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Paleopedology and stratigraphy on the Condrusian peneplain (Belgium)

with a reconstruction of a paleosol

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Abstract

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Fossil soil remnants on the Condrusian peneplain and in its surroundings were described and, if possible, dated. These soils are mainly of Tertiary age. In this way a number of important remnants of fossil soils were classified: the *flint eluvium*, that was formed during the Paleocene and Eocene; the *Neerrepen* soil from the Lower Oligocene; the *Boncelles 1 and 2* soils from the Upper Oligocene; the *Boncelles 3* soil and the *Andenne soil*, that developed during the Lower and Middle Miocene; a Middle Miocene *root horizon*; the *Onx* soil that was formed during Upper Miocene-Pliocene and the *Bolderberg* and *Heerlerheide* soils from the Pliocene.

The *Andenne soil*, a Miocene soil on Carboniferous limestone that formed the material called 'Andenne clay', was reconstructed. Leaching of silica in this soil appeared to have resulted in the chert caps that are still found on Carboniferous limestone.

The stratigraphic value of a particular soil profile depends strongly on the region where it is found.

Finally, some conclusions were made about the stratigraphic position of Tertiary sediments (*Onx*-gravels) and the time in which some features developed. The *Onx* deposits are placed in the Middle Miocene; formation of dolinas in Carboniferous rocks is thought to have begun during the Early Oligocene. Dissection of the Condrusian peneplain started as early as the Middle Miocene.

In the original version the title contained the indication ‘Ardennes peneplain’, which proved to be less correct.

It was not possible to make this correction throughout the text. When ‘Ardennes peneplain’ is used, the whole area between the Sambre-Meuse valley in the north and the Mesozoic cover of the Paris basin in the south is meant.

Contents

ERA	PERIOD	EPOCH	AGE	
CAENOZOIC	Quaternary	Holocene		
		Pleistocene	Weichselian	Würm
			Eemian	R-W. Interglacial
			Saalian	Riss
			Needian	M-R. Interglacial
			Elsterian	Mindel
			Cromerian	G-M. Interglacial
			Menapian	Günz
			Waalian	D-G. Interglacial
			Eburonian	Danube
			Tiglian	B-D. Interglacial
			Pretiglian	Biber
	Tertiary	Pliocene		
		Miocene		
		Oligocene		
		Eocene		
		Palaeocene		
MESOZOIC	Cretaceous	Late	Maastrichtian	
			Senonian	
			Turonian	
			Cenomanian	
		Early		
	Jurassic			
	Triassic			
PALAEOZOIC	Permian			
	Carboniferous	Silesian		
		Dinantian	Visean	
			Tournaisian	
	Devonian			
	Silurian			
	Ordovician			
	Cambrian			
	Precambrian			

Fig. 1. Chronological table (simplified, after van Eysinga, 1970).

1 Introduction

During fieldwork in the Belgian Ardennes in 1968 and 1969 I came across relics of fossil soils developed in Tertiary deposits covering the post Cretaceous peneplain. The idea was to investigate the fossil soils to learn more about the circumstances that caused their formation.

In the part of a peneplain influenced by transgressions and regressions the development of a sequence of soils may occur in the course of time. This sequence can only be seen if, during the transgression, the soil profiles developed during the previous regression are not entirely removed by erosion and are covered by new sediments. Only then can a succession of soil relics be dated and their weathering phenomena be compared. Thus the periods of severe weathering and soil formation and the age of important weathering residues can be inferred. Weathered layers, both in situ and replaced, of which the age has been determined in this way, can be treated as stratigraphical units. Consequently the presence of soils can be used for completing stratigraphical information.

Evidence about soil forming conditions may be expected in a limited number of cases, because processes occurring in later periods may have changed a number of features such as the nature of iron minerals and the presence of organic matter.

Although in Belgium the Tertiary series is almost complete, there are still some difficulties in studying such fossil soils, mainly caused by the following circumstances:
- because stratigraphy is usually based on fossils in marine sediments, dating of terrestric deposits is often rather difficult;
- an important part of the marine and terrestric deposits and of the corresponding soils have been removed by terrestric erosion or during the next transgression;
- complete soil profiles are absent and it may not be certain which part of the profile is present;
- soil material may be remaniated;
- the marine Tertiary deposits on the peneplain are poor in fossils and lithologically rather similar so that their stratigraphical position is not known exactly;
- in the area of the Ardennes peneplain the remnants of the Tertiary cover are mainly found in dolinas and are usually deformed or lying upside down.

The remnants of the profiles cannot be described in the usual pedological way because they are incomplete and have been disturbed by geological processes. For the same reasons their classification becomes speculative. So to describe and compare them some features that indicate soil formation were used. The most important of these are:

CHRONOLOGY			LITHOSTRATIGRAPHY Marine	LITHOSTRATIGRAPHY Terrestric	
TERTIARY	PLIOCENE	Amstelian		Reuverian	"kiezeloolite formation"
		Merxemian		Brunssumian	
		Scaldisian		Susterian	
	MIOCENE	Deurnian	Loxbergen and Diest sands Deurne sands Basal gravel		Browncoal complex in Holland
		Anversian	Antwerp sands Edeghem sand / Burcht gravel	lignites and sands	
		Houthalean	Houthalen and Bolderberg sands (former Bolderian) Elsloo gravel		
		Aquitanian		Andenne clays	
	OLIGOCENE	Chattian	Boncelles sands		
		Rupelian	Boom clay Nucula clay Berg sands		
		Tongrian	Vieux Joncs sands	Kerckom sands	
			Henis clay	Bautersem sands	
			Hoogbutsel sands Neerrepen sands Grimmertingen sands		
	EOCENE	Bartonian			
		Ledian			
		Lutetian			
		Ypresian			
	PALAEOCENE	Landenian			
		Montian			
		Danian			
CRETACEOUS	UPPER SENONIAN	Maastrichtian	Maastricht chalk / Kunrade-chalk / chalk / flint Gulpen chalk / Belemnite churchyard		
		Campanian	Vaals greensand / Aachen sand		

– changes in the clay mineral assemblage of the sediments due to terrestric weathering;
– formation of concretions due to the mobility of silica (such phenomena occur as crystals, silica cement and silicifications);
– development of red colours;
– presence of weathering residues from massive rocks;
– absence of stratification caused by pedological obliteration of sedimentary structures (not those obliterations caused by marine organisms).

1.1 Some problems concerning the Tertiary system of the Ardennes peneplain

Based on the available stratigraphic information an attempt was made to unravel the pattern of soils and the corresponding climate and vegetation. At first this approach proved fruitless because insufficient details on the stratigraphic position of the various sediments of the Ardennes peneplain were available.

It was possible, however, to collect new evidence and thus to improve the stratigraphy of the Tertiary deposits of the region concerned. After this, the main purposes of the study were to establish the periods during which the border zones of the peneplain were exposed to a terrestrial regime and to obtain more information about the climate during these terrestrial periods from the remnants of the fossil soils. This procedure was considered more adequate than relying on vegetation remains because chemical processes that are active in soil formation are often better evidence for climatic conditions.

Also in other parts of Belgium, soil relics in Tertiary sediments are known. It seemed worth while to find a correlation of these soils with those of the peneplain and to estimate geologically the length of the periods of soil formation. Finally, in some cases, it was tried to reconstruct the soil profile.

1.2 Outline of the investigations

Fieldwork was carried out in 1968 and 1969. The purpose was to locate well-developed fossil soil remnants in datable Tertiary sediments. The following maps were used: Geological maps of Belgium 1:500,000 (Société géologique de Belgique, 1954), and 1:40,000 (Commission Géologique de Belgique), and the 'Surfaces d'aplanissement dans l'Ardenne Belge' (Lefèvre, 1943) 1:300,000.

The main outcrops of Tertiary sediments and soil remains are found in the dolinas occurring in Carboniferous and Devonian limestones of the Condroz region. Most of them have been described in the annual reports of the 'Comité belge pour l'étude des argiles' (COBEA; 1942–1948) and by Calembert (1945b, 1948b), assessing the industrial properties of the clay and sand deposits, but the majority of the COBEA sites are not

Fig. 2. Simplified chronology and lithostratigraphy of the Upper Cretaceous and the Tertiary of Belgium and the southern part of the Netherlands (after van den Bosch, 1966; Gilkinet, 1922; Glibert & de Heinzelin, 1954; Romein, 1963 and Nolf, 1968b).

accessible now because of exploitation in shafts. For comparison some deposits with fossil soils in other parts of Belgium have been studied. The occurrences studied are shown in Fig. 22.

The best accessible outcrops were described and sampled. The fossils found were determined, if possible, by Dr G. E. de Groot and Dr C. F. Winkler Prins of the National Museum of Geology and Mineralogy (Rijksmuseum van Geologie en Mineralogie) in Leiden, cf. Buurman, de Groot and Winkler Prins (1970). Suitable samples for palynology could not be collected in the outcrops; samples from the peat layers in shafts and in borings were not available. The field samples were used in mineralogic studies and were analysed for grain size. Some samples were studied in thin sections. Some of the results have been published earlier, cf. Buurman & van der Plas (1968, 1970 and 1971).

2 Landscape and rocks of the peneplain

The Belgian Ardennes consist of several landscapes (Fig. 3). In the Condroz the morphology is mainly the result of the alternating Carboniferous sandstone and limestone deposits, folded in the synclinorium of Dinant. Here the landscape consists of a number of relatively straight depressions and ridges.

North of the Condroz are the Condrusian Ardennes. They form a straight zone, a few kilometers wide, with weakly inclined plateaus and deep valleys. In several places this landscape reaches the southern Meuse border. It is separated from the Condroz by a transitional zone, usually a shallow, straight depression.

North of the Condrusian Ardennes, towards the River Meuse, is another transi-

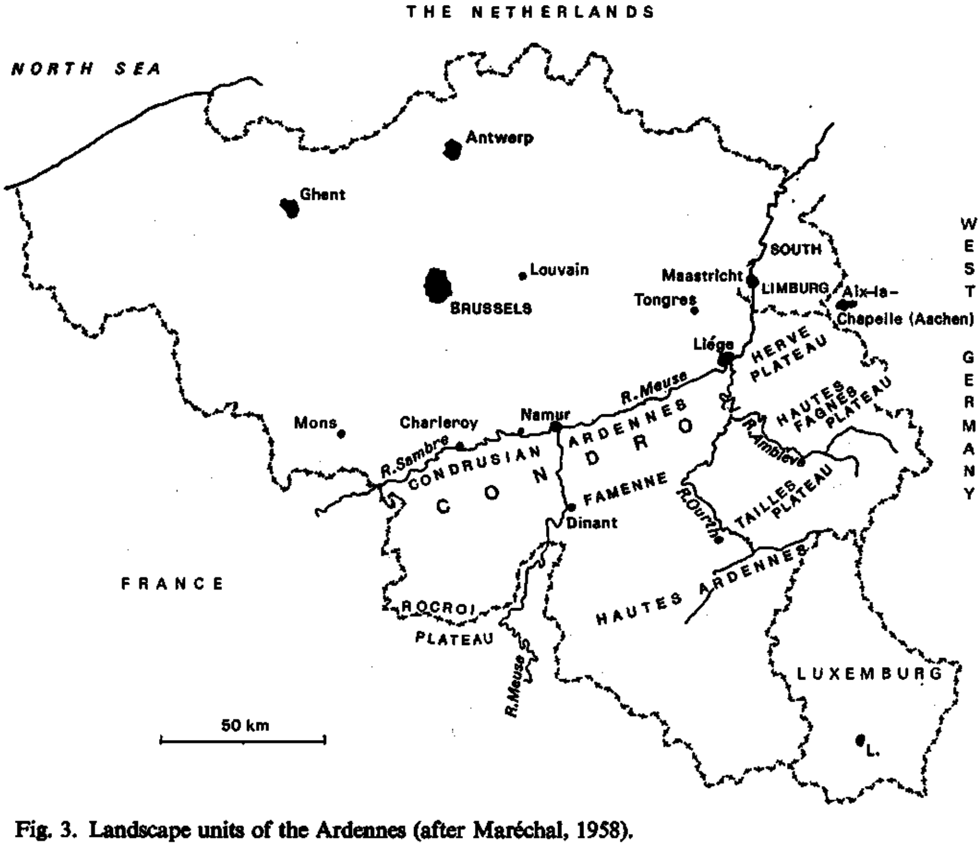

Fig. 3. Landscape units of the Ardennes (after Maréchal, 1958).

tional region. It is geologically diverse and thus forms no single landscape unit: near the River Meuse remnants of river terraces occur, north of the Meuse valley there is another area with remnants of terraces, further north the Paleozoic sediments are covered by younger deposits (Cretaceous, Tertiary).

The Famenne region, south of the Condroz, forms a different landscape. At the northern border it is very rugged, whereas its centre is flatter because of the frequent alteration of hard and soft rocks on short distances and the abundance of shales.

South of the Famenne lies the Caledonian Rocroi Massif, east of it the Stavelot Massif and the Hautes Fagnes Plateau, in the northeast the Plateau of Herve.

The Condroz and its adjacent areas are strongly affected by the river systems of the rivers Meuse, Sambre, Ourthe, Amblève and several smaller ones.

The rocks of the peneplain can be classified as follows.

2.1 Pre-Cretaceous

The oldest rocks of the Ardennes peneplain influenced by Tertiary soil formation are Paleozoic sediments. These were folded during the Hercynian orogenic period against the Caledonian Brabant, Rocroi and Stavelot massifs and abraded during the periods that followed. Nowadays these Paleozoic rocks can be found at the surface.

Erosion must have been severe during the Permian, Triassic, Jurassic and Early Cretaceous periods. No remnants of sediments from these periods are found on the present peneplain. The pre-Cretaceous peneplain was probably formed during the Permian and Triassic periods. A comprehensive description of the geology of the Ardennes is given by Rutten (1969).

The most important rocks outcropping in the Condroz region are Devonian and Lower Carboniferous sandstones, shales and limestones.

2.2 Cretaceous

Sediments of Early Cretaceous age are missing. Upper Cretaceous Turonian and Cenomanian limestones are present south of the present peneplain in the Basin of Mons. The first Cretaceous sediment which covers both the pre-Cretaceous peneplain and the surrounding basins is of Senonian age.

Upper Senonian (Campanian) Aachen and Herve sands cover a large area of the Herve plateau, south of the Netherlands border. Upper Campanian and Maastrichtian limestones are found from Mons to Maastricht; they form a large part of Netherlands South Limburg and the Plateau of Herve (see stratigraphic table, Fig. 2).

The middle part of the Maastricht and Gulpen limestones is rich in flint. This part forms a clay with flint residue when the limestone is eroded or dissolved. From the occurrence of such a clay-with-flint residue, the 'conglomérat à silex' or 'flint eluvium', it is usually concluded that there was a Senonian cover on part of the Hautes Fagnes Plateau and in the Condroz region.

2.3 Tertiary

2.3.1 Paleocene and Eocene

During the Paleocene and Eocene epochs a new peneplain was formed. In the following this peneplain will be referred to as the post-Cretaceous peneplain. Sediments of these periods were not found east of the line Dinant-Namur-Liége. It is generally assumed that the area was not covered by the sea during these epochs but that it has been exposed to weathering.

The 'flint eluvium' mentioned before is supposed to have originated during these epochs as will be discussed in Section 5.2.

If there were Paleocene and Eocene sediments in this area these have been removed before the beginning of the Oligocene epoch.

2.3.2 Oligocene

The terrestrial environment of the post-Cretaceous peneplain during the Paleocene and Eocene epochs may have lasted throughout the Early and Middle Oligocene, as sediments of these epochs are not found south of the line Namur-Liége. The most severe post-Cretaceous transgression took place during the Late Oligocene (Chattian).

Although the majority of Chattian sediments was later removed, they are known to have covered almost all of the Condroz region, the Hautes Fagnes Plateau and the Plateau of Herve. These sediments are the only known continuous Tertiary cover of this peneplain.

Nowadays, only remnants are found. The most extensive of these occur on the Cretaceous immediately north of the River Meuse between Namur and Liége and on several dissected plateaus immediately south west of Liége. Displaced remnants of this cover are also found in nearly every dolina of the Condroz.

Because Oligocene sediments play an important role in the following, they are described in more detail below.

Lithologic characteristics of the Chattian sands (Om of the geological map 1:40,000)
As mentioned before, the most extensive remains of the Chattian sediments are found near Liége. Lithostratigraphic columns from Ans (northern Meuse border) and from the plateau of Boncelles (Sart Haguet, Sart Tilman, Gonhir; southern Meuse border) are given in Fig. 4.

The thickness of the Chattian series of rocks in this area may vary from 5 to about 20 meters. Exposures in sand pits show fine, well sorted sands. Several reddened levels may occur. Near the reddened levels there are layers with rolled pebbles. At one level a glauconitic band may occur.

In the *Om* sands there are usually no fossils, except in the upper part of the series, immediately below the *Onx* gravels (to be described below). The fossils in the upper part are attributed to the Chattian because of the presence of the pelycypode *Cytherea*

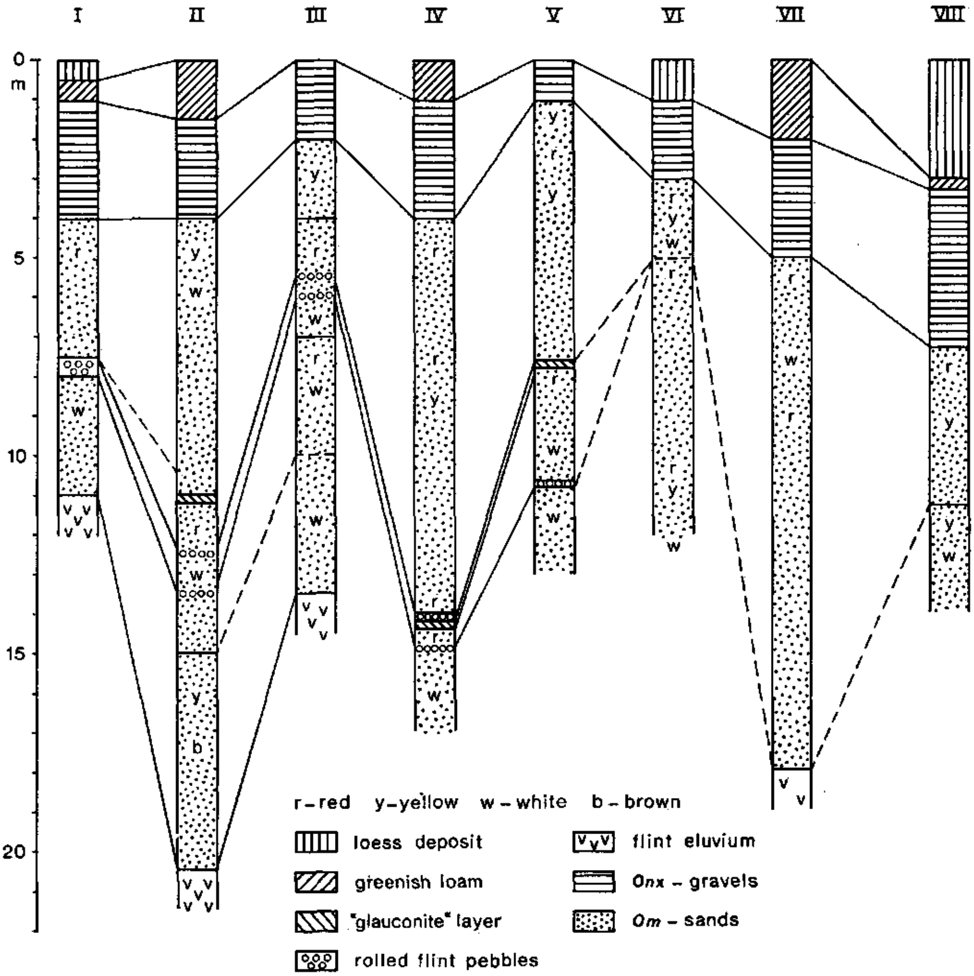

Fig. 4. Lithological columns of several Chattian deposits.
I. Sart Tilman; Lohest & Fraipont, 1911
II. Sart Haguet; Ancion & van Leckwijck, 1947
III. Sart Haguet II, Macar, 1933
IV. Sart Haguet;
V. Sart Haguet I; Macar, 1934
VI. Gonhir N. E.; Lohest & Fraipont, 1911
VII. Gonhir, E.; Lohest & Fraipont, 1911
VIII. Ans; Lorié, 1918
The 'greenish loam' is of Pleistocene age.

beyrichi Phil., which is thought to represent the Upper Oligocene.

Heavy minerals were analysed by several scientists; some are given by Anten (1919, 1921a, b). Characteristic are high percentages of zircon, tourmaline and rutile, absence of garnet and epidote, presence of some staurolite, kyanite, sillimanite and andalusite,

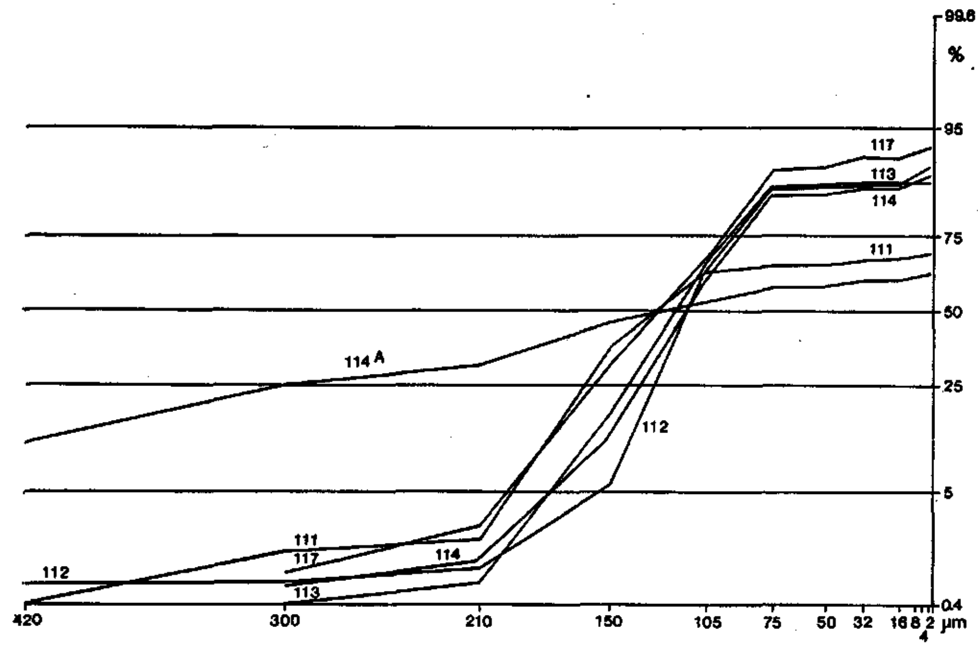

Fig. 5. Grain-size frequency distributions of a number of samples from the sand pit of Sart-Haguet near Boncelles. Numbers refer to the samples in Appendix 1 and 2.

absence of amphiboles and augite.

Throughout the profile of these *Om* sands there is evidence of marine biological activity (filled-up channels) that will have originated during deposition. Grain-size frequency distributions (Fig. 5) indicate deposition in a shallow marine environment. The Chattian sands below the 'glauconite' layer (Fig. 4, column II, IV, V) are less sorted than the overlying series, which is in accordance with a transgression phase. The grain-size frequency distributions of the sands of the Herve and Hautes Fagnes Plateaus show pronounced beach features. This may indicate the extension of the Chattian sea.

The *Om* sands may occur on Cretaceous sediments (Plateau of Herve), on Lower Oligocene deposits (north of the River Meuse between Namur and Liége) and on 'flint eluvium'. They may also occur directly on the Paleozoic rocks of the Hercynian massif, where the sands are usually, but not always, conserved in dolinas in Carboniferous and Devonian limestones. Mostly deposits on shales and sandstones are removed.

In the dolinas the *Om* deposits represent, as far as is known, the oldest filling material except for the region of Sambre-et-Meuse, west of Namur, where Landenian (Paleocene) sediments occur in dolinas.

The literature does not give grain-size frequency distributions or analyses of heavy minerals of sands preserved in dolinas, except for some samples from the Plateau of Herve (Macar, 1937, 1947) which are similar to those of the Boncelles plateau.

2.3.3 Neogene (Miocene and Pliocene)

The post-Cretaceous peneplain, covered with Chattian sediments, was exposed to a terrestrial environment during the time that several Neogene transgressions affected the region north of the line Namur-Liége. This exposure has caused severe weathering and erosion and may well be called the next peneplain formation: the post Oligocene peneplain. The only sediments known from the Neogene on this peneplain are lacustrine clay deposits (*Ona* of the geological map 1:40,000) also called 'plastic clays' or 'Andenne clays', and remnants of river terraces (*Onx* of the geological map 1:40,000). The lacustrine clays as well as the Chattian sands and the terrace deposits have been used for commercial purposes so that sand and clay pits provide many exposures.

The Neogene sediments also play an important role in the following. Their main characteristics are given below.

Lithologic characteristics of the clays (Ona) Two kinds of plastic clays are known from the Condroz and Sambre-et-Meuse regions: a residual clay, derived from Upper Carboniferous shales, can be found in situ. This kind of clay has not been studied by the present author. The second kind, a lacustrine clay deposit is only found in dolinas. A review of litterature on these clays is given in Appendix 3.

The material of the lacustrine clay deposits was derived from the immediate environment of the dolina (the dolinas are generally found at the contact of limestones with other rocks, such as sandstones and shales). Deposition in the dolina is controlled by erosion, changes in the water table in the dolina and collapse sinks. The fact that

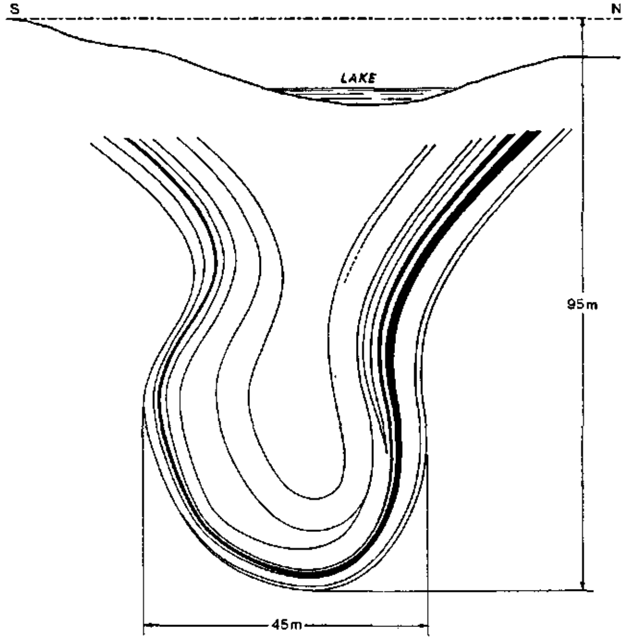

Fig. 6. Schematical cross section through a dolina, filled with lacustrine clays. White lenses represent clays, black ones peat layers.

the dolinas have been active at least from the Chattian up till present explains why next to nothing remains of the original sedimentation pattern. Fig. 6 pictures one of the more regular structures that may occur (COBEA I, p. 60). The lenticular shape of the lacustrine deposits is explained by the above reasoning.

A sand layer, attributed to the Chattian, is usually present between the lacustrine deposits and the dolina walls. The lacustrine deposits are covered by sands and gravels. The sediment usually exists of sandy clay and clay layers alternating with organic deposits.

Gilkinet (1922) determined the vegetation remains from the top-sediment of the deposit of Champseau, and placed the assemblage in the Aquitanian (Lower Miocene). The clays are considered to have been reworked from the shales of the Upper Carboniferous, but this assumption in only based on the absence of lime.

The *Ona* deposits are frequently brightly coloured. Yellow, red, gray, white and purple occur.

These clays have been analysed by the COBEA (reports I-VI), with chemical, X-ray diffraction, spectroscopic and grain-size methods. Reported clay minerals are: kaolinite, mica, halloysite and gibbsite. Grain-size frequency distributions show variations in clay content ($< 1\,\mu m$) from 30–80%. However these analyses are difficult to use because of the applied analytical methods, that differ from recent ones.

The first COBEA report (1943) mentions two tendencies in the chemical properties of lacustrine deposits: for the northern deposits a decrease in aluminum content with depth and for the southern deposits the reverse. Both turn out to be caused by the clay content and not by the mineralogical composition. There is a linear relation

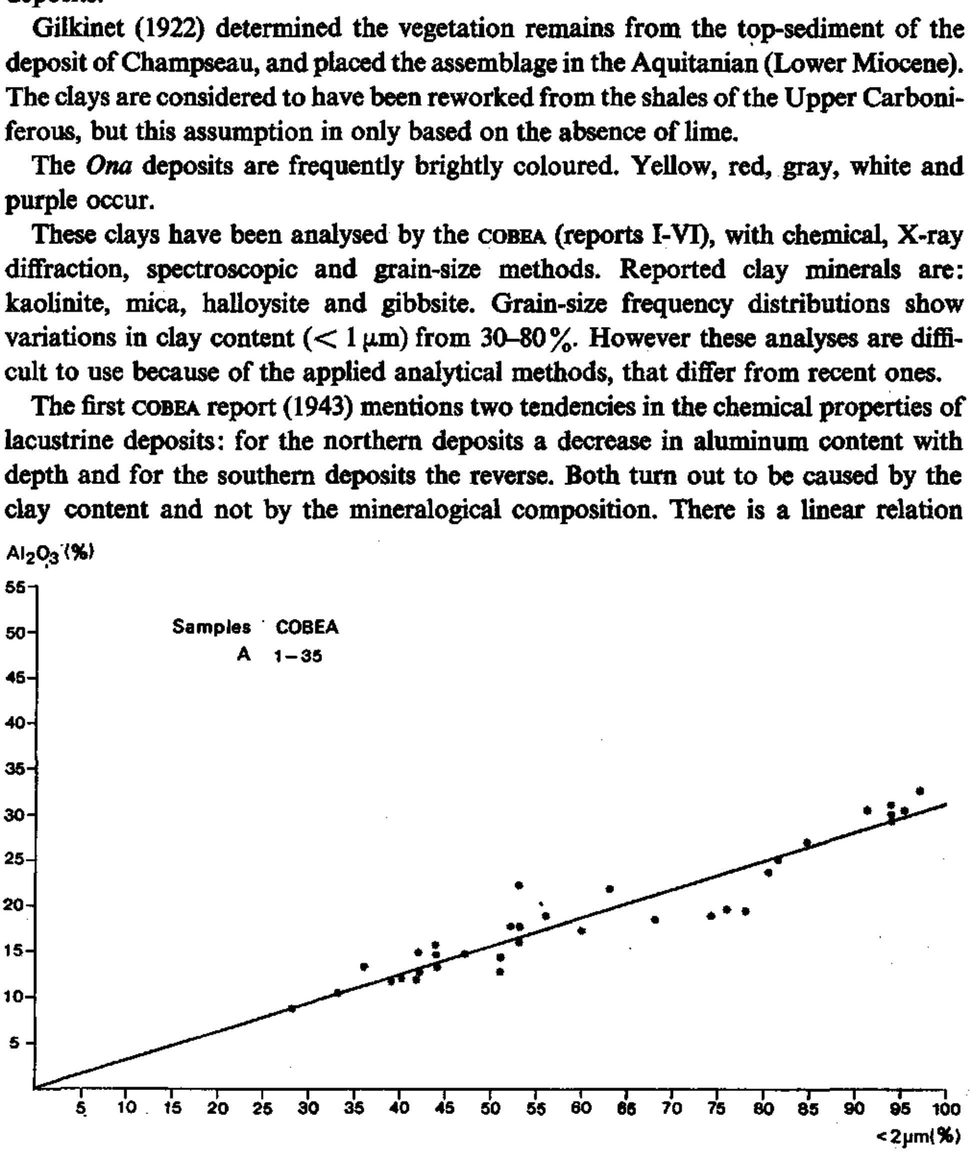

Fig. 7. Relation between clay content (smaller than 2 µm) and Al_2O_3 content of 35 COBEA samples of lacustrine clays.

Table 1. Lithological composition of the *Onx* gravels (after Macar & Meunier, 1954).

Component	Fractions	Bulk sample
Quartz	33–87%	
Rounded quartzites	14–56%	17–31%
Flat quartzites	0– 9%	
Flint		< 1%
Silicified oolites	0– 1%	
Silicified rocks	up to 5%	0.3‰
$K = \frac{100 \text{ quartz}}{\text{quartz} + \text{quartzites}}$	increasing with decreasing fraction diameter, increasing towards the east	
Flat quartzites	increasing towards the east	
Silicified oolites and rounded quartzites	increasing towards the east	

between clay content and Al_2O_3 content. For the samples COBEA. A1–35 this relation is given in Fig. 7.

The lacustrine deposits may be thicker than a hundred meters.

A mineralogical study of the underlying sands was never published.

Lithologic characteristics of the Onx sands and gravels Although many papers on the *Onx* gravels have been published, only Macar & Meunier (1954) give quantitative data about the lithological composition. They place the gravels in the Pliocene (A discussion on the age of this sediment is given in Section 5.3). Macar & Meunier divide the gravels into two groups: the 'Graviers liégeois' and the 'Traînée mosane'. The 'Graviers liégeois' mainly consist of quartz and Ardennes sandstones; there is usually no flint or chert. These gravels occur only along the River Ourthe and are regarded as an Ourthe Fan deposit. The 'Traînée mosane', the gravel deposits along the River Meuse, has been carefully studied over a distance of about 50 km. The main constituents and characteristics of these gravels are given in Table 1.

The *Onx* deposits occur frequently on *Om* sands, but may als ooccur on Paleozoic rocks of the Hercynian massif; they can be found both in situ and in dolinas.

2.4 Quaternary

During the Pleistocene epoch the Ardennes peneplain was uplifted, tilted and dissected. Most of the unconsolidated sediments (the Tertiary sediment cover and part of the soils on top of it) was removed. No marine deposits are known from the Quaternary period.

The loess deposits, formed during the Saale and Weichsel stages, and the solifluction deposits from these stages, were partly disturbed by later colluviation. A few remnants of Pleistocene terraces remain as the only relics of the period from the end of the Pliocene till the Saale glaciation.

Recent deposits of colluvial and fluvial sediments are not dealt with in this paper.

3 Remnants of fossil soils

The layers and/or horizons considered remnants of fossil soils are described in ten groups. Stratigraphical information was taken from the Belgian geological map 1:40,000 and from Glibert & de Heinzelin (1954), Fourmarier (1934), Tavernier (1938) and Calembert (1945b). Habit, parent material and cover are described systematically.

Flint eluvium The flint eluvium usually consists of brown to reddish brown clay and loam with abundant flints. It was studied in the surroundings of Epen (the Netherlands). Usually it lies on deposits of Campanian and Lower Maastrichtian age. Contact with underlying limestone shows a fairly rounded lapies relief. This suggests, as does the presence of large amounts of flints that belong in the higher strata of the sedimentary series, that the flint eluvium is probably a weathering residue of Senonian chalk. In this case, that parent material is Maastrichtian chalk.

The oldest deposits covering the flint eluvium are the Neerrepen sands (Lower Oligocene). The contact is found north of the river Meuse, between Namur and Liége.

Neerrepen soil The upper part of the Neerrepen sands, as exposed in the clay pit of Hénis (Fig. 22:2), shows distinct reddening. In the reddened part fossil root channels occur, associated with jarosite and gypsum. On top of the reddened layer is a layer of about twenty centimeters that is nearly white. The reddening is due to the presence of organic matter.

The presence of organic matter in a part of the profile, the root channels and concretions and the fact that sedimentary structures are absent in the white layer and in the upper part of the reddened layer, indicate fossil soil formation.

The parent material is, as explained before, the Neerrepen sand (Lower Oligocene). This is in the Hénis clay pit overlain by the lagoonary sediments of the Hénis clay (Lower Oligocene).

Henis peat layers The Hénis clay, as exposed in the Hénis clay pit (Fig. 22:2), shows two distinct peaty clay layers. It is evident that these developed under vegetation. Absence of discernible vegetation remains allows the term 'soil' for these layers. The lower peat member is intercalated in the Hénis clay; the upper peat member is developed in the top of the Hénis clay and covered by a clayey phase of the Vieux Joncs deposits, rich in the marine gastropod *Cerithium*.

Boncelles soils In the Upper Oligocene (Chattian) sand deposits (*Om* of the geological map 1:40,000) there are three levels with bright red colours and disturbed marine structures. These three levels are exposed in the sand pit of Sart Haguet, near Boncelles (Fig. 22:18). The sands were already described in Section 2.3.2. Below the upper reddened horizon of the youngest soil the sands are somewhat cemented. Below each reddened horizon, a series of slightly reddened bands occur. Each of the reddened horizons is discordantly overlain by the younger sediments. No traces of fossil roots are found in the reddened horizons. On top of the two lower horizons there is a niveau rich in pebbles; the upper horizon is overlain by the terrestric *Onx* deposits. The reddened horizons are supposed to be remnants of soils because of the absence of sedimentary structures, the colours and banding and the discordances on top of them.

Andenne clays (Ona of the geological map 1:40,000) The Andenne clays have been described in Section 2.3.3 as a lacustrine deposit in dolinas. The material of these lacustrine deposits is generally supposed to have been redeposited from the surroundings of the dolinas. The dolinas are usually situated at the contact between limestone and other sediments such as shales and sandstones. The material of the lacustrine deposits will have been derived from soils developed on these rocks. Bright colours (e.g. red, yellow, purple) in the lacustrine deposits, that can not possibly have formed under water, suggest that the material originated from soils.

The Andenne clays lie on Chattian sands (in the eastern part of the peneplain) or on Paleocene sands (in Sambre-et-Meuse). On the lacustrine deposits peat layers have developed that were assigned to the Lower Miocene (Aquitanian) by Gilkinet (1922). Such peat layers are also found intercalated in the lacustrine series.

Exploitation occurred till about 1950 mainly in shafts that are now closed. Recently the lacustrine clays have been exploited in open pits and therefore many deposits are accessible. However there is hardly any literature about the newer excavations.

Soil relicts in the Continental Miocene The Continental Miocene is well exposed because of its commercial importance. In the Miocene sand deposits there are several lignite levels. Both the sand and the lignite are exploited. Although the browncoal levels are very good stratigraphic guides, they are not included in this study because enough is known about their stratigraphical position. One exception will be made.

In the Beaujean sandpit near Heerlen (van der Waals et al., 1960) the Miocene below the lowest lignite seam (equivalent with the Morken seam in Germany) is exposed. In the lowest part of the excavation a root horizon crops out. This horizon is characterized by the brownish colour of the sands and abundant vertical root channels (that may have belonged to a *Taxodium* species; Dr Zagwijn, pers. commun). This horizon originated from a tidal marsh vegetation.

The parent material is a Miocene criss-cross bedded sand, perhaps contemporaneous with the Belgian sands of Houthalen. The horizon is covered by the Miocene 'Browncoal Formation'.

Bolderberg soil In marine Miocene deposits from the Bolderberg (Fig. 22:1) that according to Tavernier (1938) belong to the Diest sand, a red horizon has developed. This red horizon is also found in Diest sands from the 'Kesselse Bergen' near Louvain, the 'Kluisberg' near Ronse in East Flandres (Gaillez, 1967) and many other, relatively high places in west and middle Belgium. Mostly the reddened horizons, consisting of glauconitic sand cemented by iron, form the summits of the hills because the iron pans formed in these horizons were fairly resistant to erosion.

De Diest sands show, as did the Chattian sands, sedimentary structures such as layering and burrow holes. The reddened horizon is usually homogenized and no sedimentary structures are discernible. Colours of the reddened horizon are reddish brown to brightly red.

The reddened horizon is supposed to be a remnant of a soil because of the absence of sedimentary structures, the downward gradually vanishing red colour and the discordance on top of it.

The Bolderberg soil is usually covered by loess deposits. At the Bolderberg, near Hasselt, the Diest sand, in which the soil developed, is underlain by Bolderberg sand (probably equivalent with the Elsloo gravel).

Onx soil The *Onx* gravel deposits, the age of which will be discussed in Section 5.3, show red horizons in both the gravel deposits themselves and the intercalated sands. These soil remnants are found in the 'Traînée mosane' as well as in the 'Graviers liégeois'.

The *Onx* deposits north of the River Meuse between Namur and Liége and at Boncelles are in situ. Here reddened horizons occur on top of the gravel or sand deposits. In the Condroz and on the Hautes Fagnes plateau *Onx* deposits with soil relicts have been reworked and are found, e.g., in dolinas. Therefore, in these regions nothing can be said about the structure of the *Onx* deposits. In the reddened horizons of the *Onx* deposits north of the River Meuse between Namur and Liége, clay skins are abundant and discernible in the field. They are also present in the *Onx* deposits covering the Chattian sands at Boncelles.

The *Onx* deposits are underlain by Chattian sands or older deposits and overlain by quaternary loam or loess deposits.

Residual soils on Carboniferous limestones These soils consist of residual clays and silicified chalk (chert).

In the Condroz *residual clays* occur on limestones of Carboniferous age. The clays are brown or yellowish brown and may show shrinking and swelling features. The contact between clay and limestone shows karst features; voids and holes in the limestone are filled with clay. Remnants of the clay are generally shallow; they are covered by loess deposits or colluvia and frequently mixed with one or both of these.

The *chert caps* are frequently found on Tournaisian and Viséan limestones. They are thought to be silicified under the influence of soil forming processes. They will be discussed in Section 5.1.

Remnants of the chert covers are frequently mixed with the residual clays.
The colours of the chert can be white and gray or black.

Residual soils on Senonian limestones These soils consist of residual clays or silicified chalk.

In Netherlands South Limburg, the *residual clays* occur on chalk of Maastrichtian and Campanian age. Contact with the underlying chalk shows a karst relief; pockets in the limestone are filled with these clays (Dutch: kleefaarde).

The clays are brown or yellowish brown. They show distinct shrinking and swelling features such as cracks and slickensides. Remnants are generally shallow; they are covered by loess deposits or colluvial material.

Both in Netherlands South Limburg and in Belgian Limburg, remains of *silicified chalk* occur on top of chalk of Maastrichtian or Campanian age. They were sampled at:

a. Platte Bosch, near Simpelveld (the Netherlands) (Fig. 22:30) where it consists of soft, white, light, porous material that does not react with concentrated HCl. The silicification took place on Kunrade chalk, it is covered by Pleistocene material of the Noorbeek-Simpelveld terrace.

b. Osebos, near Gulpen (the Netherlands) (Fig. 22:21), where the material has the same appearance as at Platte Bosch and has developed on Gulpen chalk. It is not covered by other sediments.

c. Hallembaye, Belgian Limburg (Fig. 22:23) on Maastricht chalk. The material is less porous and more compact than that from the previous places. It is covered by Lower Oligocene sands (Van Rummelen, 1938). The silicified layer contains brownish flints.

4 Analytical data

The numerical results of the analyses are given in Appendix 2. The clay mineralogical composition and the heavy mineral composition were determined. Clay minerals were studied with X-ray and differential thermal methods and with the electron microscope. Grain size analyses were made.

4.1 Procedures

From various outcrops where field observations suggested the presence of fossil soils, at least two samples were taken from every soil remnant. Underlying and overlying layers were sampled only when the stratigraphic position had to be established. In dolinas horizontal as well as tilted sediment complexes that showed remnants of fossil soils were sampled, but only when their relation was clear. Of some remnants of soils undisturbed samples were taken for thin sections. In layers containing silicified fossils or chert, both the chert and the fossils were collected to determine the origin of these layers and their original position if they had been reworked. When the relation between soil and parent material was clear, the parent material was also sampled. Senonian and Carboniferous limestones were sampled to determine the original non-calcareous mineral content, especially the clay minerals.

Granulometric analysis was carried out by the methods used at the Laboratory of Regional Soil Science (see van der Plas, 1966), with fraction limits 2, 4, 8, 16, 32, 50, 75, 105, 210, 300 and 420 µm.

For clay mineralogical analysis the samples were treated with H_2O_2, sodium dithionite and dilute HCl to remove organic material, free iron and lime, respectively. The fractions < 1 µm and between 1 and 2 µm were prepared and saturated with Ca, K and Mg. The analyses were carried out on these fractions.

X-ray analysis was carried out with a diffractometer on samples kept in an atmosphere of 50% relative moisture and on samples treated with glycerol. Peak area percentages (Porrenga, 1967) of the diffractometer traces were measured. Additional Guinier-de Wolff photographs were taken of samples treated with glycerol. Glycol treatment on Mg clays was superfluous because no vermiculite was present.

Several electron micrographs were made with a Philips EM-200 apparatus.

For the differential thermal analysis, DTA-traces were made of several Ca-saturated samples kept in an atmosphere of 50% relative moisture.

The heavy minerals of the fraction 50–420 µm were separated in bromoform (s.g. 2.89). Percentages of minerals in the heavy fraction were determined by counting.

Table 2. Grain size indices (after Doeglas, 1968).

Sample	Index	Sample	Index	Sample	Index	Sample	Index
7	13340	44	14580	83	50000	112	33440
8	13340	46	15800	84	15600	113	33440
11	59000	48	23800	85	15600	114	33440
12	59000	49	13470	87	33400	114a	12400
13	58000	50	34000	89	37000	117	23340
14	58000	51	13460	90	39000	153	33440
16	15800	53	13440	91	30000	155	33440
20	47000	54	14700	92	37000	158	34780
21	47000	55	14700	93	57000	164	24440
23	14800	56	36670	94	35700	165	33345
24	26800	57	18000	95	38000	166	23330
27	02360	58	16000	96	16800	167	22334
29	24000	60	14700	97	14700	168	23330
31	56000	61	15700	98	37000	170	33440
32	15000	62	25700	99	15800	171	33340
35	35790	63	35680	100	25700	172	36790
36	25600	71	12300	102	35600	188	34440
37	15600	72	23300	104	47890	189	33440
39	34570	80	16700	105	15700	190	34440
41	13580	81	14570	106	58000	191	34440
42	12580	82	46000	111	23400		

4.2 Grain-size frequency distributions

The grain-size frequency distributions were plotted on probability paper and indexed in accordance with Doeglas' method (1968; see Table 2). The application of these indices to characterize the sedimentation environment is, however, very limited, as they are intended for fresh, unaltered sediments, whereas all sediments considered here have undergone certain changes. The graphs supply particulars on admixtures and alterations of the sediment and on its original nature. They are not reproduced here.

The samples with similar grain-size characteristics may be grouped as follows.

The samples 7–8 (Neerrepen sands from Hénis), 111–117 (Chattian sands from Boncelles), 153–155 (Oligocene sands from Hallembaye), 170–171 Neerrepen sands from Berg) and 188–191 (Oligocene sands from dolina Ouhar I) show characteristics of shallow marine deposits to which the fraction < 2 μm has been added after sedimentation.

Sample 114a (Chattian sand, glauconitic layer, from Boncelles) shows a fairly large coarse fraction, presumably because of a fluviatile influence in a shallow marine environment.

The samples 11–14 (Hénis clay from Hénis) have probably been deposited in a lagoon or on a tidal flat because of the fossil fauna; their grain-size frequency distributions support this idea.

Sample 16 (deposit from the Louveigné dolina) has grain-size characteristics pointing to a mixture of two components: a coarse fraction of fluviatile origin, and a fine fraction presumably representing a weathering product of Carboniferous limestone. It contains halloysite nodules probably derived from the limestone (Buurman & van der Plas, 1968). The sediments have been reworked and mixed after deposition in the dolina.

The samples 20 and 21 (clays from the Louveigné dolina) are from heavy clay deposits, probably weathering clays of the Devonian limestone in which the dolina has been formed. These clays have been redeposited in the dolina as a lacustrine sediment.

The samples 23 (Sprimont), 32 (Florzé I), 36 (Florzé II) 37 (Florzé II), 41, 42, 44 (Bois de Comblain), 49, 51, 53, (Ouhar I), 60, 61, 62 (Buresse), 54, 55 (from pockets in the limestone in Ouhar II) and 55, 57 (from pockets in the limestone in Ouffet) are mixtures of shallow marine deposits with weathering clays from the Carboniferous limestone. Some clay enrichment may have taken place. The coarse fractions, > 250 μm, consists exclusively of silicified fragments.

The samples 27 (Florzé I), 29 (Florzé I), 35 (Florzé II) and 39 (Bois de Comblain) have grain-size characteristics suggesting an admixture of fluviatile deposits with clay.

The samples 46 (Bois de Comblain), 48 (Ouhar I) and 50 (Ouhar I), taken from heavy clay layers intercalated in Oligocene sands, have grain-size characteristics pointing to an enrichment of shallow marine sands with clay.

The samples from the Tournaisian/Viséan limestones, 24 (Sprimont), 31 (Florzé I), 56 (Ouffet), 63 (Buresse) and 172 (Rivage) are the insoluble residues of the limestones after HCl treatment. The main part of the fractions > 150 μm are silicified fragments. Sample 56 consists of newly formed quartz almost exclusively; the fractions > 50 μm consist of aggregates, the fraction 32–50 μm of euhedral quartz crystals (see photograph 5 in Buurman & van der Plas, 1971), the smaller fractions solely contain aggregates and parts of crystals.

The samples 71–78 (*Onx* deposits north of the River Meuse) show typical fluviatile features (very bad sorting) and some admixture of clay.

The samples 80–85 (Biesme dolina), 87–94 (Orêt dolina), 96–100 (Morialmé dolina) and 101–106 (Bioul dolina), all from lacustrine deposits in these dolinas, show fluviatile influences (80, 81, 84, 85, 97–100, 102, 105) or shallow marine influences (87–94) and very good sorting towards fine fractions (82, 83, 93, 104, 106). There is an evident mixture range in the samples 87–94, with end members 87 and 93. The mixing ratio is about 5% (87) and 95% (93) (Figs. 8 and 9).

Sample 158 (silicified chalk on top of Maastricht chalk from Hallembaye) is probably a mixture of material derived from the chalk, silicified chalk and shallow marine sand from the overlying Oligocene.

The samples 164–168 (Aachen sand from the Herve plateau) show typical beach features with hardly any alteration.

4.3 Clay minerals

General remarks The clay mineralogical composition of the samples shows no tendency towards systematic variation with age of the deposit. This was, however, expected, because of the large differences in climate, parent rock and other factors that formed or altered the clay minerals. The composition reveals an assemblage pointing to a long period of exposition to various soil forming processes.

In several samples only one, or almost one clay mineral is present. This is so, e.g., in samples 163–168, 131–132, 134–140 and 7 where smectites dominate. Only mica minerals are present or they dominate in the samples 41, 49, 51, 61, 62 and in the HCl residues of Carboniferous limestones. In samples 111–118, 89–95, 40, 48 and 87 solely kandite minerals are present or preponderant.

The clay mineralogical composition is listed in Peak Area Percentages (PAP) (Porrenga, 1967). These percentages are not quantitative values: they give the relation

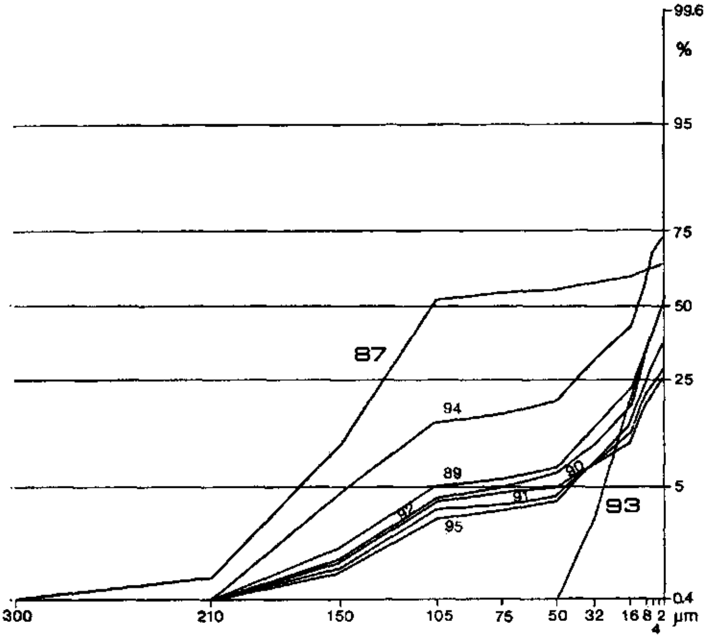

Fig. 8. Grain-size frequency distributions of the samples 87–94.

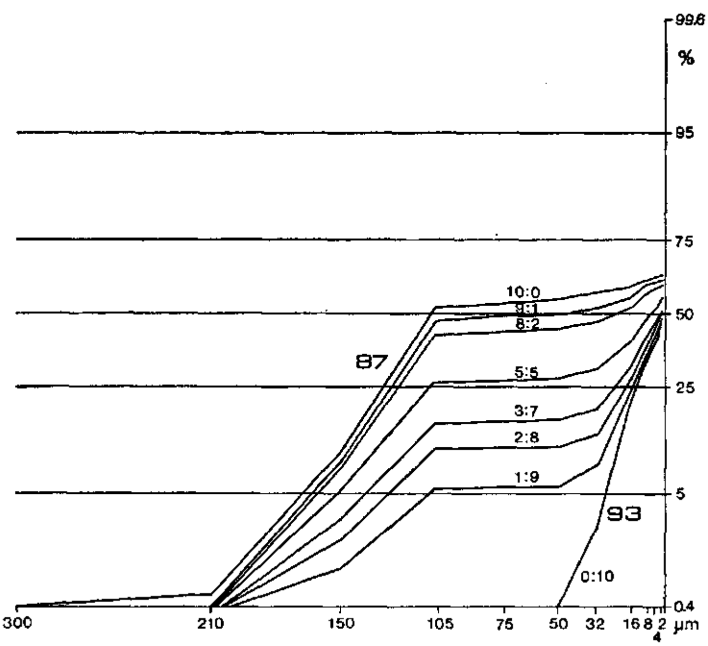

Fig. 9. Grain-size frequency distributions of different mixtures of samples 87 and 93

between the areas of the base reflexions of the minerals after a uniform treatment.

Thin sections were made from undisturbed soil samples. Any orientation of clay along voids, around structure elements or in the matrix will be mentioned in this chapter.

The different soils will be treated chronologically, starting with those which are generally considered to be the oldest. Analyses of unaltered rocks etc., are described after those of the soil remnants.

The stratigraphic conclusions will be discussed in the same order. Where our conclusions deviate from current ideas, some soils will be treated in a different sequence.

Colours of the samples after removal of organic matter, if relevant, are given in Munsell-units, or, when Munsell-units do not allow classification, in units of the Standard Soil Color Chart.

Both the composition of the fraction smaller than 1 μm and the fraction 1–2 μm have been estimated. The latter is mentioned only when it markedly differs from that of the smaller fraction.

The presence of quartz in the clay fraction is indicated with 'Q'. Minerals of the kandite, mica and smectite groups are indicated as K, M and S, respectively.

Systematic description

Upper Senonian Aachen sand

	K	M	S	
Locality: La Calamine (Fig. 22:24)				
Sample 163, upper	7	17	76	
Sample 164	+	12	88	Q
Sample 165, lower	0	19	81	Q
Locality: Gemmenich (Fig. 22:25)				
Sample 166, upper	4	15	81	
Sample 167, lower	2	14	84	
Locality: Rouscheweide (Fig. 22:26)				
Sample 168	0	2	98	Q

Although silica is evidently mobile in these profiles, it probably did not originate from the clay fraction (high smectite content). Its movement is characterized here by the occurrence of cemented sandstones and silicified wood. The samples with quartz in the clay fraction must have been taken from places where silica had accumulated.

Flint eluvium

	K	M	S	
Locality: Vijlener Bos (Fig. 22:22)				
Sample 141, colour 2.5YR 3/6, dark red	21	29	50	
Sample 142, colour 5YR 4/8, yellowish red	23	22	55	Q

The samples show a lower smectite content than the limestone from which the flint eluvium is thought to have formed. The alteration of smectite may account for the presence of quartz in the clay fraction.

The presence of mica in these clays calls for an explanation. Theoretically it is possible that the weathering of smectites results in illite, which requires a certain amount of potassium. It may also be surmised that fluviatile or aerial transport have added the illite, but the available data do not point in this direction.

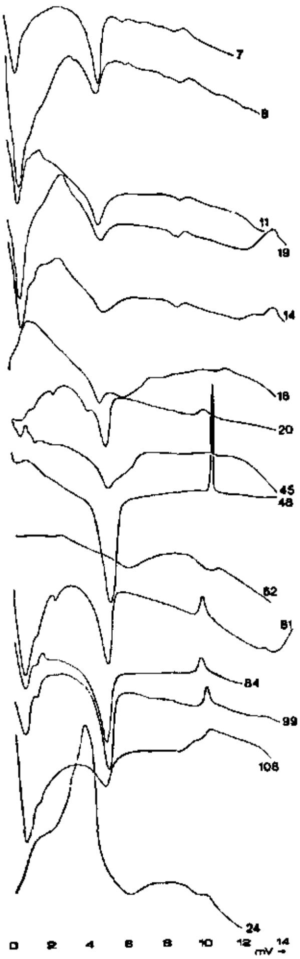

Fig. 10. DTA-traces of the clay fractions of various samples

Lower Oligocene Neerrepen sand

Locality: Hénis, Tongres (Fig. 22:2)	K	M	S
Sample 8, upper	48	29	23
Sample 7, lower	0	6	94

In the upper sample reddening is evident. This reddening disappeared after treatment with H_2O_2 and is due to organic matter. The clay composition in the upper sample is obviously altered by weathering.

DTA traces of both samples (Fig. 10) confirm the X-ray diffraction data.

Sample 7, selected for electron microscopy (Fig. 11) shows abundant smectite flakes with very diffuse outlines. Some scattered mica and kaolinite crystals occur. Fig. 12 gives the electron diffraction pattern of this sample.

Oligocene sand cover

Locality: Bemelen (Fig. 22:19)	K	M	S
Sample 131, upper	5	7	88
Sample 132, lower	5	5	90

Both samples show a very high smectite content. Soil formation has probably not affected this sediment.

Locality: Hallembaye (Fig. 22:23)	K	M	S
Sample 155: sand over fint niveau	19	13	68
Sample 153: sand below flint niveau	13	9	78
Sample 158: directly overlying limestone	7	15	78

After scanning electron microscopy sample 158 turned out to be a silicified chalk. It will probably have inherited its clay minerals from the chalk.

Samples 153 and 155 have not ondergone much soil formation; no indication of a fossil soil was found in this sediment.

The coarse fraction of the silicified chalk turned out to consist of pure quartz, with many euhedral crystals.

Lower Oligocene Hénis Clay

Locality: Hénis, Tongres (Fig. 22:2)	K	M	S
Sample 14 (upper): calcareous clay, 10 YR 7/3, pale brown	2	11	87
Sample 13: peaty clay, 7.5YR 2/0, black	8	30	62
Sample 12: peaty clay, 7.5YR 2/0, black	13	48	39
Sample 11: greenish clay, 5BG 4/1, greenish gray	20	60	20

Movement of calcium carbonate is evident in the upper part of the sediment (represented by sample 14). In this layer, and at its contact with the upper peaty clay, lime concretions are abundant. Samples 11 and 13 were selected for DTA; the traces (Fig. 10) confirm the results of the X-ray analysis.

The differences in clay mineral composition may be caused by a change in the sedimentation environment, and not by soil formation.

The electron microscope revealed the same general picture of sample 14 as that for sample 8, but the outlines of the smectite flakes were somewhat sharper.

Lower Oligocene sands from Berg (Tongres)

Locality: Berg, Tongres (Fig. 22:27)	K	M	S
Sample 170, upper layer	6	27	67
Sample 171, lower layer	17	36	47

These two samples were taken from unaltered sediments that belong to the Neerrepen sand. The samples from the Neerrepen sand at Hénis probably belong to the upper layers exposed in the Berg sand pit.

Upper Oligocene Boncelles sands

	1–2 μm			< 1 μm		
Locality: Boncelles, Sart Haguet pit. (Fig. 22:18)	K	M	S	K	M	S
Sample 111, 2.5YR 6/8, light red; upper	100	0	0	100	0	0
Sample 112, 2.5YR 5/8, red	95	5	0	95	5	0
Sample 113, 10YR 6/6, brownish yellow	90	10	0	90	10	0
Sample 114, 2.5YR 4/8, red	90	10	0	90	10	0
Sample 114a, 10R 3/4, dusky red	90	10	0	60	40	0
Sample 115, 10R 3/4, dusky red	90	10	0	60	40	0
Sample 116, 10YR 5/8, yellowish brown	90	10	0	70	30	0
Sample 117, 2.5YR 4/8, red	90	10	0	90	10	0
Sample 118, 10R 5/4, weak red; lower	90	10	0	90	10	0

Reddening is evident in this sequence.

Three soil profiles can be distinguished: samples 111–113 from the upper profile, samples 114–117 from the middle profile, sample 118 form the lower profile.

The difference in the distribution of the clay minerals in the two fractions is probably of sedimental origin. In a sediment column the kandite appeared to be bright red and the mica dark green, especially in sample 114a. The mica in this sample is a glauconitic illite (Fe_2O_3 percentage of the fraction < 1 μm about 17; see also Porrenga, 1968). A thin section showed that this glauconitic illite has developed from glauconite pellets. The samples in which the mica content in the fraction < 1 μm exceeded that in the coarser fraction will have contained some glauconite; the green clay pellets are not easily dispersed during sample preparation.

Both the soils and the clay mineralogical composition devide the Boncelles sands in three parts. Differences in the clay minerals of the three soils are only due to differences in parent material. The whole sediment is strongly weathered.

Soil remnants in the Onx sediments

	K	M	S
Locality: Champion, Namur (Fig. 22:12)			
Sample 64, 7.5YR 7/6, reddish yellow	89	7	4
Sample 65, 7.5YR 6/6, reddish yellow	45	16	39
Sample 67, 2.5YR 5/8, red	56	12	32
Sample 68, 10YR 6/8, brownish yellow	52	26	22
Sample 69, 10YR 6/8, brownish yellow	48	26	26
Locality: Cognelée, Namur (Fig. 23:13)			
Sample 70, 5YR 6/8, reddish yellow	42	28	30
Sample 71, 7.5YR 5/8, strong brown	61	22	17
Sample 72, 7.5YR 6/8, reddish yellow	58	24	18

Red and brown colours are obvious in these samples. The clay mineralogical composition shows no severe weathering. Thin sections of samples 65 and 72 show oriented clay coatings along voids, sometimes together with coatings rich in iron.

Lower Miocene lacustrine clays

	K	M	S
Locality: Louveigné (Fig. 22:3), dolina in Devonian limestone			
Sample 16, 10YR 8/2, white	14	82	4
Sample 18, 5 YR 7/2, pinkish gray	12	78	10
Sample 19, 10R 6/2, pale red	11	78	11
Sample 20, 10YR 7/2, light gray	38	9	53
Sample 21, 10P 6, purplish gray	36	7	57

Samples 16, 18 and 19 contain halloysite nodules (Buurman & van der Plas, 1968). These clays are probably weathering residues of Carboniferous limestones. The clays 20 and 21 originate probably from the limestone in which the dolina was formed (Devonian limestone).

Part of the kandites of samples 16 to 19 consists of halloysite. Sample 16, chosen for electron microscopy, turned out to consist mainly of mica crystals, ranging from 0.1 to 1.0 μm, with fairly abundant rod-shaped halloysite crystals. Some small smectite flakes and some rather large kaolinite crystals were observed (Fig. 13).

Samples 20 and 21 were selected for DTA. The trace of sample 20 (Fig. 10) confirms the opinion that the smec- tites in these samples show some vermiculite characteristics.

	K	M	S
Locality: Biesme (Fig. 22:14), dolina in Carboniferous limestone			
Sample 80, 10YR 7/6, yellow; upper	57	13	30
Sample 81, 2.5YR 7/2, light gray	68	5	27
Sample 82, 2.5Y 7/4, pale yellow	55	12	33 Q
Sample 83, 10YR 5/0, gray	66	5	29
Sample 84, 10YR 6/8, brownish yellow	50	4	46
Sample 85, 5Y 6/1, light gray; lower	50	8	42

Samples 81 and 83, two peaty clays, show higher kandite percentages, probably due to leaching.

The DTA traces of samples 81 and 84, confirm the data of the X-ray diffraction (Fig. 10).

	K	M	S
Locality: Orêt (Fig. 22:15), dolina in Carboniferous limestone			
Sample 89, 5R 6/1, pale red	90	10	0
Sample 90, 5R 5/1, weak red	90	10	0

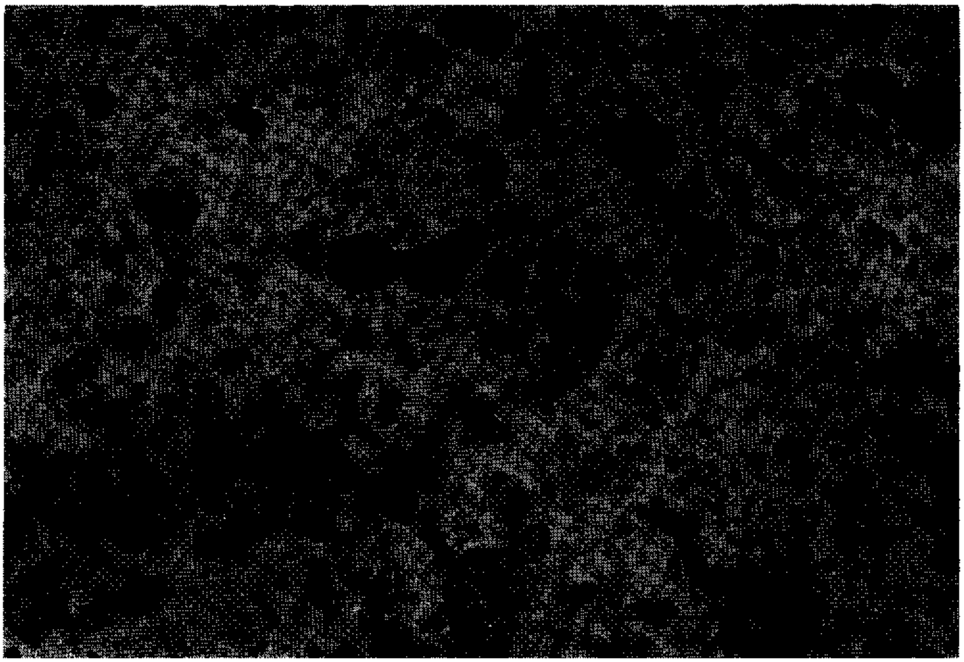

Fig. 11. Electron micrograph of the clay fraction of sample 7 (TFDL).

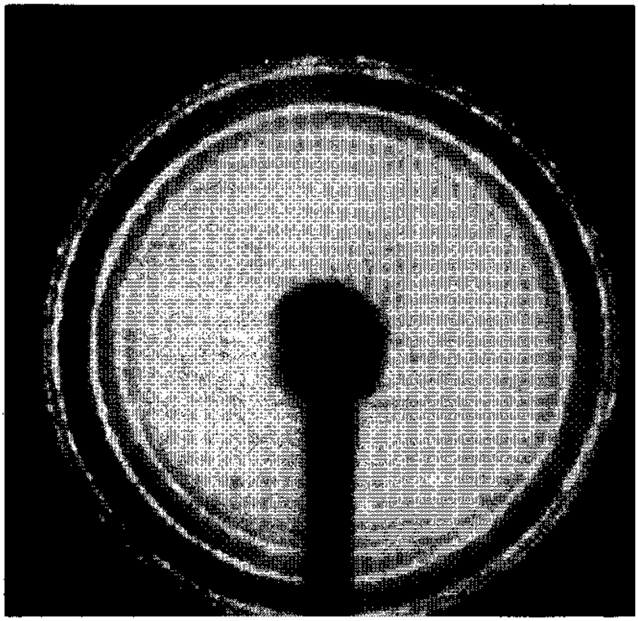

Fig. 12. Electron diffraction pattern of the clay fraction of sample 7 (TFDL).

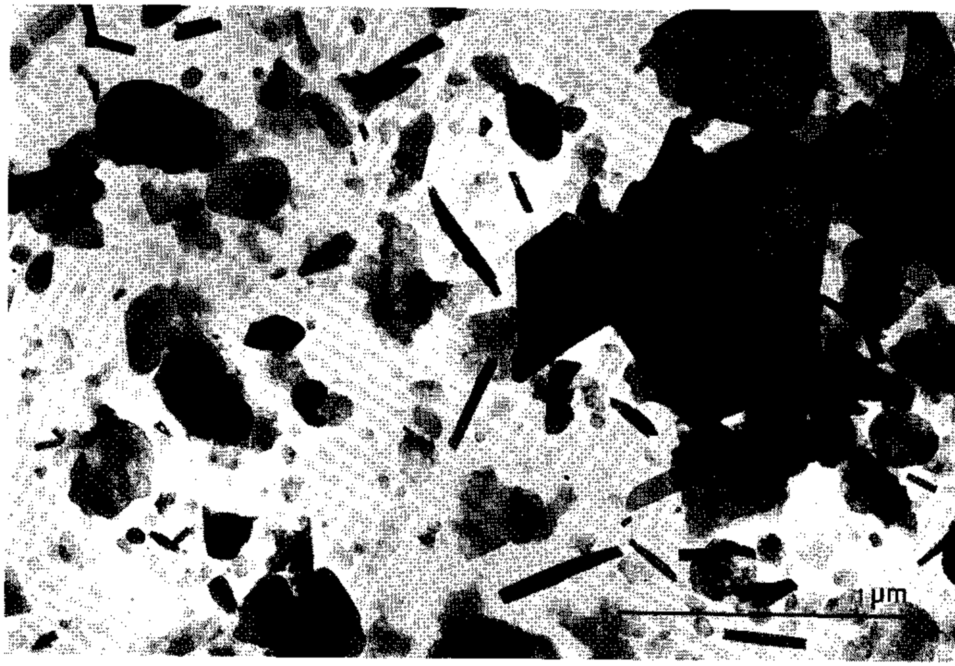

Fig. 13. Electron micrograph of the clay fraction of sample 16 (TFDL)

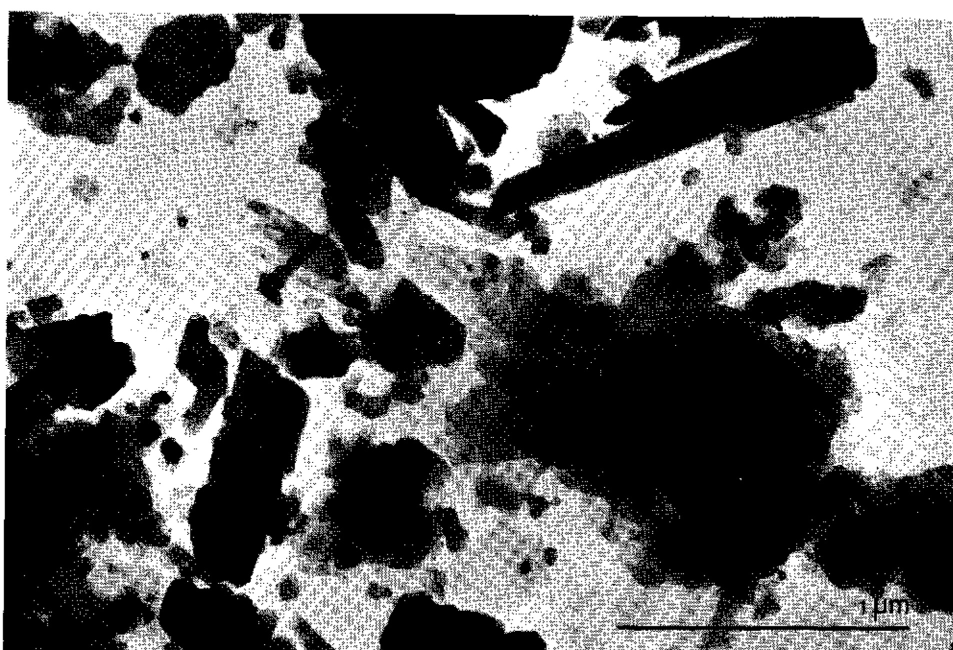

Fig. 14. Electron micrograph of the clay fraction of sample 62 (TFDL).

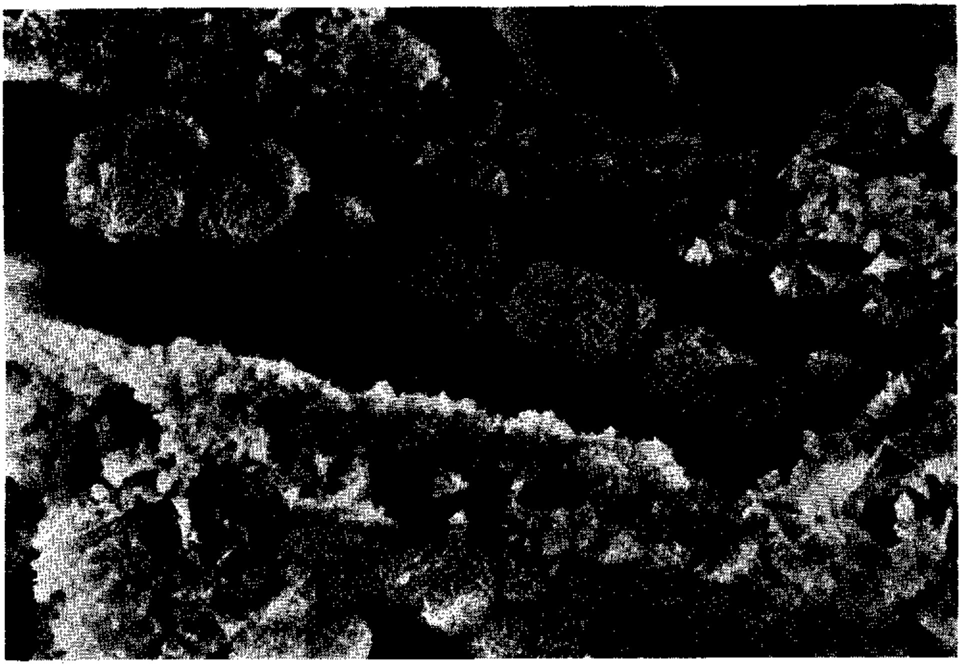

Fig. 15. Scanning electron micrograph of silicified chalk from the Platte Bos (TFDL). Magnification 2000 ×.

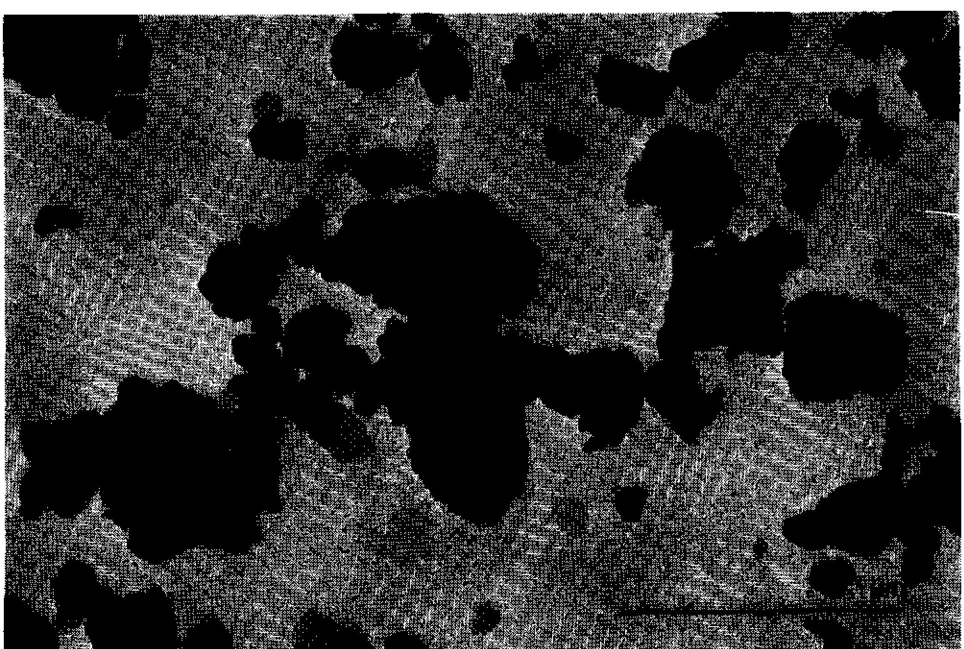

Fig. 16. Electron micrograph of the clay fraction of sample 48 (TFDL).

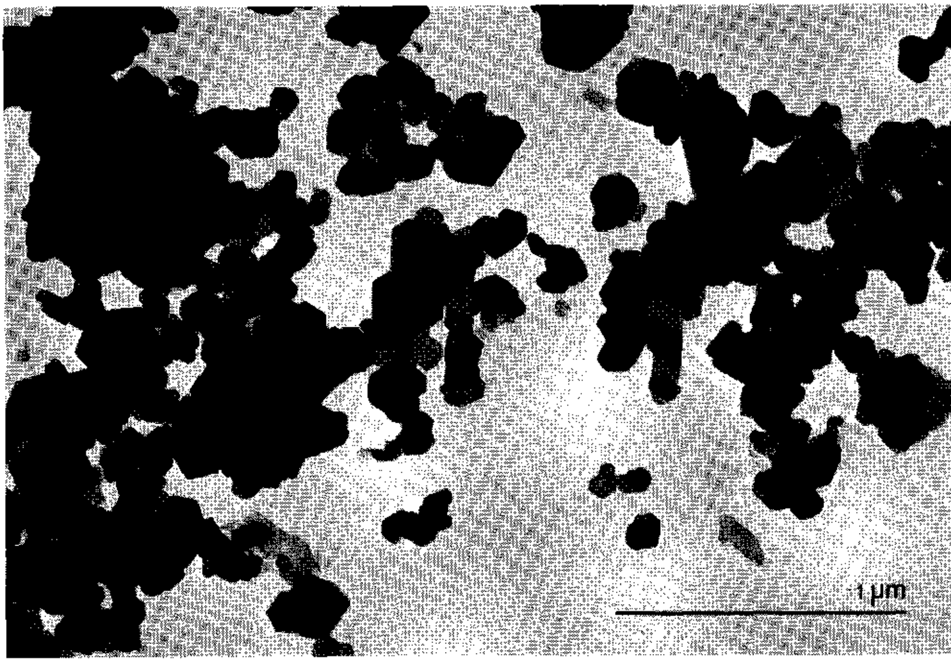

Fig. 17. Electron micrograph of the clay fraction of sample 87 (TFDL).

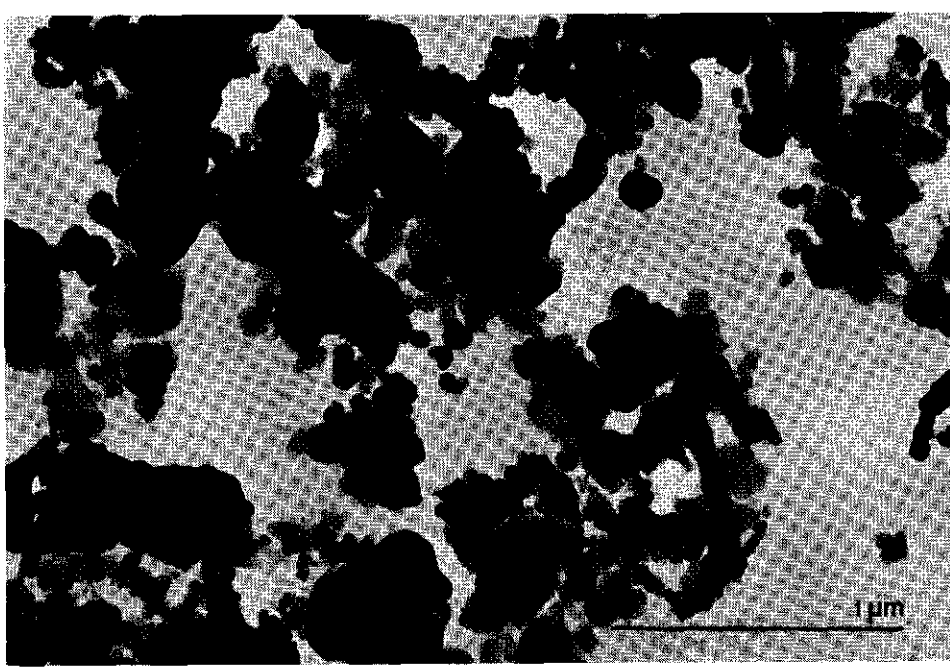

Fig. 18. Electron micrograph of the clay fraction of sample 24 (TFDL).

Sample 91, 10PB 6/1, purple gray	90	10	0
Sample 92, 10YR 8/1, white	90	10	0
Sample 93, 10R 5/2, weak red	83	17	0
Sample 94, 5Y 7/1, light gray	99	1	0
Sample 95, 5Y 7/1, light gray	93	7	0

The Orêt samples show a remarkable dominance of kandite minerals. The dolina lies in the same formation (Tournaisian and Viséan limestones) as the dolina of Biesme, but the occurrence of Landenian (Paleocene) instead of Chattian (Oligocene) sands will have influenced the clay composition. A thin section of sample 89 show pellets of oriented clay.

Locality: Morialmé (Fig. 22:16), dolina in carboniferous limestone.	K	M	S
Sample 96, N 7/, gray	42	58	0
Sample 97, 10YR 7/2, light gray	56	14	30
Sample 98, 10YR 7/6, yellow	58	3	39
Sample 99 7.5R 5/6, red	63	2	35
Sample 100, 2.5Y 6/8, olive yellow	63	7	30

Sample 99 was chosen for DTA. The trace (Fig. 10) confirms the results of the X-ray diffraction. A thin section of this sample shows a fair amount of oriented clay.

Locality: Bioul (Fig. 22:17), dolina in Carboniferous limestone	K	M	S
Sample 101, 10R 6/3, pale red	84	11	5
Sample 102, 7.5R 6/2, pale red	76	19	5
Sample 104, 10YR 7/1, light gray (peat)	0	0	0 QQ
Sample 105, 2.5YR 5/8, red	68	12	20
Sample 106, 5Y 7/1, light gray	51	21	28 Q
Sample 107, 7.5R 6/4, pale red	51	28	21

A thin section of sample 107 did not show oriented clay.

It is impossible, that colours of the lacustrine clay deposits, such as red and yellow, have been formed in a lacustrine environment.

Clays from one locality appear to have very similar clay mineral compositions (the samples from Morialmé were taken from two localities).

Clayey solifluction deposits with chert or fossils

(chert and fossils indicated with 'ch' and 'f' respectively)

Locality: Bois de Comblain (Fig. 22:7)	K	M	S
Sample 41 ch, 10YR 6/8, brownish yellow	31	69	0
Sample 42 ch, 2.5Y 8/2, pale yellow	79	21	0
Sample 44 f, 10YR 8/2, white	69	31	0
Locality: Ouhar I (Fig. 22:8)			
Sample 49 ch, 2.5Y 8/0, white	29	71	0
Sample 51 f, 10YR 7/1, light gray	29	71	0
Sample 53 ch, 5Y 7/1, light gray	71	22	7
Locality: Buresse (Fig. 22:11)			
Sample 60 ch, 10YR 7/6, yellow	35	37	28
Sample 61 f, 2.5Y 7/2, light gray	5	87	8
Sample 62 f, 2.5Y 8/2, white	1	99	0

The clays are weathering residues of Carboniferous limestone, they show alteration of mica and new formation of kandite and smectite (compare with the HCl residues of Carboniferous limestones).

Admixtures of Chattian sand occur, but their influence on the clay mineral assemblage is not important.

Sample 62 was chosen, because of its purity, both in differential thermal analysis and in electron microscopy. The DTA trace (Fig. 10) confirmed the X-ray analysis. Electron microscopy shows pure micaceous material with well developed crystal outlines (Fig. 14).

Miocene sand over 'browncoal complex'

Locality: Heerlerheide (Fig. 22:29)	K	M	S	
Sample 183, probably contaminated by illuvial clay from overlying loess; upper	27	20	53	
Sample 182, top of red profile part	50	21	29	
Sample 181, middle of red profile part	48	21	31	
Sample 180, base of red profile part	44	24	32	
Sample 179, white sand, immediately below 180	39	22	39	
Sample 178, sand over lignite	60	40	0	
Sample 177, lignite	0	0	0	QQ
Sample 176, sand directly below 177; lower	0	0	0	QQ

An important accumulation of newly formed quartz in the lignite layer and immediately below is evident. Within the red parts of the profile kandite has a tendency to increase towards the top.

Limestone weathering residues in situ

Locality: Sprimont (Fig. 22:4)	K	M	S
Sample 23, 10YR 5/8, yellowish brown	29	46	25
Locality: Florzé I (Fig. 22:5)			
Sample 32, 10YR 5/8, yellowish brown	43	19	38
Locality: Florzé II (Fig. 22:6)			
Sample 36, 10YR 6/6, brownish yellow	13	31	56
Sample 37, 10YR 7/6, yellow	28	28	44
Locality: Ouhar II (Fig. 22:9)			
Sample 54, 5YR 6/8, reddish yellow	40	32	28
Sample 55, 10YR 5/6, yellowish brown	31	64	5
Locality: Ouffet (Fig. 22:10)			
Sample 57, 10YR 6/8, brownish yellow	39	26	35
Sample 58, 10YR 7/6, yellow	38	39	23

All samples are weathering residues from Carboniferous limestones. Most residues show a fairly homogeneous distribution of the three clay minerals. When smectite content is low, mica predominates. Mica is probably the original material.

Silicified chalk

Locality: Osebos (Fig. 22:21)	K	M	S
Sample 139, lower	0	8	92
Sample 140, upper	1	6	93
Locality: Platte Bosch (Fig. 22:30)			
Sample 110	no clay minerals		

The silicified material is in all three samples a 'badly crystalline tridymite'. Fig. 15 is an electron micrograph of sample 110. The micrographs of sample 140 show the same structures, but less clearly.

Further details on this material have been given by Buurman & van der Plas (1971).

Clay layers and lenses in Chattian sediments

Locality: Florzé II (Fig. 22:6)	K	M	S
Sample 34	70	30	0
Sample 35	42	58	0
Locality: Bois de Comblain (Fig. 22:7)			
Sample 39	52	48	0
Sample 40	100	0	0
Sample 45	21	79	0
Sample 46	27	73	0
Locality: Ouhar I (Fig. 22:8)			
Sample 48	100	0	0

	K	M	S
Locality: Florzé I (Fig. 22:5)			
Sample 26	96	4	0
Locality: Orêt (Fig. 22:15)			
Sample 87	100	0	0

The colour of the samples is gray or white.

Remarkable is the absence of smectite minerals.

Samples 40, 48 and 87 consist of pure kandites. Samples 48 and 87 were chosen for electron microscopy. Samples 48 and 45 were used in DTA.

The X-ray pattern, the crystal outlines in the electron micrograph (Fig. 16) and the DTA pattern (Fig. 10) of sample 48 suggest good crystallinity, although the kaolinite of this sample is b-axis disordered. The DTA pattern shows a sharp exothermic reaction at ca. 1000°C. The electron micrograph of sample 87 (Fig. 17) reveals a well-shaped kaolinite. The DTA trace of sample 45 (Fig. 10) confirms the results of the X-ray analysis.

Thin sections were made of samples 46 and 48. No orientation of clay is found, although sample 48 shows some stress structures, probably due to movements in the dolina.

Obviously the unaltered clay layers in the Chattian sediment do not reveal a homogeneous clay composition in this sediment.

HCl residues of Carboniferous limestones (Tournaisian)

	K	M	S
Locality: Sprimont (Fig. 22:4)			
Sample 24	0	100	0
Locality: Florzé I (Fig. 22:5)			
Sample 31	5	95	0
Locality: Ouhar I (Fig. 22:8)			
Sample 56	0	100	0
Locality: Buresse (Fig. 22:11)			
Sample 63	0	100	0
Locality: Rivage (Fig. 22:28)			
Sample 172	0	100	0
Locality: Krauthausen (not on the map)			
Sample 185	0	100	0

Sample 24 was examined with the electron microscope and selected for DTA. Between 0 and 300°C the DTA trace shows a distinct exothermic reaction in air, probably because of the oxydation of organic matter (bitumen). The presence of bitumen is also suggested by the electron micrograph (Fig. 18), which shows pure mica loosely bound by unknown, non crystalline material.

Obviously, the clay minerals set free by weathering (solution) of the Carboniferous limestones are micas. However, a sample from a Viséan breccia from Florzé (not in the sample list) has a composition of about 1/3 kandite, 1/3 mica and 1/3 smectite.

HCl residues of Maastricht limestone

	K	M	S
Locality: Juliana Quarry, Bemelen (Fig. 22:20)			
Sample 134; upper	10	12	78
Sample 135	2	7	91
Sample 136	0	4	96
Sample 137	0	6	94
Sample 138; lower	0	5	95

Contrary to the Carboniferous limestones, weathering of the Cretaceous chalk results in a smectite clay. Samples 134 and 135 may have been altered by weathering.

4.4 Heavy minerals

The Tertiary sediments on the Ardennes peneplain show many local differences. The mineral assemblages have undergone long-term weathering. Therefore heavy mineral analysis cannot supply a key to stratigraphical differentaition. As will be demonstrated below, the only result of the analysis was a correlation between the heavy mineral assemblage of the Boncelles sands and that of the sands from some dolinas.

The oldest sediments will be discussed first.

Aachen sand (samples 162–168) Except for the higher anatase content the result of the analyses are similar to those of Muller (1943). Anatase content increases with decreasing grain size.

Neerrepen sand from Hénis (samples 7, 8) The analyses of the Neerrepen sand from Hénis differed from those given by Muller (1943) and Tavernier (1947) in their lower garnet and epidote contents. This difference may be because of weathering.

Neerrepens and from Berg (samples 170, 171) These samples have higher epidote contents than the sands from Hénis and are more similar to those, described by Tavernier (1947).

Hallembaye sand cover (samples 153, 155, 158) The Tertiary sands, lying on the Cretaceous at Hallembaye are supposed to be of Lower Oligocene age (Jongmans et al., 1941). The mineral content of the samples is similar to that of the Chattian sands from Boncelles. The quantities of garnet and epidote are very low for Lower Oligocene sediments. There were no weathering features evident in this sediment.

Bemelen sand cover (samples 131, 132) These sands are attributed to the Lower Oligocene (Jongmans et al., 1941). According to Muller (1943) and Tavernier (1947) they are of Middle or Upper Oligocene age because of their low garnet and epidote content.

Boncelles sands (samples 111–118) The analyses of the sands (from Sart Haguet near Boncelles) give results similar to those mentioned by Tavernier (1947).

Sands from various dolinas The outcome of the analyses of the sands from Ouhar I (188–192), Florzé II (35), Bois de Comblain (39–41) and Buresse (60) is similar to that of the Boncelles sands.

Onx sands of the 'Traînée mosane' sediments The samples from Champion (65–69) and from Cognelée (71) show a mineralogical composition similar to that of the Chattian sands.

Miocene sands from Heerlerheide (samples 176–183) The results of the analyses are similar to those given by Muller (1943) for the South Limburg 'browncoal complex' and to those of the 'continental Bolderian' given by Tavernier (1947).

Upper Miocene Diest sands (samples 2, 3). The sands from Bolderberg give results similar to those reported by Tavernier (1947) for the 'Diestian' (Upper Miocene).

5 Synthesis

5.1 Reconstruction of a Tertiary soil profile on Carboniferous limestone (Andenne soil)

Although few remnants of Tertiary soils on Carboniferous limestone have been found in situ, it is possible to reconstruct the soil that developed from the following formations linked with the occurrence of limestone:

- lacustrine clays, generally called 'Andenne clays' *(Ona)*, in the dolinas.
- chert found as a cap on top of the limestone
- solifluction deposits consisting of clays with or without silicified fossils and chert (Buurman et al., 1970). These deposits also occur in dolinas.

These three types of rocks will be discussed in the following sections.

Lacustrine clays As mentioned before, the lacustrine clays are assumed to be weathering products of Upper Carboniferous shales and eventually Lower Carboniferous limestones. Many of them, however, occur far from any Upper Carboniferous deposit and, as no other sediments with notable clay content are present, they must have originated exclusively from the limestone. The Tournaisian and Lower Viséan limestones may contain up to 30% impurities, mainly clay.

It is assumed, that the bright red and yellow colours of the lacustrine deposits can not have formed under anaerobic circumstances. Lacustrine clays have always been under anaerobic conditions after deposition. Therefore we have to suppose that the colours can not have formed in the lacustrine clays after deposition. The material must have shown them before. As no brightly-coloured older rocks are present in this part of the Ardennes, the only possible conclusion is that the colours are the result of soil-forming processes on rocks in the surroundings of the dolinas. The alternation of the colours in the dolina deposits may then point to subsequent erosion of different parts of the profile in different stages of profile development. (Fig. 19).

From the grain-size analysis it is evident, that transport during this erosion must have been very slow sometimes (some of the dolina deposits show a conspicuous accumulation of fine fraction. An analysis of the grain-size frequency diagrams shows that this must be due to sorting. Consequently the clays must have originated from the material in the immediate neighbourhood of the dolina).

That the clay mineral assemblages found in the various layers of the lacustrine deposits differ, may result from differences in composition at various depths in the soil profile, or from differences in degree of dolomitization of the limestone and sub-

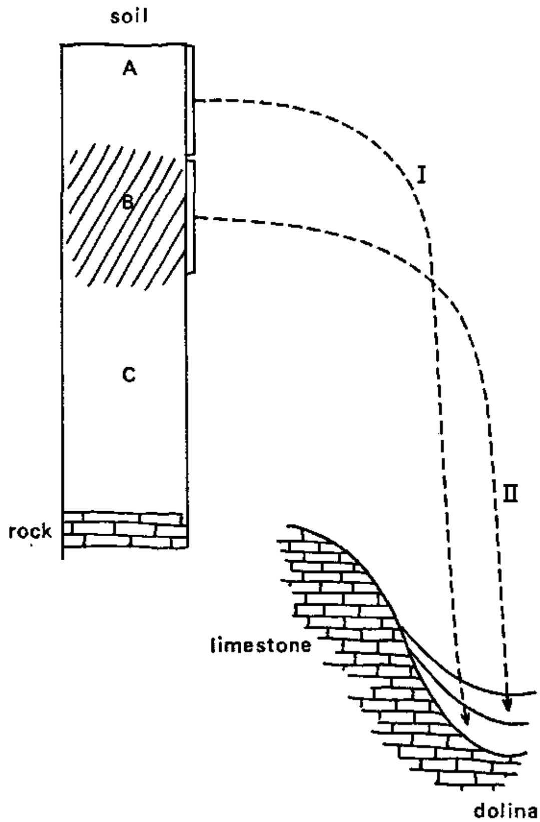

Fig. 19. Filling of a dolina by erosion in subsequent stages.

sequent formation of different amounts of smectite during weathering. In addition, in some lacustrine deposits the weathering products of the Upper Carboniferous shales and the clay from the Upper Oligocene deposits may have been admixed.

Gilkinet (1922) assumed that the peaty layers on the lacustrine deposits of Champseau were of Aquitanian age. Though they may be somewhat younger (Dr. Zagwijn, pers. comm.) the clay must have been deposited before the end of the Middle Miocene and after the Late Oligocene.

Washed in silicified fossils have been reported from the lower lacustrine deposits of Morialmé.

Chert Chert is still found as a cap on Carboniferous limestone, although most of it has been broken and removed by erosion. Chert fragments are present in younger weathering residues that are still found in dissolution pockets.

Solifluction deposits Numerous silicified fossils or chert fragments, or both, were found in solifluction deposits consisting of white or gray clay. Such deposits occur in dolinas throughout the Condroz region. The mineralogical composition of the clays varies and sometimes closely resembles that of the HCl residues of the Carboniferous limestone (e.g. sample 62). These clay deposits are thought to be weathering products of Carboniferous limestone (Buurman, de Groot and Winkler Prins, 1970). This assumption is based on their fossil content, mineralogy of the clay fraction and grain-size distribution. In the same clays, small euhedral quartz crystals (Buresse) and concretions with well-developed quartz crystals (Ouhar, Sprimont) have been found.

In solifluction beds with clearly distinguished layers, the sequence from top to bottom is clay with chert, clay with fossils and then clay. If the lower layer, the clay, was eroded first and then the overlying two this suggests an undisturbed sediment or soil profile in the neighbourhood, with the pure clay at the top, the clay with fossils in the middle, and the clay with chert in the lower part of the profile.

Although the rivers have strongly eroded the post-Oligocene Ardennes peneplain during Late Tertiary and Early Pleistocene, the limestone area of the Condroz has remained relatively undisturbed. No terrestrial deposits are known from these periods, except for some terrace deposits along rivers. Therefore, soil formation on Carboniferous limestone may have lasted throughout the Miocene and Pliocene and perhaps even the Early Pleistocene. Processes that formed the weathering residues from which the lacustrine clays were derived, may also have formed the material that nowadays constitutes the solifluction deposits. Support for this hypothesis is that silicified fossils have been found in both formations.

Thus the solifluction clays may have the same origin and the same lower stratigraphic limit as the lacustrine clays.

Reconstruction The reconstructed profile is given in Fig. 20. Gilkinet (1922) deduced from the vegetation remains of the Champseau dolina, that the climate during the Early Miocene must have been of a mediterranean type. Supposing, that this type of climate caused intensive weathering resulting in eluviation and silica liberation, the following reconstruction of the Tertiary soil profile on limestone is suggested.

Pure limestone gives a residue of pure mica clay, as is shown by the HCl residues of limestone (Section 4.3). In the top layer of the profile, mica weathers to kandite, so kandite percentages will increase towards the top. This assumed kandite formation explains the presence of different amounts of kandite and mica in the lacustrine clays and the solifluction deposits.

Such weathering causes the liberation of silica, aluminium and potassium, which is transported downwards (for downward transport rainfall should be high enough to allow percolation). Downward transport of silica and cations, and consequently higher concentrations in the lower part of the profile, causes smectites to form, as can be read from Slager & van Schuylenborgh (1970, Fig. 1).

Downward transport of silica causes silicification of fossils: fossils in limestone are more resistant to dissolution than the surrounding rock, because of their coarser calcite crystals of high purity; silica in solution has an affinity for well crystalline calcite (see Buurman & van der Plas, 1971). The remaining silica forms concretions and finally, when in contact with the calcareous bedrock, chert pans or euhedral

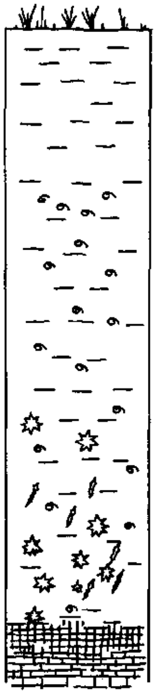

Fig. 20. Reconstruction of the *Andenne soil.*

quartz crystals in the limestone.

Smectite formation and silicification in the lower part of the profile explain the combination of chert and smectite in the solifluction clays. In dolomitized rocks, smectite may be present in the initial clay.

Finally, a dry season would result in a reddening of the upper part of the profile because of the dehydration of iron oxyhydrates. Reduction of iron in the dolina lakes and formation of iron humates may have caused the purple colours observed in some beds of lacustrine clays. The responsible agents will not have been sufficient to reduce all the iron oxides present.

The soil is supposed to have formed during the Early and Middle Miocene, although weathering may have lasted throughout the Pliocene and perhaps the Early Pleistocene. The original colours of the solifluction clays may have vanished before deposition in the dolinas, by for example, more acid leaching of the soil during younger stages of soil formation. At present these clays are white or gray. It is also possible, that the deeper layers were not affected by reddening.

5.2 Characteristics, stratigraphic position and regional occurence of fossil soil profiles

Little is known about the past and present distribution of Tertiary soils. As mapping was not the purpose of this study, the following remarks on the regional occurrence of the various soils are based on a few occurrences.

In the Introduction was explained why the description of the soil profiles could not be given in the terminology for recent soils. For soil remnants only a restricted number of properties could be estimated: the composition of the clay fraction, the presence of clay skins, and the colour of the profile. In addition these properties change with the depth of the original profile. Moreover, only a few analyses of a limited number of profiles were available, so that it has not been possible to generalize and mostly it is not even known which horizon has been analysed.

Often ages of soils can be given, ages within certain limits, as a soil does not always develop on a sediment immediately after its deposition. These limits may be several millions of years apart.

The soils will be treated in a chronological order, starting with the oldest.

Soil formation in the Upper Senonian Aachen sand The presence of silicified wood and cemented sandstones point to mobility of silica in the Aachen sand. However, on soil formation in the Aachen sand no indications have been found.

Flint eluvium The flint eluvium consists of yellowish brown to brownish red heavy clays which often show shrinking and swelling features, and are rich in flints with a conchoidal fracture. Among the clay minerals smectite predominates, varying amounts of mica and kandite may be found.

As the flint eluvium is a weathering residue of the Upper Senonian limestone, its lower limit should be placed at the end of the Maastrichtian or even of the Danian (Lower Paleocene) as limestone deposition in South Limburg ended in the Danian. The oldest deposits covering the flint eluvium are the Lower Oligocene Neerrepen sands (north of the river Meuse, between Namur and Liége). The flint eluvium must have been formed during the Paleocene and Eocene periods. It will have been widely distributed during its formation: almost the entire surface of exposed Senonian chalk could form this residue.

Today, the flint eluvium has been eroded in most places of its former extension. In South Limburg the only in situ remains are found south of the Pleistocene extension of the valley of the River Meuse.

On the Ardennes peneplain, the flint eluvium consists mainly of flint because the clay has been washed out. Shallow remnants are present on the Hautes-Fagnes plateau.

No flint eluvium is known from the Condroz, except for some very small occurrences in the eastern part. It has not been found in the area of the Paleocene and Eocene transgressions, but it may occur north of the River Meuse below Oligocene deposits.

Neerrepen soil The soil developed in the Lower Oligocene Neerrepen sand is characterized by a slight reddening of the layers about 20 cm below the top of the sand. This reddening is due to organic matter. Gypsum and jarosite concretions may occur along root channels, common in its upper part. The clay fraction is predominantly smectite, but the bleached layer and the upper part of the reddened layer may contain considerable amounts of kandite.

As both in Belgium (Tongres) and South Limburg (Schin op Geul) the soil is covered by Lower Oligocene Hénis clay, it must have developed in the period between the deposition of the sand and the clay and consequently its age is Early Oligocene.

The Neerrepen soil, first found in Hénis (Tongres), is also present in the Neerrepen sand in South Limburg. The 'Geologisch Bureau voor het Mijngebied' considers it as an indication for Lower Oligocene. Little is known about its extension in Belgium, but it may be expected anywhere between the Hénis clay and the Neerrepen sand.

Hénis peat layers The peat layers in the Hénis clay pit are black and lignitic. Smectite and mica are the common clay minerals; kandite percentages are low.

The lower layer is intercalated in the Hénis clay, the upper forms locally the boundary between the Hénis clay and the overlying Vieux-Joncs deposits, so that both are Lower Oligocene.

Their extension is assumed to be limited, because they probably were formed in a lagoon or a tidal flat area. Correlation with peat layers in other areas may not be easy. Clays, similar to the Hénis clay, that were found in South Limburg, contain layers with higher percentages of organic material.

Boncelles soils The three Boncelles soils are characterized by red colours, gradually fading downwards. Below the reddened sediment several slightly reddened narrow bands, rich in iron, occur.

Remnants of the soils intercalated in the sand series are usually thin. The clay minerals predominantly belong to the kandite group. The sediment layers with glauconitic illite are somewhat richer in mica, especially in the smaller fractions. Smectites are absent.

As the Boncelles sands are supposedly of Late Oligocene age, the intercalated soils must also have been formed during the Late Oligocene. The exact age of the soil in the top of the sands is more difficult to establish, because it is usually covered by the *Onx* sediments.

The age of the *Onx* sediments has been much discussed. As will be shown in 5.3, they cannot be younger than Late Miocene, so that the Upper Boncelles soil must have developed during the Early and Middle Miocene.

Little is known about the extension of the Boncelles soils. The sands with one or more of the three soils occur undisturbed in the environment of Boncelles and Rocourt. Remnants are also found in dolinas. It is impossible to determine to which of the three levels these remnants should be ascribed. Probably the remnants found in combination with the *Onx* sediments will belong to the upper soil.

The extension of the Boncelles soils is limited to the Condroz region and a small area north and east of it. North of the River Meuse the Chattian sediments become more marine in character and are immediately overlain by marine Miocene sediments.

Andenne soil The properties and the reconstruction of the soil related to the Andenne clays, the solifluction clays with chert and silicifications and the chert cap on the Carboniferous limestone, have been given in 5.1 and Fig. 20.

As the lacustrine clays in the dolinas generally lie over sands that are very similar to the Upper Oligocene sands, they will not be older than Early Miocene. As the peat layers on the lacustrine deposits will not be younger than the Middle Miocene (see 5.1.), the deposits must have accumulated during the Early and Middle Miocene. Consequently the Andenne soil must have developed during the same time, although this development may have continued during the Late Miocene or even longer. Its remnants on Paleozoic formations are only found in the Condroz region, where it occurs on Carboniferous (Tournaisian, Viséan) and Upper Devonian (Frasnian) limestones.

Miocene root horizon The root horizon was first found in the Beaujean sand pit near Heerlen (van der Waals et al., 1962). Later on a similar horizon was found in Belgium near Bierbeek (Louvain) (Fig. 22:32), another exists in Belgium immediately west of the Netherlands boundary, near Maaseik. The root horizon forms a brownish layer in criss-cross bedded sands with many vertical roots channels running through it. Its stratigraphical position is fairly accurately known: it has developed in the lower series of the 'browncoal complex'. Both in Belgium and in Holland this series is placed in the Middle Miocene.

The root horizon must have developed under a coastal marsh vegetation (Taxodiaceae, Dr Zagwijn, pers. comm.), so that its distribution depends on the transgressions and regressions on the former coast line. The overlying lignite deposits have been correlated over a large area. As the coast line ran east-west, the root horizon may have developed during the same period at all three sites.

Bolderberg soil and Heerlerheide soil The Bolderberg soil, characterized by strong reddening decreasing with depth has developed in Upper Miocene shallow marine deposits (Diest sands). Its development may have continued during the Pliocene, but it existed before Pleistocene erosion dissected the landscape. As the indurated pans within the Bolderberg soil are resistent to erosion, they are now found at the tops of some hills at the level of the former peneplain. Their formation cannot have lasted longer than the Early Pleistocene, because the change in climate must have resulted in a different type of soil formation.

The parent material is glauconitic sand. In some places the liberation of iron has caused a cemented crust. Structures, caused by the activity of marine organisms are evident. Shell remains filled with clay are found. The clay of the upper part of the fossil soil mainly consists of micas and kandites. In the lower parts weathering of glauconite plays an important role and both glauconitic illite and kandite are found.

The Bolderberg soil has a vast extension: next to the occurrence at the Bolderberg it is found at a distance of 140 km in East Flandres at the tops of several hills (Kluisberg, Gaillez, 1967) and 40 km away in the neighbourhood of Louvain (Kesselse

Bergen, Fig. 22:31). Today the remnants of the Bolderberg soil are restricted to the higher relics of the ancient Miocene coastal plain. Because of its extension this soil is suitable for stratigraphic correlation.

Perhaps, the reddened soil on top of the browncoal deposits in the Netherlands (*Heerlerheide soil*) is of the same age. The deposits in which this Heerlerheide soil is developed belong probably to the Upper Miocene.

Onx-soil As is stated in 5.3, the *Onx* deposits will have been formed during the Middle or Upper Miocene. Thus the soil formation on these deposits starts at about the same time as that of the Bolderberg soil. About the end of its formation again the same thing can be said as with the Bolderberg soil: the reddening in its upper horizons must have occurred before the early Pleistocene, which means that the *Onx* soil must have developed between the Late Miocene and the Early Pleistocene.

Clay illuviation (regardless of the granular composition of the parent material) may be important and even recognizeable in the field. About half of the clay minerals consists of kandite, the other half of mica and smectite.

The *Onx* soil occurs only in the *Onx* gravels and sands, but remnants cannot always be found. The extension is limited by the ancient Meuse and Ourthe beds, i.e. within some kilometers from the recent valleys. Less important rivers may have deposited material during the same time, because very gravelly layers are usually found on the *Ona* deposits (lacustrine clays), but it is not known whether remnants of soils occur in these gravels.

Residual soils on limestone Relatively young residual clays are found on both Senonian and Carboniferous limestones. They are covered by loess deposits. As the soils on Carboniferous limestone and on Senonian chalk show the same characteristics, they are treated together.

Their age can be inferred from the following facts:

In Belgium, after the development of the Andenne soil, the limestones were covered by a chert cap. A new residual clay could not be formed before this cap had been removed. Remnants of this cap, together with remnants of the overlying tertiary soil, are found in solifluction deposits that cannot be older than the Saale glacial time, as only two solifluction deposits are found in the region concerned while loess deposits are present between and on top of the solifluction layers. So the first time a new residual soil could form on these limestones was during the Eemian interglacial.

As the residual clays are covered with loess, their formation has ended in the Weichsel glacial time. Therefore their formation must have taken place during the Eemian interglacial time.

Both on Senonian and Carboniferous limestones the soils are characterized by a brownish colour and a heavy texture. The clay fraction consists on kandite, mica and smectite, in varying proportions. Distinct shrinking and swelling phenomena may be present. The limestone relief under the residual clays has a lapies character.

These residual soils are widespread, both on the Carboniferous limestones in Belgium and on the Senonian limestone in the Netherlands and Belgium. Although erosion has reduced the thickness and the extension of the residues, connecting of the levels may allow a reconstruction of the Eemian surface.

Pockets in the limestone played an important role in the conservation of these soils.

An explanation for the occurrence of silicified Carboniferous limestone (chert caps) has already been given in 5.1. Silicified Senonian chalk is found below Tertiary sands (Hallembaye) and below Pleistocene terrace material (Osebos and Platte Bos). The earliest silicification, from Hallembaye, consists exclusively of quartz, while the younger consist mainly of tridymite. This may be in accordance with the calculations of Mizutani (1966, 1967) who found that after several millions of years unstable silica phases (as crystobalite and tridymite) recrystallize to quartz.

Nothing can be said about the exact age or the extension of the two types of silicified chalk.

5.3 On the age of the Onx deposits

The *Onx* deposits can be divided in those along the River Meuse (the 'Traînée mosane') and those along the River Ourthe (the 'Graviers liégeois'). The first group consists of components both from Northern France and the Ardennes, the second group consists mainly of Ardennes sandstones and white quartzes. Silicified rocks, such as chert and flint, always play a subordinate part. Macar & Meunier (1954) suppose the *Onx* deposits to be synchronous with the 'kiezeloölite formation' ('deposits with silicified oolites') of South Limburg.

This study on fossil soils, and geomorphological data throw a new light on the age of the *Onx* deposits. The following facts should be noted:

a. the soil in the *Onx* gravels shows reddening and illuviation of clay, whereas in the kiezeloölite formation no traces of tertiary soil formation could be found

b. the *Onx* deposits immediately overlie Upper Oligocene deposits

c. in some places the dolinas of the Condroz are filled with as much as 70 m of lacustrine clays that must have been deposited during the Early and Middle Miocene.

In addition, 5.1. has indicated, on circumstancial evidence, that the main silicification phase on the Carboniferous limestones must be placed in the older Miocene (Aquitanian, Houthaléan) and that the youngest red soil profile encountered during the present investigation (Bolderberg soil) developed during the Late Miocene and Pliocene epochs. The Pliocene 'kiezeloölite formation' does not show a profile of this kind.

Because the *Onx* deposits overlie Upper Oligocene sediments, they should be placed in the Miocene epoch.

The stratified *Onx* formation consists mainly of coarse beds, indicating that erosion must have been important. Both the River Meuse between Dinant and Namur and the Rivers Ourthe and Amblève cross Carboniferous limestones over a distance of several kilometers. If the deposition of the *Onx* material took place after the main period of silicification of the limestone, one would expect more silicified rocks in the *Onx* gravels, but such silicified rocks occur very scarcely in the *Onx* terraces, especially in the 'Graviers liégeois'. This leads to the conclusion that the *Onx* formation is older than the Pliocene, moreover because of the absence of soils in the 'kiezeloölite formation'. Furthermore, it is assumed to be older than the main silicification phase of limestone, that is not younger than Middle Miocene (5.1).

Further analysis of the relation between the depths of the dolinas on the one hand, and the sea level of the Early and Middle Miocene sea on the other, corroborates this assumption. During the deposition of the lacustrine clays, which reach a thickness of 70 m, the level of the groundwater must have been at least 70 m below the surface of the peneplain. As the shore was at least 50 km away, the sea level must have been even lower. This involves a rather steep gradient, causing severe erosion. Such an erosion may account for the presence of coarse terrace deposits, and the highest terraces of the rivers dissecting the peneplain may have originated from this time onwards. The deposition of lacustrine clays stopped in the Middle Miocene. If the *Onx* gravels are indeed the result of erosion during this time, they are contemporaneous with the lacustrine clays.

6 Summary and conclusions

6.1 The soils

For the study of soil development during the Tertiary it would have been most fortunate if profiles had been available showing a continuous sequence of deposits covering the entire period. As expected, nowhere such a complete series was found. This means that a reconstruction was necessary, based on fragments of which the age was more or less accurately known.

Such fragments, or incomplete profiles, were studied in the Belgian Condroz and the region north of it and in Netherlands South Limburg.

It should be kept in mind, that soils formed on Paleozoic rocks are generally not considered. These soils are widespread, especially in the areas where older rocks are exposed, e.g., the region of Stavelot, Rocroi and the Hautes Fagnes.

For a good understanding of chronology, Fig. 2 may be used with the text below.

A remnant of the oldest Tertiary soil found in the region concerned is the so-called *flint eluvium*. The formation of this residual soil started at the end of the Cretaceous when the Ardennes were uplifted and exposed to terrestric circumstances. At that moment the whole northern part of the Ardennes was covered by Upper Senonian limestones, at the base of which some quartz sands (Aachen sand) and glauconitic marls and sands (Vaals green sand) occurred.

Soil formation affected mainly the upper members. It resulted in residual clays on top of the limestone, that may have reached a thickness of 10 m or more. Originally these clays were smectitic, because the admixtures of the Senonian limestones consisted mainly of smectite clay. Weathering of these clays may lead to the formation of kandite clays and the liberation of silica, the latter may cause silicification in the upper part of the limestone.

In the Condroz and the Herve plateau and parts of the southeastern Ardennes the formation of the flint eluvium went on from the Paleocene throughout the Eocene and the Early and Middle Oligocene. West of the line Namur-Dinant, the region of the Paleocene transgressions, flint eluvium is hardly or not formed. North of the River Meuse between Namur and Liége and in the adjacent parts of South Limburg, its formation will have lasted throughout the Paleocene and Eocene. The Early Oligocene transgressions arrested it in this area.

After the deposition of the Lower Oligocene Neerrepen sand, there has been a gentle uplift. Because of the uplift the Neerrepen sand, deposited in shallow marine environment, was exposed to soil formation.

During the Early Oligocene the climate was still warm and humid. In combination with a very shallow watertable this resulted in the formation of a wet humus podzol in the Neerrepen sand. Iron was removed from the profile and some weathering of clay minerals took place. The resulting soil has been called the *Neerrepen soil*, it may reach a thickness of about 3 m.

The soil formation lasted only for a short time as soon afterwards a transgression resulted in the deposition of lagoonary clays (Hénis clay) on top of the soil. The regional distribution of the Hénis clay almost coincides with that of the Neerrepen sand and thus all fossil soil formation on Neerrepen sand is synchronous (Early Oligocene).

In several places the properties of the Neerrepen soil have been influenced by the deposition of the Hénis clay. At the beginning of the Hénis transgression the border vegetation of the lagoon moved inland and covered the Neerrepen sand (i.c. soil) and its remains caused an accumulation of iron sulfide (pyrite) in the root channels. Later exposition to the air lead to oxidation of the pyrite and the formation of sulfuric acid, jarosite and (in combination with the Ca^{++} from the overlying layers) of gypsum concretions with diameters up to 5 cm.

The sedimentation of the Hénis clay has not been continuous. Hiates in the sedimentation are indicated by peat layers.

During the Middle Oligocene no soils developed on Tertiary sediments because the area was permanently flooded. The Oligocene transgression reached its maximum during the Chattian.

In the Upper Oligocene series several unconformities must have occurred due to short regressive stages. Two of them are presently known, they are mainly marked by reddened soil remnants, called the lower *Boncelles soils* (1 and 2).

At the end of the Chattian a regression brought the whole southern and eastern part of Belgium above sealevel. For the region south of the line Antwerp-Hasselt this situation continued up till the present. North of this line, marine sediments of Middle Miocene age occur and soil formation could only take place during the Early Miocene. During this period, most of the dry area was covered by Chattian (Boncelles) sands in which a soil developed. About the nature of its vegetation cover nothing is known, except that the fossils from the contemporaneous lacustrine deposits in the dolinas of the Condroz indicate a mediterranean type of climate. The soil from which the remnants were found in the top of the Boncelles sands developed during the Late Oligocene and Early Miocene and shows reddening, transport of iron and cementation with silica. It is called the upper *Boncelles soil (3)*. The remnants of this soil may be as much as 10 m thick.

Weathering of clay minerals could not be traced in the Boncelles soils. The whole sedimentary series excepts its glauconitic member, showed a very stable clay mineral assemblage.

Shortly after its deposition, probably during the Early Miocene, the Chattian sand was removed in some places. As a result soil formation took place on all underlying Paleozoic rocks though it could only be traced on Carboniferous limestone, because only there its remnants were preserved in dolinas (Andenne clays). Characteristics of this *Andenne soil* are reddening, clay transport, weathering of clay minerals and silicification phenomena. The soil is not found any more, it is reconstructed in 5.1 and Fig. 20. It will have been formed during the Early and Middle Miocene and may have reached a thickness of several meters. Its distribution is restricted to the limestone area of the Condroz.

Terraces of the rivers Meuse and Ourthe (*Onx*) were deposited on top of the Chattian sands and the Paleozoic rocks in parts of the Condroz area, before the end of the Miocene. Soil formation started shortly after deposition, it acted under warm and humid conditions and will have lasted throughout the Late Miocene and the Pliocene. Main characteristics of this *Onx soil* are reddening and clay illuviation. Some transport of iron may have occurred; the thickness of the soil remnants may reach several meters.

In the area north of the peneplain the deposition of marine sediments started somewhat earlier, in the Middle Miocene. Along the shore a vegetation developed that left rootchannels in the sediment. This *root horizon* is generally somewhat brownish and about 3 m thick and is characteristic for the base of the so-called 'browncoal complex' or 'continental Miocene'.

Due to a transgression during the late Miocene in the region north of the line Antwerp-Hasselt near shore sediments rich in glauconite were deposited (Diest sands). Shortly after, the shore moved northward and a soil was formed in this sediment during the last part of the Miocene and the Pliocene. Because of the warm and humid conditions this soil showed reddening and cementation by mobilized iron (weathering of glauconite): the *Bolderberg soil*. Its remnants may be as much as 5 m thick.

A similar soil developed during the same time in the upper sands of the 'browncoal formation': the *Heerlerheide soil*. It also shows reddening, but no distinct crustification. Movement of silica and weathering of clay minerals are also evident. The thickness of the profile is comparable to that of the Bolderberg soil.

The only quaternary soils considered, are the residual soils on Carboniferous and Senonian limestones. Most of these soils are formed during the Eemian interglacial. All are brown to reddish brown heavy clays with distinct shrinking and swelling features. Thickness is limited to about 1 m. In the Netherlands the soil on Senonian limestone is called 'Kleefaarde'.

6.2 The stratigraphy

The stratigraphic value of the fossil soil profiles can be deduced from Fig. 21. It shows that the stratigraphic position of a soil is closely related to its site. This is due to the fact that a transgression never covers exactly the same area as the preceding one, so that soil formation proceeds in the area not covered by the next transgression. This is especially clear with the flint eluvium. In the Condroz, for example, a sediment on the flint eluvium cannot be older than Late Oligocene, while north of the peneplain it can be as old as Early Oligocene. Consequently for some of the other soils the

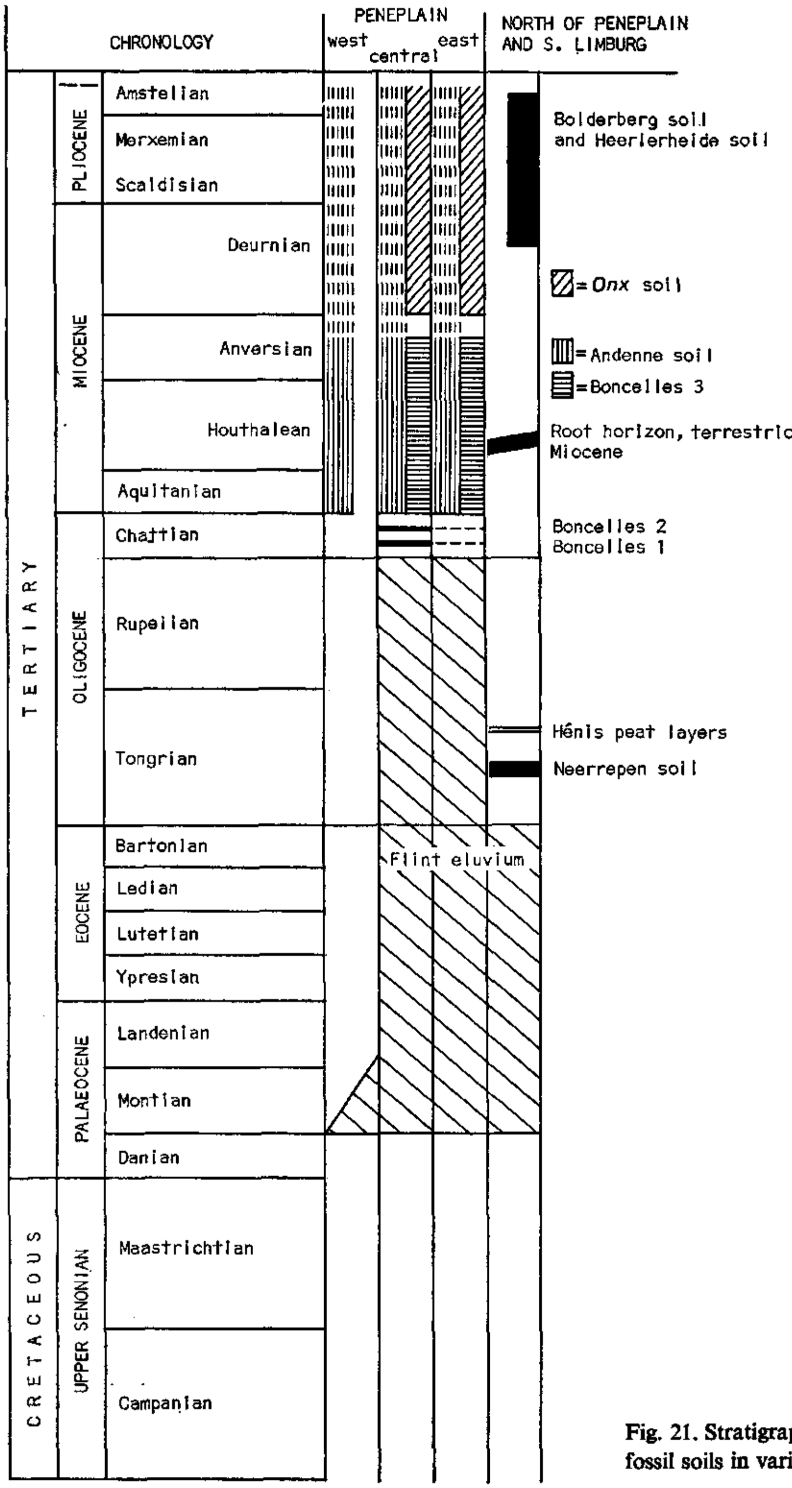

Fig. 21. Stratigraphic boundaries of fossil soils in various regions.

younger limit has to be indicated by 'may have continued throughout the Pliocene', although the lower limit is more or less exactly known. This should be kept in mind in using relics of fossil soils for stratigraphical purposes.

Nevertheless it has been possible to draw two sets of new conclusions about the stratigraphy of Tertiary sediments on the peneplain, with help of the stratigraphic position of the soils.

The first set of data refers to unconformities in sediments due to short uplift periods. They were found:

a. between the deposits of the Neerrepen sand and the Hénis clay in the Lower Oligocene,

b. within the deposition phase of the Hénis clay and between the deposition of the Hénis clay and the Vieux Joncs deposits (Lower Oligocene),

c. as two gaps in the deposition of the Boncelles sands (Upper Oligocene).

The second set of conclusions concerns the stratigraphic position of Tertiary sediments, and the time in which some features developed:

a. dolinas developed in the Carboniferous and Devonian limestones of the Condroz shortly after the Late Oligocene,

b. dissection of the post-Oligocene peneplain started as early as in the Middle Miocene,

c. the *Onx* terrace deposits will probably have formed during the Middle Miocene,

d. there is no difference in age between the gravels of the 'Traînée mosane' and the 'Graviers liégeois',

e. chert caps on the Carboniferous limestone in the Condroz have been formed during the Early and Middle Miocene.

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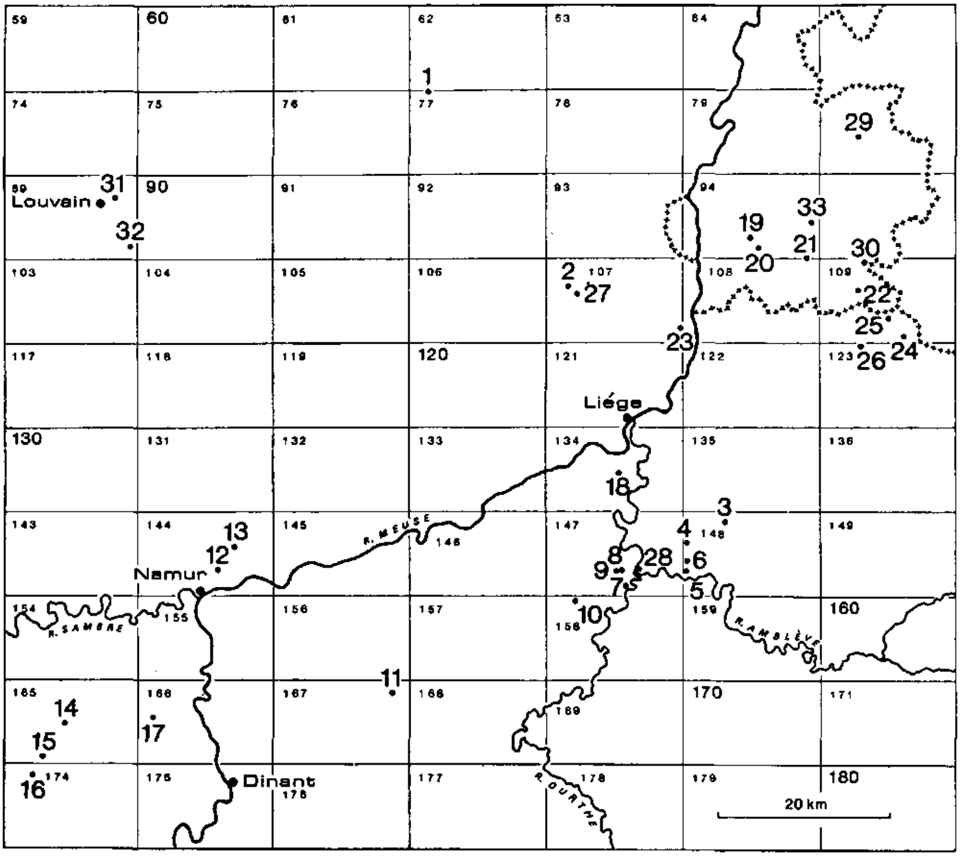

Fig. 22. Location map. Numbers in small print refer to the sheets of the Belgian geological map 1: 40,000.

1. Bolderberg
2. Hénis
3. Louveigné
4. Sprimont
5. Florzé I
6. Florzé II
7. Bois de Comblain
8. Ouhar I
9. Ouhar II
10. Ouffet
11. Buresse
12. Champion
13. Cognelée
14. Biesme
15. Orêt
16. Morialmé
17. Bioul
18. Boncelles
19. Nekami Quarry, Bemelen
20. Juliana Quarry, Bemelen
21. Osebos
22. Vijlener Bos
23. Hallembaye
24. La Calamine
25. Gemmenich
26. Rouscheweide
27. Berg near Tongres
28. Rivage
29. Heerlerheide
30. Platte Bos
31. Kesselse Bergen
32. Bierbeek
33. Schin op Geul

Appendix 1 Site and sample descriptions

Included are solely the analysed samples (see Appendix 2). Locations refer to the Belgian geological map 1:40,000 or to the topographic maps of the Netherlands 1:25,000. For location see Fig. 22, the site numbers correspond with those of this figure.

1. *Locality:* Bolderberg. Geological map 77.
Lithostratigraphy: Bolderberg sand covered by Diest sand.
Samples taken from the reddened part of the Diest sand.
sample 2: from top
sample 3: from base, ½ m below 2
Sediments strongly affected by marine biological activity.

2. *Locality:* Hénis, Tongres. Geological map 107.
Lithostratigraphy: Lower Oligocene Neerrepen sand with gypsum and jarosite concretions, covered by Hénis clay.
sample 14: clay with *Cerithium* (marine gastropod) and lime concretions from the top of the Hénis clay
sample 13: peaty clay below 14
sample 12: peaty clay, below 13 (second layer)
sample 11: greenish clay from the bottom of the Hénis clay
sample 7: top of the Neerrepen sand
sample 8: Neerrepen sand 1 m below 7
Samples 7 and 8 are somewhat reddened.

3. *Locality:* Louveigné. Geological map 148.
Lithostratigraphy: Chattian sands and lacustrine clays in dolina in Frasnian (Upper Devonian) limestone.
sample 16: clay with halloysite nodules
sample 18: red, yellow and gray mottled clay
sample 19: ditto
sample 20: gray clay with some organic matter
sample 21: red clay below 20
It was not possible to determine the stratigraphic relations between the samples.

4. *Locality:* Sprimont. Geological map 148.
Lithostratigraphy: Lower Carboniferous limestone with weathering residues in pockets.
sample 23: brown clay with some chert and silicified fossils (weathering residue)
sample 24: Carboniferous limestone (Tournaisian)

5. *Locality:* Florzé I. Geological map 148.
Lithostratigraphy: Dolina in Carboniferous limestone (Tournaisian/Viséan) filled with Tertiary sands and gravels and with solifluction deposits. Locally remnants of red profile.
sample 27: somewhat cemented white sand

sample 29: gray clay from solifluction deposit; this clay contains some crandallite in pocket
sample 31: Tournaisian limestone from solifluction deposit
sample 32: Weathering residue (brown clay) from Tournaisian limestone (solifluction deposit.)

Samples taken from solifluction deposit in a gully in the Tertiary sediments. The deposits in this gully are (from top to bottom): loess, limestone weathering clay (32) with limestone fragments (31), loess with some gastropods, white clay with abundant chert, clay with crandallite pocket (29), Tertiary gravel (*Onx*) and sand (*Om*).

6. *Locality:* Florzé II. Geological map 148.
Lithostratigraphy: Onx gravels and *Om* sands with locally remnants of a red profile. The Tertiary sediments are covered by two solifluction layers, rich in black chert. The deposit has sunk in a dolina.
samples 34 and 35: white clays intercalated in the Chattian sands
samples 36 and 37: limestone weathering residues from the upper solifluction deposit

7. *Locality:* Bois de Comblain. Geological map 147.
Lithostratigraphy: as 5 and 6. Chattian sands and clays covered by a solifluction deposit rich in chert and silicified fossils, especially corals.
sample 39: humic layer in Tertiary sands
samples 40, 45: white clay deposits in Tertiary sands
samples 41, 42: gray clays rich in chert
sample 44: gray clay rich in fossils
sample 46: gray clay with red mottles, rich in chert.

8. *Locality:* Ouhar I. Geological map 147.
Lithostratigraphy: Tertiary sands in dolina, covered by a solifluction deposit of gray clay rich in fossils, especially corals.
sample 48: clay lense, intercalated in the Tertiary sand.
samples 49 and 53: clays rich in chert
sample 51: clay rich in silicified corals
samples 188–192: samples of Tertiary sand

9. *Locality:* Ouhar II. Geological map 147.
Lithostratigraphy: Tournaisian limestone (quarry) with weathering residue on top and in pockets. The weathering residue is rich in silicified fossils, chert and quartz concretions.
samples 54, 55: brown and reddish brown weathering residue
sample 56: Tournaisian limestone

10. *Locality:* Ouffet. Geological map 158.
Lithostratigraphy: as 9.
samples 57, 58: weathering residue of Tournaisian limestone

11. *Locality:* Buresse. Geological map 167.
Lithostratigraphy: Tertiary sands with remnants of a red profile, covered by a solifluction layer of gray clay, very rich in chert and silicified fossils (corals and brachiopods), in a dolina in Tournaisian limestone. Two sandpits, nr. 2 north of nr. 1.
sandpit 1:
sample 63: Tournaisian limestone from an outcrop in the dolina
sandpit 2:
sample 60: clay with chert
samples 61 and 62: clays with silicified fossils

12. *Locality:* Champion. Geological map 144.
Lithostratigraphy: Onx gravels and sands with remnants of red profile.
sample 64: clay pebbles from the terrace deposit
sample 65: sediment from the top layer of the pit, with remnants of a red profile.
sample 66: thin clay layer, intercalated in the terrace deposit.
sample 67: from another remnant of fossil red soil
sample 68: upper sample of third remnant of fossil soil
sample 69: 1 m below 68
It was impossible to determine any relation between the three remnants of soil profiles.

13. *Locality:* Cognelée. Geological map 144.
Lithostratigraphy: Onx gravels and sands, with remnants of a fossil red soil profile.
sample 70: isolated clay occurrence in the sand
sample 71: remnant of red profile in the top of the sand
sample 72: ditto, from a different spot

14. *Locality:* Biesme. Geological map 165.
Lithostratigraphy: Ona clays (Andenne clay) on Tournaisian and Viséan limestones.
sample 80: clay
sample 81: upper lignitic layer with pyrite, wood etc.
sample 82: clay
sample 83: lower lignitic layer
sample 84: light gray clay
sample 85: yellow clay
Sample 80 taken at the top, sample 85 at the bottom of the accessible series. Thickness of layers 1–2 meters, varying from spot to spot.

15. *Locality:* Orêt. Geological map 165.
Lithostratigraphy: Ona clays (Andenne clays) on Landenian (Paleocene) sand in a pocket in Tournaisian and Viséan limestone.
sample 87: clay intercalated in the Landenian sand
samples 88–94: series of vertical, differently coloured, clay layers

16. *Locality:* Morialmé. Geological map 174.
Lithostratigraphy: Ona clays (Andenne clays) in a dolina in Tournaisian limestones.
samples 96, 97: two clay samples
sample 98: white clay
sample 99: red clay, below 98
sample 100: yellow clay below 99
Exploitation is done on a fairly large scale. Not all the deposits are used. It was therefore very difficult to estimate relations between layers observed. Samples 96–97 and samples 98–100 are taken from different clay pits. The layers of samples 98–100 were fairly horizontal.

17. *Locality:* Bioul. Geological map 166.
Lithostratigraphy: Ona clays (Andenne clays) in a dolina in Viséan limestone. Chattian sands are present. Relations between the samples are not clear.
sample 101: clay layer intercalated in the Chattian sand
sample 102: clay
sample 104: lignitic layer with wood fragments
samples 105–107: clay layers

18. *Locality:* Boncelles. Geological map 134.
Lithostratigraphy: Chattian sands with a cover of *Onx* sands and gravels. Three fossil soil profiles in the Chattian are exposed in this sand pit. The profile is given as sediment column IV in Fig. 4.

sample 111: top upper profile, 50 cm below *Onx* gravel
sample 112: upper profile, 4 m below *Onx* gravel
sample 113: upper profile, lowest part; 9 m below *Onx* gravel
sample 114: middle profile, upper part, 10 m below *Onx* gravel
sample 114a: 'glauconite' layer; 25 cm below 114
sample 115: middle profile, just below glauconite layer
sample 116: middle profile, 35 cm below 114
sample 117: middle profile, lowest part; 1.20 m below 114
sample 118: top lower profile; 1.25 m below 114

19. *Locality:* Bemelen, Nekami Quarry. Topographical map 62 A
Lithostratigraphy: Tertiary sand cover over Maastricht chalk (Upper Senonian).

sample 131: upper part of the Tertiary sand
sample 132: Tertiary sand 1 m below 131

The two samples are separated by a level of rolled flints.

20. *Locality:* Bemelen, Juliana Quarry. Topographical map 62 A.
Lithostratigraphy: Upper Maastricht chalk.

samples 134–138: superposed samples of the upper 2 m of chalk, taken at equal intervals. Sample 134 (top) is slightly silicified

21. *Locality:* Osebos. Topographical map 62 A.
Lithostratigraphy: Silicified *coap* on Gulpen chalk (Upper Senonian).

samples 139, 140: two samples from the silicified part of the chalk

22. *Locality:* Vijlener Bos. Topographical map 62 D.
Lithostratigraphy: Flint eluvium with solifluction deposits on top.

samples 141, 142: two samples from different spots in the flint eluvium

23. *Locality:* Hallembaye. Geological map 107.
Lithostratigraphy: Tertiary sand cover on Maastricht chalk.

samples 153, 155: superposed samples (153 upper) of the Tertiary sand cover, separated by a level with rolled flints
sample 158: upper part of the chalk; silicified material with an admixture of Tertiary sand

24. *Locality:* La Calamine. Geological map 109. Topographical map 62 D.
Lithostratigraphy: Upper Senonian (Campanian) Aachen sand.

sample 163: from the upper part of the pit; clay bands that are probably not related to the Aachen sand
sample 164: sand, directly above a silicified level
sample 165: sand with root holes and iron concretions, directly below the silicified level

25. *Locality:* Gemmenich. Geological map 109. Topographical map 62 D.
Lithostratigraphy: Upper Senonian Aachen sand.

sample 166: sand with clay fibres from the upper part of the excavation
sample 167: sand 1 m below 166, rich in organic remains

26. *Locality:* Rouscheweide. Geological map 123. Topographical map 62 D.
Lithostratigraphy: Upper part of the Aachen sand and basis Vaals greensand (Upper Senonian).

sample 168: sand sample in silicified level; 1 m below the basis of the Vaals greensand

27. *Locality:* Berg (Tongres). Geological map 107.
Lithostratigraphy: Lower Oligocene Neerrepen sands.
sample 170, 171: two superposed samples

28. *Locality:* Rivage. Geological map 147.
Lithostratigraphy: Tournaisian (Lower Carboniferous) limestone.
sample 172: limestone

29. *Locality:* Heerlerheide. Topographical map 60 D.
Lithostratigraphy: Probably Miocene sandcover, overlying the 'browncoal formation'.
sample 183: clay fibres from the top of a red profile in the upper part of the excavation
sample 182: top of the red profile, just below the fibre of 183
sample 181: middle part of red profile, 3 m below 182
sample 180: basis of red profile, 6 m below 182
sample 179: sand immediately below the red profie, 6.15 m below 182
sample 178: sand immediately above lignite layer, 8,5 m below 182
sample 177: lignite layer, 10 m below 182
sample 176: sand immediatly below 177, 11 m below 182

30. *Locality:* Platte Bos. Topographical map 62 D.
Lithostratigraphy: silicified layer on top of Gulpen chalk.
sample 110: silicified chalk

Appendix 2 Numerical results of analyses

Sample nr.	2	3	7	8	11	12	13	14	16	18	19	20
Granular Composition												
> 2 μm			87.2	93.8	27.7	28.5	42.4	28.2	57.0			44.3
> 4												37.1
> 8			86.7	93.0	20.0	22.1	23.4	15.6	47.4			30.6
> 16			86.4	92.0	14.1	15.1	8.8	7.7	39.7			21.6
> 32			85.9	91.0	6.7	6.5	4.6	4.5	30.0			12.2
> 50			85.9	88.7	0.4	2.2	1.9	1.3	24.2			4.8
> 75			85.4	87.7					23.2			2.5
> 105			80.4	80.8					21.9			1.2
> 150			13.9	12.9					18.8			
> 210			0.7	0.6					14.6			
> 300			0.3	0.3					10.1			
> 420			0.0	0.0					4.1			
Heavy Minerals 50–420 μm												
Opaque	77	65	68	54						33		
Tourmaline	14	5	22	12						22		
Zircon	28	29	33	32						23		
Garnet	1	1	2	0						1		
Rutile	20	24	9	12						11		
Anatase	18	28	20	26						41		
Brookite	1	0	0	2						1		
Sphene	0	0	0	0						0		
Staurolite	5	4	7	7						0		
Kyanite	2	1	3	9						0		
Andalusite	2	1	0	1						0		
Sillimanite	0	0	0	0						0		
Epidote	4	9	0	0						0		
Aggregates	3	3	1	0						3		
Hornblende	2	5	0	0						0		
Augite	0	0	0	0						0		
Rest	2	0	1	0						0		
Clay Minerals < 1 μm												
Kandite			48	0	20	13	8	2	14	12	11	38
Mica			29	6	60	48	30	11	82	78	78	9
Smectite			23	94	20	39	62	87	4	10	11	53
Quartz												
Light fraction 50–420 μm												
Aggregates				+						+		+
Quartz crystals												
Guinier photograph			+	+	+	+	+	+				+
DTA			+	+	+		+	+	+			+
Electron micrograph				+				+	+			
Micromorph. descr.												

24	26	27	29	31	32	34	35	36	37	39	40	41	42	44	45	46
72.7		87.7	43.1	49.8	35.0		80.2	72.3	73.6	96.4		78.3	80.1	91.0		61.1
64.8			37.8	42.0												
53.9		80.2	34.8	29.1	30.3		58.3	66.9	65.4	78.2		67.5	68.9	74.9		44.4
37.7		77.1	31.8	17.1	26.4		42.8	60.2	57.2	69.3		61.7	63.6	65.9		37.1
26.5		74.3	29.5	4.0	16.7		24.8	34.7	36.6	55.0		56.2	56.0	51.3		26.1
17.8		69.7	26.7	0.9	8.1		9.8	7.6	16.3	38.1		50.4	50.7	34.7		23.2
17.3		67.4	24.5	0.6	6.8		5.1	6.6	14.1	30.3		48.4	48.9	27.2		22.8
17.0		64.2	21.9	0.4	5.9		2.4	5.8	12.3	20.5		37.6	42.1	17.4		21.8
16.6		57.8	17.4	0.2	4.9		0.7	3.9	8.8	6.3		21.8	33.0	4.5		20.6
16.1		51.7	12.8	0.1	4.2		0.3	2.7	7.1	1.7		20.9	30.6	0.8		20.1
15.5		44.2	9.6		3.7		0.2	2.1	6.2	0.6		19.4	28.2	0.2		19.6
14.7		24.3	7.2		3.1		0.1	1.5	5.2	0.2		17.0	24.6	0.1		18.6
							24			47	54	49				
							2			4	12	4				
							45			40	12	32				
							0			0	0	0				
							24			9	2	12				
							20			43	47	46				
							0			0	0	0				
							0			0	0	0				
							1			3	8	1				
							1			0	11	0				
							0			0	0	0				
							0			1	2	0				
							1			0	0	4				
							0			0	1	0				
							0			0	1	1				
							0			0	0	0				
							1			0	0	0				
0	96	99	57	5	43	70	42	13	28	52	100	31	79	69	21	27
00	4	1	19	95	19	30	58	31	28	48	0	69	21	31	79	73
0	0	0	34	0	38	0	0	56	44	0	0	0	0	0	0	0
																(+)
		+	+				+				+		++	+		
			+									+				
+																+
+		+													+	
																+

Sample nr.	48	49	50	51	53	54	55	56	57	58	60	61
Granular Composition												
> 2 μm	55.2	80.2	46.4	85.6	92.7	64.2	68.1	92.9	30.4	47.3	61.5	64.1
> 4						58.7	60.2	88.4	25.5	40.6	58.1	60.8
> 8	50.1	76.6	41.9	81.0	88.5	54.9	52.3	77.9	16.9	33.1	53.3	47.6
> 16	47.8	74.0	40.0	79.0	86.4	49.5	45.5	71.2	13.0	27.2	47.7	46.8
> 32	40.8	70.1	36.5	74.4	82.7	43.1	40.0	9.9	7.0	21.4	41.5	33.6
> 50	46.0	67.0	33.6	71.6	82.2	39.9	37.9	5.2	5.4	17.6	35.1	16.3
> 75	45.3	65.1	32.1	69.9	79.8	34.0	36.5	4.7	5.2	17.0	31.4	13.7
> 105	43.7	48.9	19.1	55.2	61.1	28.8	30.8	4.3	4.7	15.5	20.3	12.5
> 150	26.9	12.4	1.7	15.0	13.2	19.2	18.2	3.7	3.9	11.9	9.9	11.7
> 210	6.3	9.8	0.7	12.8	5.4	16.7	12.0	3.3	3.6	10.9	8.4	11.1
> 300	1.6	8.9	0.5	11.9	4.3	16.3	10.8	3.0	3.4	10.4	7.7	10.4
> 420	1.1	7.6	0.4	10.3	3.5	15.9	10.0	2.6	3.1	9.8	6.9	9.3
Heavy Minerals 50–420 μm												
Opaque											59	
Tourmaline											11	
Zircon											13	
Garnet											0	
Rutile											20	
Anatase											38	
Brookite											0	
Sphene											1	
Staurolite											5	
Kyanite											1	
Andalusite											0	
Sillimanite											0	
Epidote											2	
Aggregates											3	
Hornblende											0	
Augite											0	
Rest.											0	
Clay Minerals < 1 μm												
Kandite	100	29	42	29	71	40	31	0	39	38	35	5
Mica	0	71	18	71	22	32	64	100	26	39	37	87
Smectite	0	0	40	0	7	28	5	0	35	23	28	8
Quartz			(+)				(+)					
Lightfraction 50–420 μ												
Aggregates		+	+		+	++	+	++	++	+	+	+
Quartz crystals		+			+			+				++
Guinier photograph	+				+						+	
DTA	+				+							
Electron micrograph	+											
Micromorph. descr.	+		+									

64	65	66	67	68	69	70	71	72	80	81	82	83	84	85	87	89
							73.2	68.2	58.0	84.6	44.2	6.6	63.9	66.9	64.1	47.0
											41.0		59.4			41.1
							72.2		53.9	77.0	39.0		56.0	65.0		33.5
							70.9		46.8	72.7	32.4	5.7	50.3	61.5	60.3	22.8
							68.6	67.2	23.8	53.9	18.3	3.5	37.7	47.5	58.3	13.4
							67.6	66.4	11.8	35.6	3.4	0.9	9.5	14.2	55.5	7.1
							66.0	65.9	6.6	27.6	0.9		4.0	14.2	54.9	5.9
							61.8	64.1	5.1	20.3			2.5	10.0	52.9	5.1
							49.5	55.1	4.3	13.6			1.7	7.9	10.4	1.5
							34.4	21.9	3.5	11.0			1.0	7.5	0.6	0.1
							21.9	5.1	2.2	9.3			9.0	7.3	0.2	
							10.6	1.1	0.5	7.7			8.6	7.2	0.1	
	42		40		56		67									
	12		14		4		15									
	52		46		68		40									
	1		0		0		0									
	14		17		12		13									
	7		10		8		14									
	0		0		0		0									
	0		0		0		0									
	4		6		4		7									
	2		4		2		7									
	1		1		0		2									
	1		0		0		0									
	0		0		0		0									
	3		0		1		1									
	0		0		0		0									
	0		0		0		0									
	0		0		0		0									
89	45	94	56	52	48	42	61	58	57	68	55	66	50	50	100	90
7	16	6	12	26	26	28	22	24	13	5	12	5	4	8	0	10
4	39	0	32	22	26	30	17	18	30	27	33	29	46	42	0	0
									+		+					
++	+			+										+		+
				+					+	+	+	+	+	+		+
										+			+			
															+	
	+							+								+

Sample nr.	90	91	92	93	94	95	96	97	98	99	100	101
Granular Composition												
> 2 μm	27.3	24.6	46.4	47.1	71.7	33.2	65.1	54.2	40.6	55.6	60.4	
> 4		21.1	40.9	40.6	68.5	29.4	56.7	52.0	36.4	52.5	55.6	
> 8	20.9	17.4	31.9	32.8	57.2	23.3	45.9	47.6	28.2	48.7	52.2	
> 16	12.6	11.0	18.5	19.2	42.7	14.0	34.2	45.1	21.0		47.2	
> 32	7.8	7.5	10.2	2.4	30.0	7.6	20.9	39.2	13.6	43.5	38.4	
> 50	5.0	4.2	5.6	0.0	19.3	3.8	9.8	28.2	3.2	17.4	22.6	
> 75	4.4	3.6	4.6		16.3	3.1	8.4	24.9	2.2	11.6	17.9	
> 105	3.8	3.1	3.9		14.1	2.7	7.6	22.3	1.6	8.5	13.9	
> 150	1.1	0.9	1.1		4.3	0.8	6.9	18.0	1.1	6.3	6.7	
> 210	0.2	0.1	0.1		0.2	0.1	6.5	14.4	0.8	5.0	2.6	
> 300	0.1						6.2	11.8		3.7	1.2	
> 420							5.8	8.2	0.7	2.2	0.5	
Heavy Minerals 50–420 μm												
Opaque												
Tourmaline												
Zircon												
Garnet												
Rutile												
Anatase												
Brookite												
Sphene												
Staurolite												
Kyanite												
Andalusite												
Sillimanite												
Epidote												
Aggregates												
Hornblende												
Augite												
Rest.												
Clay Minerals < 1 μm												
Kandite	90	90	91	83	99	93	42	56	58	63	63	84
Mica	10	10	9	17	1	7	58	14	3	2	7	11
Smectite	0	0	0	0	0	0	0	30	39	35	30	5
Quartz												
Lightfraction 50–420 μm												
Aggregates							+		+		+	
Quartz crystals							+				+	
Guinier photograph	+	+	+						+	+	+	
DTA										+		+
Electron micrograph												
Micromorph. descr.										+		

	105	106	107	111	112	113	114	114A	115	116	117	118	131	132	134	135	136
	54.5	44.9		69.6	90.0	87.6	88.5	62.6			92.9						
		36.6						61.4									
	50.7	20.2						61.2									
	36.8	7.1		68.2	87.4	87.3	86.5	60.6			91.7						
	25.2	1.3		67.9	87.4	87.3	86.2	60.3			91.7						
	15.3	0.3		66.1	86.7	87.1	85.4	58.8			90.2						
	11.9			65.9	86.1	86.5	84.5	58.2			89.4						
	8.2			63.8	64.8	65.3	60.4	52.4			68.8						
	4.4			36.7	5.8	17.1	12.6	45.9			30.7						
	2.7			1.9	1.0	0.7	1.2	31.0			2.5						
	1.7			1.4	0.8	0.2	0.7	25.0			0.8						
	1.1			0.3	0.7		0.3	11.1			0.2						
				55		66		63		65		61	86				
				16		21		24		12		18	13				
				26		9		40		39		24	19				
				0		0		0		0		0	0				
				11		6		12		12		10	18				
				36		55		14		21		34	37				
				1		2		0		0		0	0				
				0		0		0		0		0	0				
				6		4		13		8		5	2				
				7		3		6		3		3	2				
				0		0		0		1		0	0				
				0		0		0		0		0	0				
				0		0		1		4		0	2				
				0		0		0		0		1	4				
				1		0		0		0		0	0				
				0		0		0		0		0	0				
				0		0		0		0		0	1				
								<1 1-2	<1 1-2	<1 1-2							
	68	51	51	100	95	90	90	60 90	60 90	70 90	90	90	5	5	10	2	0
	12	21	28	0	5	10	10	40 10	40 10	30 10	10	10	7	5	12	7	4
	20	28	21	0	0	0	0	0 0	0 0	0 0	0	0	88	90	78	91	96
		+												(+)	(+)		
				+		+						+					
				+													
															+	+	+
								+									

Sample nr.	137	138	139	140	141	142	153	155	158	163	164	165
Granular Composition												
> 2 μm								91.8	93.3		90.6	
> 4								91.1	86.9		89.9	
> 8								90.5	60.9		89.3	
> 16								90.0	44.9		87.8	
> 32								89.2	39.7		85.7	
> 50							97.2	88.9	39.4		84.5	99.1
> 75							95.6	87.0	37.7		78.3	97.7
> 105							80.7	67.6	31.6		46.1	83.3
> 150							1.2	3.6	10.0		4.7	33.5
> 210							0.1	0.1	9.4		2.7	0.4
> 300									9.2		2.6	0.1
> 420									9.0		0.0	
Heavy Minerals 50–420 μm												
Opaque				54			54	50	62		38	
Tourmaline				9			20	10	17		10	
Zircon				25			15	27	12		5	
Garnet				3			0	0	0		0	
Rutile				22			13	17	13		8	
Anatase				32			28	31	39		76	
Brookite				3			0	0	3		0	
Sphene				0			0	0	0		0	
Staurolite				2			5	6	7		0	
Kyanite				0			11	6	6		0	
Andalusite				0			0	1	0		0	
Sillimanite				0			0	1	0		0	
Epidote				1			2	0	2		0	
Aggregates				2			1	0	1		0	
Hornblende				0			0	0	0		0	
Augite				0			0	0	0		0	
Rest.				0			0	0	0		0	
Clay Minerals < 1 μm												
Kandite	+	0	0	1	21	23	13	19	7	7	+	0
Mica	6	5	8	6	29	22	9	13	15	17	12	19
Smectite	94	95	92	93	50	55	78	68	78	76	88	81
Quartz						+			(+)		+	+
Light fraction 50–420 μm												
Aggregates					+			+	+	+	+	++
Quartz crystals				++								
Guinier photograph												
DTA	+	+	+	+								
Electron micrograph												
Micromorph. descr.												

168	170	171	172	176	179	180	181	182	183	185	186	188	189	190	191	192
			79.6							84.9			84.9	84.5		
			73.9							69.0						
			62.6							56.7						
			46.6							41.1			82.2			
			20.3							25.4			81.7	81.5	91.0	
96.3	96.9	96.9	9.6							0.0		94.3	80.0	79.3	89.1	
95.9	95.8	96.3	7.1									92.9	79.6	78.1	86.5	
90.7	76.0	86.6	5.4									36.7	75.6	51.3	29.2	
76.3	12.0	17.8	4.4									1.2	18.9	2.8	0.8	
28.9	0.7	0.6	4.0									0.1	0.3	0.3	0.1	
2.0	0.3	0.1	3.7											0.2		
0.3			3.3											0.1		
37	36	48		39	50			48				46	51	46	55	55
12	11	19		50	13			16				19	22	13	17	12
24	8	6		5	20			27				6	12	10	10	27
0	4	2		0	0			0				0	1	2	1	0
6	5	5		10	11			7				6	6	1	8	7
56	36	34		12	37			28				52	40	60	39	36
0	0	0		1	0			1				0	0	0	0	2
0	0	1		0	0			0				0	0	0	0	0
1	9	8		13	1			4				4	9	3	9	1
0	4	5		6	14			5				6	5	4	10	12
0	0	0		2	1			4				2	2	1	1	0
0	0	0		0	0			3				0	0	0	0	0
0	21	14		0	2			2				1	0	0	1	1
3	0	3		0	1			1				1	1	0	3	1
1	1	1		0	0			0				1	0	0	0	1
0	0	0		0	0			0				1	0	1	0	0
0	0	0		0	0			0				1	2	5	1	0
0	6	17	0		39	44	48	50	27	0	0					
2	27	36	100		22	24	21	21	20	100	100					
98	67	47	0		39	32	31	29	53	0	0					
				++												
+																

Appendix 3 A review of literature on the Tertiary cover of the Ardennes peneplain

For a good understanding of the ideas on the development of the Tertiary cover of the Ardennes peneplain and its stratigraphy, a discussion of the various relevant theories from literature is necessary. Fig. 2 may serve as a support.

The Chattian sands On the Belgian geological map 1:40,000 (± 1900) the Chattian sands (*Om*) are reckoned with the marine Tongrian.

The first notes on the Tertiary deposits of the higher parts of Belgium are from Bouesnel (1812) and Cauchy (1823) (cited by van den Broeck, 1893), but they do not express any opinion about the origin or stratigraphy.

In 1885 Lohest supposed the sands to have been deposited by rivers still unknown at the moment, and calls them 'fluviatile Tertiary'. Van den Broeck (1888) places the sands of Boncelles, Neerrepen and Grimmertingen together in the Lower Tongrian (Lower Oligocene). Lohest (according to van den Broeck & Rutot, 1888) separated the sands of lower and higher Belgian regions into two units and supposed those of the higher region to be of Eocene and those of the lower of Lower Oligocene age (the higher part of Belgium had been uplifted long after deposition of the Chattian sands). Van den Broeck (1893) considered the sands of Rocourt (west of Liége) to be identical with the Grimmertingen sands and placed them both in the Lower Tongrian. On the other hand Lohest (1895) identified the sands of the Condroz (but not those north of the line Namur-Liége) with those of the Herve plateau and placed them in the Landenian (Eocene).

According to Rutot (1908) and Destinez (1909) the Boncelles sands belong to the Chattian (Upper Oligocene) because of the fossils assemblage in the upper layers, but Velge (1909) attributed them to the Rupelian (Middle Oligocene) on a different interpretation of the same fossil assemblage. Fourmarier (1919), adopting the idea of Rutot, placed the upper Boncelles sands in the Chattian or in the Aquitanian (which was then considered to belong to the Oligocene). He supposed the series below the lower gravel layer to be a Tongrian deposit (another correlation with the Grimmertingen sands).

According to Lorié (1919) the same Boncelles complex belongs to the Rupelian (Berg sands) or the Bolderian (Miocene, Houthalen sands), but Leriche (1922) again combines the Bolderberg and the Boncelles sands into one unit though he considers them to be of Upper Oligocene age.

The sands of the Bolderberg, which are partly glauconitic and which, as the Boncelles sands, show many traces of marine biological activity (burrows), were later on placed in the Miocene again. Finally, Tavernier (1938) splitted them up in the upper sands (belonging to the Diest sands, Upper Miocene; then considered to be of Pliocene age) and the lower sands belonging to the Bolderian (Middle Miocene, at present Houthalean).

In most of the publications after 1922 (Macar, 1934, 1937, 1947; Magnée & Macar, 1936; Macar & Kolatchevski, 1935; Ancion & van Leckwijck, 1947) the sands of Boncelles, Rocourt and several small occurrences in the Condroz and east of the River Ourthe are attributed to the Chattian. Macar (1937) added to these the sands found in dolinas on the Herve plateau (Evrard, 1945), and Bourguignon (1954) supposed that part of the sands on the Hautes Fagnes plateau belong to the same series.

The gravels and sands of the Onx formation The geological map 1:40,000 (± 1900) considers these gravels to belong to the Oligocene. For the greater part they are unconformable to the *Om* formation.

On their origin various opinions have been put forward. Rutot (1907) suggests a fluviomarine origin; Fourmarier (1923, 1931) and Stevens (1945) defend marine sedimentation, but most authors adhere to fluviatile sedimentation (van den Broeck & Rutot, 1888; van den Broeck, 1893; Stainier, 1891, 1894; Lorié, 1918; Oostingh, 1925; Macar, 1945; Tavernier, 1946).

Also on their stratigraphic position there is much diversity of opinion: it has varied from Paleocene to Pleistocene. Van den Broeck (1893) attributed them to the Oligocene. Dewalque (see Lohest, 1895) drew a parallel between the gravels and the german Bolderian (which was, at that time, considered to form a part of the Oligocene). Leriche (1922) supposed the gravels from Boncelles to belong to the 'kiezeloölite terrace' and placed both in the Pliocene. Lorié (1918) splitted up the *Onx* formation in two parts, the 'Traînée mosane' and the 'Graviers liégeois'; the first he supposed to be an old Meuse terrace deposit dating from the Günz glaciation (Penck's concept), the second was considered to be an Ourthe Fan deposit and supposed to be somewhat older because of its higher topographical position. Stainier (1891, 1894) considered the gravels north of the line Namur-Liége also to be remnants of a fossil Meuse course.

Hummel (see Oostingh, 1925) compared the *Onx* terrace with the white quartz gravels at the base of the Landenian and attributed the first to the Paleocene, whereas Oostingh himself considered the gravels of Rocourt (west of Liége) to belong to the Pliocene or the Lower Pleistocene. This assumption was shared by Macar & Meunier, 1954) and by Ancion & van Leckwijck (1947), but Calembert & Gulinck (1954) considered a Mio-Pliocene age.

As was mentioned before, no generally accepted hypothesis has been published till now. The new Belgian geological map 1:25,000 (± 1965) indicates solely 'Tertiary'.

The Andenne clays (Ona) The geological map 1:40,000 (± 1900) considers these clays to be of Oligocene age.

The data before 1880 in the following review have been taken form Calembert's publication (1945b).

The Andenne clays were first described by Bouesnel (1812), but this author did not discuss their origin and supposed them to be very young. Cauchy (1826) discovered that they as a rule occur on contacts between limestone and other rocks and that the clays are not remnants of a previously continuous cover.

Both Bouesnel and Cauchy mentioned the occurrence of well-conservated wood fragments in certain layers.

D'Omalius d'Halloy (1842) was the first to attribute the clays to the Tertiary, but he supposed a hydrothermal origin ('geyserienne'). Dewalque (1868) agreed with this and supposed the clays to have originated from weathering of shales. Briart & Cornet (1867) mentioned genesis by hydrothermal influences and weathering caused by percolating rainwater.

Firket (1874) was the first not agreeing with hydrothermal origin; he believed in very rapid weathering in situ. Dupont supposed a fluviatile origin, a conviction that was shared by Lohest (1887, a, b) who supposes the former presence of narrow river courses connecting small sedimentation basins. In 1887 Lohest solely considered the possibility of lacustrine origin.

Van den Broeck & Rutot (1888) regarded the sands, intercalated in the clay deposits as synchronous with the Boncelles sands (which were considered to be Lower Tongrian) and supposed synchronity of the Hénis clay with the Andenne clays (Hénis clay is a lagoonary or estuarine Tongrian deposit). The sands would have been formed as dunes and would be synchronous with the Neerrepen sands; the complex of clays and sands would have been spared for erosion by submerging in dolinas.

Van den Broeck (1893) agreed with the attribution of the sands to the Lower Oligocene, but he also proved, that the clay deposits could not have formed a continuous cover: he regarded them as lacustrine deposits in dolina-lakes. Lohest (1895) concluded from their setting in the dolinas that the sediments had been part of a lacustrine delta and that the clays were remaniated weathering material of Upper Carboniferous shales.

A new light was thrown on the origin of the clays by Gilkinet (1922). He determined many plant remains from the lower lignite layers of the Champseau basin (south of Andenne, between Namur and Liége) and attributed the flora to the Lower Miocene (Aquitanian). This age was adopted by the later authors, who place their clays in the Chattian or in the Aquitanian. At present, the flora described by Gilkinet is supposed to be younger (Middle Miocene; Dr Zagwijn, pers. comm.).

As to the plastic (Andenne) clays, it was Calembert who, by means of an intensive study of their occurrence, came to a good understanding of their origin (Calembert 1941a, b; 1942, 1943a, b; 1945a, b; 1947a, b; 1948a, b; 1950; Calembert & Gulinck, 1954; Calembert & van Leckwijck, 1941; Reports of the 'Comité Belge pour l'Étude des Argiles' COBEA, 1942–1948). He concluded that the clays formed by sedimentation in dolina lakes or by weathering of shales in situ. He supposed both processes to have taken place during the Chattian. This was inferred from the presence of intercalated sands of shallow marine origin and from the publication Gilkinet (1922). The lacustrine deposits would have obtained their present strange lenticular patterns by deepening of the dolina and subsequent giving way of the deposits resulting in vertical and upside-down layering. Calembert supposed the weathering to have been of 'siallitic' character. The heavy clays in the dolinas point to a very slow sedimentation of material derived in the immediate neighbourhood. Combinations of weathering in situ and lacustrine sedimentation may occur.