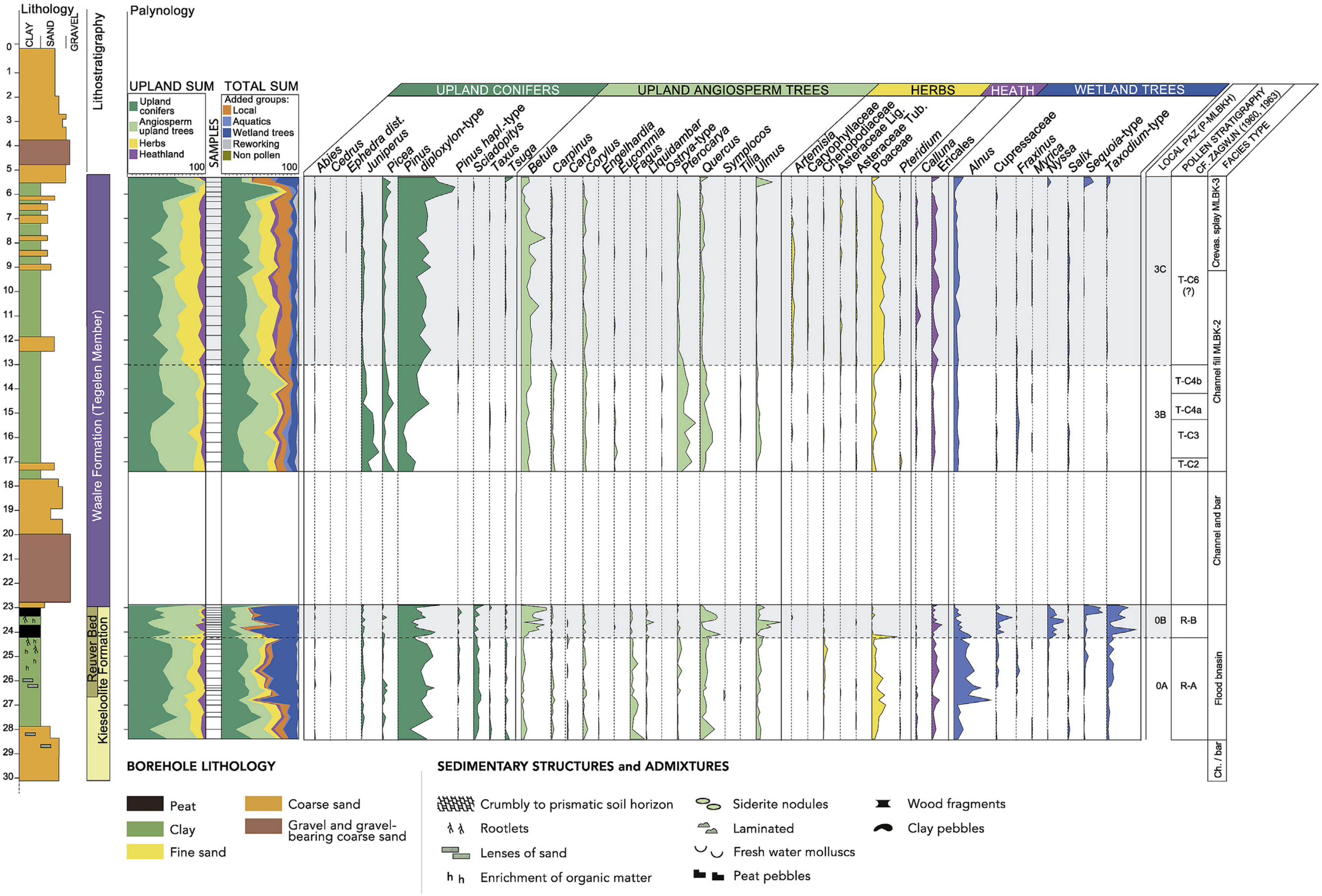

Fig. 8. Lithology, lithostratigraphy, pollen diagram and facies units of Maalbeek borehole B58E0284 (for location see Figs. 3 and 5). Local pollen assemblage zones (PAZ) are delineated by black lines, subzones by dashed lines. Alternate grey highlighted zones for visibility. T-zones indicate the classical interpretation based on the definitions of Zagwijn (1960, 1963a).

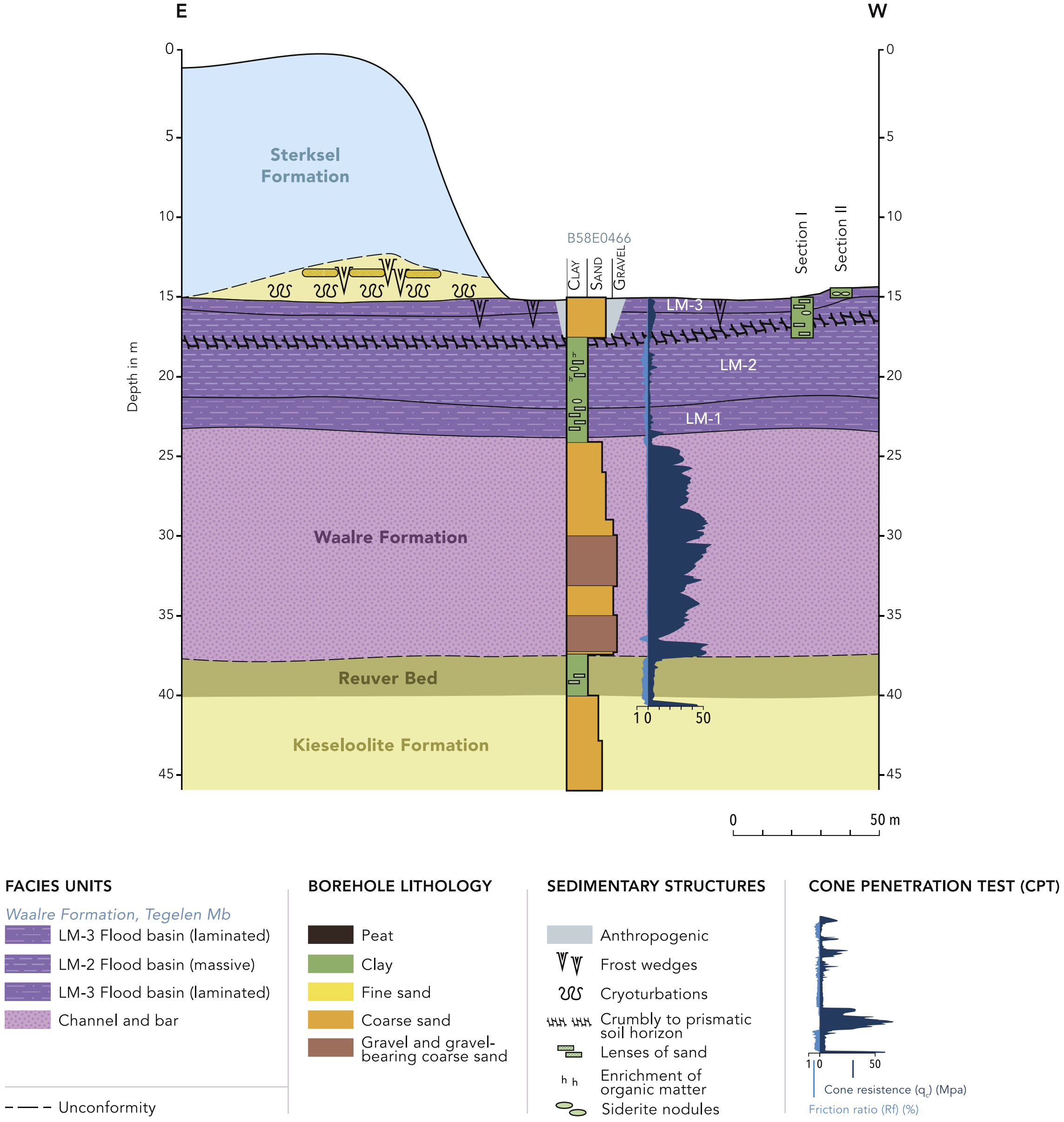

Fig. 9. Detailed cross-section from the Laumans pit. Note the frost-wedges at the top of the floodbasin clay of the Waalre Formation which form a polygonal pattern. The Stramproy Formation shows a lower level of cryoturbations and an upper level of large frost-wedges separated by a humic soil horizon.

3.1.3. *Russel-Tiglia-Egypte pit*

The Russel-Tiglia-Egypte pit (RTE) (Fig. 3) is the main key-reference site for the Tiglian stage (Zagwijn, 1998). The general stratigraphy of the pit corresponds to that throughout the area. Detailed investigations date back to the early 1960s (Kortenbout van der Sluijs and Zagwijn, 1962). Here we focus on the clayey deposits of the Waalre Formation that were subject to the pollen analytical research by Zagwijn (1963a). Note that the Tegelen Formation as mentioned in previous literature is now assigned as the Tegelen Member of the Waalre Formation (Westerhoff et al., 2003).

From the base to top three main facies types are recognised within the flood plain fines at the top of the Waalre Formation (Fig. 11).

- RTE-1: An approximately 6 m thick sequence of laminated clay that is interpreted as the infilling of an abandoned meander (Kortenbout van der Sluis and Zagwijn, 1962). This facies resembles the channel infill at Maalbeek (MLBK-2) and is much more widespread in the area than previously thought. Like similar deposits in the other pits the clay is rich in siderite.
- RTE-2: A crevasse splay deposit starting with a thin layer of fine sand with many plant macro remains (wood, seeds, fruits, and leaves) grading into sandy clay. This crevasse splay is interpreted as the result of reactivation of the incompletely filled oxbow of facies-type RTE-1.
- RTE-3: A flood basin facies consisting of fine-grained clay deposits with two intercalated peat horizons indicating swamp conditions. This facies-type forms the final part of the sequence at the site.

The entire sequence at Russel-Tiglia-Egypte is underlain by 15–20 m thick coarse-grained channel belt deposits (forming the basal part of the Waalre Formation in the area) and by the Reuver Bed (Fig. 4).

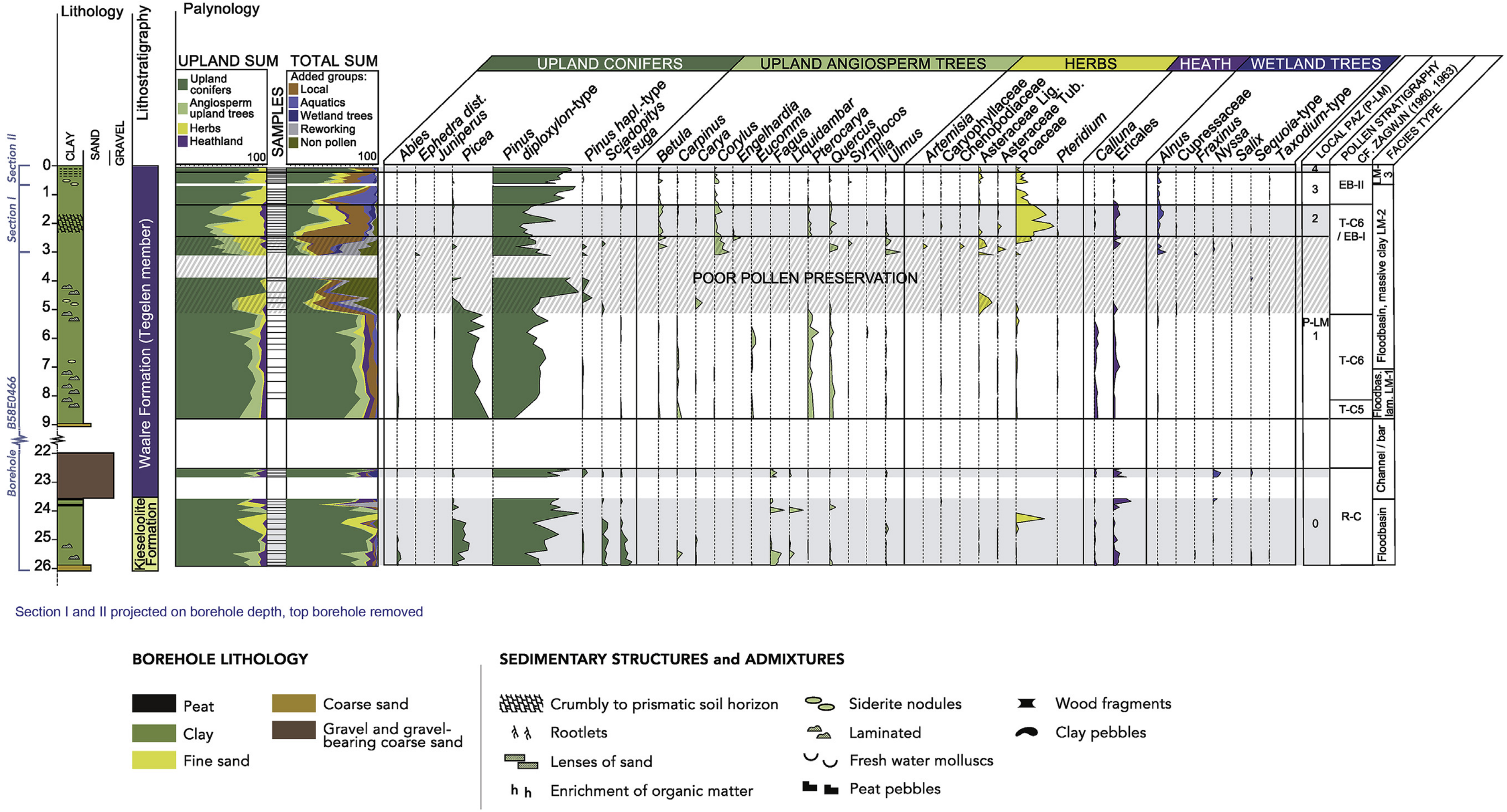

Fig. 10. Lithology, lithostratigraphy, pollen diagram and facies units from the Laumans pit. The upper 3 m of the pollen diagrams are sampled from the sections at the top of the exposed clay deposits (Fig. 9). The lower pollen diagram is derived from borehole B58E0466 that was executed in the pit (see Fig. 9). Local pollen assemblage zones (PAZ) are delineated by black lines, subzones by dashed lines. T-zones indicate the classical interpretation based on the definitions of Zagwijn (1960, 1963a). Alternate grey highlighted zones for visibility.

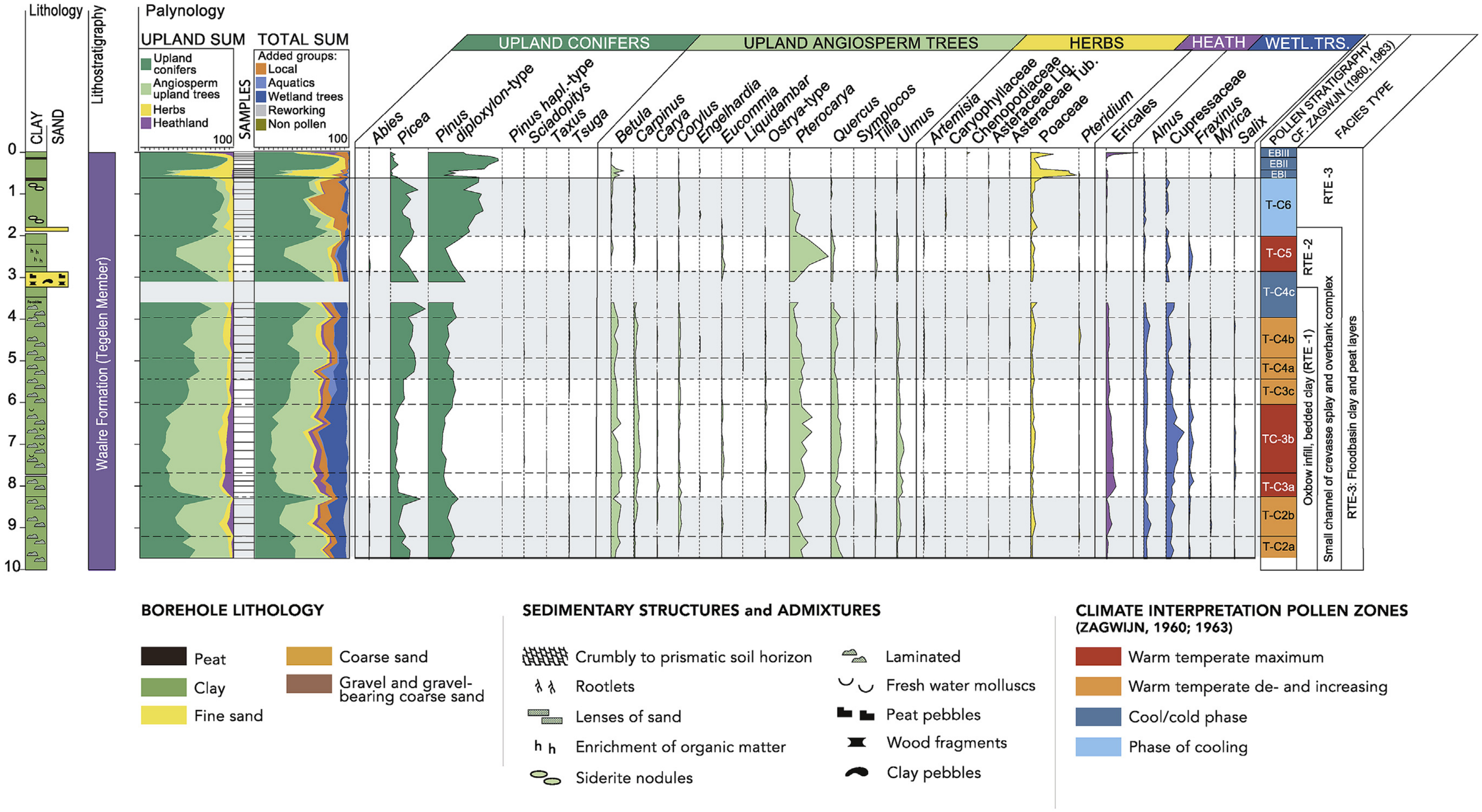

Fig. 11. Lithology, lithostratigraphy, pollen diagram and facies units from the Russel-Tiglia-Egypte pit. Recalculated pollen sums based on data published by Zagwijn (1963a). Local pollen assemblage zones (PAZ) are delineated by black lines, subzones by black and grey dashed lines. T-zones indicate the classical interpretation based on the definitions of Zagwijn (1960, 1963a). Alternate grey highlighted zones for visibility. The stratigraphical and climatic interpretations of the pollen zones are derived from the original publication (Zagwijn, 1963a).

3.2. Palynology

Several sections in the pits and material retrieved from cored boreholes in the pits or from nearby sites have been analysed for their pollen content. Here we present new pollen data from exposures and boreholes of the Maalbeek and Laumans pits and from a borehole near Eindhoven. Pollen samples are treated using the standard procedure applied at the Geological Survey of the Netherlands which basically follows that of Faegri and Iversen (1975). Counting is based on a tree pollen sum of at least 200 pollen grains. The pollen percentage sum is based on upland conifers, angiosperm upland trees, upland herbs and heathland. Groups outside the pollen sum are wetland trees, local herbs (mostly ferns), aquatics, other palynomorphs and reworked pollen (see legend in Fig. 7). Data and pollen zonations from the Russel-Tiglia-Egypte pit represents the original publication (Zagwijn, 1963a) (Fig. 11). The new pollen diagrams are described in accordance with locally defined pollen zones (Tables 2–5) and compared to the classic Tiglian substage assemblages. The raw pollen counts from all pit sections and boreholes are available in Appendix A (Supplementary Data).

Zagwijn (1963a) discerned three main pollen zones in clayey Tiglian deposits. The lower pollen zone, T-A, was first defined in the Janssen Dings pit (for location see Fig. 3) where the clay deposit is typified by high frequencies of *Fagus* pollen (Van der Vlerk and Florschütz, 1953; Zagwijn, 1963a). The next pollen zone, T-B, typified by low values for trees and dominance of non-arboreal pollen (NAP) was first defined in borehole B51G0218 near Eindhoven (Fig. 2) (Zagwijn, 1963a). The third pollen zone, T-C and a detailed subdivision, was defined in the Russel-Tiglia-Egypte pit (Zagwijn, 1963a) and is typified by a continuous presence of *Pterocarya* without *Fagus* presence. In order to allow comparisons, in the text below and pollen diagrams we will also translate the local pollen zonations into the classic Tiglian T-A, T-B and T-C terminology.

3.2.1. Maalbeek pit

The pollen analytical results of the flood plain clay of the Waalre Formation in borehole B58E0269 (Fig. 5) and that of the deeper situated Reuver Bed are shown in one composite diagram (Fig. 7). The uppermost part was sampled from the exposure itself and has been previously published (Westerhoff et al., 1998). It is presented again to demonstrate its relationship with the other data. The discerned pollen assemblage zones are summarised in Table 2.

To illustrate the palynological signal of the channel-fill (facies unit MLBK-2), the pollen diagram obtained from borehole B58E0284 is given (Figs. 5 and 8; Table 3). The interval between ~5.3 and 17.5 m comprises the sampled channel-fill deposit. The lowermost part of the diagram between ~23 and 28.5 m show the pollen content of the flood plain fines from the Reuver Bed. Table 3 summarises the description of the pollen zones.

3.2.1.1. Pliocene. The two pollen diagrams from the Reuver Bed (borehole B58E0269, Fig. 7, and B58E0284, Fig. 8) at the Maalbeek site show a striking similarity and local pollen assemblage zones are defined at the site level. The overall assemblage demonstrates the development of a local *Taxodium-Nyssa* forested wetland as soon as clastic sedimentation ceases and organic matter starts to accumulate. This coincides with a marked decline in *Alnus*. In both diagrams, *Pinus* is well represented in the clastic facies, decreases in the organic part, and tends to increase again in the uppermost parts. It is likely that the marked decline of *Alnus*, a species that prefers wet and nutrient-rich environments such as along riverbanks, is related to environmental changes that benefit the establishment of peat-forming *Taxodium-Nyssa* swamps, likely due to isolation from the active channel and associated change from flowing to still-standing water.

The pollen zones P-MLBK-0A (B58E0269) and P-MLBKH-0A (B58E0284) resemble the Reuverian A pollen assemblages as described by Zagwijn (1960). The pollen zones P-MLBK-0B and P-MLBKH-0B can be compared to Reuverian B pollen assemblages. Pollen zone P-MLBK-0C, characterised by increase of *Pinus* and decline of the 'Tertiary elements', could be interpreted as a Reuverian C pollen assemblage (Zagwijn, 1960).

The Upper Pliocene (Reuverian) age of the clay deposit at the top of the Kieseloölite Formation in the study area differs from the interpretation in Zagwijn (1960, profile IV). In that study, the Pliocene clay in the Tegelen-Maalbeek area was lithostratigraphically assigned to the Lower Pliocene Venlo Clay. This interpretation was based on the presence of ~40% *Sequoia*-type in the deposit in borehole B58F0015 near Venlo (Fig. 4), indicative of the Brunssumian Stage (Zagwijn, 1960). However, a high percentage of *Sequoia*-type is not a confident stratigraphical argument because the occurrence of the taxon depends largely on local depositional and environmental conditions (Donders et al., 2007). Furthermore, the highly variable values for *Sequoia*-type in the deposit (borehole B58F0015; Zagwijn, 1960) compared to the data presented here (B58E0269 and B58E0284) show that the pollen content of this type of fluvial swamp deposits may reveal a high degree of regional variability, while similar vegetation assemblages may occur over long periods of time. The clay deposit at the top of the Kieseloölite Formation in the study area forms the lateral continuation of the Reuver Bed in the Brachterwald (Fig. 4; Boenigk, 1970; Kemna, 2005), which is Late Pliocene in age. The separation into local and regional (wetland) trees does, however, allow detailed correlation inside the pit within this facies type (peat).

3.2.1.2. Early Pleistocene. Based on the clear presence of *Fagus* the pollen diagram of the lowermost part of the flood-basin clay (MLBK-1A, pollen zone P-MLBK-1; Fig. 7) in the Maalbeek pit corresponds with pollen zone T-A as defined by Zagwijn (1963a). The zone ends with a phase of peat formation in the flood basin.

The overlying flood-basin clay (MLBK-1B, pollen zone P-MLBK-2; Fig. 7) is typified by very low values of tree pollen and a dominance of Ericaceae amongst the non-arboreal pollen. Concurrently, *Artemisia* is present in pollen zone P-MLBK-2B (Fig. 7). Based on these observations the clay can be classified as pollen zone T-B (cf. Zagwijn, 1963a; Westerhoff et al., 1998). According to Zagwijn (1975) this particular pollen zone was not known in detail although it was interpreted in a borehole near Eindhoven in the RVG (Zagwijn, 1963a). More recently, it was demonstrated that the clay deposit at Maalbeek, formerly interpreted as part of the Eburonian Stage (Zagwijn, 1963a) in fact forms part of unit MLBK-1B (Westerhoff et al., 1998). The increased influx of reworked (old) pollen and the occurrence of fine sand lenses both at the lower side of P-MLBK-2A and P-MLBK-2B to -3 A transition (Fig. 7), indicates erosion and/or a phase of non-deposition both preceding and following deposition of unit MLBK-1B.

Pollen zone P-MLBK-3 of the section at Maalbeek pit (Fig. 7) shows that the decrease of the Ericaceae is followed by a reappearance of forest and local wetland elements. This is expressed by a small peak of *Salix*, a culmination of Cyperaceae and pollen of aquatics like *Nymphaea* and *Typhaceae*. Subsequently *Betula* and *Corylus* increase and *Pterocarya*, *Quercus* reappear. The occurrence of *Pterocarya* without *Fagus* is characteristic of pollen zone T-C (cf. Zagwijn, 1963a; Westerhoff et al., 1998). This part of the section belongs to unit MLBK-2 that corresponds to the sedimentary infill of an abandoned channel which was cut into the floodplain deposits of units MLBK-1A and 1 B (Fig. 5).

The pollen content of this up to 12 m thick channel-fill is shown in greater detail in the diagram of borehole B58E0284 (Fig. 8). That

Table 2
Pollen zones of Maalbeek pit and borehole B58E0269 in Fig. 7. Pollen sum is composed of upland taxa and excludes aquatics, spore plants Cyperaceae and wetland trees. Local elements are expressed relative to all palynomorphs.

Pollen zones Kieseloölite Formation (Reuver Bed), borehole B58E0269	
Pollen zone P-MLBK-0A (16.00–17.70 m)	Abundant *Alnus*, *Pinus* and, in the lower part, *Fagus* Clear presence of varied 'Tertiary elements' like *Sciadopitys, Liquidambar* and *Taxodium*-type while *Aesculus* has a continuous curve. Amongst the herbs Cyperaceae, Poaceae and Ericaceae show low continuous curves.
Pollen zone P-MLBK-0B (15.20–16.00 m)	Dominance of *Taxodium*-type (up to 50%), *Nyssa, Betula* and Cupressaceae. Significant *Ulmus*, *Quercus* and *Castanea* while *Pinus* has relatively low values of about 30%.
Pollen zone P-MLBK-0C (14.60–15.20 m)	Abundant *Pinus,* last continuous occurrence of *Sciadopitys* and Taxodium-type
Pollen zones Waalre Formation (Tegelen Member), exposure & borehole	
Pollen zone P-MLBK-1 (4.75–11.75 m)	Characteristic are the relatively high values and continuous presence of *Fagus,* concurrently *Alnus* and *Picea* are mostly >10%, low NAP and relatively to the rest of the section low *Pinus* (<20%).
• subzone 1 A (10.50–11.75 m in borehole B58E0269)	• Decreasing *Pinus* values with scattered *Taxodioidae* and *Cupressaceae.* A peak occurrence of *Parrotia persica.* occurs at 10.65. At 10.25, within a sandy intercalation, high values of 'Tertiary elements' suggest abundant reworked material, although. *P. persica* occurs in Pleistocene age deposits as well (files of the Geological Survey of the Netherlands; Binka et al., 2003; Nitychorouk et al., 2005). Alternations between *Alnus* and *Corylus* and irregular occurrences of *Fagus* and *Pterocarya* confirm partly reworked material.
• subzone 1 B (5.55–6.00 m of the excavation face, 7.65–10.50 m in borehole B58E0269)	• Remarkably high values of *Fagus* (up to 40%). *Alnus* shows values of 20–30%, *Quercus*, *Ulmus* and *Pterocarya* show continuous curves with stable values ~10%. Some aquatics are present, incl. *Ceratophyllum* spines. Cuppressaceae >10% and continuous presence of *Taxodium*-type and *Sequoia*-type.
• subzone 1C (4.75–5.55 m, from excavation face and 7.00–7.65 m in borehole B58E0269)	• High values of *Alnus* and *Picea* (>20%), *Fagus* decreases and disappears at the top of the subzone.
Pollen zone P-MLBK-2 (1.90–4.75 m) (exp. Maalbeek)	Dominance of high NAP values, in particular Ericaceae (up to 40%), significant *Sphagnum,* Poaceae >10% and presence of *Artemisia*.
• subzone 2 A (3.90–4.75 m	• Noteworthy is the presence of reworked Mesozoic and Cenozoic pollen, *Quercus* (5–10%) and *Corylus* (>10%) can also be partly reworked pollen. High algae, including *Botryoccus* and *Pediastrum* (25% and 15% respectively). Low but increasing Poaceae, *Artemisia* is absent; Ericaceae and *Sphagnum* spores show low abundance.
• subzone 2 B (2.00–3.90 m)	• Ericaceae and *Sphagnum* show maximum values, respectively 30–45 and 10%. *Artemisia* has values of ~5% in the lower part of this subzone. Tree pollen is nearly absent, only *Alnus* (~5%) and *Pinus* (30%) show significant values.
Pollen zone P-MLBK-3 (0–1.90 m) (exp. Maalbeek)	Arboreal pollen reaches values of 50–60% with dominance of *Pinus*, low values of *Alnus*, and continuous curve of *Pterocarya*, *Quercus*, *Corylus*, together with a slight increase of *Betula*. Cyperaceae and Poaceae dominate the non-arboreal part of the diagram. The value of Ericaceae pollen varies around 10%. *Artemisia* shows continuously presence ~5%.
• Subzone 3 A (1.50–1.90 m)	• Maximum *Pinus* >50 preceded by significant *Juniperus* and *Salix* presence. Thermophilous trees very low or absent. High *Ericaceae (>40%) Ericaceae* decline to <10%, high *Cyperaceae* 20–30%. Several aquatic plants like *Nymphaea* and Typhaceae and the algae *Pediastrum* appear in the diagram. Last continuous occurrence of *Tsuga*
• Subzone 3 B (0.60–1.50 m)	• *Pinus* is the most important tree species showing values 30–40%, Betula ~10%. *Quercus, Pterocarya, Corylus* and *Alnus relatively low (~5%).* Cyperaceae decrease below 10%, Ericaceae show low values (5–10%). *Sphagnum* spores are generally absent.
• Subzone 3C (0–0.60 m)	• *Ericaceae increase >10%, Quercus*, *Pterocarya*, *Corylus*, *Fraxinus*, and *Picea* show low values (1–5%), *Alnus* is slightly higher (5–10%). *Betula* increases towards the top of the subzone (>10%), *Salix* is present in low values. Cyperaceae and Poaceae dominate the herbs, with continuous *Artemisia* presence.

Table 3
Pollen zones of Maalbeek borehole B58E0284 in Fig. 8.

Pollen zones Kieseloölite Formation (Reuver Bed), borehole B58E0284	
Pollen zone P-MLBKH-0A (24.40–28.40 m)	*Pinus* dominant ~40% Continuous values of ~10% for *Sciadopitys*, *Fagus*, *Quercus* and *Ulmus*. Upper half of the zone Alnus increases to *Alnus* 30% followed by increase of *Taxodium*-type and *Pterocarya*. Poaceae is below <20% while Cyperaceae is low(<10%). In the lower half of the zone the presence of *Typhaceae* is noteworthy.
Pollen zone P-MLBKH-0B (22.90–24.40 m)	Lower and more variable *Pinus* (25–50%), decreased *Sciadopitys* and *Fagus* (<5%) and increased but highly variable *Betula Quercus* and *Ulmus* values (20–30%) Local wetland trees shift from *Alnus* dominance to *Taxodium*-type, *Nyssa*, *Sequoia*-type (second half) *Taxodium*-type, Cupressaceae and *Quercus* maxima correspond to the peat facies and alternate with *Betula* and *Ulmus*. Herbs, Cyperaceae and Ericaceae show low overall values.
Pollen zones Waalre Formation (Tegelen Member), borehole B58E0284	
Pollen zone P-MLBKH-3B (13.00–17.5 m).	*Pinus* initially low but increasing towards 45%. *High Juniperus, Quercus* and *Pterocarya* (~20%), continuous *Corylus* ~5% Decreasing *Ulmus* and increasing *Betula* >10%. *Picea* relatively high (max 15%) in alternation with *Juniperus Alnus* is the only remaining wetland tree with only scattered single occurrences of *Taxodium*-type, *Sequoia*-type, and *Nyssa* is absent. *Pinus* is present with moderate values while *Picea* shows a small increase towards the top of the zone. Ericaceae is the only shrub with a continuous curve although with low values. Poaceae below 10%
Pollen zone MLBKH-3C (5.26–13.00 m).	*Pinus* abundant (~45%) with a maximum of ~75% at the top *Betula* continuously around 15–20%, and *Quercus Pterocarya* and *Corylus* ~5%. Other tree species occur irregularly. Cyperaceae and Poaceae increase to ~15% with continuous presence of *Artemisia,* Apiaceae and regular other herb taxa Ericaceae and *Alnus* vary ~10%, *Salix* is low but continuous Around 5.5 m *Sequoia*-type, *Taxodium*-type and *Nyssa* show a short spike, possibly due to reworking

diagram shows two local pollen zones within the Waalre member. The lower part (pollen zone P-MLBKH-3B; Fig. 8) closely resembles the uppermost part of the pollen diagram of pit Maalbeek (pollen zone P-MLBK-3; Fig. 7). Only the pioneer *Juniperus* is more expressed in B58E0284. Pollen zone P-MLBKH-3 in borehole B58E0284 clearly points to a Tiglian C pollen assemblage and shows striking similarities with the pollen zones T-C2 to T-C4^{b} and T-C6 of the Russel-Tiglia-Egypte diagram (Zagwijn, 1963a, Fig. 11). The upper part (pollen zone P-MLBKH-3C; Fig. 8) shows abundant *Poaceae* and *Cyperaceae* (curve 'Local') which may indicate local vegetation at or near the abandoned channel, following the open water indicators in P-MLBKH-3B such as *Pediastrum*. Changes are accompanied by minor *Artemisia* and heath increases that do suggest concurrent cooler conditions. The relatively invariable taxa abundances in P-MLBKH-3C is remarkable and may result from high sedimentation rates, consistent with the sedimentary structures that typify the infill of the abandoned channel.

Summarising, the three consecutive pollen zones (i.e. T-A, T-B, T-C, cf. Zagwijn, 1963a) of the classical Tiglian stage occur on top of each other in the sequence of floodplain fines of the Maalbeek pit. So far, it is the only location where this could be demonstrated.

3.2.2. *Laumans pit*

Two sections in the uppermost part of the exposure and one borehole (B58E0466) in the Laumans pit were sampled for pollen analyses (Fig. 9). The pollen analytical results of the four analysed parts are combined in Fig. 10. The discerned pollen zones are summarised in Table 4.

3.2.2.1. Late Pliocene. The pollen diagram from the Reuver Bed (borehole B58E0466, Fig. 9), at the Laumans site also shows evidence for the forested wetland although here only *Nyssa* is clearly visible. The data from the CPT directly next to the borehole shows that this data is likely from a reworked peat fragment that is embedded in younger coarse-grained sands. The deeper pollen samples taken from the clastic sequences largely show a similar development as described at Maalbeek (Fig. 9; Table 4) indicating a Reuverian C pollen assemblage (Zagwijn, 1960).

3.2.2.2. Early Pleistocene. The lower part of the flood-basin fines at the Laumans pit (pollen zone P-LM-1, between 5 and 9 m in borehole B58E0466; Fig. 10; Table 4) is dominated by *Picea* and *Pinus* pollen, accompanied by a continuous presence of *Pterocarya*. *Quercus* shows even lower values. Other species (arboreal and non-arboreal pollen) are nearly absent or show a scattered pattern. Such pollen assemblages are comparable to the uppermost parts of pollen zone T-C (i.e. pollen zone T-C5, and T-C6, cf. Zagwijn, 1963a). However, such correlations are non-specific because Early Pleistocene deposits show few pollen-based diagnostic criteria that can be related to a specific glacial-interglacial cycle (Kasse and Bohncke, 2001; Urban, 1978).

The interval between 2.0 and 5.0 m (Fig. 10) at the top of the borehole B58E0466 and base of section I is very poor in pollen. This is probably mainly caused by post-depositional geochemical processes like the formation of iron hydroxides that result from oxidation of siderite. Selective preservation of pollen by post-depositional corrosion is also known from Holocene flood basins (Van der Woude, 1983). Reworked pollen, *Pinus, Alnus* and *Corylus* and fern spores are abundant in this interval.

Pollen zone P-LM-2 shows the development of the local vegetation formed by sedges, grasses and some *Alnus*, while ferns may form an undergrowth of the brook vegetation. The low amount of *Picea* pollen is striking and differs from the diagram of the same clay deposits published by Kasse and Bohncke (2001). The disappearance of *Pterocarya* and the dominance of *Pinus* and Poaceae in pollen zones P-LM-3 and P-LM-4 (Fig. 10) suggest a correlation with the transition of pollen zone T-C6 to pollen zones EB-I/II (cf. Zagwijn, 1963a; Kasse and Bohncke, 2001). In P-LM-4 the larger part of the *Pinus* pollen is broken and partly corroded, likely due to post-depositional geochemical processes (siderite formation and oxidation).

The facies of the flood-basin fines of the Laumans and Maalbeek pits show a similar development, as is demonstrated by the massive clay and horizons showing initial soil formation. Lithostratigraphically, both deposits belong to the same clay stratum that forms the upper part of the Waalre Formation (Fig. 4). The pollen assemblages from both deposits (pollen zone P-MLBK-2 at Maalbeek Pit and P-LM-2 at Laumans) are superficially similar as is shown by decreasing AP values and increased *Sphagnum* (within curve *local*). However, Ericaceae are much more abundant at Maalbeek and zone P-MLBK-2 has continuous *Tsuga* presence, while zone P-LM-2 at Laumans contains high Poaceae and significant *Pterocarya*. Despite the lithostratigraphical similarities and NAP and *Sphagnum* increases they correspond to different chronostratigraphical (sub)stages *sensu* Zagwijn (1963a), i.e. Late Tiglian C to Eburonian in the Laumans pit and Tiglian B in Maalbeek pit.

3.2.3. *Russel-Tiglia-Egypte pit*

The pollen analytical data from the clay deposits of Russel-Tiglia-Egypte (RTE) pit, the type section for the Tiglian C Substage, are taken from Zagwijn (1963a) (Fig. 11). A detailed sedimentary overview and description of the pollen zones are given in the original publication. The pollen diagram is composed of three sections sampled from three different excavation faces (Fig. 4 in

Table 4
Pollen zones of Laumans pit and borehole B58E0466 in Fig. 10.

Pollen zones Kieseloölite Formation (Reuver Bed), borehole B58E0466	
Pollen zone P-LM-0 (22.5 −26.0 m)	Dominant *Pinus* ~60% increasing to peak values of 90% in upper half. Lower part has significant *Picea*, *Sciadopitys* and *Tsuga* (10−15%). Deciduous trees low except for *Fagus* and occasional *Liquidambar*. Pollen preservation is poor between 23.8 and 24.7 m, and characterised by scattered herb peaks. Samples above 23.8 m are rich in Ericaceae and contain significant *Nyssa*.
Pollen zones Waalre Formation (Tegelen Member), exposure Laumans pit and borehole B58E0466; composite depth projected to borehole	
Pollen zone P-LM-1 (2.5 −8.8 m)	A near 90% dominance of arboreal pollen. *Pinus* and *Picea* are the dominant species, low *Tsuga* and *Abies* presence. *Pterocarya* and *Quercus* show continuous curves with values 5−10%. *Betula, Carpinus* and *Eucommia* are discontinuous, *Fagus* absent The non-arboreal pollen curve shows irregularly scattered species (upland, ferns and aquatic algae) towards the top were preservation is poor. The uppermost part of the borehole samples (2.7−4.8 m) overlaps with the lowermost part of section I (2.5−1.8 m) and both are poor in pollen(but many reworked), probably as result of severe diagenesis (siderite formation) in the deposit which may have affected the total pollen content.
Pollen zone P-LM-2 (1.4 −2.5 m) In section I	*Pinus* has values ~40% with a single peak to 70%. *Alnus*, *Betula*, *Corylus* and *Quercus* and *Pterocarya* are present but variable (5−10%) Scattered *Picea* and *Carpinus* presence. Poaceae show a clear maximum up to 40%, accompanied by 5−10% Cyperaceae. *Sphagnum* and Ericaceae. *Dryopteris* type has a pronounced maximum at the base of the zone together with significant *Osmunda* presence. The curve of reworked pollen is continuous and relatively high in the lower part of the zone
Pollen zone P-LM-3 (0.30 −1.4 m) In section II, and 0.00−0.75 m, section I)	*Pinus* increases to 80 dominance accompanied by low (<10%) values for *Alnus, Betula* and *Corylus*. Poaceae decrease to <10%. Cyperaceae are nearly absent. *Ranunculus* shows distinct presence, as well as *Dryopteris*-type and *Pediastrum* algae.
Pollen zone P-LM-4 (0.00 −0.30 m) In section II	*Pinus* values up to 80−90%, with occasional *Corylus* and *Alnus* and *Quercus*. Poaceae dominate the non-arboreal pollen with significant presence of Asteraceae Liguliflorae. Spores of Dryopteris-type and *Pediastrum* show values up to 15%.

Zagwijn, 1963a). Except for the pollen zone T-C1, the diagram provides a complete record of Zagwijn's detailed subdivision of the Tiglian C and transition to the Eburonian Substages.

3.2.3.1. Early Pleistocene. The oxbow infill (unit RTE-1, pollen zones T-C2 to T-C4^b) shows a high proportion of deciduous trees and this part of the oxbow fill is formed during a relatively warm temperate phase. The pollen zones T-C2 to T-C4^b resemble pollen zones MLBK-3B/C from the oxbow infill of borehole B58E0284 at the Maalbeek site (Fig. 8). At that site, high sedimentation rates controlled the uppermost part of the oxbow infill as is demonstrated by relatively invariable pollen curves.

As a result of the incomplete infilling of the oxbow lake at RTE, where *Pediastrum* indicates open water conditions during T-C4, reactivation took place with the formation of crevasse splay and overbank deposits (unit RTE-2, Fig. 11). The base of this facies unit consists of a thin layer of fine sand lacking pollen and spores. The layer has been assigned to pollen zone T-C4^c (cf. Zagwijn, 1963a, enclosure 6).

The uppermost unit RTE-3 represents the final stage of the fluvial sequence and is typified by the formation of flood-basin fines in a back-swamp area with local peat growth. The pollen diagram shows declining values of deciduous trees and a dominance of *Pinus*. Grasses and sedges are consistent with local vegetation development in the flood basin and similar pollen assemblages are found in the floodplain fines of the Maalbeek and Laumans pits.

4. Late Pliocene and Early Pleistocene sedimentary architecture, palynology and paleo-environmental interpretations of the Roer-Valley-Graven sequence near Eindhoven

4.1. Sedimentary architecture

In the context of regional correlation patterns it is of importance to compare and correlate the relatively thin sequence of Lower Pleistocene fluvial deposits in the Tegelen-Maalbeek area with that of the much thicker sequences in the Roer Valley Graben. As a standard reference for the Roer Valley Graben stack we use borehole B51D0343 near Eindhoven (Figs. 2 and 12). The stratigraphy of this borehole is very similar to the borehole data published by Zagwijn (1963a; enclosure 4, Eindhoven 1, B51G0218 and enclosure 5, Eindhoven 2, B51D0023). The borehole reveals up to ten, 6–30 m thick stacked fluvial fining-upwards cycles present between the Kieseloölite and Sterksel Formations (Fig. 12). In the borehole, the mixed Rhine-Meuse deposits of the Waalre Formation are dominated by unstable heavy mineral associations and are subdivided into three subunits (Waalre Formation subunits WA-1, WA-2 and WA-3) that intercalate with sediments containing a stable heavy mineral association (Stramproy Formation).

Subunit WA-1, which is the first sediment unit with an unstable (epidote, garnet, green hornblende dominated) heavy-minerals assemblage (Fig. 12), can be correlated with the Oebel beds in Germany (Boenigk and Frechen, 2006). This marked change in provenance results from the extension of the Rhine catchment into the Alpine area that occurred during the Late Pliocene (Boenigk, 1970, 2002; Boenigk and Frechen, 2006; Hagedorn and Boenigk, 2008; Kemna, 2005, 2008). The clear presence of 'Tertiary elements' in the pollen assemblages confirms the Late Pliocene age.

4.2. Palynology

The three lowermost zones from borehole B51D0343 (P-EHV-1 to 3, Fig. 12; Table 5) contain abundant Tertiary relict taxa, high AP% (>80–90%) and continuous curves of most deciduous tree taxa in variable proportions, consistent with a Pliocene age, and comparable to the P-MLBK-0 and P-MLBKH-0 pollen zones in the Tegelen-Maalbeek area. Zone P-EHV-4 shows increased NAP variability together with consistent *Picea*, *Pterocarya* and (low) *Tsuga* and *Sciadopitys* occurrence, but no *Fagus* or Pliocene relict taxa. Ericaceae increase and show peak values in P-EHV-5 after which *Picea, Pterocarya, Sciadopitys* and *Tsuga* occurrences become scattered. The pollen data shows a marked pattern of repeated NAP increases in subsequent zones P-EHV-6A-C and 7 A-D. The increases in NAP appear to coincide with the presence of sands and/or the base of fining upward cycles. Pollen assemblages dominated by temperate tree taxa occur in between the NAP peaks. *Pinus* abundance is minimal in P-EHV-6 while *Picea*, *Juniperus* and *Carpinus* are more common. Aspects of these assemblages are also found in the Tegelen-Maalbeek area. Zone P-MLBK-2 with a 'T-B signature' is very similar to P-EHV-5, although the preceding P-MLBK-1 'T-A' assemblage, defined as both abundant *Fagus* and *Pterocarya* but no *Taxodium*-type/*Sequoia*-type/*Nyssa*, is absent at Eindhoven. The NAP maximum from Laumans pit zone P-LM-2, a 'T-C6 to EB-I assemblage', is most comparable to P-EHV-7A judging high *Pinus*, no *Picea*, high Ericaceae and Poaceae, and *Corylus* presence. Crucially, none of the Tegelen-Maalbeek Early Pleistocene assemblages have an exact match with the Eindhoven B51D0343 borehole pollen zones, and particularly the P-MLBK-1 'T-A' assemblage seems unique to the Venlo Block area.

5. Discussion

5.1. Climate changes versus local effects and the issue of hiatuses

In the Late Pliocene and Early Pleistocene sequences of the Maalbeek, Laumans and Russel-Tiglia-Egypte pits we identified coarse-grained channel belt deposits, oxbow lake infill(s), flood-basin clay deposits with local accumulation of peat, and irregularly alternating sand-clay deposits that formed as overbank or crevasse splays. The key question that arises is how much time is present within and in between these sediment units and hence, how much time the pollen zones that were identified within these sequences represent.

Major changes are observed in the lower part of the Maalbeek-Tegelen sequence. The Reuver Bed, dominated by clays and peat with abundant presence of Tertiary pollen, are sharply overlain by coarse-grained channel belt sands. Data from the Maalbeek pit shows the channel belt is overlain by fine-grained flood basin sediments with a pollen assemblage indicative of temperate climate conditions where Tertiary elements are lacking apart from few dispersed grains (pollen zone P-MLBK-2). Generally, these facies and pollen changes are regarded to be a result of major climate changes at and surrounding the Pliocene - Pleistocene transition (Urban, 1978; Westerhoff et al., 1998; Kemna, 2005), with the coarse-grained channel belt sands being deposited during the Pretiglian. However, the exact amount of time present in this interval is unknown. The Late Pliocene sequence has normal polarity assigned to Gauss (Kemna, 2005) but the paleomagnetic characteristics of the sediments that have a T-A pollen assemblage is unknown. The marked presence of *Fagus* makes that a latest Late Pliocene age for the latter sediments cannot be ruled out (cf. Westerhoff et al., 1998).

Data from the Maalbeek pit shows a subsequent strong decline of thermophilous tree taxa like *Quercus, Pterocarya* and *Fagus* and transition into an open herb dominated vegetation (zone P-MLBK-2). We regard the significant decline of thermophilous tree taxa to be the result of climatic cooling since the majority is an in-situ fine-grained deposit. Relatively high values for NAP with Ericaceae and low amounts of thermophilous tree taxa were also regarded as

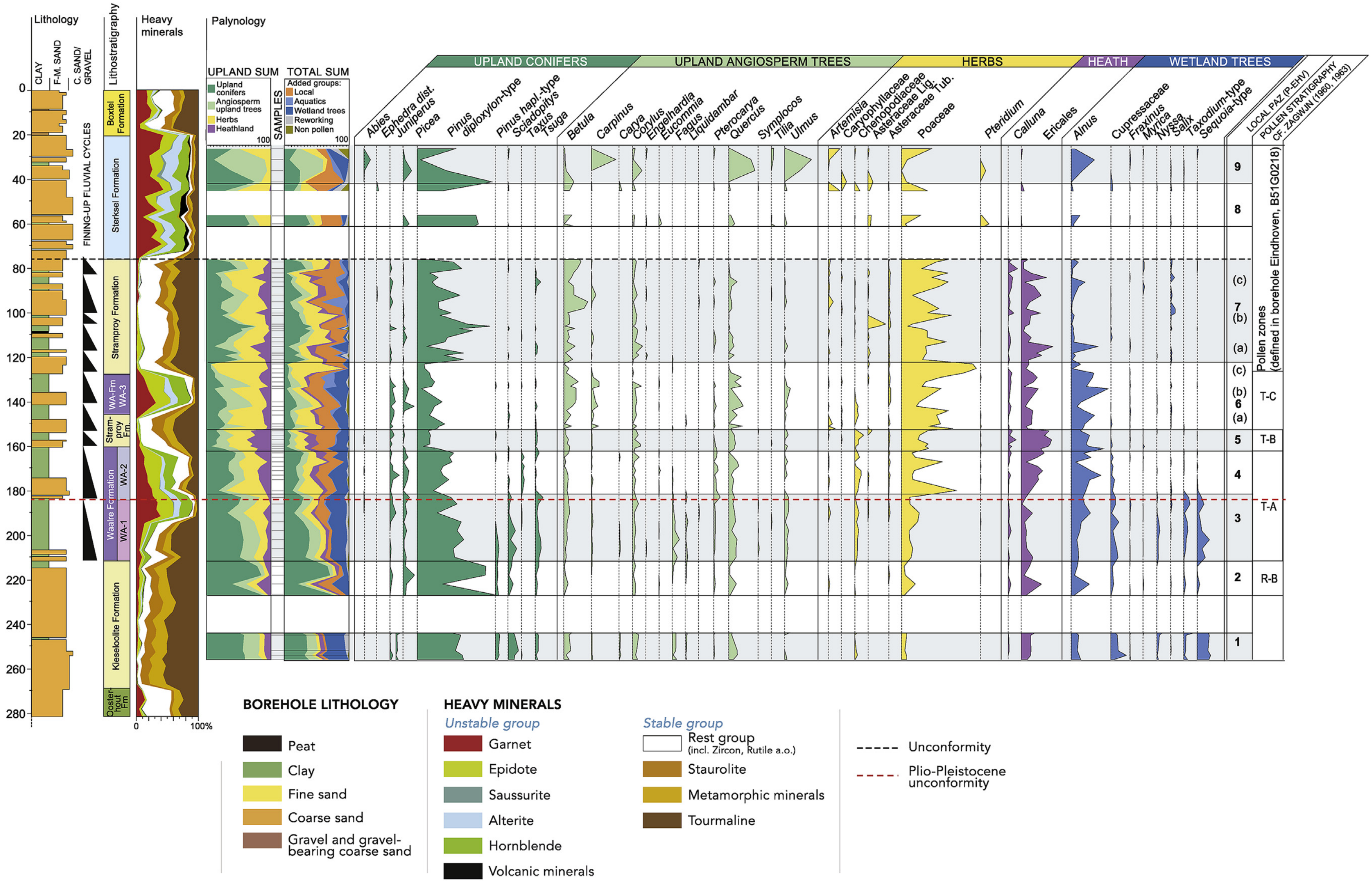

Fig. 12. Lithology, fluvial fining upward cycles, lithostratigraphy, heavy-minerals and pollen diagram of borehole B51D0343 (Eindhoven). Main pollen assemblage zones (PAZ) are delineated by black lines, subzones by dashed lines. Alternate grey highlighted zones for visibility. The pollen zones adjacent to the summary pollen diagram are according to the interpretation of Zagwijn (1963a).

Table 5
Pollen zones of Eindhoven borehole B51D0343 in Fig. 12.

Pollen zones Kieseloölite Formation, borehole B51D0343	
Pollen zone P-EHV-1 (244–267 m)	Dominant *Pinus* ~40% with significant *Sciadopitys* and continuous Tsuga and *Picea* presence Wetland trees with abundant *Taxodium*-type with significant, *Sequoia*-type, Cupressaceae and *Alnus.* Ericaceae ~15%, NAP below 5% except lowermost sample which also contains significant *Osmunda*, *Drypoteris*-type and *Sphagnum*
Pollen zone P-EHV-2 (212–227 m)	Dominant *Pinus* increasing further up tõ70% with continuous *Sciadopitys* and *Picea* presence and low *Tsuga* Scattered broad-leafed taxa. Wetland trees significant *Alnus* Ericaceae ~15%, Poaceae increases to ~10% and significant *Osmunda*, *Drypoteris*-type and *Sphagnum* presence
Pollen zones Waalre Formation, borehole B51D0343	
Pollen zone P-EHV-3 (181–212 m), WA-1	*Pinus* around 30%, significant *Sciadopitys*, Tsuga, *Quercus* and continuous *Picea*, *Betula* and *Ulmus* curves. *Fagus* is continuous but decreases toward the top. Low presence of *Pterocarya* and *Carpinus. Alnus* increases to ~20% and *Taxodium*-type, *Sequoia*-type, Cupressaceae are common. *Nyssa* present but not abundant Ericaceae<10%, Poaceae (10–20%) dominate NAP, *Artemisia* is continuous but low(<5%), with some spores toward the top
Pollen zone P-EHV-4 (162–181 m), WA-2	AP minimum to <40% with *Pinus* around 25%, *Quercus* is significant and *Picea*, *Pterocarya*, *Taxus* and *Juniperus* are continuously present. *Sciadopitys*, Tsuga occurrence is scattered, and *Betula* and *Ulmus* curves irregular. *Fagus* has its last single occurrences. *Alnus* increases up to ~30% with common Cupressaceae while *Taxodium*-type, *Sequoia*-type are absent. Ericaceae are >20% and Poaceae vary between 10 and 40% with significant *Artemisia* >5% and abundant spores throughout.
Pollen zones Stramproy & Waalre Formation, borehole B51D0343	
Pollen zone P-EHV-5 (153–162 m)	AP decline to ~35% with *Pinus* around 15%, *Quercus, Betula and Corylus are* significant and *Tsuga, Juniperus* are continuously present. *Sciadopitys* is absent and *Pterocarya* occurrence is scattered, while *Carpinus* and *Ulmus* curves are irregular. *Alnus* is ~20% while Ericaceae increase to ~30%. Poaceae vary between 20 and 40% with *Artemisia* peak at the top. Abundant spores (*Dryopteris*-type, *Osmunda*) throughout.
Pollen zone P-EHV-6 (122–153 m), WA-3	This zone has three successive AP minima, labelled **6 A-C** *Pinus* varies between 10 and 25%. *Betula* and *Quercus* are significant> 10% with irregular *Juniperus*, *Picea*, *Corylus*, *Ulmus* and *Carpinus* occurrences ~5%. *Tsuga* has a few isolated occurrences. Ericaceae is relatively stable ~10%. Subzone C has high Poaceae (70%) abundance and very low AP (~10%) with *Plantago* (A/B) and *Thalictrum* (C) presence, Cyperaceae >5% and abundant *Dryopteris*-type and *Pediastrum* in 6Ce.
Pollen zone P-EHV-7 (75–122 m)	This zone has three successive AP minima, labelled **7 A-C** *Pinus* increased relative to EHV-6 and varies between 15 and 50%. *Betula* is abundant, particularly around 7 C. *Corylus* is common while *Quercus Juniperus*, *Picea* and *Carpinus* occur irregularly. Ericaceae vary between 10 and 25% and Poaceae between 10 and 50%. 7A/B has peak Asteraceae Lig. Cyperaceae are high (10–30%) and strongly variable, *Sphagnum* presence significant and continuous.
Pollen zone P-EHV-8 (38–61 m)	High and variable *Pinus* (20–70%) with abundant *Betula* (10–20%) and low *Picea* and *Quercus*. Variable but abundant Poaceae with Asteraceae, *Artemisia* and Chenopodiaceae peaks. Cyperaceae ~10%, various spore peaks and common reworking
Pollen zone P-EHV-9 (26–38 m)	Low *Pinus* and succession from *Picea*, *Corylus/Quercus*, *Ulmus* to *Carpinus/Alnus.* Short *Abies* peak. *Azolla filiculoides* at the base and renewed NAP increase toward the top.

indicative of cool climatic conditions by Zagwijn (1963a, 1975) and subsequent work (e.g. Kasse, 1988, 1993; Kasse and Bohncke, 2001; Donders et al., 2018). Whether or not the transition towards cool climatic conditions (T-B) occurs directly after the termination of the warm climatic phase (T-A) is unknown. The sharp transition, reworking of pollen and influx of sand makes that we cannot rule out a significant hiatus in between the two units.

Data from the Maalbeek pit shows that the herb dominated vegetation (T-B) is replaced by thermophilous trees and local wetland taxa, described as pollen zone T-C. This large change in pollen assemblage can only be explained by a transition into warmer climate conditions. Throughout the Maalbeek-Tegelen area, sediments that bear the T-C pollen assemblage occur as the infill of paleo meanders (Westerhoff et al., 1998). Prior to deposition of the fines, channel scour caused significant erosion of older deposits, making that the presence of an hiatus, although of unknown duration, in between T-B and T-C assemblages is well possible.

The data from the pits shows that the changes observed within the T-C pollenzone, seem to follow changes in sedimentary facies (Fig. 11). The oxbow infill described in both pits Maalbeek and Russel-Tiglia-Egypte (facies units RTE-1 and MLBK-2), shows a high proportion of deciduous trees (pollen zones T-C2 to T-C4^{b}) suggesting it infilled during relatively warm temperate climatic conditions. High sedimentation rates controlled the uppermost part of the oxbow infill as is demonstrated by the relatively invariable pollen curves (Figs. 8 and 11). Likely as a result of the incomplete infilling of the oxbow, *Pediastrum* indicates open water conditions during T-C4 at RTE, reactivation took place with the formation of crevasse splay and overbank deposits (units RTE-2 & MLBK-3; aquatics curve of Figs. 8 and 11 and supplementary data). In RTE the base of this facies unit consists of a thin layer of fine sand lacking pollen and spores. The layer has been assigned to pollen zone T-C4^{c} (cf. Zagwijn, 1963a, enclosure 6). In RTE, where the sequence is most complete, the uppermost unit RTE-3 represents formation of flood-basin fines in a back-swamp area with local peat growth. The pollen diagram shows declining values of deciduous trees and a dominance of *Pinus* and increased Ericaceae. Grasses and sedges (curve *local*) could represent local vegetation development in a moist flood basin, similar to pollen assemblages found in the floodplain fines of the Maalbeek and Laumans pits. However, exclusion of the Cyperaceae and wetland trees from the terrestrial pollen sum excludes most local influence and points to a more regional cause of the *Pinus* and Ericaceae increase, likely a moderate climatic cooling since deciduous trees are low but still present. The top of RTE-3 unit sees sharp Poaceae and *Betula* increase and disappearance of most mesophilous taxa, which is a clear cooling signal consistent with the Eburonian pollen zone.

Explaining the nature of changes of the pollen assemblages within pollen zone T-C is challenging. The combination of the facies changes and coinciding changes in pollen assemblage at RTE suggests the entire T-C zone as defined at this location could reflect only a very short period in time, especially for the bedded oxbow infill (unit RTE-1). The absence of pollen in the sand layer at the base of the crevasse-overbank deposit (RTE-2) can be explained to be a result of the initial crevassing phase that usually begins with flood events. It is unlikely that such rapidly deposited sand layers contain reliable pollen assemblages owing to unfavourable preservation conditions. Another indication for a limited depositional time is that is that the pollen assemblages below and above the sand are largely identical, suggesting rapid deposition of the crevasse sediments under more or less the same environmental conditions. Taking into account generally accepted models of Holocene fluvial facies development, in this view, the formation of the superimposed facies units within the T-C pollenzone of RTE, Maalbeek and Laumans, could have occurred in several thousand years or less (Bridge, 2005; Miall, 1996; Berendsen and Stouthamer, 2001; Blum and Törnqvist, 2000).

The view presented above is in strong contradiction with earlier views on pollen developments that placed changes at these proximal type sections in a direct climate-stratigraphic context. Critical in this regard is the pollen zone T-C4c. Based on its poor pollen content, the dominance of *Pinus*, the decline of thermophilous trees, and correlations to other sites, Zagwijn (1963a) concluded that the mean summer temperature during this pollen zone declined considerably. While similar strong cool (glacial) phases have been observed in the coastal and shallow marine domain (e.g. Kasse and Bohncke, 2001; Donders et al., 2018), this is unlikely to have preserved well in the floodplain deposits of the Tegelen-Maalbeek area during a phase of sea level lowering. As this cold phase is not well registered in the sequence of RTE it was believed that a major hiatus should exist between units RTE-1 and RTE-2. This interpretation was supported by the red-colored weathering at the top of the bedded clay of the oxbow infill (lake clay cf. Zagwijn, 1963a) that was interpreted as a soil. However, we do note that soil formation in clayey and poorly drained deposits of flood basins is typically gleyed and weakly developed. Under temperate climate conditions, they hardly develop as red soils (Birkeland, 1974; Retallack, 1994, 2001; Bridge, 2005). Red colors are a commonly observed feature in the clay deposits of RTE and adjacent pits and are attributed to oxidation of siderite, which is abundantly present in the deposits. It develops rather quickly after exposure of the siderite-bearing deposits. In summary, based on the sedimentary and pollen data alone, a short period of deposition of the T-C bearing sediments at RTE is plausible.

Mammalian data, however, contradicts a short period of deposition for the entire T-C bearing sediment units in the Tegelen-Maalbeek area. The upper part of the laminated channel fill at Maalbeek (Unit MLBK-2; Fig. 5) yielded a fossil assemblage of several hundred remains of mainly smaller mammals (Insectivora, Rodentia). The composition of this faunal assemblage is comparable to the smaller mammal fauna from Unit RTE-2 in the Russel-Tiglia-Egypte pit (Fig. 11) (Tesakov, 1998; Westerhoff et al., 1998). The preliminary analyses of the voles of the genus *Mimomys*, however, show that the molars from Maalbeek are in some aspects more primitive than those from Russel-Tiglia-Egypte. These differences suggest that the assemblages found at Maalbeek are slightly older than those found at RTE (Tesakov, 1998; Westerhoff et al., 1998).

Clearly, the mammalian data exclude a short millennia-scale deposition time for the entire Maalbeek-Tegelen T-C zone, although this seems appropriate based on the sedimentary and palynological observations alone. The deposits with a T-C pollen assemblage are most probably represented in multiple interglacials that in discontinuous sequences are very difficult to differentiate (Kasse and Bohncke, 2001). Based on correlations to the paleomagnetic time scale and the Mediterranean area, it was previously assumed that the duration of the Tiglian C Substage is approximately 200–400 kyr (Fig. 1) (Van Montfrans, 1971; Zagwijn, 1975; Zagwijn and Suc, 1973, 1983). The methods used for these inferences were probably not adequate, and the deposition of individual units similar to those found in Holocene fluvial facies development was likely relatively rapid (Bridge, 2005; Miall, 1996; Berendsen and Stouthamer, 2001; Blum and Törnqvist, 2000). In principle these units can occur in close proximity if we assume the channel fill - crevasse stacks of both Maalbeek and Tegelen are one and the same system of the same age. However, since the mammal data indicates a significantly longer total duration, the stack at RTE is most likely younger than the one at Maalbeek. It implies that in the channel - crevasse stacks at one position hiatuses are minimal but that time is present when comparing stacks at different lateral positions. Renewed paleomagnetic and geochronological study is needed to resolve this issue.

5.2. Correlation with the Roer-Valley Graben

According to Zagwijn's interpretation of the nearby borehole Eindhoven II (1963 ^{a}), zone P-EHV-3 in borehole B51D0343 (Fig. 12) with increasing unstable heavy minerals should represent the equivalent of pollen zone T-A (distinct values for *Fagus*) and is therefore Early Pleistocene in age. The main reason for this interpretation was the assumption that the change in heavy-mineral composition around ~ -210 m marked the Plio-Pleistocene boundary (Zonneveld, 1947^{a}, 1950). The stable heavy-mineral pre-Alpine Rhine signature and abundant presence of 'Tertiary' elements indicate P-EHV-3 in borehole B51D0343 is Pliocene in age. The interval would be more consistent as a continuation of the below Reuverian B assemblage, which is of Late Pliocene age. This either suggests that pollen zone T-A is absent in the boreholes near Eindhoven or that the *Fagus* dominated pollen zones are Pliocene in age. The taxon is lacking, or nearly absent in the overlying zone P-EHV-4 in subunit WA-2 (Fig. 12). This confirms the observation that *Fagus* is missing regularly in Early Pleistocene deposits (Meijer et al., 2006).

In borehole B51D0343 we observe several peak occurrences of arboreal taxa alternating with relative maxima in non-arboreal taxa. The most significant NAP increase of predominantly Ericaceae occurs in zone P-EHV-5. The same intercalation occurs in the Eindhoven II borehole and was previously assigned to pollen zone T-B (cf. Zagwijn, 1963a). Zagwijn (1963a, p. 60 and p. 68) stated that "perhaps the minimum in thermophilous trees at 154 m represents zone T-B″, and "pollen zone T-B must have witnessed low temperature, but data are scanty". We argue that although the Ericaceae maximum and tree composition in P-EHV-5 is most similar with the T-B signature in the Tegelen-Maalbeek area it is not unique to a specific level since similar occurrences are present around ~ -172 m, ~-134 m, ~-115 m and ~90 m (Fig. 12).

Between 144 and 158.60 m the subunits WA-2 and WA-3 of the Waalre Formation are intercalated by quartz-rich sand and stable heavy-mineral associations typifying the Stramproy Formation. This intercalation (Fig. 12) indicates that during its deposition, the Rhine-Meuse system had temporarily abandoned the RVG (Westerhoff et al., 2008) causing regional reorganisation of fluvial patterns. The apparent cooling, indicated by vegetation cover changes during P-EHV-5, could therefore also have been affected by changing depositional patterns and dynamic floodplain conditions locally leading to more open vegetation.

In aggregate, a definitive correlation of this interval (T-B, cf. Zagwijn, 1963a) with zone P-MLBK-2 from the Maalbeek Pit (Fig. 7) is difficult. Moreover, the lack of a *Fagus* dominated pollen zone underneath the interval make such correlations rather insecure. The same holds for the interval between 126 and 144 m (zone P-EHV-6). Although it shows characteristics of the T-C pollen zones (cf. Zagwijn, 1963a), detailed subdivisions and correlations to the key-reference site Russel-Tiglia-Egypte cannot be made without independent chronological tie points since the stacked sequences of the RVG contain a repetition of comparable pollen assemblages.

5.3. Implications for Quaternary chronostratigraphy

The term Tiglian was introduced in the early 1950's as a result of thorough investigations that provided a palaeontological framework for the subdivision of the Quaternary (Van der Vlerk and Florschütz, 1950, 1953). Large and small mammal remains, molluscs, plant macro fossils and pollen formed the main elements for defining the substages. Further elaboration of the concept was mainly based on extensive pollen analytical research (Zagwijn, 1957, 1960; 1963a; 1963b; Kasse, 1988; Kasse and Bohncke, 2001). The application of paleomagnetic methods and long-distance correlations to the Mediterranean finally provided indications of absolute ages (Van Montfrans, 1971; Zagwijn, 1974; Zagwijn and Suc, 1973, 1983; Kasse, 1996) although, as stated earlier, these paleomagnetic results are only indicative at best.

The Early Pleistocene pollen zones originally defined by Zagwijn (1963a) have gradually transferred into chronostratigraphical substages and thus the resulting chronostratigraphical subdivision of the Early Pleistocene is used as a standard throughout NW Europe (Zagwijn, 1992). Considering the discussion of the key sites stated above, it is questionable whether the extrapolation of local-defined pollen zones has such a wide regional stratigraphical significance. From the previous lithostratigraphical descriptions, the sedimentary facies interpretations, and the palaeobotanical interpretations it appears that the three-fold subdivision of the Tiglian Stage is too simplistic and lacks a sound stratigraphic basis:

- The Tiglian A Substage is defined by the presence of *Fagus* in a clay deposit exposed in the former Janssen-Dings pit near Belfeld (situated just south of the Maalbeek site, Fig. 3). This pit may serve as exemplary stratotype. However, there is no proper published description of this already long abandoned excavation. Even more important is that the T-A zone cannot be positively identified in the RVG, making its stratigraphic relevance questionable.
- The Tiglian B Substage was first described in the Eindhoven I and II boreholes (Zagwijn, 1963a) but it essentially has no properly defined stratotype. Our results show that the T-B signature in the Tegelen-Maalbeek area is not unique to a specific level since similar assemblages are present at other depths in the Roer-Valley-Graben sequence.
- The fluvial sequence of Russel-Tiglia-Egypte pit serves as the stratotype (type section) of the Tiglian C Substage. It is a nominal and exemplary stratotype and not a boundary-defining stratotype (Walsh, 2005). Although the combination of the facies changes and coinciding changes in pollen assemblage at RTE suggests the entire T-C zone could reflect only a relatively short period in time, the mammal data suggests that somewhere within the T-C sequence in the Maalbeek-Tegelen area, more time is present. This uncertainty makes the projection of these local pollen zones into a larger scale chronostratigraphic framework questionable.

Similar remarks could be made on the definition of the Tiglian Stage itself. The area of Tegelen-Maalbeek area could serve as a nominal stratotype but there is no type section where its boundaries can be defined. The same holds true for some other pollen-defined stages of the Early Pleistocene. Initially they have been formulated as part of a climate-stratigraphic concept, i.e. the alternation of warm and cooler phases (Zagwijn, 1957, 1960, 1963a; 1963b). However, the results of deep sea research have shown that climate alternated in a much greater detail than was believed to be possible over fifty years ago. This difference is clearly demonstrated by comparing the pollen-defined temperature curve for the Pleistocene with the Marine Isotope Stages (Fig. 1).

The evidence presented above clearly shows that the pollen record of the fluvial sequence of Tegelen-Maalbeek area reveals indications for climate change. However, it does not show diagnostic criteria for assignment to a specific glacial-interglacial cycle. As long as absolute age determination cannot be used for subdivision of the Early Pleistocene, it will remain difficult to correlate local recorded climatic changes to the Marine Isotope Stages. The sequence of stacked fluvial deposits in the RVG probably reveals a more detailed record of climate change when it is analysed in greater detail. However, it must be realised that even the thick accumulation of fluvial deposits in the RVG likely contains hiatuses. Major fluvio-deltaic accumulations of Neogene deposits occur in the central depocenter of the North Sea Basin. Several recent studies have demonstrated that the sequence preserved in that region is suitable for high resolution stratigraphical analyses (Huuse et al., 2001; Michelsen et al., 1998; Overeem et al., 2001; Overeem, 2002; Kuhlmann, 2004; Kuhlmann et al., 2006; Donders et al., 2018; Dearing-Crampton Flood et al., 2020). Detailed integrated analysis of these marine sections, followed by correlation to the upland regions from a sequence stratigraphic perspective is the way forward to place the terrestrial sequences in proper context. Glacials of minor amplitude are more likely to have preserved, and possible candidates for the T-A/B/C sequence at Maalbeek are within MIS 95-91 that follow strong glacials (MIS 96/98/100, Fig. 1) during which likely erosive conditions existed in the Maalbeek-Tegelen type area.

6. Conclusions

The sediments of the Waalre Formation in the Tegelen-Maalbeek area consist of a fluvial fining-up sequence with clay deposits up to 10 m thick in its upper part. Sedimentological analyses of these deposits has demonstrated that within the floodplain fines three main facies associations occur repeatedly: flood-basin or back-swamp deposits, crevasse splay and overbank deposits and fine-grained infillings of oxbow lakes. The pollen content of the floodplain fines reflects the facies development to some degree. Definition of an alternative pollen sum, excluding wetland trees, does resolve most of the local overprint on regional forest cover.

The well-known pollen zones of the Tiglian Stage are all present in the fluvial sequence of Tegelen-Maalbeek. At the T-A/T-B, and T-B/T-C pollen zone transitions (Zagwijn, 1998) hiatuses may be present. Whether hiatuses are present within the T-C pollen zone is unclear. The sedimentological interpretation of the individual sedimentary units at the stratotype of the Tiglian C Substage does not support the previously presumed long time duration (~10^5 years) of deposition. However, mammalian data point to significant evolutionary-scale hiatuses between different sites where the T-C pollenzone is identified. The lack of pollen in the so-called T-$C4^c$ zone likely results from the onset of locally occurring crevasse-splay formation instead of a (supra) regional depositional hiatus during a period of cool conditions.

Extrapolation and correlation of the palynological record from Tegelen-Maalbeek to the thicker stacked fluvial sequences of Early Pleistocene age in the RVG is highly problematic since the RVG record appears to have several stacks of sequences comparable to at least the Tiglian B/C zones. Part of formerly Tiglian A-aged deposits in the RVG, near Eindhoven, is of Late Pliocene age and is equivalent to the Oebel Beds in the Brachterwald area in Germany and best included in the Reuverian B.

The chronostratigraphical subdivision of the Early Pleistocene (Zagwijn, 1998), based on palynological characteristics and palaeobotanical analyses alone, requires reconsideration. Therefore, the three-fold subdivision Tiglian A, Tiglian B, and Tiglian C as chronostratigraphical Substages of the Tiglian Stage should be discontinued unless independent chronological data confirms the stage concepts.

Rather, shallow marine sequences with independent age control could provide the basis of an improved regional pollen stratigraphy. Additional detection of paleomagnetic reversals and independent dating methods, such as electron spin resonance, are needed to assign ages to the pollen records from the fragmentarily preserved fluvial sequences at Tegelen-Maalbeek.

When up-scaling of pollen zones into chronostratigraphical substages of regional significance is applied, pollen associations of only local environmental significance should be avoided.

Author contributions

Wim E. Westerhoff: Conceptualization, Methodology, Investigation, Writing - Original Draft. Timme H. Donders: Methodology, Investigation, Writing - Review & Editing. Nikki Trabucho Alexandre: Visualization. Freek S. Busschers: Methodology, Investigation, Writing - Review & Editing, Supervision.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106417.

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