# 2 Concise description of the soils in the Netherlands

## 2.1 Introduction

The main purpose of this thesis is to describe the chemical composition of the soils in the Netherlands. In this chapter, the most important factors that ultimately determine the soil composition are reviewed. Most of the soils in the Netherlands were derived from unconsolidated Quaternary sediments, which acted as the soil parent material. Therefore, the origin and mineralogical composition of these sediments serves as a starting point for further insight in the composition of the soils. Hereafter, soil forming processes have lead to a redistribution of components and the formation of soil horizons, which have influenced the inorganic composition of the soils as well. In addition to these natural processes, mankind has had a considerable impact on the composition of the soils, either indirectly by changing the natural conditions, or directly by adding materials with a different chemical composition (e.g. fertilizers).

Much research has occurred into the geology and pedology of the Netherlands, which has been summarized in various standard works (e.g. Zagwijn and Van Staalduinen, 1975; De Bakker, 1979; De Bakker and Locher, 1987; Locher and De Bakker, 1987; De Bakker and Schelling, 1989; De Mulder et al., 2003). Moreover, there is a wealth of related information for example about the historical land use and agricultural production (see e.g. CBS, 2001). Unfortunately, this information is often only available in the Dutch language. Moreover, our pedological classification and definition of various lithological properties shows considerable differences with the classification systems used abroad (see e.g. De Bakker, 1979).

The purpose of this chapter is to give an introductory overview of the surfacial geology, pedology and land use history in the Netherlands, which is meant for readers not familiar with the Netherlands and as the general reference for this study in later chapters. This description is neither exhaustive nor complete, but it reviews the most important topics that will be of relevance for the later chapters in this thesis. To ensure clarity and consistency of terminology, I furthermore describe the geological and pedological nomenclature used throughout this thesis.

The surface geology of the Netherlands is reviewed in section 2.2 and the composition of the soil parent material is described in section 2.3. Other natural soil forming processes are briefly described in section 2.4, whereas the historical land use and anthropogenic impact on the soils can be found in section 2.5. Having reviewed the major soil forming factors in the Netherlands, the soil classification system of the Netherlands is briefy explained in section 2.6. A brief recapitulation, that may also be useful to the more knowledgeble is presented in section 2.7.

## 2.2 Surface geology

### 2.2.1 Introduction

The country of the Netherlands is located in northwestern Europe where it is bordered by Germany, Belgium and the North Sea (fig. 2.1). It is part of the subsiding North Sea Basin that is enclosed by the Brabant Massif in the South and the Rhenisch Massif in the East. The two massifs are separated by an active rift system – the Ruhr Valley Graben System (RVGS) – that extends from the Dutch North Sea coast southeastwards into the Lower Rhine Embayment. The RVGS is an integral part of the Cenozoic mega-rift system crossing western and central Europe (see e.g. Ziegler 1988; Ziegler 1990; Ziegler, 1992; Michon et al., 2004).

As a result of extensive subsidence and sedimentary infill of the North Sea Basin during the Cenozoic, the subsurface of the Netherlands largely consists of a thick layer of unconsolidated sediments. The older, often consolidated sediments only sparsely crop out in the east and southeastern parts of the Netherlands. The depth of the base of the Cenozoic sediments is generally in the order of 200 m, but ranges up to more than 500 m in the western parts of the Netherlands (Zagwijn and Doppert, 1978; Zagwijn et al. 1985). Most of the sediments found close to or at the surface in the Netherlands were deposited during the Quaternary period and are of Pleistocene or Holocene age (table 2.1). They consist of fluviatile, marine and glacigenic sediments and of sediments with a more local geogenesis, such as eolian deposits and peat (table 2.2).

*Table 2.1* Simplified Cenozoic time table (after Westerhoff et al., 2003b).

| System | Period | Series | Age (Ma BP) |
|---|---|---|---|
| Quaternary | | Holocene | 0.01 – present |
| | | Pleistocene | 2.6 – 0.01 |
| Tertiary | Neogene | Pliocene | 5.3 – 2.6 |
| | | Miocene | 23.8 – 5.3 |
| | Paleogene | Oligocene | 33.7 – 23.8 |
| | | Eoceen | 53 – 33.7 |
| | | Paleocene | 53 – 65 |

*Table 2.2* Description of major lithological units in the Netherlands and the different formations discerned (P = Pleistocene, H = Holocene, nomenclature after Weerts et al. 2003).

| Geogenesis | Lithology | Formations |
|---|---|---|
| Marine deposits | Often calcareous, silty and clayey deposits, interlayered with (fine) sandy deposits. | Maassluis (P), Eem (P), Naaldwijk (H) |
| Fluviatile deposits | Pleistocene formations have fine to coarse sands, including gravel, locally some clay and peat layers. Holocene formations are more clayey. | Waalre (P), Sterksel (P), Urk (P), Kreftenheye (P), Peize (P), Appelscha (P), Echteld (H), Beegden (H+P) |
| Glacigenic deposits | Various glacial deposits: glacial till and boulder clay, fluvio- and lacustro-glacial deposits (clay to coarse sand) | Peelo (P), Drenthe (P) |
| Local deposits | Either fine to medium, sometimes loamy, sandy deposits (eolian and local fluvial), loess deposits and peat (various types). | Sand: Stamproy (P), Boxtel (H)<br>Peat: Woudenberg (P), Nieuwkoop (H) |

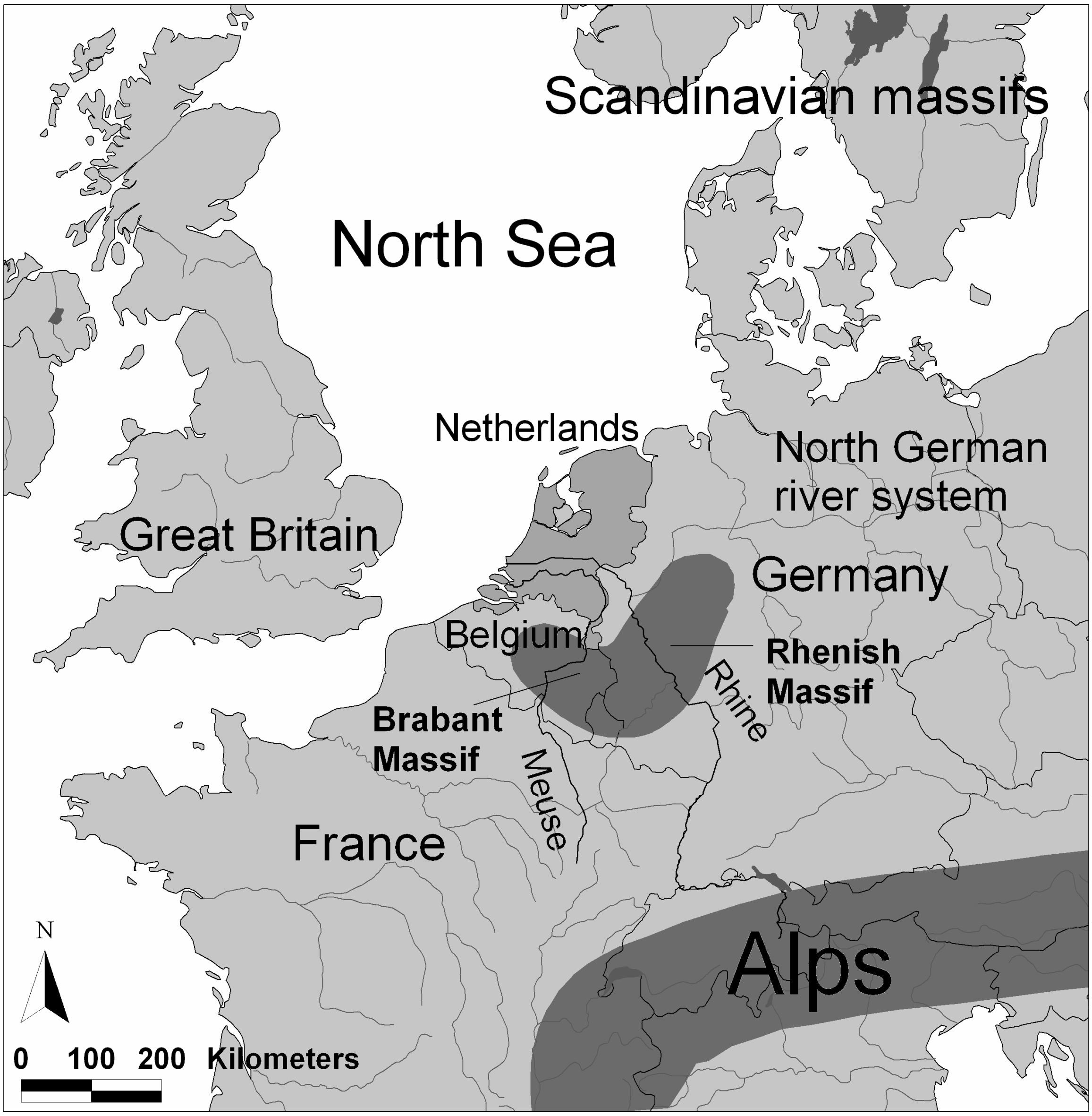



*Figure 2.1* Overview of northwestern Europe showing the Netherlands (darker grey) and surrounding countries. The major sediment sources for the Netherlands during the Quatenary are indicated by arrows (basemap data from www.esri.com).

During the Pleistocene, the sedimentation was mainly confined to the land (fluviatile, glacigenic and local terrestrial deposits), whereas during the Holocene, marine sedimentation together with peat formation becomes more important. The major sediment sources for the Netherlands are summarized in figure 2.1. Because the Pleistocene and Holocene sediments form the parent material of most soils in the Netherlands, I start this chapter with a brief description of their geogenesis and lithological characteristics. Pre-Quaternary formations, which are rarely found close to the surface, as well as formations restricted to the North Sea, are left out of this overview (see e.g. Westerhoff et al., 2003b).

It should further be noticed that the lithostratigraphy of the Netherlands has recently been revised (Weerts et al., 2003). In contrast to the previous lithostratigraphy of Doppert et al. (1975), formations have been classified more strictly on the basis of their lithological properties and stratigraphical position, and much less by their biostratigraphical age. The following geological description is largely based on the recent work by Weerts et al. (2003) and Westerhoff et al. (2003a&b). The definitions of lithological properties used in this description are found in Appendix I.

### 2.2.2 Pleistocene

The Pleistocene - here considered as the period from 2.6 Ma to 0.01 Ma years before present (BP) – is characterized by several alternating warmer (interglacial) and colder (glacial) periods. During the Pleistocene, both climate as well as tectonics (increased subsidence) were the main factors that determined the depositional environment in the Netherlands. As a result of a relatively low sea level, continental sediments were deposited over what is now the Dutch land surface (fig. 2.2).

At the beginning of the Pleistocene, however, major parts of the Netherlands were still covered by a shallow sea, which left marine sediments over an extensive area (Maassluis formation, see figure 2.2). As a result of transgression that started in the Early Pleistocene (Pretiglien), the depositional environment acquired a more continental character. Large rivers like the Rhine, Meuse and the North-German (or Eridanos) river system progressively extended their alluvial plains westwards. These large braided river systems left thick layers of dominantly coarse sediments including coarse sand and gravel. The Early Pleistocene sediments of the Rhine, Meuse and the North-German river system are respectively known as the Waalre, Beegden and Peize/Appelscha formation (fig. 2.2). Besides these fluviatile deposits from the large river systems, local fluviatile and eolian sediments were deposited in the southern parts of the Netherlands (Stamproy formation).

At the start of the Middle Pleistocene (Cromerien), the sedimentation in the Netherlands was still dominated by fluviatile input. Though the North-German river system changed its course more northwards, the Rhine and Meuse still delivered large amounts of sediments to the prograding Dutch delta. The collective deposits of the Rhine-Meuse system in the central parts of the Netherlands belong to the Sterksel formation (fig. 2.2). Throughout the Pleistocene as well as Holocene period, the deposits from the upper course of the Meuse belong to the Beegden formation, which is confined to the southeast of the Netherlands (fig. 2.2).

In the Elsterien, the northern part of the Netherlands was covered by glaciers as a result of the second North European glaciation. Here, both glacigenic and periglacial sediments derived from Scandinavian crystalline massifs were deposited. These sediments are collectively known as the Peelo formation. The sediments of the Rhine-Meuse system deposited during the Elsterien and Holsteinien, belong to the Urk formation. As before, these rivers left coarse grained sediments like sand and gravel. The local fluviatile and eolian deposits, which formed from the Elsterien up to the Early Holocene, belong to the Boxtel formation (mainly fine to coarse sand).

During the third North European glaciation in the Saalien, the ice sheets extended even further into the Netherlands, covering roughly the northern and central parts. As a

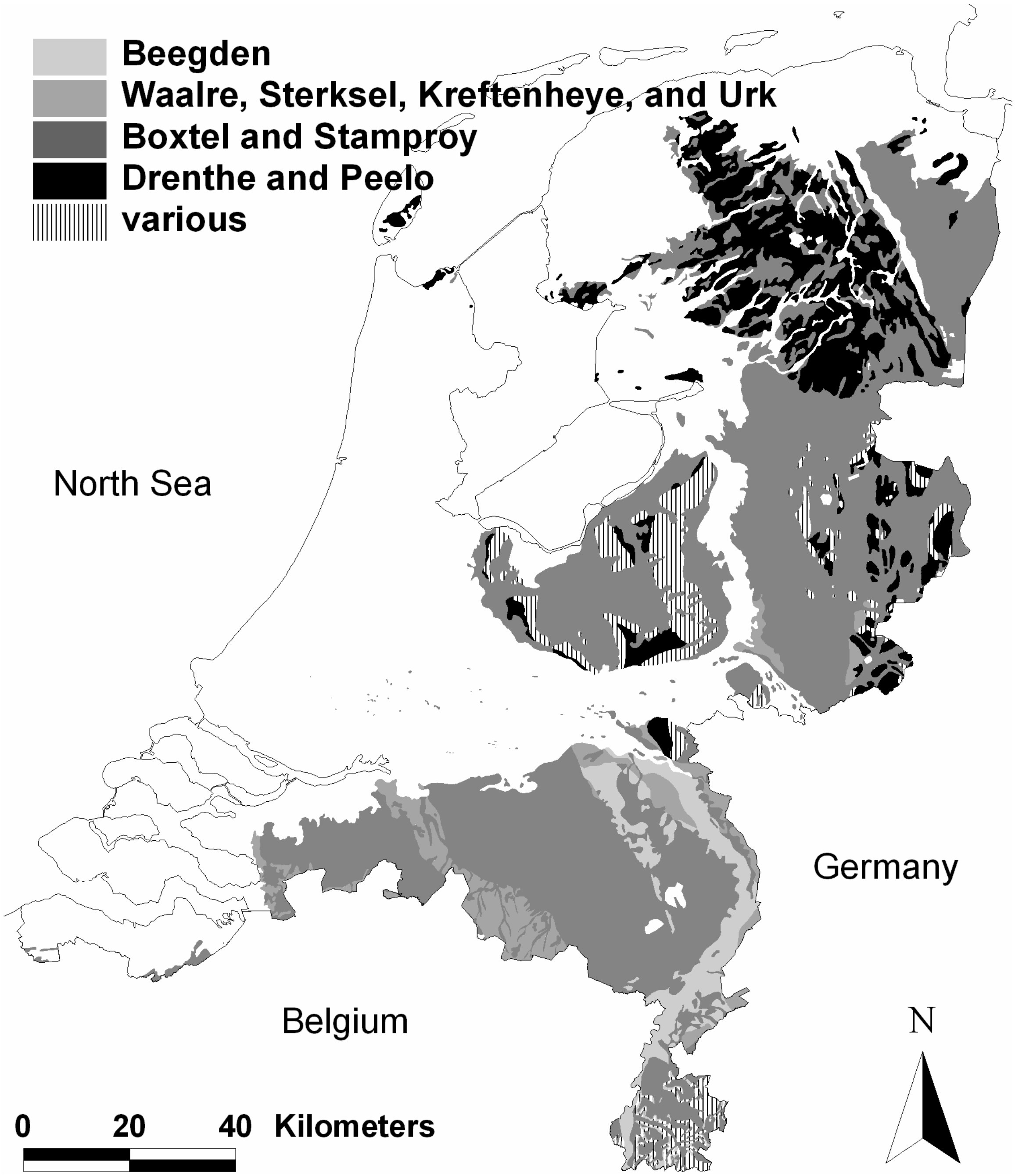



*Figure 2.2* Simplified lithostratigraphy of Pleistocene formations in the Netherlands (only formations that crop out at the land surface, nomenclature after Weerts et al., 2003).

result, the older fluviatile deposits in the north were largely covered by ground moraine (glacial till, boulder clay) of northern origin. These deposits are, together with fluvio-and lacustroglacial sediments of that period, regarded as the Drenthe formation. In the central and mid-eastern parts of the Netherlands, ice-pushed ridges were formed that are currently still found as hills of up to ~100 m. As a consequence, the courses of the Rhine and Meuse were forced in a more western direction, parallel to the east-west extension of the ice sheets. From the Saalien up to the Weichselien, their collective deposits are regarded as the Kreftenheye formation (mainly coarse sand).

The beginning of the Late Pleistocene (Eemian) was characterized by a warm, interglacial period. During the Eemian, marine sediments were deposited over a restricted area, confined mainly to the central Netherlands (Eem formation). At the margins of these marine deposits, thick layers of peat developed that are known as the Woudenberg formation.

The fourth North-European glaciation in the Weichselien marks the end of the Pleistocene. During this glacial period, ice sheets did not extend into the Netherlands, but the tundra climate in combination with very limited vegetation resulted in wind-blown deposits forming a cover of one to several meters (cover sand deposits). During this period both eolian sediments, including sand and loess, as well as fluvio-periglacial deposits were formed. These sediments are also classified under the Boxtel formation (fig. 2.2). Whereas loess deposits crop out primarily in the most southeastern part of the Netherlands, the sandy deposits (cover sands) make up a large extent of the current land surface. An overview of the lithography of the Pleistocene deposits that are found close to the surface in the Netherlands is given in figure 2.3.

### 2.2.3 Holocene

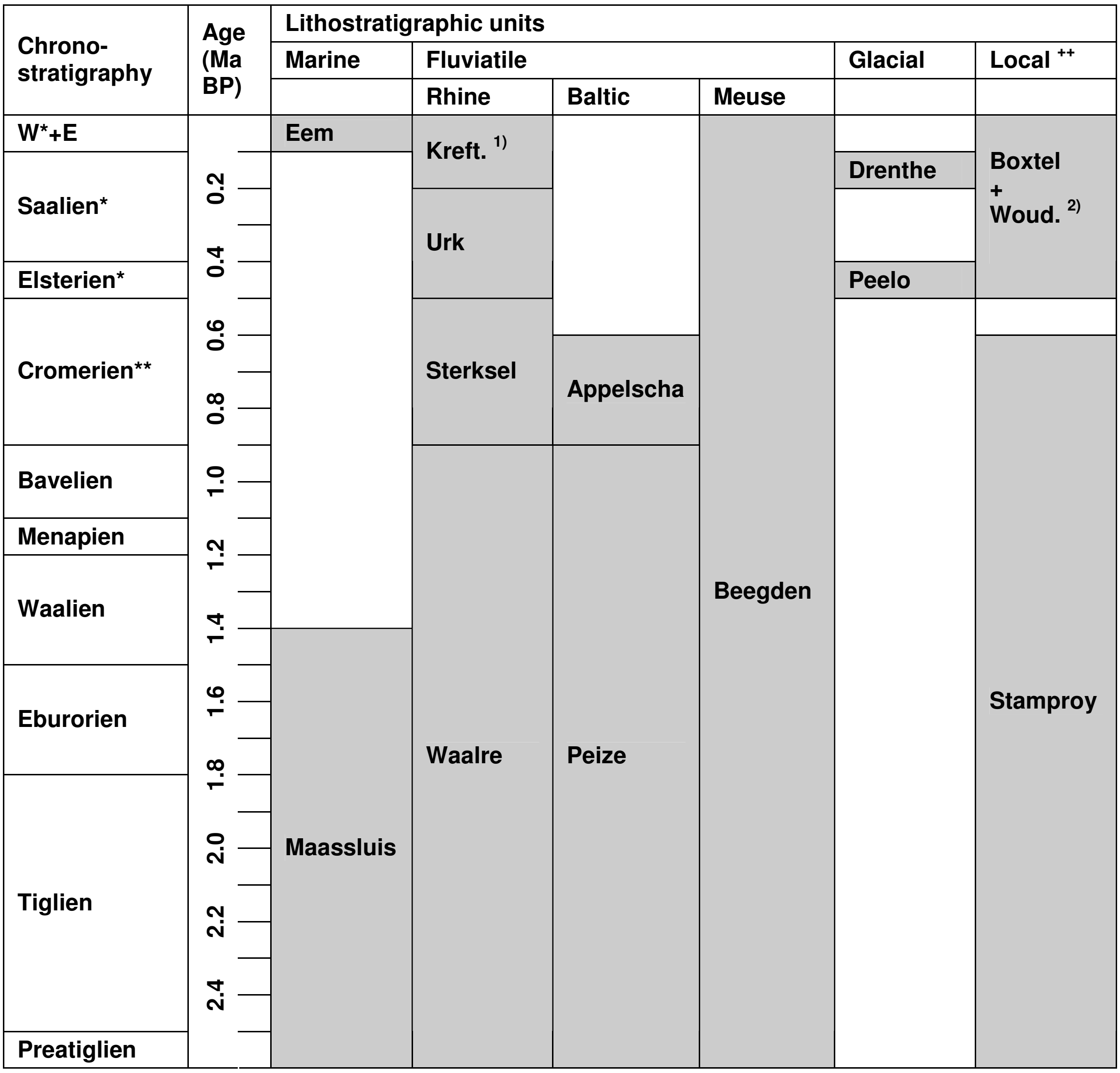
The Holocene is an interglacial period that started roughly 10.000 $^{14}$C-years ago and continues up to the present. Compared to the glacial periods in the Pleistocene, the Holocene is relatively warm and humid. The sedimentation is mainly confined to the coastal parts of the Netherlands and consists of marine, estuarine and perimarine deposits, including peat formation. The Pleistocene sediments in the elevated eastern half of the Netherlands remain largely unaffected by the marine influence. Based on pollen analysis, five climatic periods are discerned within the Holocene: Preboreal, Boreal, Atlanticum, Subboreal and Subantlantic period (fig. 2.4).

In the Early Holocene (Preboreal and Boreal), the initially low sea level gradually rose as a result of melting of the glaciers of the Weichselien, but did not reach the current coastal border of the Netherlands. The large rivers Rhine and Meuse changed to more meandering / anastomosing systems, leaving on average finer sediments than during the Pleistocene. Since then, their collective deposits consist dominantly of clay and fine to medium sand, and to a lesser extent coarse sand and gravel (Echteld formation). The on average coarser sediments from the upper course of the Meuse are, as for the Pleistocene period, assigned to the Beegden formation (fine to coarse sand and gravel).

In the largely unaffected eolian and local fluviatile Pleistocene sediments that overlie major areas of the Netherlands (sand and loess of the Boxtel formation, figure 2.3), soil formation takes place as a result of extensive vegetation cover and the relatively warm and humid climate. Local streams and brooks developed in the low-lying areas in the Pleistocene region. Here, sand or clayey sand was deposited and locally some peat developed. As for the Pleistocene period, these local terrestrial deposits are regarded as the Boxtel formation (fig. 2.4).

At the beginning of the Middle Holocene (Atlanticum), the relative sea level further rose so that large tidal basins and lagoons formed at the present coastal margins of the Netherlands. Here, (peri)marine, often calcareous, sediments consisting of fine sand and sandy to silty clay were deposited (Naaldwijk formation). At the margins of the extensive

*Figure 2.3* Overview of Pleistocene formations that occur close to or at the surface in the Netherlands (within at least the first 1-3 meters). The areas in which the Pleistocene formations are overlain by thick Holocene deposits are left blanc (see also fig. 2.2). The Beegden, Waalre, Sterksel, Kreftenheye, and Urk formations are of fluviatile origin. Other fluviatile deposits like the Appelscha and Peize formations (derived from the North German river system) were left out due to their very restricted occurence close to the surface. The Boxtel formation, and in the south also the Stamproy formation, are of local eolian origin. The Drenthe and Peelo formations are of glacigenic origin, whereas "various" includes different pre-Quaternary as well as Pleistocene formations.




* Cold period (glacial).
** Compex of cold and warm periods.
1) Krefetenheye.
2) Woudenberg (peat).
++ Eolian and local fluviatile deposists as well as peat.

*Figure 2.4* Simplified lithostratigraphy of the Holocene formations of the Netherlands (only formations that crop out at the land surface, nomenclature after Weerts et al., 2003).

| Chrono-strati-graphy | Age (ka BP) | Lithostratigrahic units | | | | | |
|---|---|---|---|---|---|---|---|
| | | Marine | Fluviatile | | | Local | |
| | | | Rhine* | Baltic | Meuse | Aeolian + | Peat |
| Sub-atlanticum | Present - 2.6 | Naald-wijk | Echteld | | Beegden | Boxtel | Nieuw-koop |
| Subboreal | 2.6 – 5.0 | | | | | | |
| Atlanticum | 5.0 – 8.0 | | | | | | |
| Boreal | 8.0 - 9.0 | | | | | | |
| Preboreal | 9.0 - 10 | | | | | | |

* includes lower course of Meuse.
+ includes local fluviatile deposists (fine sand, clay).

intertidal areas, mesotrophic to eutrophic peat developed (Nieuwkoop formation). Towards the end of the Atlanticum, the sea level further rose and reached the maximum extent observed in the Holocene. In this period, the tidal basins were filled with sediments that were largely derived from erosion of the Pleistocene formations as well as input of fresh fluviatile sediments. Peat, assigned to the formation of Nieuwkoop, further developed in large areas in the western and northern parts of the Netherlands.

In the Subboreal, the sandy barriers that developed at the coastal margins further developed as a result of increased sediment transport along the coast. Finally, the barriers became interconnected closing the marine input. Hereafter, the western coastal area prograded in a westerly direction, whereas the northern coastal area, which will later form the Wadden sea, remained an intertidal basin. Extensive peat lands further developed behind the western coastal barriers and on the northern Pleistocene sandy area. At the same time, the fluviatile input by the Rhine and Meuse became more restricted and was mainly confined to the central and southeastern parts of the Netherlands.

In the Subatlanticum, the westward extension of the Dutch coast came to an end and the influence of the sea gradually increased again. As a result, the low-lying peat was partly eroded or overlain by marine sediments (mainly clay). In the southwest of the Netherlands, the Scheldt estuary also further extended in a coastal direction, thereby draining and eroding the peat lands that had previously formed. At the same time the Rhine and Meuse extended their realm further westwards and developed various intertwined branches (Neder-Rijn, Lek, Waal). Here, the peat was partly covered with fine grained fluviatile sediments.

During the Subatlanticum, the human influence becomes progressively important over the natural sedimentation pattern. Much of the low-lying and periodically flooded areas were reclaimed by endykement, whereas much of the peat stopped growing as a result of drainage and excavation. Thereby, deforestation and overgrazing of the poor sandy soils resulted in large uncovered areas in which wind blown deposits formed (inland dunes). These very recent deposits consist of fine sand derived from older (podzolic) soils and occur locally in the Pleistocene region. The land reclamation history and human impact on the landscape will be further worked out in section 2.5. An overview of the Pleistocene and Holocene deposits that crop out in the Netherlands is given in figure 2.6.

## 2.3 Parent material

### 2.3.1 Introduction

Whereas geology is mainly concerned with the source provenance and lithostratigraphy of different formations, pedology is concerned with the physical and chemical characteristics of the upper sediment layer, or parent material, in which soil formation has taken place. As the "soil" in the Netherlands is arbitrarily defined as the first 120 cm of the profile below the litter layer (Locher and de Bakker, 1987), although the depth of soil formation in these sediments is often much less. Furthermore, the soil profile often contains different formations with different lithogenetical characteristics.

The different types of parent material in the Netherlands are classically grouped into five districts: sand, loess, peat, fluviatile and marine clay (see e.g. Stiboka, 1965; De Bakker and Locher, 1987). Though this classification shows some overlap with the lithogenetical classification used in geology, there are also many differences. In the classification of parent materials, most of the glacigenic sediments as well as a part of the Pleistocene fluviatile deposits are assigned to the sand district (unless overlain by Holocene clay deposits). In contrast, the loess deposits are within the geological classification considered as a member of the Boxtel formation, whereas in the pedological classification they are regarded as a different class of parent material.

In general, the classification of parent materials is more closely related to the textural properties of the sediment and much less strictly based on their geogenesis. This is on the one hand caused by the fact that the soil profile is defined for a constant depth, often irrespective of the geological formations, but also because there was simply more need for textural information in pedology. Geogenesis for sediments with comparable texture was often only of secondary importance, mainly for agricultural land use.

In this section I review the geology of the soil profile in the five parent material districts in the Netherlands. This is to get a more detailed understanding of the geogenetical characteristics of the parent material and its variation throughout the profile. Or in a broader sense: to incorporate geological knowledge such as geogenesis and source provenance into the pedological framework in the Netherlands. In the following description I have used the classification of parent materials employed for the 1:200.000 soil map (Stiboka, 1961), which in my opinion is the best combination of textural properties as well as different geogenetical groups (e.g. marine vs. fluviatile). De Gans et al. (1987) gave a comparable overview in terms of the former geological classification of

Doppert et al. (1975). For the nomenclature of formations and members, see Weerts et al. (2003). An overview of the districts can be found in table 2.3 and figure 2.6. The definitions of lithological properties used in this description are found in Appendix I.

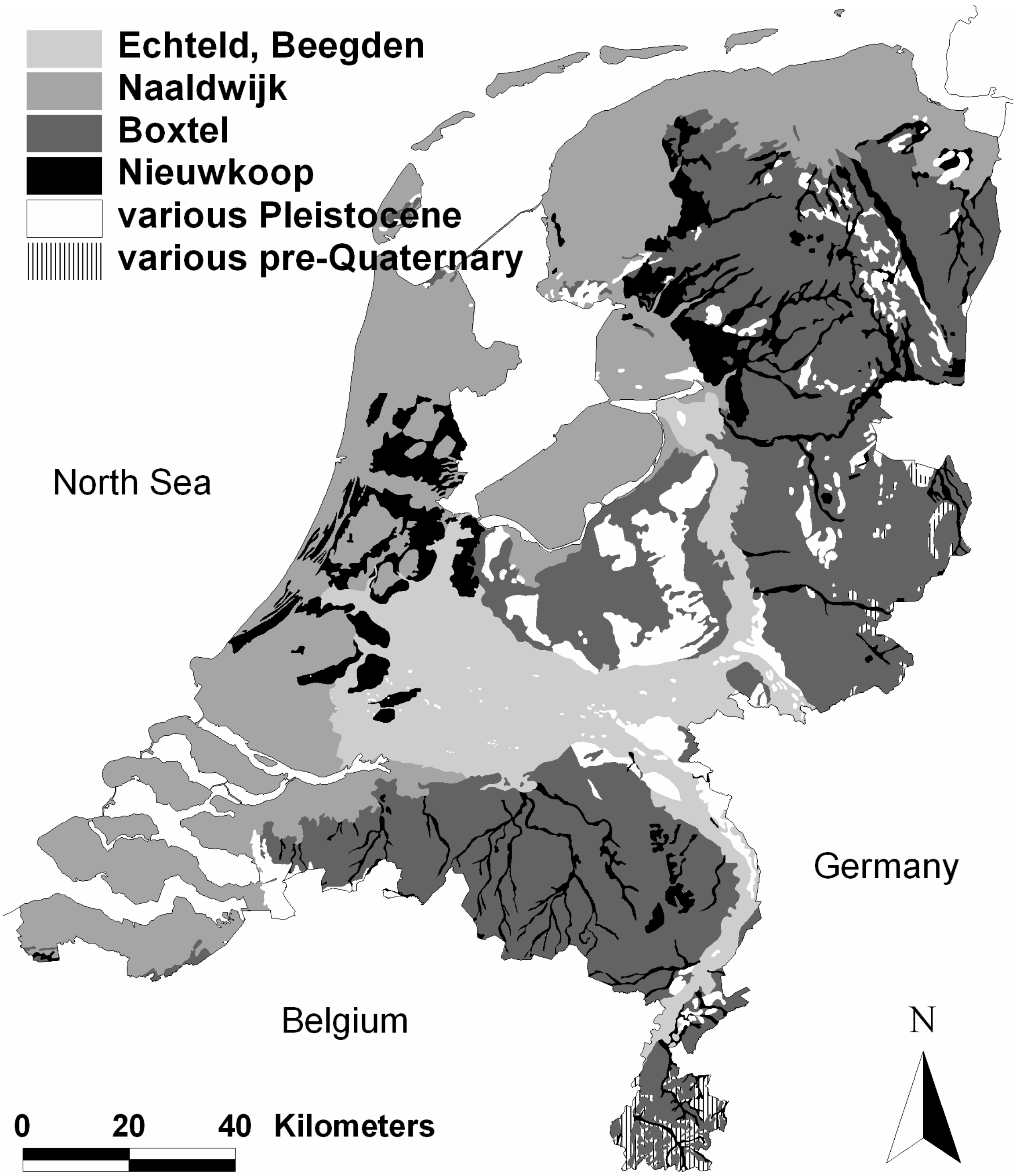



*Figure 2.5* Overview of the major Holocene and Pleistocene formations occuring at the surface in the Netherlands. The various Pleistocene deposits include the Drenthe and Peelo formations, Stamproy formation, and various fluviatile formations in the ice-pushed ridges, which are found in the central and eastern parts. The various pre-Quaternary formations are found only in the southern and eastern parts of the Netherlands and were not described in the text.

*Table 2.3* Overview of five soil parent material districts in the Netherlands and the Holocene formations and members commonly occuring in the topsoil layer (after De Gans et al., 1987; nomenclature after Weerts et al., 2003).

| District | Formation | Member | Geogenesis and lithology |
|---|---|---|---|
| Sand | Boxtel | Kootwijk | Eeolian sand (fine to medium sand) |
| | (Naaldwijk) | Schoorl | Eolian dunes (fine to medium sand) |
| Peat | Nieuwkoop | Griendtsveen | Oligotrophic sphagnum-mosses peat (high moor) |
| | | Singraven | Mesotrophic wood peat formed in local streams (brook deposits) |
| | | Hollandveen | Meso- to eutrophic reed, sedge and wood peat |
| | | Basisveen | Meso- to eutrophic reed, sedge and wood peat |
| Fluviatile | Echteld | - | Fluviatile deposits of Rhine and Meuse (mainly clay and silt to fine and coarse sand, locally some peat) |
| | Beegden | Rosmalen | Fluviatile deposits, upper Meuse only (mainly silt to clay) |
| | | Wijchen | Fluviatile deposits, upper Meuse only (fine to coarse sand, some gravel) |
| Marine | Naaldwijk | Walcheren | Marine and perimarine deposits (mainly fine sand to clay) |
| | | Wormer | Marine and perimarine deposits (mainly silty clay to clay) |
| | | Zandvoort | Coastal bars, beaches (fine to medium sand) |

### 2.3.2 Districts

#### Sand district

The parent material in the sand district (fig. 2.6) consists mainly of eolian deposits of the Late Pleistocene age, the so-called cover sand deposits. These sediments are mainly fine to medium sized non-calcareous sands, which belong to the Boxtel formation (mainly the Wierden member). The majority of profiles in the sand district have this parent material over the full soil profile (De Bakker and Locher, 1987). Other eolian deposits found within the profiles in the sand district include the Middle Pleistocene deposits which are partly also of a local fluvial origin (Stamproy formation). This formation occurs within the deeper profile in the southeasternmost part of the sand district.

Much younger eolian deposits include the inland and coastal dunes. The inland dunes also belong to the Boxtel formation, but are designated as a different member (Kootwijk). These are medium sized non-calcareous sands – often derived from local podzols - that overlie Pleistocene formations, especially in the central parts of the Netherlands. The coastal dunes are restricted to the outermost coastal areas of the Netherlands. In the geological classification, these dunes are assigned to the marine formations (Naaldwijk formation, Schoorl member). In this thesis they are however assigned to the sand district because they are eolian deposits. In contrast to the inland dunes, the coastal dunes can be calcareous, especially in the deeper profile.

Besides eolian sediments, also a variety of glacial and peri-glacial deposits are treated under the sand district. These deposits mainly underlie the cover sand deposits, but are sometimes found at the surface. The occurrence of these formations is restricted to the northern, central and eastern parts of the sand district, where glacial deposits and peri-glacial deposits of Elsterien and Saalien age are found (Peelo and Drenthe formation). These deposits include loamy to clayey sediments like glacial till and boulder clays, which are mainly found in the north, but also fine to very coarse sandy fluvio-glacial sediments (peri-fluvioglacial).

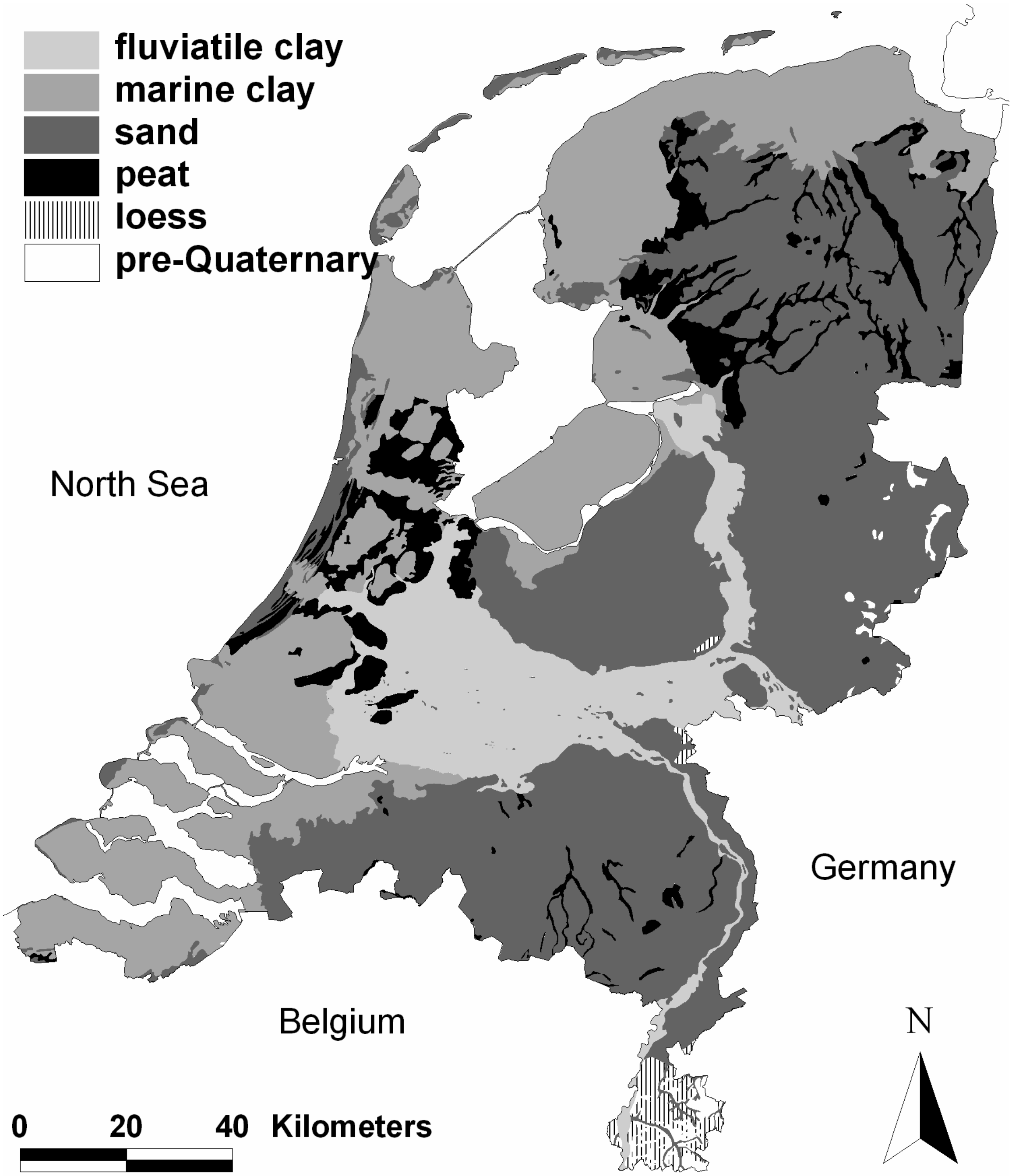



*Figure 2.6* Spatial representation of the five soil parent material districts in the Netherlands (roughly after Stiboka, 1965; De Bakker and Locher, 1987). The pre-Quaternary formations are not included within these parent material districts due to their very restricted occurence.

Also treated under the sand district are the dominantly coarse grained, non-calcareous fluviatile sediments of Middle and Late Pleistocene age. The oldest fluviatile deposits are found in the ice-pushed ridges in the central and eastern parts of the sand district and consist of pre-Saalien sediments. These were either derived from the collective Rhine-Meuse system (Waalre, Sterksel and Urk formation) as well as the North

German (or Eridanos) river system (Appelscha and Peize formation). Beyond the extension of the glaciers in the southern parts of the sand district, comparable coarse grained fluviatile sediments occur in the deeper profile. These belong to the Waalre, Sterksel, Urk and Kreftenheye formations (Rhine-Meuse) and Pleistocene deposits of the Beegden formation (upper Meuse).

The local fluviatile sediments from small rivers that drain the Pleistocene sandy area also belong to the sand district. Here, often more loamy to clayey sediments as well as mesotrophic wood peat are found. The peat, however, is part of the peat district. Other Holocene deposits, like marine and fluviatile clays and different types of peat commonly overlie the Pleistocene sands. As such, a wide variety of profiles can be found in the sand district (see De Gans et al. (1987) for a more thourough discussion).

### Loess district

The parent material of the loess district (or loamy soils after Stiboka, 1965) consists of silty eolian sediments that were deposited during the Saalien and Weichselien (Boxtel formation, Schimmert member). Commonly, the upper layers of loess deposits eroded and were re-deposited locally in valleys (colluvial loess). Texturally, loess can be classified as silty loam or sandy loam (see Appendix I). The upper loess deposits are non-calcareous as a result of extensive decalcification, but calcareous material is commonly found deeper in the sediment (2.5-3 m). The loess deposits are part of the middle European loess belt and comparable loess deposits are found in the adjacent countries Belgium and Germany.

The occurrence of loess close to or at the surface is confined to the southern and southeastern parts of the Netherlands and covers roughly 2% of the land surface (fig. 2.6). Local deposits occur in the province of Brabant and Gelderland, but the dense occurrence of loess is restricted to the southeastern parts of the Netherlands. Here it overlies a variety of Pre-Quarternary formations such as limestones and marls as well as Pleistocene formations (mainly coarse fluviatile sands, Beegden formation). Locally, younger fluviatile and eolian sediments overlie the loess.

### Peat district

The profiles in the peat district are defined as having a high organic matter contents over at least 40 cm of the first 80 cm of the profile (see Appendix I and section 2.6.3). All surfacial peat belongs to the Nieuwkoop formation and was formed during the Holocene (fig. 2.6). The mineral layers underlying the peat formations are often of Pleistocene age (mainly sand), but also of Holocene age (marine/estuarine clays). In the midwestern parts of the Netherlands, the peat is often overlain by sediments of Holocene age (mainly clays).

The peat developed under a variety of conditions. In the inland parts of the Pleistocene sandy area, oligotrophic sphagnum-moss peat developed (Griendtsveen member). In local rivers and brooks that drain the Pleistocene sandy area, mesotrophic wood peat formed (Singraven member). The different peat layers that were formed in the coastal margins of the Netherlands during the Holocene consist of mesotrophic to eutrophic reed, sedge and wood peat that grew under saline, brackish or fresh water conditions (Hollandveen member and Basisveen layer).

Since Roman times, much of the peat has been excavated (see also section 2.5.2). As a result, there are few profiles left that have peat over the full length of the profile. The majority of peat lands have a non-organic sandy or clayey top layer, which is often of anthopogenic origin.

### Fluviatile district

The parent material in the fluviatile district consists mainly of fluviatile clay and sand deposited by the Rhine, Meuse and their tributaries during the Holocene (Echteld and Beegden formation). These deposits can be calcareous or non-calcareous and often show a wide variety of grain size distributions ranging from coarse sands to heavy clays. The deposits of the upper Meuse, assigned to the Beegden formation, are generally much coarser and consist either of coarse to very coarse sands or of sandy to silty clay. The various member in the Beegden formation are not discussed here.

The Echteld formation, which was deposited by the collective Rhine-Meuse system during the Holocene, consists of sandy deposits as well as sandy to heavy clays. Within the Echteld formation, no further members are discerned. Instead, various types of lithogenetic groups are discerned which are based on the depositional environment, such as channel, crevasse and flood plain deposits (see e.g. Berendsen 1982; Törnquist, 1993; Weerts, 1996).

Commonly, the Holocene fluviatile sediments reach down to 120 cm and show a distinct fining upward in the profile. Locally, older formations are found deeper in the profile; most notably coarse sand and gravel (sometimes clay) of the formation Kreftenheye as well as aeolian and local fluviatile deposits from the Boxtel formation (sand, loam and locally peat). Further assigned to the fluviatile district are the old fluviatile clay deposits that locally crop out in the southeastern parts of the country. These are older sandy to clayey deposits of the Rhine-Meuse and Meuse (mainly Kreftenheye formation, also Beegden formation).

### Marine district

The parent materials in the marine district are of Holocene age and consist of tidal, intertidal and perimarine deposits of the North Sea (Naaldwijk formation). The deposits are often calcareous (shell fragments) and their texture ranges mainly from fine sand to (heavy) clay. Within the marine Naaldwijk formation, various members are discerned. The Wormer member consists of intertidal deposits and generally shows a fining upward sequence from fine sand to (heavy) clay. Especially in the southwestern parts of the Netherlands, this layer is overlain by the younger Walcheren member, which consists of fine sand and sandy to silty clay. It is also found at the surface of the large polders around the central lake of the Netherlands. The eolian deposits (coastal dunes) of the Naaldwijk formation are for this overview assigned to the sand district.

In the west of the Netherlands, the marine parent material often overlies the peat of the Nieuwkoop formation as well as fluviatile deposits of the Rhine and Meuse (Echteld formation). In the northern parts of the Netherlands, marine deposits commonly overlie sandy Pleistocene deposits of the Boxtel formation. Also, large areas in the marine district consist either of lakes or coastal areas that were reclaimed, thereby uncovering the underlying marine deposits of the Wormer member (see also section 2.5.2).

### 2.3.3 Texture and mineralogy

In the previous section, the soil parent material and the formations discerned herein have been described in terms of geogenesis and texture. The natural range of grain size distributions in these sediments is shown in figures 2.7a and 2.7b. They reveal considerable overlap in texture between eolian sediments (sand and loess district) and non-eolian sediments (marine and fluviatile clay districts), although the formaer are more silty. In general, for these well sorted sediments there exists a clear relation between texture and sediment mineralogy in terms of broad mineralogical groups (table 2.4). As can be seen, the three most important grain size fractions - sand, silt and clay - have their own distinct composition in terms of the broad mineralogical groups. It will be seen that the mineralogical composition of the sediments within the various districts forms a continous range within the limits set in table 2.4.

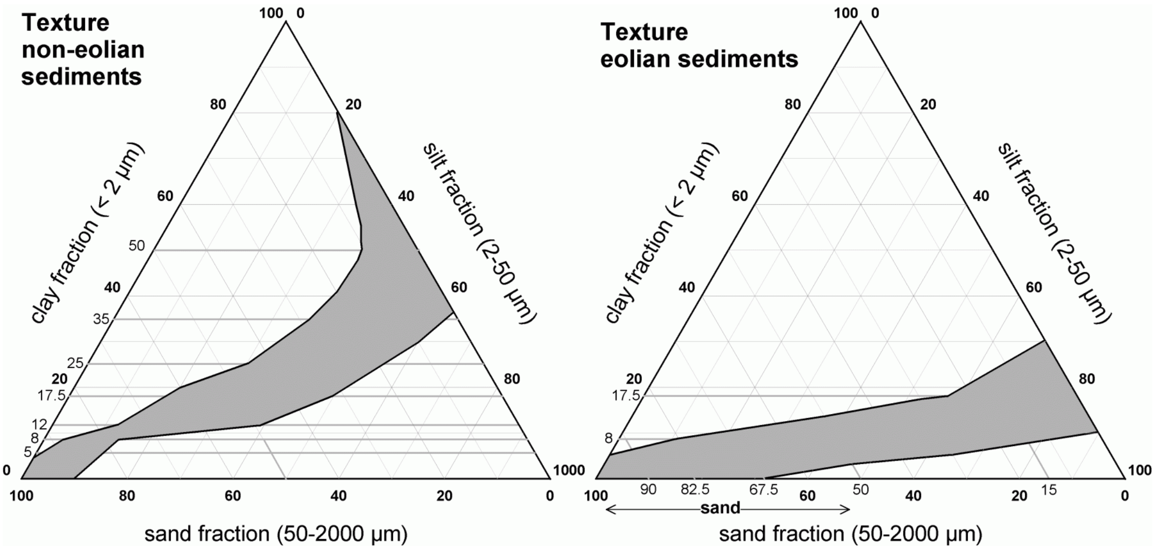



*Figure 2.7a and 2.7b* Common textural range found for eolian (a) and non-eolian (b) sediments in the Netherlands (after De Bakker and Schelling, 1989). For terminology see Appendix I.

*Table 2.4* Estimated mineralogical composition of four grain size classes of various Dutch sediments (after Breeuwsma (1987)), partly combined with the data of table 8 for the clay fraction.

| **Mineral (group)** | **Sand fraction** | **Coarse silt fraction** | **Fine silt fraction** | **Clay fraction** |
|---|---|---|---|---|
| Quartz | 80-95 | 65 | 40 | 5-10 |
| Feldspars | 5-10 | 20 | 20 | <5 |
| Micas | 1-5 | 10 | 0 (?) | 0 (?) |
| Chlorite | < 3 | <5 | 0 (?) | <10* |
| Clay minerals | 0 | 0 | 35 | 60-80* |
| Heavy minerals** | 0.5 | ? | ? | ? |
| Free $Fe_2O_3$*** | 0.1-3 | ? | ? | 2-5 |
| Free $Al_2O_3$ | 0.1-1 | ? | ? | 1-3 |
| Free $SiO_2$ | ? | ? | ? | 2.6 – 7.4 |

(?) Absent from original table, but interlayered forms may occur (see text).
* Combined with data from table 8.
** Locally much higher values beach sands.
*** Locally much higher values in seepage areas.

Compared to lithological and pedological properties, the overall mineralogy of these sediments and soils has been studied much less. Often these studies focused on specific grain size or density fractions only, and to my knowledge, there is no study that gives the total mineralogical composition of the sediments in the Netherlands. Moreover, most of the data is semi-quantitative (grain counts or estimated compositions from XRD patterns) and commonly lacks mineralogical detail, e.g. only the general groups are given.

In the next subsections, I give an overview of the scarce information of the mineralogical composition of the soil and sediments in the Netherlands. For the nomenclature, chemical composition and the delineation of (alumino-)silicates, the work of Deer et al. (1992) is followed.

**Quartz**

Quartz ($SiO_2$) is one of the most abundant minerals and occurs as an essential constituent of many rock types and sediments. It is especially concentrated in the sand fraction (up to 95 wt%) and is a major component of the coarse silt fraction (table 2.4). Quartz is therefore the dominant mineral phase of sandy and loamy sediments as well as the "lighter" clays having up to ~40 wt% clay fraction. Also in the coarser fractions like gravel and pebbles, quartz is the domiant mineral phase (see Maarleveld, 1956).

Quartz is mainly in the form of crystalline quartz and dominantly occurs as detrital grains. The coarse grained fluviatile sediments derived from the North-German river system (Peize and Appelscha formation) generally have higher amounts of quartz grains (80-90 %) than comparable sediments from the Rhine-Meuse system (60-70 %). In the latter, both lithic framents and micas/chlorite are more dominant (Breeuwsma, 1987). Coarse grained sediments from the upper course of the Meuse (Beegden formation) have even lower concentrations of quartz grains (40-50%) and relatively high concentrations of lithic fragments (50-60%), which also dominantly consist of siliceous material (Maarleveld, 1956).

Besides crystalline forms of quartz, amorphous quartz of biogenic origin can play a role in the total amount of quartz. Compared to sandy sediments, marine and fluviatile deposits show slightly higher amounts of amorphous silica (Breeuwsma, 1987). In soils with a humus rich A-horizon, secondary amorphous quartz occurs in concentrations ranging between 1-4% wt.% (Breeuwsma, 1987).

**Feldspars**

The feldspar group is described in terms of the three end members: orthoclase ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$). Solid solutions between orthoclase and albite are referred to as alkali-feldspars, whereas the anorthoclase-albite series is termed plagioclase feldspars-series. Very restricted solid solution between K- and Ca-feldspars occur.

Like quartz, feldspars are abundant minerals that occur throughout many rock types. With respect to texture, highest concentrations of feldspars are found in the (coarse) silt fraction (up to 20 wt%; table 2.4) and to a lesser extent also in the sand fraction (5-10 wt%). The highest concentrations of feldspars therefore occur in the loamy and sandy sediments, as well as the sandy to silty clays.

The distribution of various feldspars in the light fractions of sediments in the Netherlands has been studied semi-quantitatively by Van Baren (1934). He showed that K-feldspars are usually the dominant feldspars, consisting of orthoclase and smaller amounts of microcline. Albite (/oligoclase ?) is the second dominant feldspar, which often occurs together with K-feldspars. Plagioclase (anorthite) is less common and its occurrence appears more erratic. According to Van Baren (1934), relatively high concentrations of microcline (and whitish orthoclase) are characteristic for southern input (Rhine/Meuse), whereas high concentrations of albite are considered as indicative for a northern input (glacial deposits). The latter is often associated with reddish orthoclase.

More anorthitic feldspars were so far not described as separate minerals in the Netherlands, though labradorite and bywtonite have been described in glacial boulders (Van der Lijn, 1973). Other types of feldspars (high temperature forms like sanidine) are unlikely to occur in the Netherlands due to their low stability and restricted occurrence in the hinterland.

### Micas

The mica-group consists of a variety of platy minerals with a perfect basal cleavage. The most common non-brittle micas include muscovite, paragonite, glauconite, biotite-phlogopite, lepidolite and zinnwaldite. The majority of the micas occur as separate minerals and form only limited solid solutions. Biotite, however, occurs as a full solid solution with phlogopite and its compositional boundary is arbitrarily defined as having $Mg/Fe < 2$.

The micas are one of the least studied mineral groups of the Netherlands. As estimated by Breeuwsma (1987), maximum amounts of micas (up 10 wt%) are found in the fine silt fraction and they generally show the same distribution pattern as chlorite. From table 2.4 it is clear that the concentration of micas is considerably higher in the silty clay and loamy sediments, and much lower in the coarse sandy sediments and very fined grained heavy clays.

Very little is known about the distribution of the various micas in the Dutch soils. On the basis of a few clayey sediments studied by Van Baren (1934) it is clear that muscovite is likely to be the most common mica, whereas biotite is not always present and will occur in smaller amounts. No differentiation was made into the other micas like paragonite, phlogopite and zinnwaldite, nothing is known about the distribution of these phases.

The occurrence of glauconite is better understood, mainly due to the fact that it is more easily recognizable; larger amounts of glauconite give a greenish color to the sediments (so-called “green sands”). Its occurrence is however largely restricted to Tertiary marine sediments (not described here), which are found only very locally close to the surface (see Zagwijn and Van Staalduinen, 1975). Glauconite does occur in small amounts in local eolian sediments that were derived from these Tertiary sediments (Van der Lijn, 1973).

Glauconite is regularly considered under the clay minerals (see e.g. Breeuwsma, 1987). Here, I have followed Deer et al. (1992), mainly because glauconite forms rather coarse aggregates and is therefore also found in the coarser fractions (sandy to silty marine sediments).

### Chlorites

The chlorites are a mineral group that closely resembles the micas in many respects. Besides its common occurrence in many igneous and low-grade metamorphic rocks, chlorites occur in sediments, either as a detrital or an authigenic phase. The common formulae for chlorites is $(Mg,Al,Fe)_{12}[(Si,Al)_8,O_{20}](OH)_{16}$, but the chlorite group shows a wide range of compositions. The $Fe^{2+}/(Fe^{2+}+Mg)$-ratio can lie between zero and unity. Further mineralogical description of the chlorites falls beyond the scope of this review (see Deer et al., 1992).

Again little is known about the distribution of chlorite in Dutch soils. Just like the micas, maximum concentrations ranging to up to 10 wt% of chlorite are found in the fine silt fraction (table 2.4). However, comparable amounts are also found in the clay fraction (table 2.6). Here, it might occur as interlayered with clay minerals like vermiculite, which is a common weathering product of chlorite. The distinction between chlorite and clay minerals is not clear-cut, but the amount of chlorite will obvisouly be highest in fine grained clayey and loamy sediments.

### Clay minerals

Clay minerals are basic constituents of many fine grained sediments and (meta-) sedimentary rocks (e.g. mudstones, shales and slates). In general, clay minerals are characterized by their small size – commonly less than 2 μm –, their platy interlayered structure as well as their relatively large, mostly negative surface charge. They are basically categorized on the basis of the number of silicon tetraeder layers vs. the number of aluminum octaeders per unit cell, which can be 1:1 or 2:1 (table 2.5). Based on their basal spacing, clay minerals are further subdivided in four groups: kaolinites (kandites), illites, smectites and vermicultes (table 2.5).
The clay minerals are of course the most abundant in the clay fraction of sediments where they comprise 60-80 wt%. They do occur in smaller amounts in the fine silt

*Table 2.5* Overview of clay minerals groups and their general composition (after Deer et al. 1992).

| Clay mineral group | Type | Octahedral component | Interlayer cation | Common minerals | Paragenesis |
|---|---|---|---|---|---|
| Kaolinites | 1:1 | di-octahedral | none | Kaolinite, halloysite | Alteration of acids rocks, feldspars etc. |
| | Formula: $Al_4Si_4O_{10}(OH)_8$, little variation | | | | |
| Illites | 2:1 | Mostly di-octahedral | K | Illite, phengite | Alteration of micas, feldspars etc. |
| | Formula: $K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O20](OH)_4$ | | | | |
| Smectites | 2:1 | Di- or trioctahedral | Ca, Na | Montmorrilonite, beidelite, nontronite, saponite | Alteration of basic rocks, volcanic material. |
| | Formula: $(0.5Ca, Na)_{0.7}(Al, Mg, Fe)_4(Si,Al)_8O_{20}(OH)_4.nH2O$ | | | | |
| Vermiculites | 2:1 | Mostly tri-octahedral | Mg | Vermiculite | Mainly alteration of biotite, also chlorites, hornblendes etc. |
| | Formula: $(Mg, Ca)_{0.7}(Mg, Fe^{3+}, Al)_6(Si,Al)_8O_{20}(OH)_4.8H2O$ | | | | |

fraction (table 2.4). In this overview I do not go into the details of clay mineralogy and interlayering of different clay minerals (e.g. illite-smectite clays). The before mentioned clay mineral groups will be used without further differentiation.

Various studies exist on the distribution of clay minerals in Tertiary and Quarternary formations (Tebbens, 1998; Huisman, 2000) and different soils or parent material types (Breeuwsma, 1985; Breeuwsma, 1987; Van der Salm, 1998). Often, these studies have specifically focused on the mineralogy of the clay fraction (< 2 μm) only. As can be seen in table 2.6, the range of concentrations of various clay minerals is quite comparable for the different soil types. In all cases, illite and smectite are the dominant clay minerals, followed by smaller amounts of kaolinite and vermiculite. Illite, kaolinite and vermiculites all show a quite narrow range of variation, whereas smectites have a much broader concentration range. Marine and fluviatile clays have quite comparable clay mineralogy, though on average, marine clay soils have higher smectite and much lower vermiculite concentrations compared to fluviatile clays.

*Table 2.6* Mineralogical composition of the clay fraction (< 2 μm) of various sediment types in the Netherlands. Remark: Irion and Zollmer (2000) have set the data of the four clay mineral groups to 100% (average indicated between brackets).

| | **Fluviatile clay** | | **Marine clay** | **Marine sand** | **Loess** |
|---|---|---|---|---|---|
| **Mineral group** | **Breeuwsma, 1987** | **Van der Salm et al., 1998** | **Breeuwsma, 1987** | **Irion and Zöllmer, 2000** | **Van der Salm et al., 1998** |
| Quartz | 5-10 | 2-5 | 5 - 10 | NA | 3-12 |
| Feldspars | <5 | <5 | <5 | NA | <5 |
| Chlorite | <5 -10 | 5-6 | <5 - 10 | 3-19 (12) | < 3-11 |
| Kaolinite | 5-10 | 11-14 | 5 - 10 | 2-23 (10) | 13-24 |
| Illites | 30-40 | 31-46 | 30-40 | 34-67 (51) | 20-41 |
| Smectites | 10-35 | 34-43** | 10-50 | 5-53 (27) | 20-38** |
| Vermiculites | 5-20 | | <5* | NA | |
| Free $Fe_2O_3$ | 3.9-4.3 | NA | 2.1-3.2 | NA | NA |
| Free $Al_2O_3$ | 1.4-2.4 | NA | 0.6-1.3 | NA | NA |
| Free $SiO_2$ | 3.4-4.8 | NA | 2.6-7.4 | NA | NA |

* Up to 20 wt% in intermediate marine-fluviatile (brakish) clays.
** Interlayered clay mineral consisting of illite, smectite and vermiculite.

Though micas are not indicated as a component of the clay fraction (table 2.4), van Baren (1934) found considerable amounts of muscovite in the 1-5.5 μm fraction of clayey sediments. The distinction between muscovite and clay minerals is, like for chlorite, not always clear and intermediate forms like hydro-muscovite and interlayered muscovite-illite exist. The same applies to the occurrence of chlorite in the clay fraction, which can range up to 10 wt %, but it is not clear to what degree chlorite is interlayered with smectites or vermiculites.

### Heavy minerals

Heavy minerals consist of a mixed bag of minerals and mineral groups commonly defined by having densities larger than 2.8 g/cm$^3$. In general, the heavy minerals occur as minor components (< 1 wt %) in a wide variety of rock types and sediments. The total amount of heavy minerals in the Dutch sediments is generally below 0.5 wt% (Breeuwsma, 1987). They are most often used for sediment provenance studies as they are generally resistant to weathering and often characteristic for a certain rock type or geological setting. The provenance studies in the Netherlands were mainly focused on the (coarse) fluviatile sediments.

Originally, Edelman (1933) discerned six provenances in the Quarternary sediments of the Netherlands. Currently however, only a broad distinction between between stable and unstable heavy minerals groups is made (table 2.7). Typical minerals of the stable heavy mineral suite include andalusite, kyanite, sillimanite and staurolite. These are typical heavy minerals of the fluviatile sediments from the Meuse (Beegden formation, also Stamproy formation), which were derived from the more strongly weathered rocks of the Rhenish and Kempish. Fluviatile sediments from the North-German river system are also characterized by a stable heavy mineral suite (Peize and Appelscha formation; section 2.2.2). Other stable heavy minerals such as zircon, rutile and tourmaline are also found, but they are less typical as they also occur in sediments with unstable heavy mineral associations.

The Pleistocene sediments from the Rhine are derived from the relatively unweathered crystalline rocks in the Alps and southern Germany. As a result, they show a dominantly unstable heavy mineral association, characterized by relatively high concentrations of garnets, epidote, hornblende and augite (Waalre, Sterksel, Urk and Kreftenheye formation cf. Weerts et al., 2003).

*Table 2.7* Overview of common heavy minerals used for provenance studies in the Netherlands (composition after Deer et al., 1992).

| Mineral | Formula | Paragenesis |
|---|---|---|
| **Stable** | | |
| Tourmaline | $Na(Mg, Fe, Mn, Li, Al)_3Al_6[Si_6O_{18}]\ (BO_3)_3(OH, F)_4$ | Granite pegmatites, some granites and metamorphic rocks |
| Staurolite | $(Fe^{2+}, Mg)_2(Al, Fe^{3+})_9O_6\ [SiO_4](O,OH)_2$ | metamorphosed pelitic sediments |
| Kyanite/ sillimanite/ andalusite | $Al_2SiO_5$ | Wide range of metamorphic rocks |
| Zircon | $ZrSiO_4$ | Igneous rocks, especially (Na-rich) plutonic rocks |
| Rutile/anatase/ brookite | $TiO_2$ | Medium grade metamorphic rocks |
| Topas | $Al_2[SiO_4](OH,F)_2$ | Acid igneous rocks |
| **Unstable** | | |
| Epidote | $Ca_2Fe^{3+}Al_2O.OH[Si_2O_7][SiO_4]$ | Regional metamorphism |
| Hornblende | $(Na, K)_{0-1}Ca_2(Mg, Fe^{2+}, Fe^{3+}, Al)_5[Si_{6-7}Al_{2-1}O_{22}](OH,F)_2$ | Intermediate plutonic rocks to basic and ultrabasic rocks |
| Augite | $(Ca, Na, Mg, Fe^{2+}, Mn, Fe^{3+}, Al, Ti)_2\ (Si,Al)_2O_6$ | Gabbros, dolerites and basalts |
| Saussurite | See epidote | Alteration of epodite |
| Garnet | Al-silicates contaning variable amounts of 2 to 3 major cations such as Ca, Fe, Mg and some Mn, Cr and Ti. | Mainly high grade metamorphic |
| Chloritoid | $(Fe^{2+}, Mg, Mn)_2(Al, Fe^{3+})Al_3O_2\ [SiO_4]_2(OH)_4$ | Metamorphosed pelitic sediments |

In the loess deposits (Boxtel formation, Schimmert member) zircon is appearently the dominant heavy mineral (Edelman, 1933). As mentioned by Edelman (1933), this could be related to a grain size effect, e.g. preferential occurrence of zircon in the silt fraction. Other important heavy minerals in the loess include epidote, garnet (variable), rutile and hornblende.

Very locally, increased concentrations of heavy minerals of up to ~28 wt. % have been found in the fine sand fraction of beach sands (Schuiling et al., 1985). However, no commercial placer deposits are known for the Netherlands. The dominant heavy minerals in the heavy mineral fraction of these enriched beach sands are garnet (~60 %), ilmenite (~10 %), zircon (~ 10 %), epidote (~6 %) and rutile (~3%). Other heavy minerals described in these sands include tourmaline, magnetite, monazite and others.

**Secondary mineralogy**

All minerals formed after deposition of the sediment are here considered as secondary minerals. They consist of a variety of mineral groups, of which the most important are the carbonates, oxides, sulphides and phosphates. In general, their total concentration is less than a few wt%, but these secondary minerals can be enriched, e.g. in seepage areas and/or organic rich sediments.

Secondary carbonates - carbonates formed after deposition of the sediment – can be divided into biogenic carbonates, mainly calcitic shell fragments and carbonates formed as a result of chemical precipitation. Biogenic calcite ($CaCO_3$) is formed in all types of marine, fluviatile, or lacustrine environments. These biogenic fragments can occur in high amounts, especially in sandy marine sediments (up to 30 wt %), whereas the more heavy clays (both marine and fluviatile) are generally non-calcareous. Also the Pleistocene deposits are generally non-calcareous as a result of progressive weathering. Chemically precipitated calcite is often the result from degassing of $CO_2$-rich groundwater, which e.g. occurs in seepage zones. Thereby, in organic rich sediments like peat and brook deposits, siderite ($FeCO_3$) can occur.

The most important secondary oxides and hydroxides are those of iron, aluminum, silicon and possibly manganese. Total free iron concentrations range form 0.1 to 4 wt % $Fe_2O_3$. In local brook deposits with extensive seepage, however, the total concentrations of secondary iron in the clay fraction can reach up to 50-60 wt% $Fe_2O_3$ (Breeuwsma, 1987). Secondary iron mainly occurs in the form of goethite (β-FeOOH). In the presence of abundant $Fe^{3+}$, ferrihydrite is commonly formed as an amorphous intermediate Fe-mineral. Occasionally, green rust is precipitated as an amorphous intermediate $Fe^{2+}/Fe^{3+}$-mineral. This occurs especially in soils with an alternating groundwater table and abundant organic material, for example soils formed in brook deposits. In peat, the goethite polymorph lepidocrocite (α-FeOOH) can be the dominant Fe-(hydr)oxide. Also, the hematite polymorph maghemite ($\gamma$-$Fe_2O_3$) is occasionally found (Breeuwsma, 1987). In general, the concentrations of secundary iron are found to be higher in fluviatile clays (3.3-4.3 wt.% $Fe_2O_3$) compared to marine clays (2.5-3.0 wt.% $Fe_2O_3$). On the other hand the $Fe_2O_3$ bound to alumino-silicates is 1-3 wt% higher in marine clays compared to the fluviatile clays (for a range of total Fe-concentrations between 4-7 wt% $Fe_2O_3$; Breeuwsma, 1987).

Secondary aluminum always occurs in lower concentrations than secondary iron (0.1 -1 wt % $Al_2O_3$), mostly as gibbsite ($Al(OH)_3$). Compared to marine clays, fluviatile clays generally contain less secondary aluminum (1-2 wt% $Al_2O_3$, compared on a total Al-concentration of 20 wt% $Al_2O_3$; Breeuwsma, 1987). Other commonly occuring secondary oxides, besides secondary silicon (see under quartz), are those of manganese. Pyrolusite (β-MnO2) has been described for the Dutch soils, though so far always in concentrations less than 0.5 wt % MnO (Breeuwsma, 1987).

Secondary sulphides in the Netherlands include mainly pyrite ($FeS_2$) and less stable intermediate iron sulphides like mackinawite (FeS) and greigite ($Fe_3S_4$). They often occur in small concentrations in reduced (marine) soils that have increased concentrations of organic matter (anoxic settings). Iron sulphides occur also in sandy sediments/soils that are close to an organic layer as well as peat soils. These sediments should then have been under marine influence in order to have enough sulphur for considerable sulphide formation. By weathering of the sulphides, jarosite ($KFe_3(SO_4)_2(OH)_6$) forms giving a typical yellow mottled color to these soils (acid sulphate soils). These soils commonly occur in coastal and inland reclamations in the marine and peat districts.

Another group of secondary minerals includes the phosphates. The most common are phosphates of calcium (apatite, hydroxy-apatite), iron (vivianite, strengite) as well as magnesium/ammonium (struvite) and aluminum (variscite). However, no detailed information on their occurrence in the Dutch soils is available. In general, the total amount of phosphate minerals in the soils is less than 0.1 wt %. Vivianite ($Fe_3(PO_4)_2 \bullet 8H_2O$) occurs in organic rich reduced fluviatile sediments. High concentrations of vivianite and possibly strengite ($Fe(PO_4).2H_2O$) can occur also in brook valley deposits, where they often occur together with siderite.

## 2.4 Soil forming factors

### 2.4.1 Introduction

In pedology, soils are classified according to the compositional and textural variations that occur throughout the profile. As mentioned, the soil profile in the Netherlands is arbitrarily defined as the 0-120 cm layer of the sediment (excluding the litter layer). The different layers observed in the soil profile can have a geogenetic origin (different formations/laagpaketten) or a pedogenetic origin, e.g. as a result of organic matter accumulation in the topsoil or transport of secondary Fe/Al-(hydr)oxides. In the latter case, these layers are termed horizons which are the basic properties used in further soil classification (section 2.6.3).

In contrast to geogenic layering, which was described in the previous sections, these horizons result from various soil forming processes. These soil forming processes in turn are governed by a variety of soil forming factors, which are: parent material, climate and vegetation, topography and hydrology, time (soil age) and human impact. The parent material is described in the previous section and here only the climate, vegetation, topography and hydrology and soil age are reviewed. In the Netherlands, the human impact on soil forming factors such as hydrology, topography and soil age, as well as on the geogenic layering of the profile has been extensive. The human impact on soils will therefore be further worked out separately (section 2.5).

The following is largely based the work of De Bakker (1979), De Bakker and Locher (1987) and Locher and De Bakker (1987)

### 2.4.2 Climate and vegetation

Soil formation in the Netherlands essentially started after the last glacial period (Weichselien) when the temperature rose and vegetation started to stabilize the unconsolidated sediments. During the Holocene, the temperature was rather constant and the climate was comparable to the current climate. Only during the Atlanticum the average yearly temperature probably a few degrees above the current temperature (Westerhoff et al., 2003).

Currently, the Netherlands have a moderate sea climate (Cfb according to Köppen) and average daily temperatures range from 2 °C in January to 16 °C in July and the relative humidity is generally between 80-90% (Huisman et al. 1998). The coastal parts of the Netherlands have slightly milder winters and cooler summers compared to the inland areas, but the regional differences are restricted as a result of the limited size and flat topography of the Netherlands. The average annual precipitation in the Netherlands is 750 mm, which is rather constant over the land surface (10-15% deviation; Huisman et al. 1998). While the spatial variation of the average precipitation is small, temporal fluctuations are much more pronounced. The interannual variability ranges from 400 - 1200 mm/year, whereas the mean monthly precipitation ranges between 40-50 mm in early spring to 80-90 mm in summer.

Due to the seasonal variation of climatic parameters, the evapotranspiration also varies throughout the year. Between October and March a precipitation surplus of 300 mm is built up, whereas a maximum deficit of 100-150 mm accumulates between April to September (Huisman et al. 1998). The mean annual evapotranspiration for the whole of the Netherlands is in the order of 550 mm, leading to an average yearly precipitation excess of 200 mm. The precipitation excess results in a net leaching of the soils (De Bakker, 1979).

The natural climax vegetation under this climate would be a deciduous forest consisting of alder, ash, beech, birch, elm, hornbeam, oak and willow with variable undergrowth (De Bakker 1979). Before human interference, these rather monotonous forests covered large parts of the Netherlands during the Holocene. As a result of extensive land cultivation (section 2.5) there is virtually no natural vegetation left in the Netherlands. In contrast to climate, the role of natural vegetation on various soil formation processes in the Netherlands, except for formation of peat soil, is less well understood and probably of minor importance compared to the impact of agricultural land use.

### 2.4.4 Topography & surfacial hydrology

The Netherlands has very little elevation differences and gently slopes from the southeast (322 m above mean sea level) to the northwest (several meters below mean sea level). The elevation of the extreme southeastern part of the Netherlands is due to its location on the northern foothills of the Ardennes massif. The remaining part of the Netherlands has a more or less flat topography, except for the relief formed by glaciers during the Weichselien (ice pushed ridges) and the wind-blown inland and coastal dunes. In the coastal parts of the Netherlands, local minima in elevation (down to 6.6 m below mean sea level) occur in drained lakes and coastal reclamations. With respect to the elevation, the Netherlands can be divided in a “high” Pleistocene area (including Holocene dunes), which lies well above sea level, and a “low” Holocene area (clays and peat), which lies at or below sea level (see also fig. 2.6).

The average altitude in the Pleistocene area is mainly between 2.5 and 30 m, but ranges up to 200-300 m in the loess district. The Pleistocene sand and loess districts are well drained and the surfacial run-off of excess rainwater is generally restricted (0-50 mm/year). The local occurrence of less permeable layers close to the surface (e.g. the glacial till in the north of the Netherlands) and shallow water tables result in an increased overland run-off of 50-250 mm/year. Groundwater recharge is in the order of 100-200 mm/year and even > 300 mm/year for the highly permeable sandy and loamy areas. The groundwater flow pattern is horizontal and the groundwater discharges in (local) rivers. The deeper groundwater flow of the Pleistocene area can even reach the coastal zone, including some large polders. During the last few centuries, the area has been further drained by a network of ditches and canals.

Except for the coastal dunes, the soils in the Holocene area lie close to, or even below sea level (generally between +2.5 and –2.5 m.). The area mainly consists of relatively impermeable clays and peat on clay and shows a relatively shallow groundwater table. Therefore, the area receives hardly any recharge from local precipitation (< 10 mm/year) and the excess precipitation is thus mainly removed by overland run-off (> 200 mm/year). Often, the fresh ground water only forms a thin layer overlying the brackish water ($Cl^-$ > 150 mg/l) derived from seawater found deeper in the aquifer. Locally there is seepage of brackish ground water to the surface water in these areas. This is enhanced by the artificial lowering of the ground water table by a dense network of drainage pipes, ditches and canals, which are continuously pumped.

For soil formation in the Netherlands, the depth to the ground water table is often regarded as the most important hydrological parameter (De Bakker, 1979; De Bakker and Locher, 1987). As a result of variable recharge, the depth of the ground water table shows a clear yearly fluctuation. During the summer period, the ground water table in the Netherlands is commonly well below 80-120 cm. In the some of the low lying areas, however, the groundwater table is found at depths of less than 50 cm. In winter, the highest groundwater levels are found, ranging between 25-40 cm over large parts of the Netherlands. Only in the elevated sandy soils (e.g. ice-pushed ridges), the water tables are found at depths well below 80 cm.

### 2.4.5 Time

Time is an important soil forming factor as it determines to which extent the other soil forming factors have collectively acted on the parent material. With the factor time, the duration of soil formation processes in the toplayer is meant, which is not necessarily the same as the time since the deposition of the sediment. In addition to natural sedimentation, mankind has had an enormous impact on soil age through large scale reclamation of inland and coastal areas. The historical land reclamation is here described in very broad terms and is further worked out in section 2.5.

As is clear from the previous sections, the soils in the Netherlands either have a late Pleistocene (sand and loess) or late Holocene age (most of the clay deposits and peat). See figure 2.4 for an overview of their distribution. The oldest soils in the Netherlands which are 12000-10000 years old, are found in the loess district as well as in large parts of the sand district. Similar ages hold for the soils that formed in older sediments, for example the Pleistocene fluviatile deposits that are exposed in the ice-pushed ridges. Locally, younger soils are found in the sand district, for example in brook deposits formed during the Holocene. The eolian sediments deposited in the late Holocene include coastal dunes, which vary in age between 4300 to less than a few 100's of years old, and the inland dunes (500-50 years old). In these sediments, soil formation is often restricted to the first 20 cm of the profile.

The peat soils have formed during the late Holocene and their top layer will generally be much younger than a thousand years. However, most of the peat in the Netherlands has been disturbed through excavation. In these areas, the remaning peat layer can have a considerable older age. In some cases, the peat layer has been completely removed. As a result, older sediments like Pleistocene sand and older marine clays have recently become exposed to the surface. The age of these former peat soils is then related to the time of excavation, generally somewhere between 1200-1900 AD, unless soil formation had already taken place (paleosols).

The soils of the marine district are mainly of a late Holocene age; more than three quarters of the marine sediments are even younger than a thousand years. Only the so-called marine old-land deposits (formation Naaldwijk, laagpakket of Wormer) are somewhat older (900-3500 years). The younger soils of the marine district were largely reclaimed from the sea and inland lakes that resulted from peat excavation practices. In the period from 1200 to 1930 AD, some 500000 ha of land were reclaimed from tidal marshes (coastal polders: 400000 ha) and lakes (drained lakes: 100000 ha) with a maximum activity around 1600-1625 (see De Bakker, 1979). In the period 1933-1968, an additional 165000 ha was reclaimed from the large central lake in the Netherlands (IJsselmeer), which was until 1930 connected to the sea (then called Zuyder Zee). The four so-called Zuyder Zee-polders - the Wieringermeerpolder, Noordoost-polder, Oost and Zuid Flevoland – are the youngest soils found in the Netherlands (see fig. 2.10a). Most of these reclaimed soils consist of marine clays.

Also the soils in the fluviatile district are mainly younger than a thousand years, though soils developed on the elevated natural levees generally have a somewhat older age. The periodically flooded, more clayey areas such as flood basins were largely reclaimed during the last thousand years. The sediments of the so-called old fluviatile clay soils (section 2.3.2) have ages ranging from 3000 to 5000 years. Soils formed in these sediments can be found locally in the mid eastern parts of the Netherlands (so-called "brick" soils, see section 2.6.3).

## 2.5 Agricultural land use and reclamation

### 2.5.1 Introduction

The territory of the Netherlands, including the inland as well as territorial waters of the North Sea, measures some 41.528 km$^2$, of which 33.873 km$^2$ is considered as total land surface (CBS, 2004). As in many deltaic areas, the Netherlands with its 16.105.000 inhabitants is a densely populated country (average density of 475 inh/km$^2$). About one third of the population is living in the three major cities in the midwest of the Netherlands: Amsterdam, Rotterdam and the Hague (collectively known as the "Randstad").

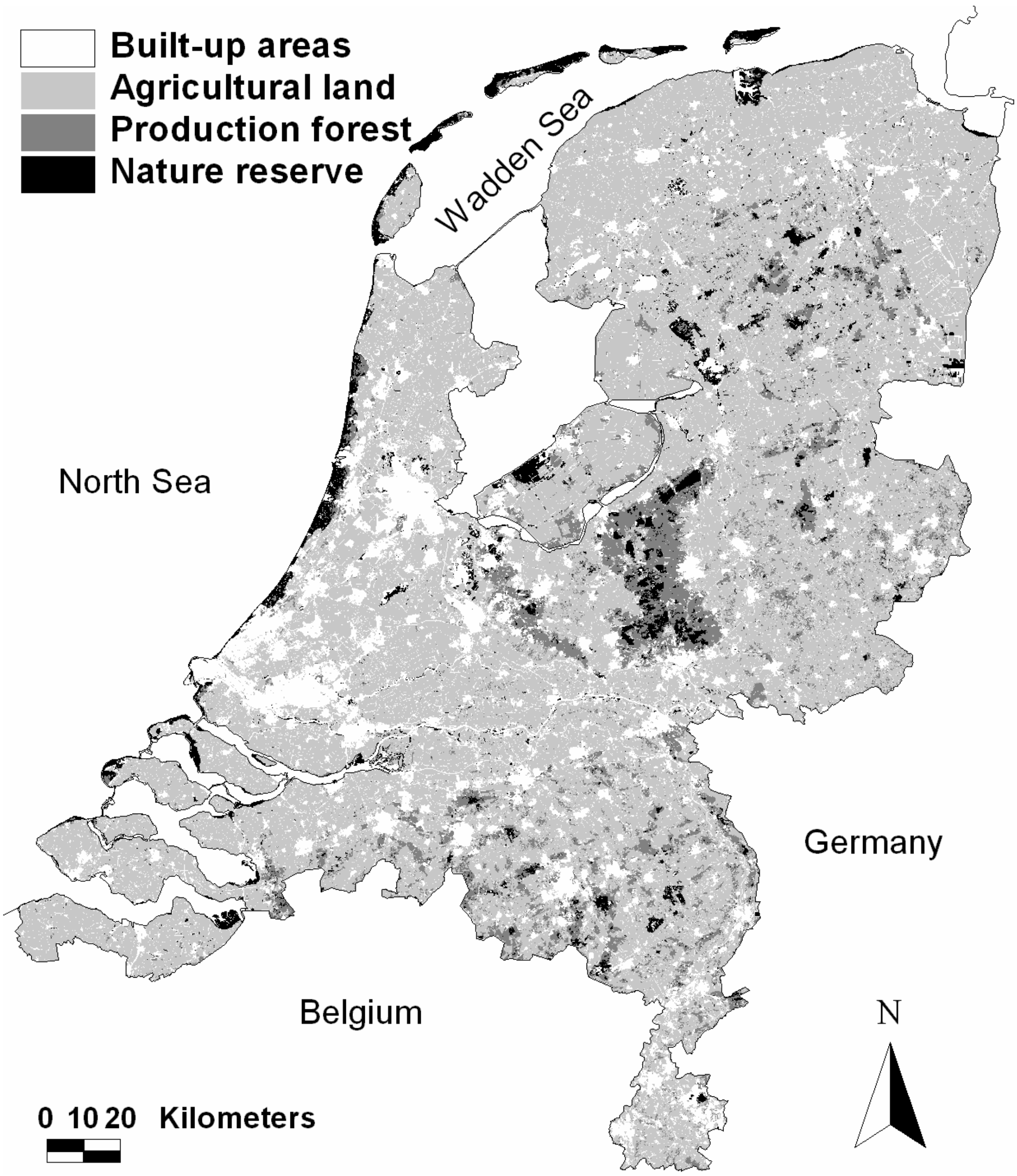



*Figure 2.8* Overview of basic land use types in the Netherlands in the year 1989 (data from CBS, see www.cbs.nl).

In total, about 17% of the available land surface is built-up area like cities, industrialized areas, roads and roadsides (5.754 $km^2$). Most of the land surface (70 %), however, is used as agricultural land (23.508 $km^2$), whereas only 13 % is used as production woods (3.233 $km^2$) and natural areas (1.379 $km^2$). The latter include semi-natural heath lands, small forests and various types of wetlands. Figure 2.8 gives a spatial overview of the distribution of the various basic land use types in the Netherlands.

*Table 2.8* Overview of the amount of land used for the production of various crops and their yield in 2000, together with a historical overview of the yield of grain, potatoes and sugar beet (CBS, 2001; CBS, 2004). Total amount of arable land in the year 2000 amounts to 806.000 ha. Others inlcude grass seed, peas and carrots.

| | **Area (1000 ha)** | **Aarable land (%)** | **Production ($10^6$ kg)** | **Yield (100 kg/ha)** | | | | |
|---|---|---|---|---|---|---|---|---|
| | **2000** | **2000** | **2000** | **2000** | **1998** | **1951** | **1900** | **1851** |
| total grain | 192 | 24 | 1473 | 258 | 231 | 117 | 82 | 58 |
| wheat | 137 | 17 | 1143 | 83 | | | | |
| rye | 6 | 1 | 29 | 48 | | | | |
| barley | 47 | 6 | 288 | 61 | | | | |
| oat | 2 | 0.2 | 13 | 65 | | | | |
| | | | | | | | | |
| total potatoes | 180 | 22 | 8127 | 887 | 683 | 503 | 307 | 135 |
| consumption | 87 | 11 | 5961 | 462 | | | | |
| plant/seed | 42 | 5 | 2166 | 425 | | | | |
| starch | 51 | 6 | | | | | | |
| | | | | | | | | |
| sugar beet | 111 | 14 | 6728 | 606 | 500 | 435 | 321 | - |
| feeding corn | 205 | 25 | - | | | | | |
| onions | 14 | 2 | 821 | 586 | | | | |
| brown beans | 1 | 0.1 | 3 | 30 | | | | |
| coleseed | 1 | 0.1 | 3 | 30 | | | | |
| hemp | 4 | 0.5 | 27 | 68 | | | | |
| others | 98 | 12 | | | | | | |

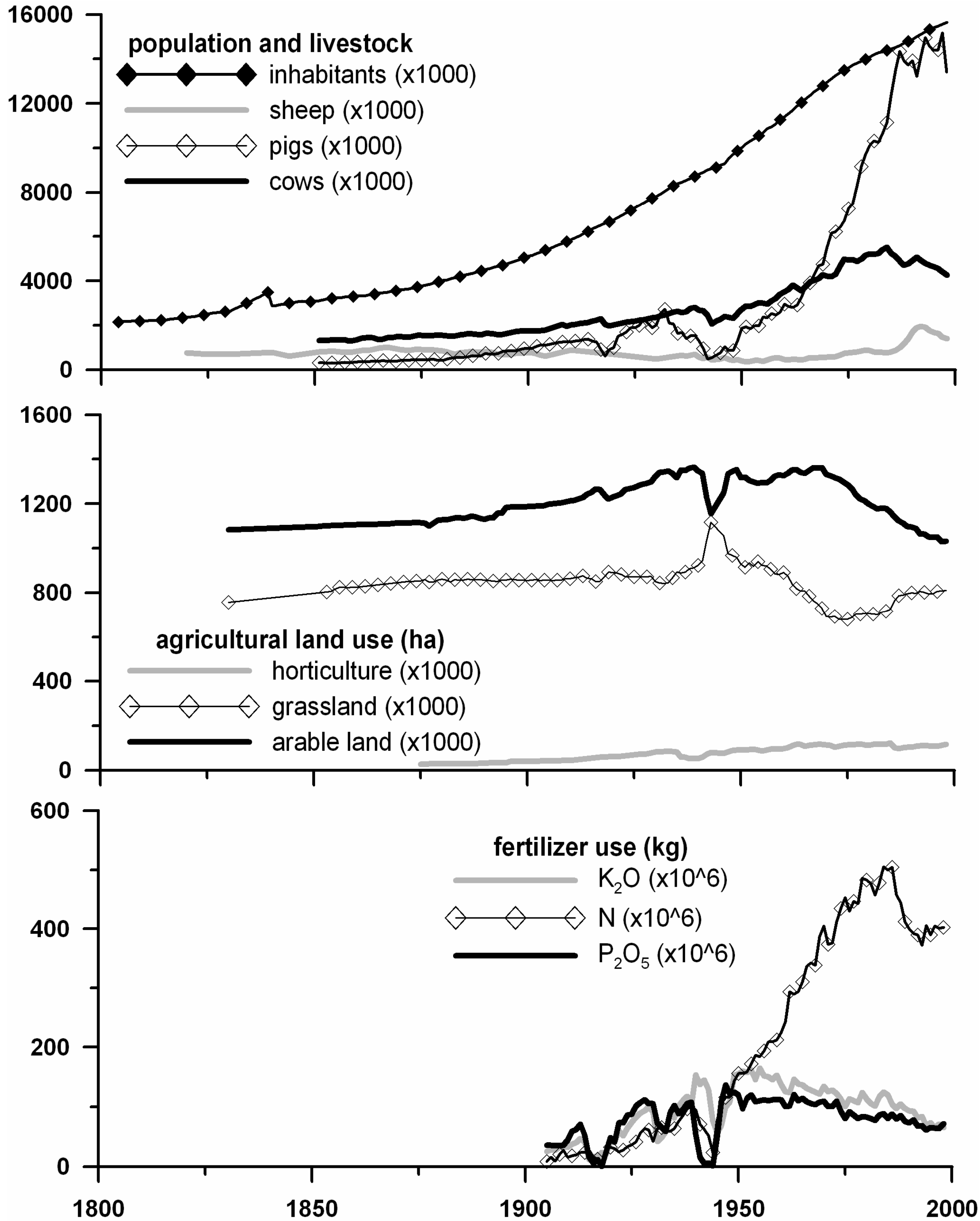
Especially during the last two centuries, the population of the Netherlands increased rapidly: from ~2 million inhabitants around 1800 to ~16 million inhabitants in 2000 (fig. 2.9a). Besides further urbanization and industrialization of the Netherlands, agricultural practice was strongly intensified. This resulted in an increase of the crop production and live stock by a factor of 2-5 over the last 200 years (table 2.8, fig. 2.9b). This increase could, amongst others, be realized through application of large scale soil improvement techniques, such as fertilizing (fig. 2.9c) and improved drainage.

Because of the tremendous impact mankind has had on the soil profile and soil properties, it should be considered one of the most important soil forming factors in the Netherlands. In the following sections, the historical and more recent land reclamation and agricultural land use patterns are reviewed in relation to soil type. Much of the historical information was taken from Barends et al. (2000), whereas the more recent land use patterns were derived from Maas et al. (1995) and CBS (2001). Finally, various soil improvement techniques are discribed.

### 2.5.2 Historical land use and reclamation

At the start of the Neolithicum (~7000 BP), the first agricultural activities occur in the Netherlands. The first settlements developed on the relatively fertile loess soils in the southeastern parts of the Netherlands. The elevated loess soils were mainly used as arable land, whereas grassland for cattle and hay production was located in the lower valleys.

At around 6000 BP, cultivation of the Netherlands extended further towards the elevated sandy soils in the southern part of the Netherlands. On these soils, small patches of arable land were created, whereas the low lying areas and brook valleys were used as grassland and hayland, mainly for cows. Large heath lands formed as a result of progressive




*Figures 2.9a, 2.9b and 2.9c* Population, live-stock and agricultural land use types over the past 200 years, and the use of fertilizer during the past century (CBS, 2001).

deforestation of the rather unfertile sandy soils, which were used for grazing livestock (mainly sheep). For a long time, large forests remained that were used for wood production.

The elevated arable lands in the sand district were locally raised with sods of heath and forest litter, which was often first used as absorbent in animal stables. This soil improvement technique started around 1300 in the southern sandy soils and slowly extended to the east and the north of the Netherlands, resulting in the formation of plaggen- or thick earth soils (section 2.6.3). These raised arable lands, so-called “essen” or “enken”, were first mainly used for the production of rye and later also hemp and barley. Of course, this led to further infertility and degradation of those soils were the sods/plaggen were derived from. At around 1500 AD, large open sandy areas started to erode as a result of overgrazing and sod-cutting for plaggensoils (Kootwijk member of the Boxtel formation, section 2.3.2). From the 17th and 18 th century onward, the extent of arable land further increased as a result of more effecient fertilizing methods (“potstal”-approach) and larger live stock.

The coastal area in the west and northwest of the Netherlands used to be covered with large areas of peat and swamps that were located behind the coastal dunes. The human settlements in this area date already from ~3000 years BP, but were first restricted to the coastal dunes. Here, the elevated old beach sands were locally used as arable land (rye and potatoes). The low lying peat lands that were located behind the dunes, were increasingly used as grassland, or were excavated. First, the surfacial “dry” peat was excavated, especially after 1100 AD, but later also the peat below the water level was excavated by dredging. These excavations resulted in the formation of large lakes, which were increasingly reclaimed after 1500 by artificial drainage using mills and pumps (“droogmakerijen”). Together with reclamation of periodically flooded land from the sea, this has lead to a strong increase of the areal extent of marine clay soils in the western coastal area. Most of these reclaimed soils are quite fertile and were commonly used as arable land (grain).

Peat excavation in the north and northeastern parts of the Netherlands started much later as a result of much lower developement compared to the south and east of the Netherlands. Excavation here started around 1600 AD and continued until the last century. In contrast to the mid- and northwestern reclamations, the subsurface often consisted of poor, Pleistocene sand, which was mixed with the remaining lower peat layer in order to improve the soil structure. Though the soils in the so-called peat colonies were used mainly as arable land, some livestock was needed to provide sufficient manure.

A part of the peat was not excavated and these areas make up the remaining peat soils in the Netherlands. Most of this peat has permanently been used as agricultural land and is mainly found in the midwest and northwest of the Netherlands. Due to its infertility and difficult hydrological properties, these soils were cultivated the latest (~2000 BP). Especially the low-lying meso- and eutrophic peat was used as agricultural land, whereas the elevated oligotrophic peat was used for fuel. As such, drainage of these peat lands was very important, which was achieved by creating a very dense network of ditches and canals. Thereby, the topsoil was often raised with mud to improve the soil stability. In the early times, the peat was both used as grassland for cattle, but also and as arable land in the better drained parts. From the 15th century onward, dairy farming became the dominant activity in these areas and since then the land has been dominantly used as grassland.

The first settlements in the marine realm are found in the northern areas and date from ~2600 BP. In order to prevent periodic flooding, the people raised patches of land with mud, organic waste and manure, so-called dwelling mounds (or “terpen”). These dwelling mouds became redundant when the northern marine area became fully endyked around 1200. From this moment on, people started to actively reclaim land from the sea, resulting in the first polders in the Netherlands (section 2.4.4). Both endykement and reclamation allowed the use of much larger amounts of land for agricultural production, mainly for cattle (cows and sheep), but also for crop production like barley, hemp and also beans.

In the southeastern marine area, the first settlements were probably disturbed by transgression between 1700 to 1400 years BP. As a result, the southeastern marine area became inhabited after 1400 years BP. The people first lived on the natural elevated areas (Old Land). As a result of successive endykement and reclamation in the period 1200-1910 AD, large areas areas of fertile land were created (New Land). These soils were mainly used as arable land for crop production. Later, fruit orchards were planted on the more heavy clay soils.

The soils in the fluviatile clay district show signs of significant habitation since 2000 BP. Cultivation was at first restricted to elevated natural levees. These were used for dwelling as well as for agricultural purposes, the low lying flood basins were grazed during the summer period, whereas the intermediate areas were kept as grassland and for hay. After large scale endykement that was finished around 1300 AD, the low lying flood basins could be used permanently. Most of these soils are difficult to work and have a poor drainage, so they were often used as grassland or for horticulture. As the dykes did not fully protect the land from periodic flooding, people commonly lived on dwelling mounds.

### 2.5.3 Recent land use and reclamation

At the beginning of the 20th century, large parts of the Dutch landscape were turned into agricultural land. Due to local variations in soil properties like fertility and highly variable ground water tables, this landscape was very diverse and the relations between soil properties and agricultural land use type were quite strict. For example, most elevated soils were used as arable land, whereas the low-lying soils with a poor hydrology were used as grassland for cattle (cows). On the relatively unfertile soils with low ground water tables, extensive heath lands were found that were still grazed by sheep. These heath lands and forests were largely cultivated in the period 1900-1950. The poor and very dry sandy soils are currently used as production forest (dominantly coniferous) or remained (semi-) natural areas (heath lands). The richer sandy soils with better hydrological properties were largly turned into agricultural land (now mainly grassland).

Around 1900, the bulk of the arable land is found on both the marine clay soils in the northeast and southwest as well as on the loess and sandy plaggen soils in the southern parts of the Netherlands (fig. 2.10a). The most important crops grown on these lands include potatoes, grain and sugar beets (table 2.8). In total, their spatial extent is about equal to the soils with dominantly grasslands or with a mixed land use type (arable land, grassland and horticulture) (fig. 2.8a). Horticulture, including fruit orchards, plays a

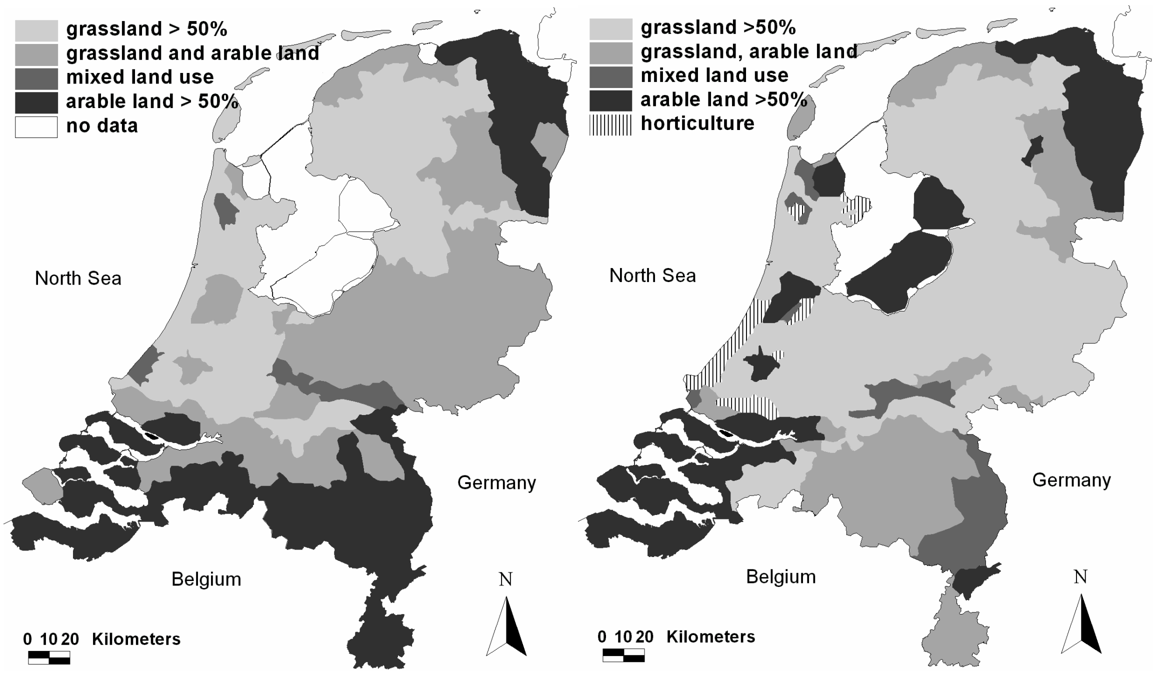



*Figure 2.10a and 2.10b* Overview of dominant agricultural land use types in the Netherlands in 1910 and 1986 (after Maas et al., 1989). Mixed landuse in both figures refers to areas with grassland, arable land, and horticulture. No data in figure 2.10a refers to areas that were reclaimed after 1910.

minor role in the agricultural landscape. It is mainly found on heavy fluviatile clays in the central parts of the Netherlands (fig. 2.8a).

After the second world war, the demand for self-sustainability with respect to crop production led to the reclamation of more arable land (the Zuyderzee-polders, figure 2.10a). Whilst the area of new arable land grew, existing arable land and mixed land use was increasingly changed into grassland (fig. 2.10b). The grasslands were needed for the rapidly expanding livestock (fig. 2.9a). In that period the area of land used for horticulture also increased, including green house horticulture (mainly in the midwest).
Most of the arable lands on the clayey soils are now used for crops like potatoes, various cereals (wheat, barley and rye) and sugar beets. Other products, which are produced in smaller quantities include beans, carrots, onions and coleseed. Some of the heavier clay soils are used for fruit orchards. Arable land in the sandy district is mainly used for the production of animal food (maize and turnips). Locally, these lands are used for consumption potatoes or sugar beets (e.g. peat colonies).

Currently, the majority of soils in the Netherlands are used as grassland, which include sandy, peaty and clayey soils that are often less well suited for crop production (fig. 2.10b). On these grasslands cows, and to a much lesser extent sheep, are kept. The remaining live stock is mainly formed by pigs and chicken, which are concentrated in the southern, central and eastern parts of the country. Peat lands are often not suitable for crop production, unless the peat layer has been excavated (e.g. peat colonies). They have often been used as permanent grassland for cattle and hay.

### 2.5.4 Profile improvement

Until the beginning of of last century, the crop yield and live stock production was restricted by fertility and physical limitations of the soils. Due to extensive use of soil improvement techniques such as deep-ploughing and fertilizing, current agricultural land use has increasingly become independent of soil type. Some of these soil improvement techniques are reviewed here, mainly because they were applied at a large scale and had a significant impact on the physical properties and layering of the original soil profile.

The physical soil properties that can restrict production are texture, organic matter content, density, layering of the profile and local topography. In general, soils with either a very high or a very low clay content and soils with a high or very low organic matter content are most difficult in terms of agricultural workability and production (Van Wijk and Willet, 1987). In order to improve these restrictive properties, three approaches can be discerned: whole profile improvement, topsoil improvement and leveling (Windt, 1969).

Whole profile improvement aims at improving soil moisture supply and root-aeration by textural changes of the full profile in combination with an optimal depth of the ground water table. This can be achieved by deep-ploughing (1-2 m) or deep-mixing (up to 4 m) of the profile, sometimes applied in combination with improved drainage (drainage tubes). Historical examples include the excavation of the northeastern peat areas (peat colonies) and subsequent reclamation by drainage, followed by mixing of the remaining peat layer with the Pleistocene sand.

Whole profile improvement was also applied to many clay-on-sand soils in the marine district (southwestern parts and young inland polders). Also, the sandy soils with a shallow impermeable layer e.g. glacial till, which are found in the north of the Netherlands, were often improved by deep-ploughing/mixing. Very poor sandy soils that were reclaimed in the 1900-1930 period were often also mixed over at least 80 cm of the profile.

Improvement of the topsoil aims at better soil workability and stability, which is especially important for soils used for grazing (disturbance by cattle). Problems of this kind occurred for example in heavy clay soils in the marine and fluviatile district, and clay and organic matter poor soils in the sand district. Often this was solved by mixing the toplayer with different subsoil material by deep-ploughing, and this approach therefore overlaps with the whole profile improvement approach. Topsoil improvement techniques for peat soils mainly include bringing up and mixing of sand as well as other material e.g. dredged mud and compost. Increased drainage (drainage pipes) also led to better stability of these soils and was therefore applied on a large scale.

Leveling of local topographical differences and upscaling of land parcels was needed to allow the efficient mechanization of agricultural practice. Reduction of local variations in topography yielded more constant soil moisture retention properties of the land. Though small scale leveling has been applied since the first agricultural activities, large scale mechanical leveling was only possible after the 1950’s. This approach was however not without negative consequences and was therefore applied only locally (Van Wijk and Willet, 1987). Upscaling of land parcels was achieved by filling up ditches and joining parcels. This frequently involved “swapping” parcels between land owners, which occurred extensively throughout the Netherlands.

As is clear, the effect of soil profile improvement techniques on the original soil profile has been considerable. Though there is no overview of the full extent of soil profile improvement practices in the Netherlands, it is clear that large areas were disturbed and lost their original geogenic layering and/or hydrology. Moreover, the large scale application of land additives like fertilizers (see fig. 2.9c), which amongst others has lead to a remarkable shift in the original vegetation, imply that not only in a physical sense, but also in a chemical sense, these soils can not be regarded as strictly natural.

## 2.6 Soil classification

### 2.6.1 Introduction

As a result of the restricted age of the parent material and a moderate climate (section 2.4), the soils in the Netherlands are poorly developed compared to those in other parts of the world. Thereby, the human influence on the soil and the soil profile has been so extensive that it should be considered as a serious soil forming factor in itself (section 2.5.6). As a result, the Dutch soil classification system deviates significantly from other classifications like those of the Food and Agriculture Organiztion of the United Nations

*Table 2.9* Soil forming processes used for classification of the two highest levels of the Dutch soil classification system (nomenclature after De Bakker and Schelling, 1989; FAO, 1998) and their occurrence within the various soil parent material districts.

| Order process | Order | FAO | Suborder process | Suborder | District |
|---|---|---|---|---|---|
| Strong organic matter accumulation | Peat soils | Histosols | Formation of mineral top layer (often also anthropogenic) | Earthy peat soils | Peat |
| | | | - | Raw peat soils | |
| Podzolization (Clear podzolic B-horizon) | Podzol soils / Podzols | Podzols | Non-amorphous humus (moder) formation | Moder podzol soils | Sand |
| | | | Amorphous humus (mull) formation | Humus /mull podzol soils (xero and hydro) | |
| Clay illuvation (“brick” layer) | Brick soils | Luvisols | Formation of hydromorphic features/gley | Hydrobrik soils | Loess (Fluviatile clay) |
| | | | - | Xerobrick soils | |
| Development A1-horizon / mineral “earth” layer | Earth soils | Fimic Anthrosols /gleysols | Anthropogenic A-horizon | Thick earth soils | Sand Marine clay Fluviatile clay (Loess) |
| | | | Formation of hydromorphic features /gley | Hydroearth soils | |
| | | | - | Xeroearth soils | |
| Little soil formation | Vague soils | Fluvisols /arenosols | Soil ripening | Initial vague soils | Marine clay Fluviatile clay (Sand) |
| | | | Formation of hydromorphic features /gley | Hydrovague soils | |
| | | | - | Xerovague soils | |

(FAO-ISRIC-ISSS, 1998) or US department of Agriculture (SSDS, 1993). For general comparison, the approximate FAO classes are given for the major soil types in the Dutch system (table 2.9). For a comparison with other classification systems, the reader is refered to De Bakker (1979).

The history of the Dutch soil classification starts in 1860 when Staring produced the first soil map of the Netherlands. This map – as well as the second soil map by Van Baren (1915) – was still very much a geological/lithological map. Both due to the complex depositional history and the lack of knowledge about soil forming processes, soil formation and anthropogenic influences played a limited role in these early maps.
Much of the later work on soil surveying and classification was done by the Soil Survey

Association of the Netherlands (Stiboka). In the later classifications, the attention shifted more towards soil profile characteristics that were the result of soil formation (as opposed to geogenic layering). Though still unfinished for the lower levels (beyond subgroups), the classification proposed by De Bakker and Schelling (1989) is considered the basis for the current soil classification in the Netherlands. An overview of the five major soil types in the Netherlands is given in figure 2.11.

### 2.6.2 Soil classification in the Netherlands

As mentioned in the introduction, the current Dutch soil classification system has a strong focus on soil formation processes and pedogenetic layering within the profile. It has a hierarchical structure consisting of four levels: Order, suborder, group and subgroup (De Bakker and Schelling, 1989). At the highest levels (order and suborder), the differential criteria that are used are related mostly to dominant soil formation processes (table 2.9). Towards the lower levels (groups and subgroups), geogenic layering of the profiles becomes increasingly important for further classification.

At the highest level of the classification, five orders are discerned: Peat soils (strong organic matter accumulation), podzolic soils (podzolization), “brick” soils (clay illuvation), “earth” soils (thick A1-horzion) and soils that show very little soil formation (“vague” soils). Apart from the hierarchy in four levels, there is also a hierarchy of criteria within one level, which means that the sequence in which they are applied is important too. For example, at the highest level podzolization is considered a more important process than the development of an A1-horizon. As such, there can be podzol soils with a clear A1-horizon, but there will be no earth soils with extensive podzolization.

The differential criteria used at the level of suborder are related to soil forming processes like gley-formation and ripening. Most important herein is the presence or absence of groundwater, which is often related to gley-formation. Gley is often found in clayey soils, but in sandy soils, these processes are defined on the basis of other criteria than gley formation (see below). Further, physical ripening of the mineral soil (for earth and vague soils) and the anthropogenic influence on the topsoil (for earth and peat soils, table 2.9) are used as differentiating criteria. Podzol soils are further classified according to the humus type (moder vs. mull) as well as the occurrence of ground water/hydromorphic features in the profile. In total, thirteen suborders are discerned (table 2.9).

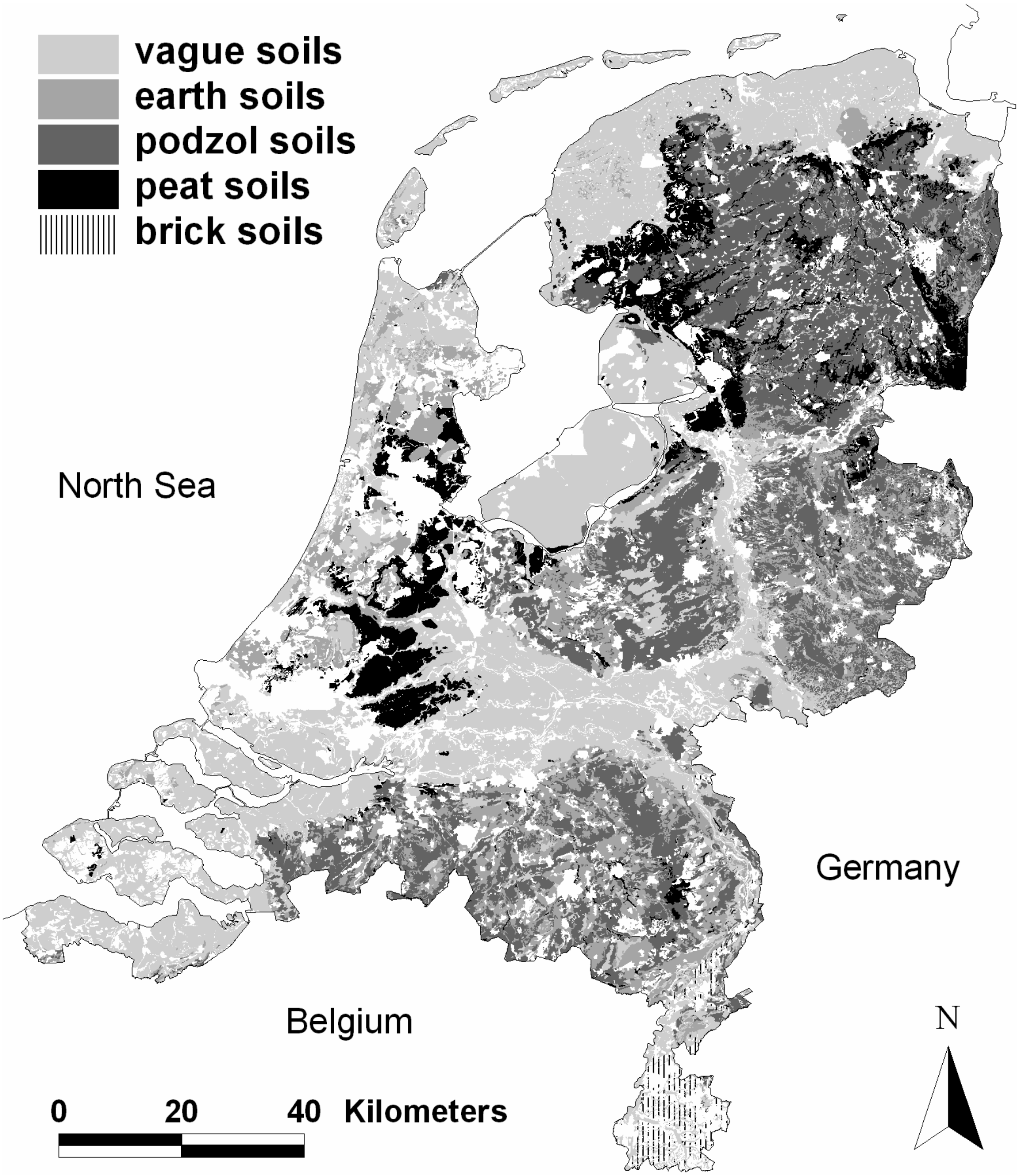



*Figure 2.11* Overview of the five major soil types in the Netherlands (after soil map 1:50.000, Steur and Heijinck, 1987). Areas that consist of inland water or built-up areas were left blank. The so-called soil associations – areas with close occurences of two or more soil types – were also left blank.

Only at the two lowest levels (groups and subgroups) are differences in parent material and the geogenic layering within the profile used as further distinguishing criteria (not shown). In total, 60 different soil classes are discerned at the level of subgroups and a description of these classes is considered beyond the scope of this overview (see for their formal definitions and description De Bakker and Schelling, 1989). The definitions and characteristics of the higher levels (order and suborder) as well as their occurrence within the previously described soil districts will be summarized next. The terminology used for the basic soil horizons is given in table 2.10.

*Table 2.10* Description of the major soil horizons used in the Dutch soil classification system (after De Bakker and Schelling, 1989).

| **Horizon** | **Description** |
|---|---|
| A0 | Organic rich horizon consisting of fresh to partially degraded organic material, which is still recognizable as such |
| A1 | Mineral or organic horizon in which the organic material is partially or fully degraded by biological activity |
| A2 | Mineral horizon, often lighter colored (bleached) as a result of eluvation of Fe/Al-sesquioxides and/or clay minerals. |
| B | Mineral horzion, often darker colored as a result of illuvation of humic substances, Fe/Al-sesquioxides and/or clay minerals from the upper horizons |
| B2 | Strongest developed part of the B-horizon |
| C | Mineral or organic horizon that is little to not affected by soil formation |
| D | Mineral or organic horizon little to not affected by soil formation, but containing different material than topsoil |
| G | Mineral or organic horizon comparebale to a C-horizon but under anaerobic conditions |
| DG | Mineral or organic horizon comparebale to a D-horizon but under anaerobic conditions |

### 2.6.3 Major soil types

#### Peat soils

Peat soils have been formed during the Holocene on both marine clays and older sandy deposits, which used to cover large areas of the Netherlands (see e.g. Stiboka, 1965). Within the current classification, peat soils are defined by having peaty material sensu lato (including "moerig", see Appendix I) over a depth of at least 40 cm within the first 80 cm of the profile. This means that these soils can have a substantial mineral topsoil (either sandy or clayey) and/or have sand or clay deeper in the profile. The sandy deeper soils can have a podzol B-horizon derived from earlier soil formation.

Peat soils are further subdivided on the basis of the organic matter content of the topsoil, which can be mineral (earthy peat soils) or organic (raw peat soils). The so-called raw peat soils are rare and are found locally throughout the Netherlands, often in nature reserves. Earthy peat soils are more common and often used as agricultural land. Here, the mineral top layer can be of depositional origin (marine/fluviatile clay) or the result of leveling. The latter can be achieved with sand (in the Pleistocene areas) or with clay-rich material (dredge mud), or city waste ("toemaak") in the Holocene areas. Often, these peat soils were excavated first, after which the remaining peat was covered. As a result, large areas of peat soils have disappeared during the previous centuries (see section 2.5).

It should further be noticed that the other soils – which will be defined below - can have an organic layer within the first 80 cm as well, but then the thickness of the layer is less than 40 cm (so-called "moerige" layer). These intermediate profiles occur rather commonly in hydro-podzol, hydro-earth or hydro-vague soils. Within the major classification of the soil map 1:50.000, these soils are therefore grouped separately under the "moerige" soils (Steur and Heijnck, 1985). As these properties are used at a lower classification level (groups) they are not further discussed here.

**Podzol soils**

Podzol soils formed exclusively in the sandy Pleistocene sediments (fig. 2.11). They are defined by the presence of a clear podzol-B-horizon below a depth of 20 cm and the lack of a thick anthropogenic A1-horizon (< 50 cm.). The definition of a "clear podzol B-horizon" is based on the extent and intensity of the illuvation of both humic substances and Fe/Al-sesquioxides, giving a typical orange/reddish color to this horizon. B-horizons where only humic substances (or only sesquioxides) are illuvated are not considered as podzol-B-horizons. The same is true when clay minerals are transported down the profile, which is reserved for the brick soils. The exact definitions for this horizon are too lengthy to be explained here: the reader is referred to De Bakker and Schelling (1989) for a formal definition and De Bakker (1979) for examples.

Depending on the type of humic substances (amorphous vs. non-amorphous), two types of podzol soils are discerned: humus podzol soils and moder podzol soils. Humus podzols are further divided based on the presence of hydromorphic features in the profile. The moder podzol soils are restricted to areas with low groundwater tables and often related to parent material rich in alumino-silicates ("mineral rich" sands). Humus podzol soils are found in areas with both low or higher ground water table and are often related to mineral poor sands. The "dry" podzol soils are characterized by iron coatings around the grains in the deeper profile and there can be a clear bleached A2-horzion. These features are absent in the "wet" hydro-(humus)podzol soils that then have a whitish or grayish (sometimes blue/greenish) color below the B-horizon.

**Brick soils**

Brick soils in the Netherlands were all formed in loamy or clayey material, mainly loess and to a lesser extent some old fluviatile deposits (fig. 2.11). Brick soils are defined by the preeminence of a textural-B-horizon (brick layer) that starts within the first 80 cm of the profile. The textural-B-horizon is characterized by the illuvation of clay minerals and sometimes also Fe/Al-sesquioxides, which is shown by a darker (browner) color and denser consistency of the material. The thickness of this horizon should at least be 15 cm and it should contain at least 10% clay fraction within the most illuvated part (De Bakker and Schelling, 1989).

Further subdivision of the brick soils into xero- and hydro-brick soils, are based on the presence (or absence) of hydromorphic features, which for brick soils are characterized by the occurrence of rusty mottles and manganese concretions in the A2 and B2-horzion.

**Earth soils**

Earth soils have been formed mostly in the sandy Pleistocene deposits, but are also found on Holocene clay and sand deposits (fig. 2.11). Earth soils are characterized by a substantial mineral (humus rich to moderately humus poor) A1-horizon, which was formed by biological degradation of organic material and/or raising with organic material, heath sods and dredged mud. The A1-horizon should have a thickness between 15-50 cm (and not have any clear B-horizon, or be >50 cm thick (anthropogenically raised; Ap-horizon). The A1-horizon should consist of humus rich or moderately humus poor material (see Appendix I). In the latter case, the A1- horizon should be distinctively darker than the C-horizon.

Further subdivision of the earth soils into xero- and hydro-earth soils, is again based on the presence or absence of hydromorphic features, which for earth soils depends also on the type of parent material. In general, the hydro-earth soils have a non-aerated C-horizon within the first 80 cm depth and/or have non-ripened material within the first 80 cm. This applies mainly to clayey soils, where also rusty or gray mottles should begin within 50 cm. In sandy soils there is an absence of iron coating around the grains below the A-horizon.

**Vague soils**

The vague soils make up a considerable part of the Netherlands (fig. 2.11) and give its pedology a rather unique character. Vague soils are characterized by the lack of substantial soil formation and occur commonly in the younger Holocene deposits (both clay and sand) in the Netherlands. These soils are actually defined as having none of the previously defined characteristics, that is that they lack a substantial organic layer (peat soils), a clear B-horizon (podzol or brick soils) and a clear A1-horizon (earth soils). Especially in (recently) reclaimed coastal areas and inland lakes, the time of soil formation is very restricted (700-30 years, section 2.5) and these soils have only developed a shallow A-horizon. Also, the inland and coastal dunes are of very restricted age and show very little horizon formation. As such, the composition of these soils will be largely comparable to that of the unaltered parent material.

## 2.7 Summary

The main purpose of this thesis is to describe and understand the bulk inorganic chemical composition of the soils and their parent material in the Netherlands. This chapter gives and introductory overview of those aspects that ultimately govern the bulk chemical composition of these soils, which are: (i) the surface geology, which makes up the parent material of these soils, (ii) the natural soil forming processes that have acted on this parent material, as well as (iii) the human influences on the soil profile and soil formation. Because the bulk soil chemistry is most directly related to its primary and secondary mineralogy, special attention was paid to the occurrence of various minerals in these soils.

The surfacial geology of the Netherlands is dominantly made up of Quaternary sediments, which were mainly derived from the rivers Rhine, Meuse and to a lesser extent also the Scheldt. The surface geology of the Netherlands can be divided in a Pleistocene lithology, made up of coarse river deposits and various glacigenic deposits, which are largely overlain by locally reworked terrestrial sediments. In contrast, the Holocene lithology largely consists of clayey marine and fluviatile sediments alternated with extensive peat layers. The Pleistocene deposits are mainly found in the elevated northern, eastern and southern parts of the Netherlands, whereas the Holocene deposits are mainly confined to the low lying coastal areas in the southwest, west and north.

The shallow Quaternary sediments formed the parent material of most soils in the Netherlands. On the basis of the lithogenesis of the top soil layer, five parent material districts, or regions, were discerned; the sand, loess, peat, marine clay and fluviatile clay district. The first two consist of mainly local eolian sediments with a Pleistocene age, whereas the non-eolian sediments have a (Late) Holocene age. If, however, not only the top layer is considered, but the whole soil profile instead (defined as 0-120 cm below the litter layer), various lithogenetic formations/members are commonly observed in these soil profiles. As a result, the classification of the soil parent material districts often cross-cuts the lithogenetic classification used in geology.

Soil formation in the Pleistocene deposits (sand and loess) started around the end of the Pleistocene, but much later in the recent Holocene deposits (marine and fluviatile clays and peat). During the Holocene, the climate has been rather constant and classifies as a moderate sea climate. The average daily temperatures range between 2 ºC in January and 16 ºC in July and the yearly precipitation varies between 400-1200 mm. Due to the restricted evapotranspiration, there is an average precipitation excess of ~200 mm, resulting in a net leaching of the soils. The Netherlands has very little elevation and can be divided in a high Pleistocene area, which lies on average 2.5-30 m above mean sea level, and a low Holocene area, which lies between 2.5 m above to 6 m below mean sea level. Whereas the sandy Pleistocene areas are generally well drained (ground water table generally > 80 cm), the more clayey Holocene deposits are much less permeable and have a shallow ground water table (25-120 cm).

In the Netherlands, mankind has had an important impact on the soil profile and soil forming processes since the Neolithicum. Much of the peat layers that used to cover the Netherlands have been excavated for fuel since Roman times. Also, the unfertile sandy soils were raised with heath sods and forest litter, often mixed with animal manure, resulting in so-called "plaggen" soils (anthrosols). More recently, mechanical improvement of the soil profile, such as deep-ploughing and leveling was commonly applied throughout the Netherlands. Furthermore, a considerable part of the coastal areas, as well as inland lakes, were reclaimed mainly in the period 1200 to 1976. Most of these soils hardly show any soil formation.

The current land surface of the Netherlands (excluding the inland water) amounts to 33.873 $km^2$, which supports a population of about 16.1 million inhabitants. About 70% of the land surface is used for agricultural purpose, whereas some 17% is of the land surface consists of built-up areas. The remaining 13% is used as production forest and nature reserves. Especially during the last century, the population as well as the agricultural production and livestock strongly increased. In addition to mechanization and physical improvement of the soil profile, the increased agricultural production was realized through the application of fertilizers and other land additives. Since the last decades the agricultural land use, which consisted up to then of roughly equal amounts of grassland and arable land, has been shifting towards more grassland for livestock (mainly cows) and arable land for animal feed, at the expense of arable land for crop production for human consumption.

The current classification of major soil types in the Netherlands is based on natural as well as anthropogenic soil forming processes that occurred in these relatively young soils. The classification of course only applies to the relatively undisturbed soils found in agricultural or semi-natural areas, which make up about 80% of the current land surface. In total, five major soil types (orders) are discerned: Peat soils (strong organic matter accumulation), podzol soils (podzolization), "brick" soils (clay illuvation), "earth" soils (thick A1-horzion) and soils that show very little soil formation ("vague" soils). The geogenetic layering of the profile as well as the geology of the parent material is considered a less important criterion, which is used only for further classification into lower levels. Both the podzol and the uncommon brick soils are found exclusively in the Pleistocene areas. Earth soils are dominantly found in the Pleistocene areas, but also occur in the Holocene area, to which the peat and vague soils are confined. As such, the Dutch soils in general are characterized by a restricted horizon formation and a considerable human influence on the soil profile.