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2 A revised lithostratigraphy of Upper Pliocene and Lower Pleistocene fluvial deposits from Rhine, Meuse and Belgian rivers in the Netherlands

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Abstract
A thorough revision is presented of the lithostratigraphical units of Upper Pliocene and Lower Pleistocene fluvial deposits in the south-eastern part of the Netherlands. Two new formations are defined:

1. The Waalre formation includes all mixed Rhine-Meuse deposits. The heavy-mineral composition is characterised by predominantly unstable associations.

2. The Stramproy Formation includes all deposits that are formed by northward flowing rivers that drained the central and northern part of Belgium. The heavy-mineral composition is dominantly stable. Their lower and upper boundaries are formed by regionally extensive and marked stratigraphical horizons like the Reuver Bed at the top of the Kieseloolite Formation, and the unconformity at the base of the Sterkveil Formation.

The Waalre Formation is subdivided into three informal subunits of which the lower one (WA-1) forms an equivalent of the Late Pliocene Oebel Beds in Germany. The middle subunit (WA-2) mainly occurs in the northern part of the Roer Valley Graben and grades laterally into the shallower marine deposits of the Maastrichtian Formation. The upper subunit (WA-3) extends over the central and western part of the Netherlands into the present North Sea.

Sediments supplied by the Belgian rivers provided infilling of the remaining accommodation space in the Roer Valley Graben and adjacent areas after the abandonment of the Rhine-Meuse system from these areas. Both formations occur at least for a part adjacent to each other and show repeated intercalations as a result of the combined effect of tectonic movements and climate change.

The revised lithostratigraphic units are defined strictly by lithology and stratigraphic superposition and therefore provide a firm framework for the development of 3-dimensional (numerical) geological models and palaeogeographical reconstructions.

2.1 Introduction
Sedimentary sequences and ages of rocks formed the initial issues studied by stratigraphers. The evolution of stratigraphy has gradually included other aspects such as: morphological lithology, fossil content, geophysical and geochemical properties. As a consequence stratigraphy now can comprise all kinds of characteristics and attributes of rocks units. However, the core-business of stratigraphy (i.e. the ordering of rock units) still is focused on bio-, chrono-, and lithostratigraphy. Lithostratigraphy thereby is seen as the basic step in stratigraphic research. It provides a framework for all kinds of geoscientific studies, especially for geological mapping and subsurface modelling (Wester & Westerhoff, 2006).

This paper focuses on a pure lithostratigraphical approach for the Upper Pliocene and Lower Pleistocene fluvial deposits in the southern part of the Netherlands (Fig. 2.1). These deposits have been studied already for more than a century (see overview of references by Meijer, 1998) based on their fossil content (small and large mammals, plant macro remains, and pollen); they have played a central role in the establishment of the Quaternary (Rtho) stratigraphic framework of the Netherlands (Zagwijn, 1960, 1963; Doppert et al., 1975). However, due to the initial interest in the palaeontological content of the deposits and an overestimated impact of climate change on them, the lithostratigraphic subdivision of the Lower Pleistocene fluvial deposits (cf. Doppert et al., 1975) became strongly intermingled with bio- andchronostratigraphic criteria. As a result a justified lithostratigraphical assignment often has to be carried out with help of microscopic techniques. Initially, lithology formed a main criterion to make distinction between rock units. However, the palaeontological subdivision of the Pleistocene (Van der Vliek & Fleschutz, 1953; Zagwijn, 1957) and palaeogeographical reconstructions (Zonneveld, 1958) determined strongly the concepts of the geomorphic and depositional architecture (Zagwijn, 1967). As a consequence the latter aspects provided an increasing influence on the lithostratigraphical classification. The intermingling of various criteria eventually has led to restricted possibilities for use of the lithostratigraphical units thus defined in digitally designed numerical subsurface models that can be used in applied geoscientific research.

According to the lithostratigraphical scheme of Doppert et al. (1975) the Upper Pliocene and Lower Pleistocene fluvial deposits are assigned to three superimposed lithostratigraphic formations (Fig. 2.2). The lowest comprises all Pliocene fluvial deposits and was assigned as Kieseloolite Formation. The middle unit is known as Tegelen Formation, a mixed Rhine-Meuse deposit with an assumed (pre)Tiglian to Early Eburonian age. The third unit is termed the Eedukenh Formation. It overlies the Tegelen Formation and therefore comprises all fluvial (mixed Rhine-Meuse and Belgian rivers) and local deposits that post-date the Tiglian Stage.

3 The terms Pliocene and Pleistocene are used here according to the ICS-timetable 2008 where the base of the Pleistocene Series is indicated as identical to the base of the Galenian Stage at 2.588 Ma (ICS-2008: www.stratigraphy.org).
Fluvial deposits in The Netherlands (according to Zonneveld, 1947b; Doppert & Renard, 1992; Van den Berg, 1996) in south Limburg and the Meuse valley (Klostermann, 1983). The RVG is confined by the ultrastructural rift system within the Netherlands are the southwestern Netherlands shows four main types of approaches. However, it should be understood that they did not develop independently but show close interrelationships.

2.2 Depositional setting

Technically, the southwestern Netherlands forms part of the lower Rhine Embayment (LRE) which is the most southerly branch of the North Sea Basin. The generally subsidizing LRE is bounded to the north by the palaeo-coast of the uplifted Rhine Massif. The main tectonic features of this Cenozoic rift system within the Netherlands are the subsidizing Roer Valley Graben (RVG) situated between the Campine Block to the west and the Peel Block to the east (Dekul et al., 1994). The latter forms part of the so-called Venloër Scholle (Klostermann, 1983). The RVG is confined by major faults systems. The Feldbiss and Gute Rijen faults form the southern and western border while the Peul Boundary fault is the major fault along the east side of the RVG (Fig. 2.1).

During the Tertiary Period marine sedimentation dominated in the western part of the LRE while peat was formed in extensive swamps in the middle part and southeastern parts. Induced by uplift of the Rhine Massif, fluvial deposition began during the late Miocene. These oldest fluvial sediments in the LRE were deposited by a pre-Rhine drainage system that did not extend into southern Germany (Boesing, 1978a; Gless and Hager, 1978). During the Pleistocene, the Meuse established a course through the so-called East Meuse Valley (Zonneveld, 1947; Kasse, 1986, 1989; Jürgen and Renard, 1992; Van den Berg, 1996) in South Limburg and entered the alluvial plain of the Rhine just north of Jülich. Rivers draining the central and northern part of Belgium generally flowed in a north-eastern direction across the Campine Block. It has to be noted that the well-known Rupel and Campine cuestas in Belgium did not exist at that time (De Ploey, 1961; Plassart, 1974; Tavenar and De Moor, 1974; Van den Berg and De Smit, 1979; Kasse, 1986).

Late Pleistocene and Early Pleistocene fluvial sedimentation progressed gradually westwards in the LRE. At the same time a progressive shift of the coastline took place in western and northwestern directions. Extrastrome depositional conditions predominated in the transitional zone to full marine environments (Kasse, 1986, 1988). The distribution of these extrararne deposits seems to cover a much larger area than thought. In the south-western part of the Netherlands and in the central part of the BVG marine sediments of the Maasvlies Formation interdigitate with the Lower Pleistocene fluvial sediments. Future research on these marine deposits might probably contribute to a better understanding of the palaeogeography and ages of the deposits in this part of the Lower Pleistocene sedimentary record.

2.3 Brief review of former stratigraphical approaches

The history of Pleocene and Lower Pleistocene stratigraphical research of the fluvial record in the southern part of the Netherlands shows four main types of approaches. However, it should be understood that they did not develop independently but show close interrelationships.

2.3.1 The mapping approach (1)

Lotie’s (1907) partition of Onderste Grond (Lower Course), Middelste Fijn (Middle Fine) and Bovenste Grof (Upper Coarse) was the first lithostratigraphic classification of Pleistocene deposits in The Netherlands (Fig. 3). It was purely based on lithological characteristics. A slightly adapted version was applied by Rauwerda and Waterschoot van de Graaff (1913). As a geological mapper Tsch (1934, 1937) subdivided the deposits according to a mixture of morphostratigraphical, biostratigraphical and lithostratigraphical criteria. He correlated the fluvial Pleistocene deposits with the ‘Kieseloolith Stufe’ in the German part of the LRE (Fliegl, 1907; Kaiser, 1907; Tsch, 1908, 1911, 1934; Wunstorf and Regel, 1910) and linked them to the Scandinavian and Russian-based marine Pleistocene stratigraphy. The Lower Pleistocene fluvial deposits were classified by Tsch as ‘Praeglacial older than Main Terrace’. The lower part of it was thought to be the equivalent of the ‘Praetegelen’ continental deposits (Van der Vlerk and Fletschert, 1953, Pannekoek, 1956). These continental ‘Praetegelen’ deposits were correlated with the marine Amsterdam, a stage typified by a mollusk assemblage indicative of cool climatic conditions. The overlying marine deposits belonged to the Icelanian Stage. Tsch made no distinction on the basis of the origin of the fluvial deposits.

2.3.2 The sediment-petrographical approach (2)

The stratigraphical approach based on the petrographical composition and provenance of sediments (Edelmann, 1933, 1939, 1938) has proven to be a powerful tool for the characterisation of deposits and mapping of the distributional areas. Zonneveld (1947a, 1950, 1958) thoroughly elaborated this in his sediment-petrological studies and was able to reconstruct a comprehensive stratigraphy. He also considered the lowermost fluvial sequences typified by a stable heavy-mineral content as an equivalent of the German Kieseloolit deposits. Within the Lower Pleistocene fluvial deposits Zonneveld distinguished the Zone of Tegelen (unstable heavy-mineral associations with a clear presence of garnet) and recognised them as Rhine deposits. Based on age correlations Zonneveld considered the terrace deposits of the Meuse in South Limburg as contemporaneous with (but not part of) the Zone of Tegelen. Deposits with a dominant stable heavy-mineral assemblage which overlie the sediments of the Zone of Tegelen were termed the Lower Fine Zone (Zonneveld, 1947b) and subsequently as Sterksel van Kedichem (Doppert and Zonneveld, 1955). The typification serie was chosen because it was expected that ongoing research would reveal a number of similar zones. Later, Zonneveld (1958) and
study of fossil molluscs was focussed on marine deposits but authors had adopted biostratigraphy as a fundamental approach in stratigraphic research. Regarding the fluvial deposits in the southern part of The Netherlands much attention was paid to the faunal and floral composition of the clay deposits near Tegelen and Reuver (e.g. Dubois, 1905; Fleig & Stoller, 1910; Tisch, 1911, 1928, 1934; Reid & Reid, 1915; Bernsen, 1930, 1930-1932, Schruder, 1943, 1950).

Figure 2.2: A lithostratigraphy of Early Pleistocene fluvial deposits in the southern part of The Netherlands (after Zonneveld, 1958; Doppeet al., 1959; Wettengel et al., 2000). The table of Van der Vlerk (1960) was the first lithostratigraphical scheme with a Pleistocene chronology based on the pollen-defined subdivision introduced by Zagwijn (1957). This work essentially describes a biostratigraphy of the Pliocene. It was the first time in the Netherlands that several papers were published and used to establish a subdivision of the Pleistocene based on stages. These authors placed the Reuver Clay in the Late Pliocene Reuverian Stage that later was presented in more detail by Zagwijn (1960). The onset of the Pleistocene Series was defined by these workers as Pretiglian. One should notice that this Pretiglian (cf. Van der Vlerk & Florschütz, 1953) includes all deposits between the Reuver Bed and the Tegelen Clay and disregards the logical entity of sedimentary fluvial cycles. So, this first definition of the Pretiglian is a purely lithologically defined subdivision. Furthermore Van der Vlerk & Florschütz (1953) defined a Tiglian Stage, based on their studies of the Tegelen Clay exposed in several excavations in the vicinity of Tegelen. The post-Tiglian period was assigned as Taxandrian, a stage that lasted until the Needelian. The latter is correlated nowadays with the Middle Pleistocene Holsteinian. Apart from studies in exposures, Van der Vlerk & Florschütz (1953) were able to distinguish some of the stages in boreholes. Subsequently Zagwijn developed this approach in detail by analysing a great number of borehole sequences. Based on this pollen analytical evidence a further subdivision of the Early Pleistocene was established in a number of consecutive stages (Zagwijn, 1957, 1960).

2.3.4 The (litho)stratigraphy of the Geological Survey (4)

In the early 1950s the Geological Survey of the Netherlands began a new national mapping programme at a 1:50 000 scale. As a consequence, the Geological Survey took a strong lead in all types of stratigraphic studies. The main goal was to establish a stratigraphic framework that could be applied in the mapping programme. Such a system not only required formalisation of lithostratigraphical units, but should also provide a reasonable insight in the chronostratigraphical subdivision of the Plio-Pleistocene period. For this purpose, the work of Van der Vlerk & Florschütz (1953) and Zonneveld (1947) was taken as a starting point. In particular the first authors had adopted biostratigraphy as a fundamental approach in stratigraphy and had abandoned the well-known morphological lithostratigraphical subdivisions based on the concepts of Peuck & Brücker (1909). Apart from this, it was believed that a systematic pollen analytical survey of Quaternary peat and clay strata could contribute to a detailed biostratigraphical subdivision. In numerous outstanding publications Zagwijn (1957, 1960, 1961, 1963a, 1963b; Zagwijn & Zonneveld, 1956) elaborated a biostratigraphy for the entire Pliocene and Early Pleistocene.

Doppe et al. (1955) made the first attempt to compile a more formal lithostratigraphy by combining the pollen (pelagial) and sediment-petrological evidence. Their lithostratigraphical units were named zones and series, and ordered into a stratigraphic framework by combining superposition and biostratigraphical evidence. One of the important conclusions was that the hitherto Mindel Riss stage of the Serie van Kedichem appeared to be older and could be seen as part of the Early Pleistocene. In a following paper Zagwijn (1958) adopted the formal stratigraphical nomenclature of formations (Hedberg, 1954) and subdivided the Upper Pliocene and Lower Pleistocene fluvial deposits respectively into the Kieseloolite, Tegelen and Rieschd formation. (see also Fig. 2.2). He omitted the various terrace deposits of the Meuse in South Limburg from these formations, as was done later by Doppe et al. (1975).

Zonneveld’s lithostratigraphical terminology was also applied by Zagwijn (1960, 1967) who established the definitions of the lithostratigraphical units in more detail, and also the chronostratigraphical subdivision into stages and substages that was based on the palynological evidence.

2.4 The newly defined Waalre and Stramspoy Formations

2.4.1 Introduction

In the revised lithostratigraphical system the Upper Pliocene and Early Pleistocene fluvial deposits in the southern part of the Netherlands are subdivided into two newly defined formations. Both formations are situated between the Kieseloolite Formation and the Sterksel Formation. Deposits formed by the mixed Rhine-Meuse river system are referred to the Waalre Formation whilst the Strannspoy Formation comprises deposits formed by rivers that drained the central and northern part of Belgium together with deposits of more local origin. A brief summary of the main characteristics is given below. Full descriptions can be consulted on the lithostratigraphical pages of DINOLOKET (www.dinoloket.nl).

2.4.2.1 The Waalre Formation (WA)

The holotype of the Waalre Formation is defined in the intervals between 126-144 and 158-206 m of borehole SSDN043 at Waalre (Fig. 2.1, 2.4).

2.4.2.1.1 General lithology

The Waalre Formation deposits consist of a number of stacked fining upward cycles with grain-size variations ranging from coarse-grained, gravel-bearing sand in the basal parts to clay with a low silt content in the upper parts of individual cycles. Sand forms the dominant lithology but clay layers may be widespread on a regional scale. Gravel occurs more frequently in the lower parts of the formation. Generally, a decrease in the mean grain size can be observed in north-western and western directions. Locally, dark brown to black thin (< 0.5 m) peat layers may occur in the clayey parts of the formation. The sediments are characterised by low to moderate amounts of mica flakes, dark-coloured particles in the fine sand fraction, and red-brown components in the coarser grained fractions. Below the groundwater level grey colours predominate the sandy parts while clay is often blue-grey in colour.
Figure 2.4. Lithology, heavy-minerals and lithostratigraphy of borehole 51D0343 (near Eindhoven); holostratotype of the Waalre Formation.

Figure 2.5. Lithology, grain-size distribution, and lithostratigraphy of borehole 49G0204 (near Huijbergen); hypostratotype of the Waalre Formation.
The Waalre Formation also includes deposits that were formerly attributed to the upper part of the Kieseloolite Formation, i.e. that part typified by Rhine deposits with unstable heavy-mineral assemblages. Mixed Rhine-Meuse deposits formerly considered as part of the Kieseloolite Formation, cf. Doppert et al. (1975) now form part of the Waalre Formation. Lithologically they do not show any difference with other Rhine-Meuse deposits of the Waalre Formation. Their assumed post-Tiglian age is not a criterion that justifies their assignment into a separate lithostratigraphic unit.

Influences of coarse-grained Rhine-Meuse deposits formerly assigned as the so-called ‘Runnik Rhine’ influence within the Harderwijk Formation (cf. Doppert et al., 1975; see also Jelgersma & Zandveld, 1978) are now included in the Waalre Formation (see 2.6).

### 2.4.3 The Stramproy Formation (SY)

The holostatotype of the Stramproy Formation is defined in borehole 57H0058 at Stramproy in the interval between 46.50-136.80 m (Fig. 2.1, 2.7).

#### 2.4.3.1 General lithology

The deposits of the Stramproy Formation consist predominantly of fine to coarse-grained sand with a high quartz content. Medium to coarse-grained gravel locally forms thin ‘lag’ deposits. Clay deposits may contain very fine sand and silt. In the southern part of the distribution area, clay layers are relatively thin and seldom exceed 2 m in thickness. In the western part of the distributary area clay layers may occur over vast areas and can reach a thickness of several metres. Thin (< 1 m) dark peat layers in between the sandy deposits are irregularly distributed throughout the formation. Humic or peaty horizons may occur sporadically within the clay layers. The sand deposits of the formation are usually light brown to light grey in colour. The clay is generally olive grey to brown grey.

#### 2.4.3.2 Additional lithological characteristics

For the larger part the sediments of the Stramproy Formation lack carbonates, although there may be some local exceptions. Humic soil horizons may occur repeatedly in the formation, especially in the sandy deposits of the southern part of the RVG. Parts of the formation are also affected by cryoturbation, frost wedges and other periglacial phenomena. In geographical wells the sandy parts of the formation are characterised by a very low response of the Gamma Ray curve (Fig. 2.7). The heavy-mineral content of the formation is dominated by 90% of stable minerals (e.g. zircon, staurolite, metamorphic minerals and tourmaline).

#### 2.4.3.3 Genesis/sedimentary characteristics, distribution, thickness and age

The deposits of the Stramproy Formation comprise a wide range of fluvial, estuarine, periglacial, and aeolian facies types. The larger part of the formation consists of fluvial facies related to the fluvial systems that drained the central and northern part of Belgium. To the west and northwest estuarine facies types become increasingly important. Local and aeolian deposits are irregularly distributed and mainly upward cycles of the formation. The fluvial fining upward cycles range in thickness between 7-12 m. Thicker sequences up to 20-30 m typify deposition in estuarine environments.

The heavy-mineral content of the deposits shows a 90% dominance of unstable heavy-minerals (garnet, epidote, saussurite/alumite, hornblende; see also Fig. 2.4).

#### 2.4.2.3 Genesis/sedimentary characteristics, distribution, thickness and age

The Waalre Formation includes fluvial and estuarine sediments supplied by the Rhine-Meuse fluvial system. All facies types that are characteristic of fluvial and estuarine deposits occur within the formation. As observed in excavations the sand and gravel deposits of the Waalre Formation show channel and pointbar facies types. Gravel-bearing channel 'lag' deposits characterise the lower part of the formation. The fine-grained and clayey deposits of the Waalre Formation exhibit four characteristic facies types:

- Channel fills, formed in shoal lakes. They usually consist of horizontally bedded clay deposits. Thin (cm-dm) sand layers, often showing climbing ripple structures may occur in between 5-40 cm thick individual clay beds. Local white-coloured enrichment of sidetree can accentuate the sedimentary lamination and the amount of sidetree may increase to values of 90%. When the sidetree is oxidised it shows red-brown or rust colours.
- Flood-basin fines: deposits consisting of silt and very fine sand formed in the (extensive) floodbasins in between active channel belts. Such clayey deposits have a massive appearance and contain hardly any sedimentary structures. Locally, thin humic horizons consisting of peat or brown-coal may occur. Sometimes the clay has a crumby or prismatic structure as a result of initial soil-forming processes.
- Crevasse splays and levees, consisting of small scale (cm-dm) alternations of fine-grained sand and clay.
- Estuarine and/or lagoonal clay deposits, consisting of clay with a variable content of silt and very fine sand. Locally thin peat layers may occur in the uppermost part. The transition to underlying sandy deposits is always characterised by strongly alternating bedding of thin sandy and clayey strata (Fig. 2.5).

The distributional area of the Waalre Formation is shown in Figure 2.7. Due to erosion the formation is absent on large parts of the Peel Block area. The thickness varies from a few metres on the Peel Block to over 90 m in the RVG. The Waalre Formation is of Late Pliocene to Early Pliocene age.

#### 2.4.2.4 Subdivisions

Only one member is defined formally within the formation: the Tegelen Member. This Tegelen Member comprises the remnants of the Waalre Formation on the Peel Block.

#### 2.4.2.5 Relation to previously defined units

With the exception of the Early Pleistocene terrace deposits of the Meuse in South Limburg the Waalre Formation encompasses the deposits of the Tegelen Formation cf. Doppert et al. (1975). The Early Pleistocene terrace deposits of the Meuse are now incorporated into the Beegden Formation (Weerts et al., 2000, Winterhoff et al., 2003). The
2.4.3.5 Relation to earlier defined units

The Stramproy Formation is Early Pleistocene in age. Based on its stratigraphic position (Fig. 2.8), it is concluded that parts of the formation are formed concurrent with the Waalre Formation. This implies that the age of its lower boundary is older than generally believed for the former Redichem Formation (Westerthoff et al., 2008).

2.4.3.4 Subdivisions

Thus far, the Stramproy Formation has not been subdivided into members status units.

2.5 Characterisation of the Upper Pliocene and Lower Pleistocene fluvial deposits in the southern part of the Netherlands, with regard to their provenance and sedimentary facies

The Pliocene and Lower Pleistocene fluvial deposits in the southern part of the Netherlands are derived from different sources: the pre-Rhine and Rhine drainage system, the Meuse, and a system of consequent rivers that drained the central and northern part of Belgium (Fig. 2.1). Together these major river systems have formed an extensive wedge of alluvial sediment in the southern part of the North Sea Basin. The petrographic composition of the deposits is controlled by their provenance. Lithology and sedimentary characteristics of the deposits reflect the depositional conditions which are largely determined by climate and tectonic forcing. The spatial relationships of the lithostratigraphical units can be mapped over a large area and form the basis of further unravelling of the fluvial history in the area. The outlines of the revised lithostratigraphic framework in the southern part of the Netherlands are illustrated by a few example cross-sections (Figs. 2.8, 2.9, 2.11) and will be discussed below.

2.5.1 The Pliocene fluvial record

The first fluvial deposits formed in the LRE were derived from the strongly weathered outcrops of the Rhenish Massif and are assigned to the Kieseloolite Formation. In general they consist of light coloured, medium to coarse-grained sands and some gravel. The sediments show a high percentage of quartz and a dominant stable heavy-mineral assemblage (e.g. Fig. 2.7, the interval between 136.8-277.0 m). The Kieseloolite Formation reaches a thickness of about 200 m in the southern part of the RVG (Figs. 2.8, 2.9) but thins out towards the northwest in the vicinity of ‘s Hertogenbosch. Sand bodies, up to several tens of metres thick, interrupted by 6-10 m thick clay strata characterise the Kieseloolite Formation in the southern part of the RVG (Figs. 7, 8, 9). The clay strata show repeated intercalations of peat and brown coal. The vertical lithostratigraphic composition is clearly expressed in Gamma Ray logs: increasing values for the clayey deposits and relatively low values for the sandy parts. At the top of the formation a widespread and easily mapped clay layer occurs. It always shows a Reuvetian type pollen assemblage and is lithostratigraphically assigned to the Reuvet Bed (Reid & Reid, 1915: Zagwijn, 1960; Boenigk & Prechen, 2006).

The lowermost part of the formation in the southern part of the RVG might form the northern continuation of the so-called Indener Schichten (indicated by the dashed line in Figs. 2.8, 2.9) which is thought to be of Late Miocene age (Schafer et al., 2005).

The main source area of the deposits occurs in the pre-Rhine drainage basin (Boenigk, 1979; Claase & Hager, 1978). Upstream of the confluence with the Meuse the Kieseloolite Formation consists of pure pre-Rhine deposits with some admixture of local tributaries (Kemna, 2005, 2007). Downstream of the confluence the formation consists of mixed pre-Rhine and Meuse deposits with some admixture of material supplied by the Belgian rivers. All deposits supplied by these river systems are typified by a high quartz content and dominantly stable heavy-mineral associations. As a result, deposits of the Meuse and Belgian rivers cannot be mapped separately from pre-Rhine deposits. Only a slightly higher amount of metamorphic minerals may indicate that the Meuse and/or the Belgian rivers contributed sediment to the Kieseloolite Formation. Locally, an increase of Meuse influence can be distinguished from Rhine deposits by increasing values of fent and quartz in the gravel fraction (Boenigk, 1970, 2002). Terrace deposits of the Meuse in the East Meuse Valley in southern Limburg are included lithostratigraphically in the new defined Beegden Formation that comprise all pure (i.e. not mixed with Rhine) Meuse deposits (Werts et al., 2000; Westerthoff et al., 2003). The deposits of the Kieseloolite Formation were formed in a vast lowland area that was situated near the coast and had a generally low gradient. Deposition of the thick clay strata and intercalated peat took place in extensive floodbasins where peat accumulated in swamps and back-barrier areas. It is likely that their formation was promoted by regional high sea-level stands.

2.5.2 Late Pliocene and Early Pleistocene Rhine-Meuse sequences

During the Late Pliocene the catchment of the Upper Rhine extended southwards into southern Germany and the Alpine foreland. As a result, the petrographic composition of the Rhine sediments deposited in the LRE changed drastically (Boenigk, 1970, 2002; Boenigk et al., 1972, 2004; Hagedorn, 2004; Hagedorn & Boenigk, 2008; Kemna, 2007, 2008). This can be seen macroscopically by the abundance of mica flakes (i.e. muscovite), feldspar grains, some red-brown components, the higher carbonate content in the assemblages, and the generally grey colour of the deposits. The marked change in petrographic composition is also well-demonstrated by an almost complete shift to a 90% dominance of unstable heavy-minerals (e.g. garnet, epidote, albitrite/saussurite).
and hornblende, see also Fig. 2.4, at about 210 m).

Downstream of the Rhine-Meuse confluence near Jülich these Rhine deposits are mixed with sediment supplied by the Meuse. However, being the larger river, the sediments of the Rhine dominate the Meuse influence in the assembled deposits. This effect is even more important in the heavy-mineral composition because Rhine sediments contain a considerable higher amount of heavy-minerals when compared to Meuse deposits (Zonneveld, 1947, 1950). Generally, the contribution of Meuse sediment can be recognised only in the gravel fraction (Kurtz, 1913, 1917). Boenigk (2003). The mixed Rhine-Meuse deposits which are characterised by unstable (Alpine) heavy-minerals overlie the Kieseloolite Formation and are lithostratigraphically assigned to the Waalre Formation. In the RVG three subunits of the Waalre Formation, respectively labelled WA-1, WA-2 and WA-3, can be distinguished from bottom to top (Figs. 2.4, 2.8).

The lowermost deposits of the Waalre Formation are typified by a marked change in petrography and show the increase to a nearly full dominance of unstable heavy-mineral associations (Fig. 2.4). These deposits are indicated as subunit WA-1 and are found in several boreholes in the RVG (Figs. 2.8, 2.9). They are also known from the Brachterwald area (east of Tegelen) on the Peel Block (i.e. the pits near Oelbe and Holter Stal) (Boenigk, 1970, 1978; Kemna, 2005, 2008; Westerhoff, 2004, chapter 6). Generally they consist of a complete fining-upward cycle of fluvial deposits with a gravel-bearing basal part and a thick clay layer at the top. The clay usually shows two or more peat or browncoal intercalations. The thickness of the unit varies between 15-25 m. The Reuver Bed forms a marked clay deposit with intercalated brown coal layers at the top of the Kieseloolite Formation and is overlain by subunit WA-1. The latter shows a fining-upward trend with a fluvial basin clay at the top. Subunit WA-1 is overlain by gravel-bearing deposits of subunit WA-2 that characterise an unconformity which has been observed in large parts of the RLV (Boenigk, 2002; Boenigk & Frechen, 2006). Due to the lithostratigraphic position and the characteristics of the deposits the WA-1 subunit can be correlated with the so-called Oelbe Beds that are known from several sites in the RLV (Boenigk, 2002; Heumann & Litt, 2005, 2008; Kemna, 2005, 2006; Westerhoff et al., 2008). The currently known area of occurrence (Fig. 2.6) must be seen as a minimum. The poorly described lithology in several (older) borehole data often hampers the possibilities for an adequate recognition of the deposits of subunit WA-1.

The gravel-bearing basal part of subunit WA-2 marks an erosional boundary that can be traced in the RLV and large parts of the LRE. In the southern part of the RVG subunit WA-2 consists of a fluvial fining-up cycle with a thickness of 10-15 m (Figs. 2.8, 2.9). Here, in the most subsided part the subunits WA-1 and WA-2 are separated by an intercalation of deposits of the Stramproy Formation (Fig. 2.9). In the northern part of the RVG a much thicker accumulation (> 40 m) of subunit WA-2 is shown. The basal part consists of 20-30 m thick channel deposits that are overlain by fluvial sands. At least two fluvial fining-upward cycles are observed in the northern part of the RLG. Apart from the relative small areas where remnants of subunit WA-1 occur the WA-2 subunit is overlain by deposits of the Kieseloolite and Oosterhout Formations. At the western and north-western distribution limit the deposits of subunit WA-2 gradually grade into shallow marine and near-coastal deposits of the Maassluis Formation. In a zone along the Belgian border, west of the RLG, marine deposits of the Maassluis Formation are repeatedly intercalated within fluviatile/fluvial deposits of subunit WA-2. These marine intercalations show rather irregular distribution patterns and therefore they cannot be mapped individually on a regional scale or subdivided into separate lithostratigraphical units.

Within the RLG the occurrence of the WA-1 subunit is limited to the tectonically deepest parts (Figs. 8, 9; Michon et al. 2003) and can be traced from the Dutch-German border area to the vicinity of Eindhoven (Fig. 2.6). Here, in the Waalbe bomhole (Fig. 2.4) the heavy-mineral content shows fairly well the marked change from stable to unstable associations. Isolated finds of deposits of subunit WA-1 in the southern part of the RVG and the adjacent area of Germany indicate that after its deposition intensive erosion may have taken place (Kemna, 2005, 2006; Westerhoff et al., 2008). The currently known area of occurrence (Fig. 2.6) must be seen as a minimum. The poorly described lithology in several (older) borehole data often hampers the possibilities for an adequate recognition of the deposits of subunit WA-1.

The uppermost part of the Waalre Formation, subunit WA-3, is well-developed in the northern part of the RLG and can also be found in the area west of the RLG (Figs. 2.6, 2.8, 2.10). The deposits of subunit WA-3 consist of a number of stacked fining-upward cycles. In comparison with subunits WA-1 and WA-2 the basal parts of the depositional cycles of subunit
WA-3 have a considerable lower mean grain size and contain hardly any gravel. Thick clay deposits (> 6 m) formed in extensive floodplains characterised the terminal depositional cycle of the WA-3 subunit in the RVG and the adjacent area west of it. Their occurrence is widespread throughout the study area. The maximum thickness of the WA-3 subunit in the RVG can amount up to 80 metres.

In the RVG a clear break exists between subunit WA-2 and WA-3. It is well-expressed by intercalating deposits of the Stramproy Formation at a depth of about 140-160 m near Eindhoven (2.8). Further to the North marine mollusc-bearing deposits of the Maassluis Formation interdigitate with subunits WA-2 and WA-3. North of the distribution limit of subunit WA-2 (fig. 2.6) all deposits of subunit WA-3 are overlain by the Maassluis Formation. In the central and western part of The Netherlands the mixed Rhine-Meuse deposits of the WA-3 subunit interdigitate with the Peize Formation (Weerts et al., 2000; Westerhoff et al., 2003). The latter consists of fluvial deposits supplied by the Ertsdorps fluvo-deltaic system that drained the Baltic area during a large part of the Neogene and Quaternary (Rijnsma 1981, Overeem, 2002). In the western part of the Netherlands deposits of the Waalre Formation may also overlie the Peize Formation (Fig. 2.10).

2.5.3 Deposits of the Belgian rivers

Fluvial systems that drained the central and northern part of Belgium form the third main sediment source of the Lower Peizeocene fluvial deposits in the southern part of the Netherlands. Lithostratigraphically their deposits are assigned to the Stramproy Formation. During the Early Peizeocene a system of southwest to northeast orientated consequent rivers drained the eastern part of the present-day Schelde catchment and flowed across the Campine Block towards the RVG (Tavernier & De Moor, 1974, Kasse, 1988). As soon as these rivers entered the Rhine-Meuse floodplain their sediments became intermingled with those of the Rhine-Meuse. Due to the lithological overprint of the Rhine-Meuse, the deposits of the Belgian rivers can no longer be recognised separately. So, the deposits of the Belgian rivers can only be mapped when they are not mixed with Rhine-Meuse material. The deposits of the Stramproy Formation consist of fine to medium-grained quartz-rich sand and are dominated by a stable heavy mineral content (Heidema & Stramproy, 2.7). The near absence of well-developed thick clay layers in the southern part of the RVG is noteworthy here. The Stramproy Formation can reach a thickness of 80-90 m. The (local?) intercalation of the Stramproy Formation in between subunits WA-1 and WA-2 of the Waalre Formation (Fig. 2.9) indicates a temporarily diminished influence of the Rhine in the southern RVG after the deposition of subunit WA-1. Similar influxes of material from the Stramproy Formation are found in the Waalre Formation at the Brachterwald area (Boenigk, 1970, Kemna, 2005, 2008, Westerhoff et al., 2008). As stated above the presence of such well-recognisable deposits of the Stramproy Formation can only be explained by absence of the Rhine-Meuse river system. A main cause for this can be sought in shifting positions of the main active stream belts of the Rhine-Meuse system. As the Rhine-Meuse system disappears from the southern RVG the available accommodation space can be filled by material supplied by the Belgian rivers.

In the transitional zone from the southern to northern RVG (between Asten and Eindhoven) the deposits of the Stramproy and Waalre Formations seem to intergrade. A major intercalation of the Stramproy Formation which subordinates the WA-2 and WA-3 subunits, is mapped in the vicinity of Eindhoven and northwards. Here, it also indicates a temporary interruption of Rhine-Meuse sedimentation. Deposits of the Stramproy Formation also intergrade with deposits of the Waalre and Maassluis formations in the area west of the RVG (Fig. 2.10). Here, the northwards fluxes of the deposits of the Stramproy Formation seem to be directly related to lower sea levels during glacial periods (Kasse, 1988, 1990; Kasse & Rohnke, 2001).

The uppermost part of the Stramproy Formation overlies the deposits of the Waalre Formation (WA-3) in the northern part of the RVG, on the Peel Block, and the area to the west of it. This upper part of the Stramproy Formation shows a considerable thickness near the fault junctions just south of Eindhoven. Further to the North and West deposits of the Stramproy Formation consist generally of one or two fine-grained cycles which end in thick clay layers formed in extensive flood-basins. The Stramproy Formation is widespread in the southern and western part of the Netherlands (Fig. 2.6).

2.6 Discussion

2.6.1 Stratigraphical position of the Waalre and Stramproy Formations

The deposits of the Rhine, Meuse, and Belgian rivers form an extensive wedge of Pliocene and Quaternary deposits in the southern part of The Netherlands. Three main features of stratigraphical significance in this depositional sequence can be recognised and traced over a large part of the area:

- The marked change in petrography between the pre-Rhine deposits typified by stable heavy mineral associations and the (Alpine) Rhine deposits typified by unstable heavy mineral associations.
- The erosional boundary at the transition from Upper Pliocene to Lower Pleistocene material.
- The easily-mappable coarse-grained gravel-bearing base of the Sterksel Formation which represents a major unconformity that occurs over large parts of the LNE (Boenigk & Frechen, 2006).

The Waalre Formation occurs between the marked change in petrography and the regional unconformity at the base of the Sterksel Formation (Fig. 2.11). The Stramproy Formation is positioned between the erosional boundary at the top of the Upper Pliocene deposits and the regional unconformity at the base of the Sterksel Formation. The distinction between the two formations primarily depends on their differences in provenance.

Compared to the former Tegelen Formation (cf. Doppert et al., 1975), the lower and upper boundary of the Waalre Formation are not determined by pollen-defined substages (i.e. Ruvierian and Early Rhonian) but by a clear lithostratigraphical position that is distinguished using easily-mapped major changes in lithology.

2.6.2 Waalre Formation

The threefold subdivision of the Waalre Formation that can be mapped over a vast area and forms an essential element for reconstructing a regional lithostratigraphic framework. It shows a rather consistent picture of the stratigraphic sequences preserved in the different areas as defined by tectonic structures (Fig. 2.11).

2.6.2.1 Subunit WA-1

The lowestmost subunit WA-1 is found in the tectonically deep parts of the RVG (Fig. 2.6) and locally on the Peel Block south of Tegelen. The subunit can be correlated positively with the so-called Oebel Beds of Kemna (2005, 2008) and Boenigk & Frechen (2006). Isolated finds of WA-1 deposits south of Boemond may point to tectonically (NE tithing) induced erosion after its deposition. This agrees closely with the observations made by Boenigk & Frechen (2006). The strong lithological resemblance of the uppermost clay deposit of subunit WA-1 or the Oebel Beds with the Reuver Bed of the Kieseloolite Formation has for a long time hampered a formal distinction between these deposits (Kemna & Westerhoff, 2007). Consequently the traditionally defined Reuver Bed often includes the equivalent deposits of the Oebel Beds or WA-1 subunit. Kemna (2005, 2008) assigns the by stable heavy-mineral associations typified Reuver Bed as Reuver Bed s.s..
Subsequently he describes the combined sequence of Reuver Bed s.s. and Obel beds as Reuver Bed s.l. However, the deposits of subunit WA-1 (Obel Beds) have all characteristics of the Alpine-influenced Rhine deposits (Boenigk, 2002; Boenigk & Pechenschke, 2006). The latter authors therefore included the Obel Beds into the lower part of the former Tegelen Formation. This corresponds with the subdivision presented here as the lowermost unit of the Waalre formation. Apart from the occurrence of subunit WA-1 in the RVG deposits of the subunit are also known from the area west of the present Meuse (fig. 2.6). Since no major intercalations of other material are observed in the Waalre deposits on the Peel Block, a further subdivision cannot be made here. Therefore the deposits of the Waalre Formation on the Peel Block are assigned to the Tegelen Member. So far, there is no strong evidence to equate the deposits of the Tegelen Member to one of the subunits of the Waalre Formation as observed in the RVG.

At the northern distribution limit, the deposits of subunit WA-2 interdigitate and grade into estuarine facies types which eventually continue as shallow marine deposits of the Maassluis Formation (fig. 2.10). Here the lowermost deposits of the Waalre Formation protrude from northwestern directions (fig. 2.8). At the same time, material of the Stramproy Formation is seen in the area west of the RVG subunit WA-2 can be traced in a zone along the Belgian border. Here an increasing marine influence is indicated by a number of intercalations of the Maassluis Formation. In the same area repeated infills of material of the Stramproy Formation are also seen in the Lower Pleistocene sequence (fig. 2.10). The alternations of fluvial deposits of the Stramproy Formation and estuarine deposits of the Waalre and Maassluis formations reflect Early Pleistocene relative sea-level changes and related climate change (Kasse, 1988, 1990, Kasse & Bohncke, 2001; Bogermans 1999). Due to erosion during the estuarine depositional events, the remaining deposits show an irregular and patchy distribution pattern. As a result it is impossible to map these individual alternations in the sedimentary record on a regional scale. This is the main reason why individual sediment wedges have not been designated to formally defined lithostratigraphic units. For example, as demonstrated by Bogermans (1999), the Hogerherbe Member (cf. Kasse, 1988) is just one of the clayey units of the fluvial/estuarine record of the Waalre Formation (Kempen Group in Belgium; Gullentops et al., 2001) and reflects just one of the periods in which a relatively high sea-level occurred during the Early Pleistocene.

In the northern part of the RVG subunit WA-2 is overlain by a wedge of fluvial sediment of the Stramproy Formation that originates from south-westerly directions. At the same level a wedge of marine deposits belonging to the Maassluis Formation protrudes from northwestern directions (fig. 2.8). A similar situation occurs in the area west of the RVG. Here the lowermost deposits of the Waalre Formation are tentatively correlated with the WA-2 subunit because of their corresponding lithostratigraphical position. The deposits show a full estuarine development and part of...
them were formerly classified as the Hooigerheide Member (Kasse, 1988, 1990). The influence of material supplied by the Rhine-Meuse rivers is rather high as is shown by the relatively high frequency of stable heavy-minerals in these sediments (Fig. 2.10). However, the intercalations of pure material of the Stramproy Formation has suffered from erosion and remnants are only locally preserved. In main intercalation of deposits of the Stramproy Formation in the Lower Pleistocene sequence west of the KVG is correlated with the Beers Member in Belgium (Kasse, 1988, 1990; Gullens et al., 2001). This deposit typified by periglacial phenomena overlies the WA-2 subunit. To the northwest the deposits of subunit WA-2 interdigitate with the marine deposits of the Maassluis Formation. A comparable interfingering of subunit WA-3 and the Maassluis Formation is found in the northern part of the KVG (Fig. 2.8, chapter 6).

2.6.2.3 Subunit WA-3

Subunit WA-3 forms the uppermost part of the Waalre Formation and can be distinguished in the northern part of the KVG and the area west of it. The lower boundary is marked by the intercalations above mentioned of the Stramproy Formation (Figs. 2.8, 2.10, 2.11) and the Maassluis Formation. Over entire large part of the southern and western Netherlands it is overlain by deposits of the Stramproy Formation (Fig. 2.8, 2.10). The uppermost part of the Waalre Formation extends far into the western and even north-western part of the country (Fig. 2.4). The formerly described Woensdrecht Member (Kasse, 1988, 1990) forms part of the uppermost deposits of the Waalre Formation in the south-western part of the distribution area (Fig. 2.10).

2.6.2.4 Relation to the Peize Formation

In the central part of the Netherlands the Rhine-Meuse system is mainly represented by the southern lobes of the Erindus fluvio-deltaic system and its deposits laterally grade into the Peize Formation (Fig. 2.10). Wierink et al. (2003). The deposits of the latter in that area dominate the general lithological composition. These characteristic Rhine-Meuse elements are found only as coarse-grained gravel components in the Peize Formation. Furthermore the Rhine-Meuse influence can be seen regularly in the heavy mineral composition of the deposits of the Peize Formation (chapter 6). However, pure Rhine-Meuse deposits are present at the top of the Peize Formation in the central and western part of the Netherlands. This indicates that the south-western influence of the Erindus system came to an end and the Rhine-Meuse system shifted from its southern positions to a more north-westwards direction.

2.6.2.5 Relation to former subdivisions of the Lower Pleistocene Rhine-Meuse deposits

The Waalre, as well as the Hooigerheide Member (Kasse, 1988), are not retained in the Waalre Formation. Although both members can be distinguished in vertical sections their lateral mappable are at a regional or larger scale is limited because of a gradual lateral change into other facies types. This hampers their use in a lithostratigraphical framework for numerically designed subsurface models. The four members defined within the former Tegelen Formation (i.e. Belfeld Gravel and Belfeld Clay and Tegelen Gravel and Tegelen Clay, Zagwijn, 1963, Doppeart et al., 1970) are also not retained in the Waalre Formation. The main reason is that distinction could only be made by pollen analyses (i.e. absence or presence of Fagus). Furthermore both clay members (the Belfeld Clay and the Tegelen Clay) are defined in the same fluvial sequence on the Peel Block near Tegelen (chapter 3, 6) and extrapolation of this 15-25 m thick sequence to the up to 90 m thick stacked Rhine-Meuse deposits in the KVG (Zagwijn, 1963) is very problematic. The thin fluvial sequences near Tegelen probably reflect only a minor time period of the depositional history as registered in the KVG. Moreover the deposits all exhibit comparable lithological, petrographical, and depositional conditions. So, it is hard to determine which sedimentary cycle in the KVG corresponds to the Tegelen area.

2.6.3 Stramproy Formation

The quartz-rich and stable heavy-minerals dominated deposits of the Stramproy Formation can be traced over the whole study area. So far, no further subdivision into members has been made. This is mainly because of gradual lateral changes in lithology and the absence of distinct marker horizons. However, in spite of the absence of intra-formation boundaries, it seems possible to make a three fold subdivision based on the lithological composition (mainly grain-size distribution): In the southern part of the KVG the top up to nearly 100 m thick sequence of the Stramproy Formation is dominated by sandy deposits and relatively thin clay layers and peat horizons (Figs. 2.7, 2.8, 2.9). In the northern part of the KVG, the formation shows well-expressed fining-upward cycles with thick clay deposits in the upper part. These cycles always overlie the WA-3 subunit (Fig. 2.8). The third group of deposits is characterised by a predominance of extrafine facies types and occurs in the area west of the KVG and the western part of The Netherlands. Based on the stratigraphical position in the southern part of the KVG it can be concluded that the lower part of the Stramproy Formation was deposited concurrently with the subunits WA-2 and WA-3 in the northern part of the KVG (Fig. 2.8). This observation strongly contradicts the concept of the former Kedemken Formation (cf. Doppeart et al. 1970). The latter unit was thought to have been formed during post-Tiglian times on top of the Rhine-Meuse sequence of the former Tegelen Formation. In addition the uppermost deposits of the Stramproy Formation overlie subunit WA-3 in the larger part of the southern Netherlands (Figs. 2.8, 2.10). These uppermost deposits of the Stramproy Formation have a distribution area that extends into the central and western part of the country (Figs. 2.6, 2.10). Their development results from a (gradual) shift to the northwest of the main pathway of the Rhine-Meuse system. As a result stream belts of the Rhine-Meuse system abandoned the areas of the northern KVG and the adjacent Peel Block. Subsequently, the existing accommodation space in the central and western part of the Netherlands was filled with deposits supplied by Belgian rivers. These shifts of the depositional domains of the two river systems (Rhine-Meuse and Belgian rivers) make it likely that the age of the deposits of the Stramproy Formation become progressively younger towards northwest.

2.7 Conclusions

The lithology and sedimentological composition of a specific lithostratigraphical unit depends on the depositional conditions and geomorphological setting (high-low energy, position in the floodplain). Its petrographical composition reflects the provenance. The stratigraphical position forms another major criterion for the definition of a lithostratigraphical unit. In case of the Upper Plio-Pleistocene fluvial record of the southern Netherlands, the three criteria (lithology, stratigraphical position and provenance) enable a subdivision of the fluvial deposits into three formations, i.e. Kiesloofloite Formation, Waalre Formation and Stramproy Formation.

In the revised lithostratigraphical scheme, the Kiesloofloite Formation remains for its larger part unaltered. Compared to former definitions, the authors now exclude the uppermost part of this unit because of its unstable heavy-mineral content which indicates that it is part of an Alpine connected Rhine system. These deposits now form the lowestmost part of the Waalre Formation (Wa-1) and have been mapped in the subsurface of the KVG (Figs. 2.6, 2.8, 2.9, 2.11, 2.12). They also form the equivalent of the Oobel Beds in Germany and the Pleisse terrace deposits of the so-called East Meuse which show a pure Meuse origin, are now no longer included in the Kiesloofloite Formation but form part of a separate unit (Beegden Formation) describing all Plio-Pleistocene Meuse deposits.

The revision of the Tertiary and Quaternary lithostratigraphy of the Netherlands has revealed two new units describing the
Upper Pliocene and Lower Pleistocene fluvial and estuarine record of the southern part of The Netherlands, i.e. the Waalre Formation and its equivalents. Both formations comprise the full record of Lower Pleistocene fluvial/estuarine deposits. This means that age and biostratigraphical arguments no longer play any role in determining the lithostratigraphical position as they did previously with the Regel and Kedichem Formations.

The three-fold subdivision of the Waalre Formation used in this paper seems to be consistent in the larger part of the southern Netherlands and is therefore of regional significance.

Lithology and petrographic composition distinguishes the mined Rhine-Meuse deposits from the sediments supplied by rivers draining the central and northern part of Belgium. The repeated influxes of stable material from the Belgian rivers to the mixed Rhine-Meuse deposits demonstrate that the lower part of the Stramproy Formation was deposited concurrently with the Waalre Formation. Due to northward shift of the main Rhine system the Stramproy Formation gradually extended its depositional area to the west and North.

Both the Waalre and the Stramproy Formation encompass widespread estuarine deposits in the southern and central part of The Netherlands.

The lithological differences between the Waalre and Stramproy Formation, and also the Pliocene Kesioloilite Formation, the lithological differences between the Waalre and Stramproy parts of the Netherlands. This is in accordance with the fluvial archives of the Rhine system. Quaternary Science Reviews 25: 550-574.

References


Abstract

Detailed studies of recently exposed Lower Pleistocene clay deposits and their fossil content (pollen, plant macrofossils, mollusks and mammals) in the Maalbeek pit near Tegelen are presented. Two main sedimentary units are distinguished within the exposed clays. The lower one is interpreted as a flood-basin clay initially formed in a large stagnant waterbody with peat growth. The second clay unit is deposited in an abandoned channel which was incised into the lower stranded flood-basin clay and consists of a typical laminated clay. Based on the high amount of pollen from Fagus the lower part of the flood-basin clay is assigned to pollen zone T-A. The overly clay of the flood-basin clay is characterised by a pollen assemblage dominated by Ericoaceae and Artemisia indicating a less dense vegetation cover and/or cooler climatological circumstances. It represents the pollen zone T-B. The uppermost part of the flood-basin clay and the overlying laminated channel fill are characterised by pollen assemblages that represent the upper part of the pollen zone T-C. The molluscan, mammalian and palaeobotanical data all point to these conclusions.

The earlier ascribed Euranian age for the clay dominated by Ericoaceae and Artemisia in the Maalbeek pit can now be rejected. This adjustment of the Early Pleistocene stratigraphy in the Maalbeek pit corresponds better with the generally accepted mammalian stratigraphy in Europe.

3.1 Introduction

The excavation of Lower Pleistocene clay at Maalbeek (Fig. 3.1, SE of Tegelen) has drawn attention of geologists since the beginning of the 20th century. During the early part of the century it was thought that all clay deposits in this pit could be ascribed to the Tegelen Clay. The first introduction of the Tegelen Clay in a lithostratigraphical sense was made by Eugene Dubois (1905) followed by Reid and Reid (1915) who introduced the stage name Teglian (=Tiglian). Several authors (e.g. Van der Vlerk & Florschütz, 1953; Zagwijn, 1963) showed the complexity of the Early Pleistocene stratigraphy. Nowadays, all fluvial deposits supplied by the Rhine and Meuse are in the Early Pleistocene stratigraphical sense assigned to the Waasland Formation. Deposition took place during the Periglacial and Tiglian Stages.

The facies of the Tegelen Clay at Maalbeek is well-known because of finds of molars of Anancus arvernensis and Tapirus arvernensis (Kortenbout van der Sluy, 1960, Zagwijn, 1963). Pollen analytical studies of clay layers in the pit were carried out by Zagwijn (1963) and Urban (1978). Nota (1956) and Boenigk (1970) published heavy-mineral-analyse and the pollen from Maalbeek pit, as published by Zagwijn (1963).

All authors conclude that the clays are of early pleistocene age and are of Euranian age. The lower part of the Tegelen Clay in the neighbourhood of Tegelen is characterised by pollen assemblages of pollen zone T-C. Lithostratigraphically, these clays are ascribed to the Tegelen Clay (Zagwijn, 1963). As already mentioned, deposits belonging to the pollen zone T-A have been reported until now from a site south of Maalbeek, known in the literature as the Jansen-Dings pit (Van der Vlerk & Florschütz, 1953; Zagwijn, 1960, 1963, Boenigk, 1978). The clay from this pit has been termed lithostratigraphically the Belfeld Clay (Zagwijn, 1963). It is stratigraphically below the Tegelen Clay.

The Maalbeek site is well-known because of finds of molars of Anancus arvernensis and Anancus tigliensis (Kortenbout van der Sluy, 1960, Zagwijn, 1963). Pollen analytical studies of clay layers in the pit were carried out by Zagwijn (1963) and Urban (1978). Nota (1956) and Boenigk (1970) published heavy-mineral-diagrams from sections exposed in the Maalbeek pit. All authors conclude that the clays are of Early Pleistocene age. However, there is confusion about the precise position in the stratigraphy (Boenigk, 1978, Zagwijn, 1974, Van Koldfochten & Van der Meulen, 1986). The mammal remains from Maalbeek have been significant for a long time in the debate on the stratigraphic position of the deposits. They all suggest an Early Pleistocene age older than the Tiglian fauna from Russel-Tiglia Egypt (Schneider, 1950, 1959; Kortenbout van der Sluy, 1960, Van Koldfochten & Van der Meulen, 1986). However, this suggestion is inconsistent with the palaeomagnetic data from a clay layer in the Maalbeek pit, as published by Zagwijn (1963). Based on pollen studies of several deposits of Tiglian age and assuming that the clay bed exposed at Maalbeek belongs to the Tegelen Clay Member, Zagwijn (1963) concluded that...