7 Conclusions

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7.1 Introduction

The general aims of this study are focussed on the revision of the lithostratigraphical framework of Upper Pliocene and Lower Pleistocene fluvial deposits in the southern part of the Netherlands, a sedimentology-based review of the key reference sites which form the basis of the Early Pleistocene pollen-defined stratigraphical subdivisions, and the compilation of the Early Pleistocene depositional history of the southern part of the North Sea Basin.

7.2 The lithostratigraphical framework

The revised lithostratigraphical scheme of Upper Pliocene and Lower Pleistocene deposits in the southern part of the Netherlands (chapter 2) provides a firm framework for unravelling the depositional history at the margins of the southern North Sea Basin (Chapter 6). The Upper Pliocene and Lower Pleistocene fluvial and marine deposits can easily be mapped at the formation level. Consequently, these lithostratigraphical units form the building-blocks for subsurface modelling and characterisation of the subsurface composition. The main constituents of the units identified are distinguished on the basis of their lithology, petrographical composition (i.e. provenance) and their stratigraphical position. Regarding the fluvial deposits involved, the lithostratigraphical framework clearly demonstrates that the complex composition of the subsurface geology in the Roer Valley Graben (RVG) and adjacent areas results from the interaction of three major river systems i.e., the Rhine, the Meuse, and the rivers that originate in Belgium. In addition, the deposits of the Rhine-Meuse system clearly interdigitate with those of the Eridanos fluvio-deltaic system in the central and western part of the Netherlands. The latter originates in the Baltic region.

The deposits of the pre-Rhine fluvial system are assigned to the Kieseloolite Formation and represent the north-westward directed advance of the river system during the Pliocene. The capturing process of the pre-Rhine to the Alpine drainage system took place during the Late Pliocene. As a result, a marked change of the petrographical composition of sediment transported by the Rhine occurred. This change shows a complete change from deposits of the Kieseloolite Formation, dominated by stable heavy-minerals, to the unstable heavy-mineral-dominated deposits of the Waalre Formation. Since the latter occurs downstream of the Rhine-Meuse confluence, it consists of mixed deposits laid down by both rivers. Within the RVG three informal subunits of the Waalre Formation can be recognised, termed respectively WA-1, WA-2, and WA-3. The lowermost subunit (WA-1) is correlated with the Late Pliocene Oebel Beds in Germany. Subunit WA-1 (Oebel Beds) is defined by its lithological and petrographical characteristics and its (litho)stratigraphical position overlying the Reuver Bed, a flood-basin clay deposit at the top of the Kieseloolite Formation. As a result, the uppermost part of the latter formation occurs within in the Upper Pliocene: i.e. the upper boundary of the Kieseloolite Formation is situated (well) below the Plio-Pleistocene boundary. Remnants of subunit WA-1 have been observed at several places in the RVG. They occur as far west as the area around Eindhoven which is much further westwards than previously thought.

The distinction between the Waalre Formation subunits WA-2 and WA-3 is primarily based by the stratigraphical position in the northern part of the RVG. They are separated by major intercalations of marine deposits (Maassluis Formation) and fluvial deposits supplied by the Belgian rivers (Stramproy Formation) which occur at the same level. The Stramproy Formation comprises all the Lower Pleistocene deposits supplied by rivers that drained the central and northern part of Belgium. In the southern and eastern part of the RVG the Waalre and Stramproy formations repeatedly interdigitate, indicating that parts of both formations were deposited concurrently.
Owing to the substantial overprint of the Rhine-Meuse sediment on the deposits of the Belgian rivers the lithological characteristics of the later are soon unidentifiable after their confluence with the Rhine-Meuse system. This observation is of importance because it indicates that the Stramproy Formation deposits can only be preserved when they are not intermixed with those of the Rhine-Meuse system. Thus, the presence of the Stramproy Formation at times in the RVG demonstrates that Rhine-Meuse deposition did not occur in the area during these periods, either because of sediment bypass or as a result of shifting of its main stream belts to positions outside the RVG. This phenomenon is well-demonstrated by the thick Stramproy Formation deposits (up to 100 m) in the southern part of the RVG which proves that the Rhine-Meuse system had abandoned the southern part of the RVG for a large part of the Early Pleistocene.

The Waalre Formation particularly consists of stacked fluvial fining-upward cycles, each consisting of a coarse-grained basal part that fines upwards into regionally extensive flood-basin fines. However, a detailed subdivision of the Waalre Formation into members or beds based on these fluvial fining-upward sequences is generally not possible and exceeds the resolution of the applied lithostratigraphical classification. The primary reason is that all the sediment that forms part of the formation show a uniform petrographical composition. Secondly, the different deposits of this fluvial system are lithologically variable and this does not correspond to lithostratigraphical levels but to facies units within those levels. A similar reasoning holds for the Stramproy Formation. Although there are some weakly developed regional lithological differences within this formation, a lithostratigraphical subdivision makes no sense as long as their bounding surfaces cannot be mapped using lithostratigraphical criteria alone.

Both the Stramproy and Waalre formations include extensive estuarine deposits that grade into the marine deposits of the Maassluis Formation in the south-western and western part of the country. The complex pattern of marine, estuarine and fluvial deposits in these areas indicates that they are affected by Early Pleistocene sea-level changes.

Differences in the subsurface composition can easily be shown in regional lithostratigraphical schemes. They provide information, such as stratigraphical position and thickness, and spatial interrelations (e.g. intercalations between formations and their deposits). Such regional lithostratigraphical information contributes to the understanding of the three-dimensional geometry of the defined rock units and forms the main building-blocks for compiling subsurface models and the geological history of the district.

7.3 The Early Pleistocene key reference sites

Several exposures in clay pits along the Dutch-German border area near Tegelen (south of Venlo) form key reference sites for pollen-defined Early Pleistocene chronostratigraphical stages and substages. Of particular concern are the sites where the Tiglian and Eburonian Stages and parts of their substages have been defined.

Field observations in pits enlarged since the late 1980s have provided a comprehensive sedimentological and lithostratigraphical framework for the exposed Upper Pliocene and Lower Pleistocene fluvial deposits. Lower Pleistocene fluvial deposits of the Waalre Formation are exposed in the pits of the Maalbeek-Tegelen region while in more southerly quarries Upper Pliocene fluvial Kieseloolite Formation deposits are also excavated.
The deposits of the Waalre Formation consist of fining-upwards fluvial deposits, with coarse sand and gravel formed in channels and bars that end in fine-grained clayey floodplain deposits. The regional extensive clay deposits are up to 10 m thick while the underlying sand and gravel deposits vary between 4 and *c.* 20 metres (Chapters 3 & 4).
Based on the observations in the Maalbeek pit three different facies type can be distinguished in the fine-grained floodplain deposits. Amongst them flood-basin deposits are the most widespread. Within these flood-basin fines lignite or peat layers may occasionally occur, and crumbly to prismatic structured soil horizons occur more frequently. The second facies type consists of bedded clay that infills abandoned channels (oxbow lakes) which are incised in the underlying flood-basin deposits. The third facies type is characterised by crevasse-splay deposits consisting of irregular and chaotic distributed sand and clay. Similar facies types are observed in pits situated nearby the Maalbeek pit. All facies types are closely related and may grade gradually and sometimes by distinct boundaries into each other. The complete flood-basin fines assemblage forms the uppermost part of the fluvial fining-upwards sequences that overlie coarse-grained channel-belt deposits. The latter thicken in the direction of the NE-orientated tectonic tilting and may have resulted from deposition in amalgamated channel belts. The flood-plain fines represent the final stage of the fluvial system preserved here .

Detailed pollen-analytical investigations in the Tegelen-Maalbeek area have shown that three distinct pollen zones of the Tiglian Stage (respectively, pollen zone T-A, T-B and T-C) occur in the exposed fluvial deposits (Chapter 3, 4). Pollen zone T-A, characterised by a predominance of *Fagus* pollen, occurs in the lowermost part of the fine-grained flood-basin deposits of Maalbeek pit. A similar type of pollen assemblage is known from the already long abandoned Janssen-Dings pit situated nearby. This particular flood-basin deposit is overlain by a second flood-basin sequence that yields a pollen assemblage assigned to pollen zone T-B. This zone is characterised by high values of non-arboreal pollen and the almost total absence of tree pollen. The abundance of grasses and sedges and inwashed pollen of Ericaceae and spores of *Sphagnum* correspond to this local flood-basin environment. However, the presence of *Artemisia* pollen probably indicates that the deposits of the flood-basin were formed during a period of cool climate conditions. In Maalbeek pit these flood-basin deposits, characterised by pollen zones T-A and T-B are overlain by bedded clay that forms the infill of an abandoned channel. The latter shows pollen assemblages of pollen zone T-C and the same holds for the overlying crevasse-splay deposits. In the 1960s the part of the flood-basin deposit characterised by pollen zone T-B in Maalbeek was interpreted as a part of the Eburonian Stage. However, the results obtained from the current investigations demonstrate that this deposit was formed during an earlier phase of the Pleistocene. This re-evaluation corresponds closely to the generally accepted stratigraphical pattern of the large mammal remains of *Anancus arvernensis* and *Tapirus arvernensis* that have been found at Maalbeek.

The pollen content of the uppermost flood-basin fines of the Waalre Formation investigated in the Tegelen-Maalbeek area are at least, in part, determined by the sedimentary facies development of the deposits. There are signs of climate change recorded in the pollen-analytical evidence, but the supposed substantial differences in age between the three different Tiglian Stage pollen zones of the are difficult to explain from the sedimentary record. All newly and previously obtained pollen evidence from the Tegelen-Maalbeek area is derived from the uppermost fine-grained deposits of the Waalre Formation and it is not likely that this fining-upward sequence had been formed during a prolonged period of several hundred thousands of years as is generally believed for the duration of the Tiglian Stage. This statement is well-illustrated by the sedimentological interpretation of the fluvial sequence at the Tiglian C Substage stratotype in the now abandoned Russel-Tiglia-Egypte pit. From the bottom to top this sequence consists of bedded clay deposited in an oxbow lake and it is overlain by a complex of crevasse-splay and overbank deposits. This grades progressively into a flood-basin clay. The lack of pollen in pollen zone T-C4^{c} in this sequence is interpreted to result from sedimentary processes (i.e. the onset of crevassing), instead of a depositional hiatus during a period of cold climate. Furthermore, it has been demonstrated that the flood-basin deposits often show severe oxidation of the large amounts of siderite they contain. It is argued that these hydro-geochemical processes may have preferentially influenced the preservation of the pollen in the deposits.

Extrapolation and correlation of the palynological record from the Tegelen-Maalbeek area to the much thicker, stacked Early Pleistocene fluvial sequences in the RVG is still highly problematic. The innate fragmentary and discontinuous fluvial record in the RVG is the main reason that this arises. In addition, the resolution of the pollen evidence obtained is not sufficient to characterise and correlate individual clay deposits of the Lower Pleistocene fluvial sequences. Consequently, it is unlikely that the fluvial record of the RVG can provide a reliable framework for the chronostratigraphical subdivision of the Early Pleistocene.

7.4 The fluvial history of the southern North Sea Basin

The lithostratigraphical framework presented in this study provides the key for unravelling the fluvial history of the Netherlands and the southern part of the North Sea Basin (Chapter 5, 6).

During the Pliocene the Rhine and Meuse were confluent north of Aachen on the Rurscholle. Their deposits (i.e. Kieseloolite Formation) occur in the RVG and the adjacent Peel Block. They grade into shallow marine deposits (Oosterhout Formation in the northern part of the RVG and the area to the west).

The remarkable petrographical change of the Rhine sediments that took place in the course of the Late Pliocene allows the continuation of the Oebel Beds to be mapped from the German part of the Lower Rhine Embayment (LRE) into the RVG as far west as Eindhoven. These deposits, characterised by 'Alpine' mineralogy, form the lowermost part of the Waalre Formation. One main course of the Rhine-Meuse system was situated in the RVG and a second on the Venloer Scholle/Peel Block, while a third course of the Rhine is thought to have been located in the eastern part of the LRE. The contribution of the Belgian rivers to the Late Pliocene Rhine-Meuse river system cannot be mapped separately because their lithological and petrographical signal is lost after the confluence with the much larger Rhine-Meuse river system. A regional unconformity marks the transition from the Pliocene to the Pleistocene. Renewed deposition by the Rhine-Meuse system subsequently probably inherited the Late Pliocene hydrographical pattern. This can be deduced from the presence of its deposits in the southern part of the RVG and on the adjacent Peel Block. However, the Rhine shifted northwards, induced by tectonic movements, and abandoned the Rurscholle and Erft Block in Germany early in the Early Pleistocene. As a consequence, the Meuse was able to deposit sediment on the Rurscholle at the continuation of the East Meuse Valley in southern Limburg. During the Early Pleistocene, the depositional domain of the Meuse in Germany advanced in north-eastwards and prevented the Rhine from adopting a pathway through the southern part of the RVG. As the subsidence of the southern RVG continued, the available accommodation space was infilled by deposits supplied by Belgian rivers. These major changes in the hydrographical patterns explain why relatively thin deposits of the Rhine-Meuse system in the southern RVG are overlain by Belgian river deposits up to 100 m thick (Stramproy Formation).

A different situation existed in the northern part of the RVG (i.e. the area north of Eindhoven) where Rhine-Meuse deposits up to 100-120 m thick were formed. The larger part of these Rhine-Meuse deposits were supplied by a Rhine course that passed across the Peel Block. Repeated intercalations of deposits from the Belgian rivers occur at the southern limits of the distribution area of the Lower Pleistocene Rhine-Meuse deposits. This indicates that both river systems were occupied the area concurrently. The preservation of Belgian river deposits furthermore indicates that the Rhine-Meuse river system repeatedly ceased to deposit sediment in the RVG or shifted out of the RVG during northward orientated advances of the depositional domain of the Belgian rivers. The WA-2 and WA-3 subunits can be distinguished within the northern part of the RVG. In the Eindhoven area they are separated by a major intercalation of deposits from the Belgian rivers, while in the northern part a clastic wedge of marine deposits occurs at the same level. A similar subdivision of the Rhine-Meuse deposits is present in the area west of the RVG where the intercalation of the Belgian rivers is correlated with the so-called Beerse Member of the Belgian lithostratigraphical scheme. The shallow marine sediments in the northern RVG, and the repeated intercalations of these marine deposits that occur in the area west of the RVG, indicate that sea-level changes affected the lower alluvial plain of the Rhine-Meuse system during the Early Pleistocene.

Lower Pleistocene Rhine-Meuse deposits also occur in the central and western part of the Netherlands. It is likely that they were supplied by a main Rhine branch situated in the eastern part of the LRE. The Rhine-Meuse deposits in the central and western part of the Netherlands interdigitate with those of the so-called Eridanos system, a large fluvio-deltaic system that supplied sediment from the Baltic region to the North Sea Basin. The southernmost advance of the Eridanos system took place during the deposition of Waalre Formation subunit WA-3. However, the main depositional zone of the Eridanos system was situated north-west of the present coastline of the Netherlands. Following the starvation of the Eridanos system, during the latest part of the Early Pleistocene, the main pathway of the Rhine-Meuse system migrated to the north-western part of the Netherlands, while extensive flood-basin areas developed in the northern part of the RVG and the area to the west. Estuarine conditions prevailed for a very long time in the westernmost part of the country.

As a result of the north-westward shift of the Rhine-Meuse system's main course the depositional realm of the Belgian rivers gradually extended to northwards. Thus, the Early Pleistocene fluvial history shows a gradual shift into northern and north-western directions of both the Belgian rivers and the Rhine-Meuse system. The marine depositional zone, which covered the larger part of the Netherlands during the onset of the Pleistocene, shows a similar retreating trend towards the northwest, so that by the end of the Early Pleistocene the larger part of the southern North Sea basin was filled by fluvial deposits.

Generally, the Early Pleistocene fluvial deposition in the southern Netherlands is characterised by a low ratio between accommodation space and sediment supply. Large amounts of the transported sediment by-passed the area and were deposited further north and north-west in the North Sea itself (Maassluis Formation). The RVG is an exception to this general pattern throughout much of the Early Pleistocene. Here, a relatively thick sequence of Lower Pleistocene fluvial deposits formed as a result of locally increased accommodation space resulting from tectonic subsidence. Nevertheless, the Lower Pleistocene fluvial sequence in the RVG is fragmentary and discontinuous, either as a result of repeatedly occurring sediment by-pass and/or shifts of the main channel belts of the Rhine-Meuse river system to areas outside the RVG.
The lower Rhine-Meuse alluvial plain, and its continuation into the marine area, were strongly controlled by regional changes of base level, which were driven by climatically induced sea-level changes. Based on the conceptual framework described in chapter 6 it seems likely that erosion prevailed during lowstands in large parts of the Early Pleistocene alluvial plain in the modern onshore areas. In contrast, deposition of fine-grained floodplain deposits seems to be dominant during sea-level highstand periods. However, during the Early Pleistocene multiple changes of climate change occurred and it remains uncertain whether or not the response of the fluvial system to these changes shows a similar cyclic pattern. Base-level changes primarily affect the lower end of the fluvial system, but during low-stand situations the Rhine-Meuse system in the central part of the Netherlands was situated far upstream of the coastline. Consequently, fluvial system autogenic processes may have been dominant over the allogenic cycles in these more upstream areas. This observation might explain why parts of the Lower Pleistocene fluvial sedimentary record diverge from a linear interpolation solely based on the changes of base level. However, the conceptual framework presented for the Early Pleistocene Rhine-Meuse system in the southern Netherlands forms a solid basis to explain the palaeogeographical development of the region.

7.5 Future research

The results of this study have contributed to a better understanding of the nature of the Upper Pliocene and Lower Pleistocene fluvial sedimentary record in the southern part of the Netherlands. Additional high resolution sedimentological, geophysical and stratigraphical evidence may be required to test and refine the proposed model for the Early Pleistocene fluvial record in the area. High-resolution seismic data is needed to improve the lateral correlation of different depositional units and their major bounding surfaces. Furthermore, high-resolution analyses of multiple proxies in both the marine deltaic and the onshore fluvial sequences may further contribute to a well-established land-sea correlation and should provide an integrated chronostratigraphical framework for the Plio-Pleistocene period. In order for this to be achieved, continuous coring is needed in both the marine-deltaic and the fluvial regions. Therefore it is a multi-disciplinary approach combining palaeomagnetic, biostratigraphical, lithostratigraphical, sedimentological and orbital-tuning methods that is advocated for these investigations. As a result a firm Early Pleistocene chronostratigraphical framework can be established that strengthens the land-sea correlations. In addition, the development of reliable dating methods is required because the period involved lacks well-controlled age-determinations. Based on the stratigraphy and sedimentary architecture, numerical modelling of the Lower Pleistocene fluvial system can be used to test the hypotheses on the fluvial development. Modelling results can provide additional evidence to amplify the existing explanations. For example, model simulations of sediment-volume partitioning as a function of varying accommodation space may improve insight to the preserved genetic sequences that are arranged in seaward off-stepping, vertical-stacked and landward-stepping patterns. In addition, detailed reconstructions of the palaeo-catchments may show palaeogeomorphological and sedimentary changes, and can contribute to a better understanding of the balance between authigenic and allogenic controlling factors on the fluvial systems.

The depositional history of the southern North Sea Basin forms an important archive of the response of fluvial and shallow marine systems on tectonically and climatically controlled changes. Unravelling the complex fluvio-deltaic history of the prograding fluvial systems in the Pleistocene North Sea Basin will contribute to a better anticipation on the use and sustainable management of subsurface resources. It also provides a framework to develop tools to anticipate on the impacts of natural and human-induced changes that will affect future developments of the lower Rhine-Meuse fluvio-deltaic system and of comparable systems elsewhere.