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Genesis of the flint eluvium and related beds in South Limburg, The Netherlands

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Abstract

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The flint eluvium in South Limburg and Belgium is a dissolution residue of Upper Cretaceous chalk which may occur either at the present surface or below a cover of Early Oligocene sand. Eluvia with sand cover contain weathered glauconite and iron accumulations but no birefringent, oriented clay. Similar eluvia without sand cover show strong orientation of clay throughout the residue. Such orientation of residual clay immediately follows dissolution of the chalk and is not derived from overlying deposits. As eluviation and orientation of clay are strictly bound to subaerial weathering, eluvia with this property must have formed after erosion of the Early Oligocene sands. Eluvia that are covered by sand do not represent a pre-Oligocene soil formation, but have formed below the sand cover. The *kleefaarde*, a weathering residue without flints, but with properties similar to those of the eluvia without sand cover, is probably a lateral equivalent of the latter and much older than presumed. Accumulation at the base of the beds continues to this day, but weathering at the soil surface is different from that during the Tertiary. The paper presents a dynamic model of the formation of such eluvia.

Introduction

Clay-with-flints or flint eluvium (Dutch: vuursteeneluvium; French: argile à silex; German: Feuersteineluvium) is a dissolution residue of (Cretaceous) limestones. It is found at or near the surface in the southern part of Dutch South Limburg, and adjacent Belgium in those areas which have not been affected by Late Tertiary transgressions or by the Pleistocene Meuse River. Similar deposits are encountered on the chalk of southern England and in France.

Clay-with-flints consists of a mixture of flints, which remain after dissolution of the chalk, with varying amounts of loamy to clayey material. This material consists of the pure, partly altered non-carbonate residue of the chalk, but may also be partly derived from overlying deposits (Hodgson et al. 1967). In South Limburg, the composition of the residue is strongly related to the insoluble components of the chalk. The lower part of the Gulpen Formation (Zeven Wegen chalk, Beutenaken chalk, and Vijlen chalk) gives a clayey to loamy residue with a low flint content; the upper part of the Gulpen Formation (Lixhe and Lanaye chalk) and the lower part of the Maastricht Formation

(Maastricht chalk) give a residue with a very high flint content and much lower amounts of residual clay, generally not enough to fill the spaces between the residual flints. The Kunrade chalk and the upper Maastricht chalk (Maastricht Formation) give clayey residues without appreciable amounts of flint (Kuyl 1980). Although the latter residues (*Kleefaarden*) are not normally included in discussions of the flint eluvium, they occur in similar positions and should not be left out. Breteler (1958) described the occurrence of *kleefaarden* in South Limburg.

Apart from variations in parent rock lithology, the habit of the flint eluvium is determined by the presence or absence of a continuous cover of Tertiary sands. If an uninterrupted cover of Tertiary sands is absent, the residue has a yellowish brown colour and pockets of sand in the residue are generally restricted to the upper layers. If a sand cover is present, the residue has a lighter colour, but strong brown colours due to impregnation with iron compounds may occur locally. Pockets of sand are found throughout the eluvial layers down to the contact with the chalk. In both types, flint banks may be found in their original sequence. At the weathering front, clay tends to accumulate under subsiding flint banks (Fig. 1).

While there is a general agreement on the eluvial character of the material, authors disagree on its time of formation and on the mechanism involved. Conclusions on the stratigraphic position are interrelated with concepts of genesis. If both types of eluvium – either below cover of Tertiary sand, or at the surface – have similar properties, the material has either formed through dissolution below a sand cover or by surface weathering prior to the deposition of the sand cover. In the first case, its age is post-sand cover, in the second pre-sand cover. In both cases, formation at the residue-chalk contact may still proceed. If the two types of eluvium have different properties, one type may either result from dissolution below a sand cover or represent a pre-sand cover phase of soil formation, while the second type is necessarily formed after reduction or removal of the sand cover and may contain properties of the first type overprinted with features of post-removal weathering or soil formation. Ages would then vary from pre-sand cover to postremoval of sand cover. In the literature, authors have always regarded the two types of eluvia as one unit.

Van den Broek & Van der Waals (1967) attributed the eluvium to soil formation and weathering at the surface of a Late Tertiary peneplain in South Limburg. Buurman (1972) also attributed the eluvium to soil formation but placed its formation in the Early Tertiary (Late Paleocene to Early

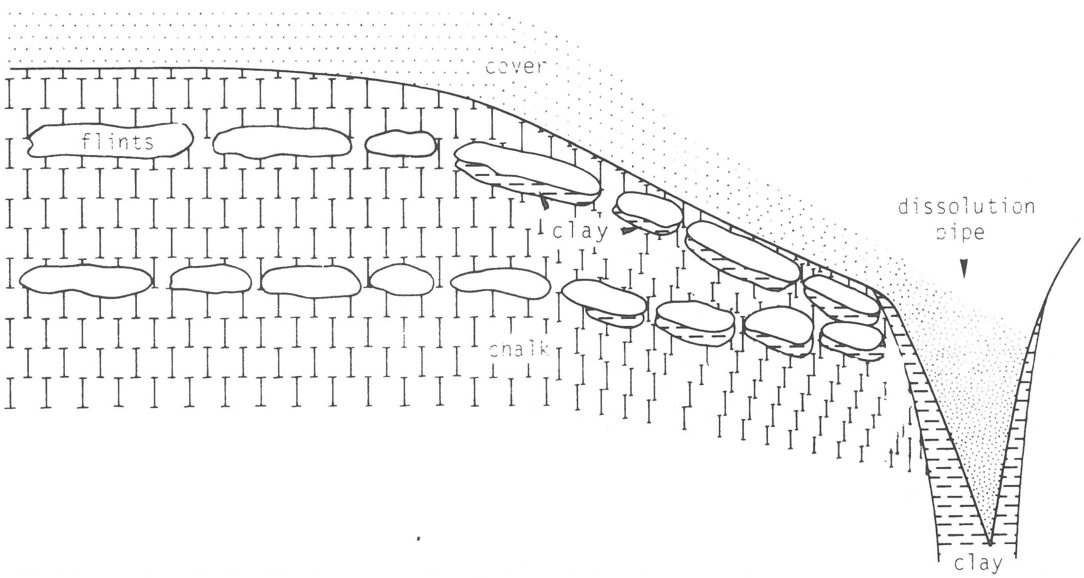


Fig. 1. Subsidence of flint layers and accumulation of clay near a dissolution pipe in chalk. Example from Halembaye. Cover consists of Tertiary sands.

Oligocene). Contrarily, Felder et al. (1978) and Albers & Felder (1979) assigned the flint eluvium to post-Oligocene dissolution of chalk below a cover of Oligocene sands and silicified chalk under the influence of organic acids. Kuyl (1980) stated that 'In the eluvial deposits, fossil soil formation is locally found in addition to recent soil formation', thus emphasizing recent or Holocene soil formation.

In order to solve this dispute, information is needed regarding the question whether the eluvia at the present surface and those below a cover of Tertiary sands have the same properties. If the eluvia under a sand cover do have characteristics which are associated with soil formation and which cannot be explained by subsurface weathering alone, they are necessarily older than the sand cover. If on the other hand, the eluvia under a sand cover have characteristics of subsurface weathering alone, while the exposed eluvia have soil characteristics, the two phases are genetically different and the soil characteristics of the exposed eluvia should be younger than the sand cover. Detailed study of several deposits may disclose the phases of weathering and soil formation that led to their present habit. To this end, flint eluvia with and without a cover of Tertiary sand were sampled at various localities.

Materials

1. Flint eluvia without cover of Tertiary sands

One of the well-known exposures is in the Vylener Bossen. A map of this occurrence is presented by Kuyl (1980) and sections are given by Felder (1961) and by Felder et al. (1978, p.139). The sections show a karstified limestone surface fully covered by flint eluvium. The latter may attain a thickness of 15 m and is locally overlain by Tertiary sands (Holset Sands; Kuyl 1980). The lower boundary of the sand is irregular due to subsidence upon dissolution of chalk after deposition of the sands. The whole sequence is covered by a solifluction layer which is a mixture of clay-with-flints and Tertiary sands. Locally, a loess cover is found on top of the solifluction deposit. The eluvium is mainly derived from chalk of the Gulpen Formation. This chalk contains 10-40% impurities, apart from the flint beds (Kuyl 1980). Two samples were taken at the exposure Zevenwegen, 2 and 4 m below the present surface. These samples were analyzed mineralogically by Buurman (1972, samples 141 142); thin section numbers are 84076 and 84077.

A profile was sampled near the village of Ulvend (Topographic Map 1:25 000, sheet 62C; coordinates N 307 750, E 186 040). The location is at an altitude of 212 m above sea level, on a remnant of the Late Tertiary peneplain. The profile exposes the upper 1.2 m of the flint eluvium. The material is somewhat reworked and the upper part has an admixture of loess. This profile was sampled and analyzed in detail. Thin section numbers are 83057 through 83070.

Further samples were taken of eluvia exposed in the CPL and CBR quarries at Halembaye and Lixhe, South of Maastricht. A description of this location and a map are given by Felder (1983). The flint eluvium is 3 to 6 m thick. At the highest part of the landscape it is overlain by 5 to 10 m sand which is attributed to the Klimmen Deposits (Tongeren Formation, Lower Oligocene), but this sand cover is absent elsewhere.

Two eluvium samples were taken at the CPL quarry, 3.5 m below the base of the solifluction deposit in eluvium characterized by flints of the Lixhe chalk (Gulpen Formation). Thin sections are 84067 and 84068. Three samples were taken at the CBR quarry, northern part. These samples are of a clay layer, 2-10 cm thick, which marks the contact of eluvium and chalk, under a flint block of 1 m across (Fig.1). At the site, the flint eluvium is covered by Pleistocene terrace deposits and loess. Thin section numbers are 84072 through 84074.

2. Flint eluvia with cover of Tertiary sands

Two locations were sampled in the CPL quarry (see above). One sample was taken in the southern part of the quarry, immediately above the karstified chalk. The sample was 4 m below the top of the eluvium. The Tertiary sand cover was more than 2 m thick and overlain by loess. The thin section number is 84069. This sample was taken within 50 m of samples 84067 and 84068 of the preceding section.

Two samples were taken in the northern part of the quarry. The Tertiary sands have been excavated at this site, but their thickness was several metres. The eluvium has many pockets of sand. The samples were taken of clayey material close to the chalk contact. Thin section numbers are 84070 and 84071.

3. Clayey material in dissolution pipes

Infillings of dissolution pipes in the chalk have visual properties similar to those of the flint eluvium, except for high flint contents. Two locations were sampled, one with and one without sand cover. One sample was taken of a dissolution pipe infilling at the Juliana II quarry, Schiepersberg. There is no sand cover. The sample was taken about 3 m below the top of the surrounding chalk. Thin section number is 78087.

One sample was taken of a dissolution pipe infilling under more than 5 m of Tertiary sand at the Curfs quarry, Houthem-St.Gerlach. The sample was taken 1 m below the top of the surrounding chalk. Thin section number is 84080.

4. Dissolution residues without flints, Kleefaarden

These residues have been extensively studied by Sevink & Verstraten (1979) and Verstraten & Sevink (1979a,b). New samples have not been taken because published material allows for adequate comparison of data.

Methods

A description of the Ulvend profile was made according to the terminology described in FAO (1977). The Ulvend samples were analyzed for grain size (dry sieving and pipette method) and clay minerals. Samples for clay separation were treated as follows: 1. removal of carbonates with acetic acid buffer at pH 5; 2. removal of organic matter with buffered H_2O_2; 3. dispersion in 0.005 N NaOH; 4. separation of fraction smaller than 2 microns by sedimentation and decanting; 5. sedimentation on porous ceramic sample holders. Diffractometer traces of Mg-saturated samples were obtained after three pretreatments: 50% relative humidity, glycerol saturation, and heating to 600°C, respectively. Additional X-ray photographs of the clay fraction were made with a quadruple Guinier-De Wolff diffraction camera using Co-K alpha radiation.

Undisturbed samples of the full Ulvend profile, and of all other locations, were taken in steel boxes. Samples were impregnated with synthetic resin and thin sections were prepared (see Fitzpatrick 1970). Thin sections were described using the terminology of Brewer (1964), with the aid of a petrographic microscope. Semi-quantitative chemical analyses on thin sections were obtained with a JEOL GSM 35C Scanning Electron Microscope in combination with an EDAX 9100 analyzer.

Results

1. The Ulvend profile

The Ulvend profile has been subdivided into the following horizons: Ap, 0-20 cm, dark brown silty clay loam, overlies 2Bt1, 20-40 cm, strong brown clay with inclusions of overlying material; 40-60 cm, 2Bt2, yellowish brown clay with red mottles, overlying 2Bt3, 60-95 cm, yellowish brown and brownish gray clay with red mottles, and finally, 2Bt4, 95-120 cm, dark red and light brownish gray clay with red mottles. Structures are angular and subangular blocky; flint content increases with depth. Flints belong to the Lixhe and Lanaye members of the Gulpen Formation (Felder 1975). (This description has been strongly abbreviated. Details are not relevant in the present scope. Full description available upon request).

Grain-size frequency distribution

Grain-size frequency distributions of the Ulvend profile are reported in Table 1. Details of the fractions finer than 50 microns are presented in Fig. 2. The profile does not have appreciable admix-

Table 1. Grain-size frequency distribution of the Ulvend profile.*

Sample	Depth (cm)	<2	2-50	50-75	75-105	>105μ μ
1	0 - 10	28.2	57.7	4.1	2.3	7.7
2	10 - 20	29.5	55.4	4.5	1.7	8.7
3	20 - 30	51.0	37.2	3.9	1.6	6.3
4	30 - 40	65.0	25.0	3.4	1.6	5.0
5	40 - 50	68.1	22.5	2.8	1.5	5.1
6	50 - 60	69.8	21.8	2.4	1.4	4.6
7	60 - 72	70.3	21.4	2.3	1.2	2.8
8	72 - 84	69.0	23.6	2.1	1.2	4.1
9	84 - 95	63.1	25.5	2.7	1.9	6.6
10	95 -107	64.5	24.9	3.5	2.1	5.0
11	107 -120	61.7	28.0	2.8	1.7	5.8

*Weight percentages of fraction finer than 2 mm; details of fraction finer than 50 microns are given in Fig. 2.

tures of Tertiary sand. The upper two samples contain a fair amount of loess material, the contamination of which is less in sample 3. Samples 4 through 11 have very homogeneous grain-size distributions and probably reflect the composition of the chalk weathering residue. The fraction larger than 50 microns contains a fair amount of flint fragments.

Micromorphology

In the uppermost 20 cm, skeleton grains consist of quartz. Fragments of flint occur throughout the profile; their amount increases with depth. Weathering of flints is discussed in the next paragraph.

The fine fraction (plasma) consists of clay minerals and iron compounds and has a strong brown to yellowish brown colour. From 20 cm downwards the plasma has a sepic fabric, i.e. it shows reorientation. Below 60 cm part of the plasma has a grey colour. Below 20 cm, skeleton grains are scarce and dominantly glauconitic. Biogenic pores decrease with depth, while shrinkage structures (skew and craze planes) increase. Between 20 and 120 cm depth, the following features were encountered:

a. clay coatings (cutans) in present channels and on planes (Fig. 3a). The majority of these coatings is found in the grey parts and has lost much of its birefringence and has a grainy appearance. The thickness of such cutans varies between 0.02 and 0.1 mm. Papules (subrounded bodies of oriented, birefringent clay), 0.08-0.2 mm across, with similar characteristics and probably derived from the cutans, are mainly found in the grey matrix.
b. clay coatings (cutans) in dissolution pores of weathered flints (Fig.3b). These cutans are yellowish brown, have high iron contents and a strong, continuous orientation pattern. They are never grainy. The thickness of these cutans is 0.02-0.1 mm.
c. clay papules with a high birefringence (Fig. 3c,d). These papules, 0.2-2 mm across and somewhat angular, are either of homogeneous appearance or have strong parallel orientation. They occur in clusters and bands and are commonly surrounded by plasma orientations (pressure cutans).

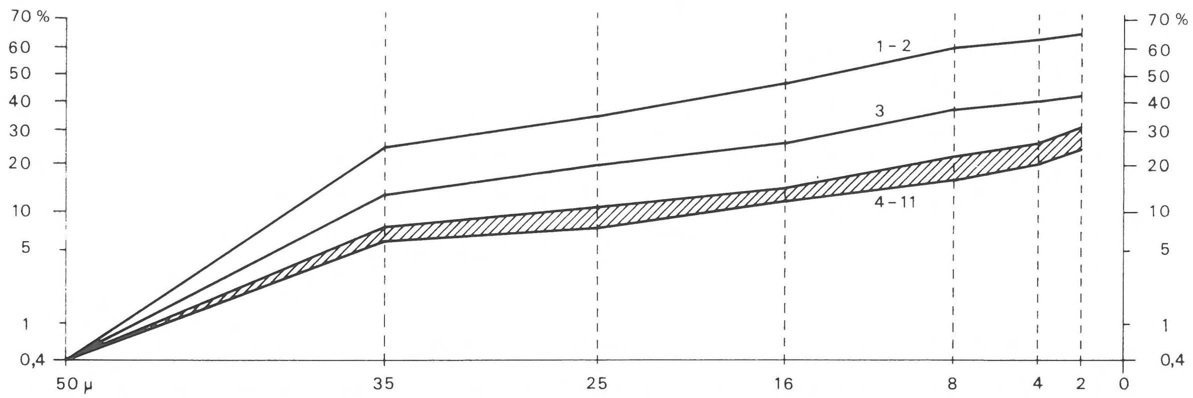
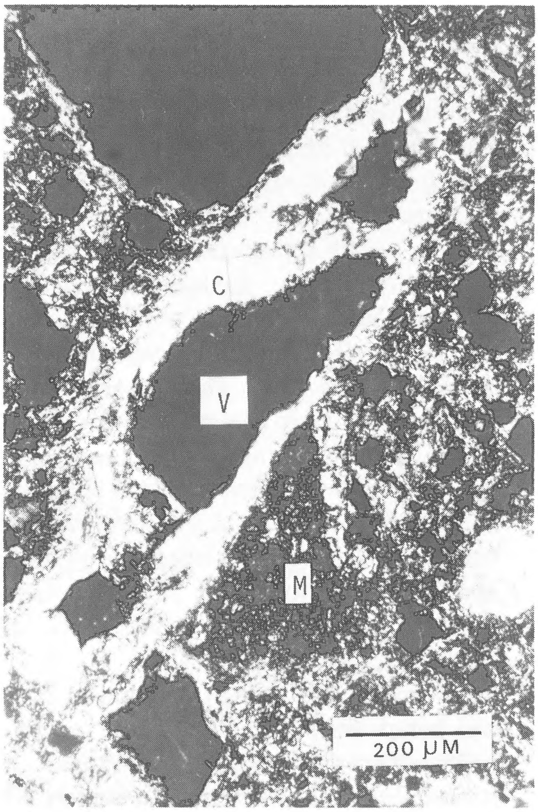
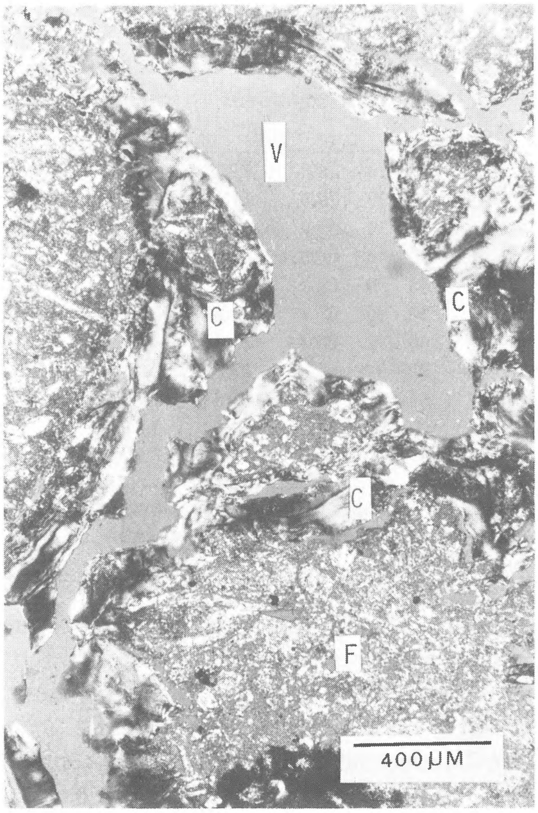


Fig. 2. Grain-size frequency distribution of the Ulvend profile. Cumulative curves of fractions finer than 50 microns. For sampling depths see Table 1.



a



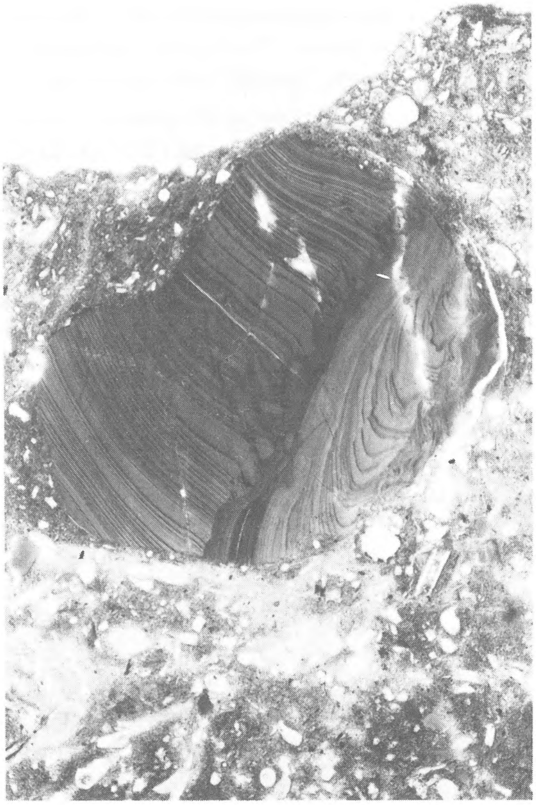
b

Fig. 3. Micromorphological features.
a. Type *a* clay coating. Section 83164, crossed polarizers.
b. Type *b* clay coatings in flint. Section 83168, partially crossed polarizers
c.d. Type *c* papule consisting of regularly in irregularly stratified parts. Section 83160, c. plain light, d. crossed polarizers.
C= coating; F= flint; M= matrix; V= void.

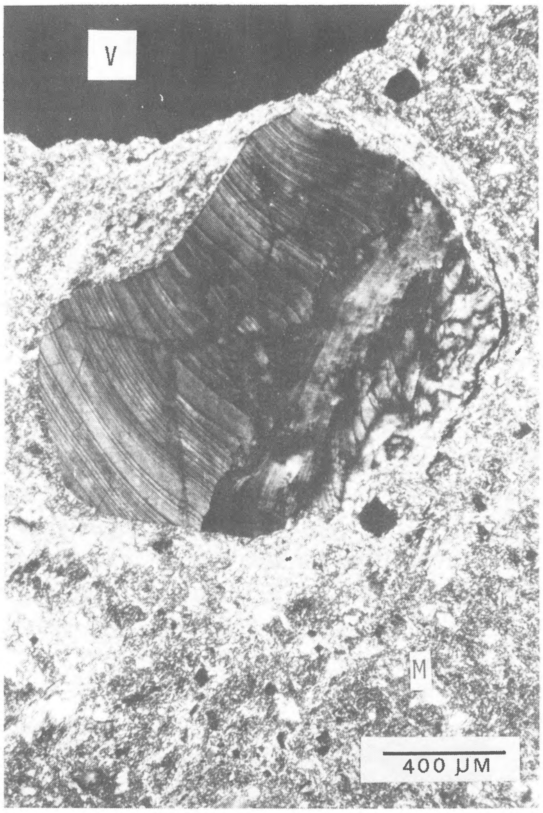
d. clay papules with a high birefringence, similar to *c,* but with a wavy lamination. Type c and d papules are ferri-argillaceous papules; they may be covered with type *a* cutans, or occur in type *g* bodies.
e. clay papules with a 'flecked' orientation pattern. These papules show varying birefringence and are not laminated. They are somewhat angular, 0.1-2 mm across and usually occur in clusters (glauconitic papules).
f. ferric papules. Angular and spherical iron compounds of amorphous to crystalline habit. The latter have a flecked orientation. These papules are never layered and do not have concentric structures.
g. rounded bodies of matrix material with sharp boundaries. These bodies are frequently surrounded by type *a* clay accumulations or by pressure coatings; they may contain type *c, d, e* and *f* papules.
h. oriented coatings of matrix and clay (matri-ferri-argillans; Van Schuylenborgh et al. 1970) are found in larger channels in the lower part of the profile; they locally alternate with cutans of type *a*.
i. iron coatings (neo and quasi ferrans). These coatings may cover clay coatings and papules; their abundance increases with depth.

Flint weathering phenomena

Flints occur in relatively unweathered to strongly weathered conditions. Unweathered fragments are 5-50 mm across and angular to subrounded. They consist of chalcedony with locally clusters of calcareous and siliceous fossils (foraminifera, sponge spicules). Part of the flints still contains calcite,



c



d

either in the form of fossils or as idiomorphic crystals or crystal aggregates. Crypto-crystalline parts may contain pyrite or pseudomorphs after pyrite, and scattered glauconite grains. Dissolution of flints mainly affects the cryptocrystalline parts. These parts dissolve, while coarser parts remain. This leads to porous structures in which the coarser-crystalline silicified fossils remain as circular and acicular structures. Dissolution voids are frequently lined with cutans of oriented clay (type *b*). Recrystallization of silica is found as chalcedonic rims on the flint surface or, more frequently, as fine sphaerulitic crystalizations in the porous structures. In the final stage of weathering, sphaerulites and silicified microfossils are found loose and sometimes closely packed around unweathered flint fragments. Fresh flints mostly have white outer rims. These outer rims consist of silica (chalcedony) cement with considerable amounts of calcite. The calcite occurs in the form of microfossils or calcite crystals and clusters. Weathered flints still feature a white outer rim, but here the white colour is due to occlusion of air, and sometimes to amorphous silica.

Clay mineralogy

All clay samples of the Ulvend profile contain the clay minerals kaolinite, illite and smectite. The smectite reflection increases with depth, with respect tot the other minerals. Accessory minerals in the clay fraction are quartz, goethite, and anatase. Potassium feldspar and plagioclase are found in minor amounts in the upper 20 cm.

2. Other eluvia without cover of Tertiary sand

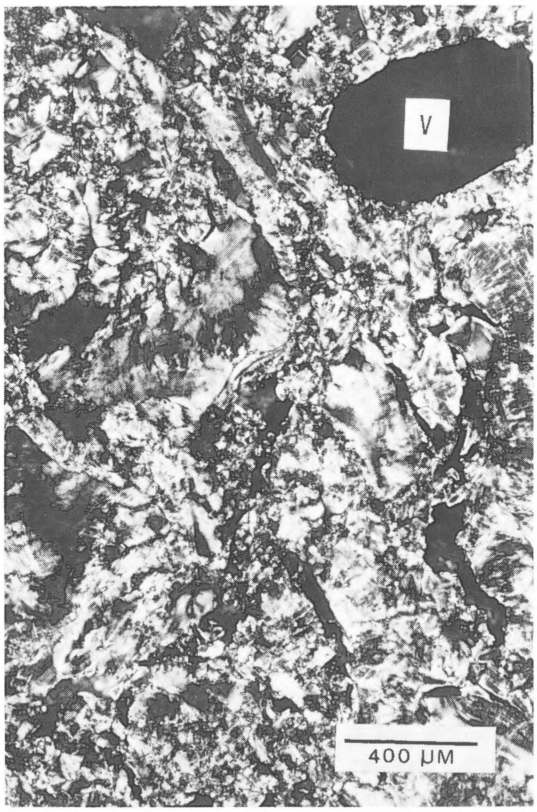
The eluvia from the Vylener Bossen (84076/77) have the same characteristics as those of the Ulvend profile, but features *a* and *h* are of subordinate importance.

The samples from the CPL quarry, Halembaye (84067/68) have the following micromorphological characteristics. The samples contain pockets of quartz grains of uniform size (50-150 microns, Tertiary sand). Glauconite is found in various stages of weathering and occurs as grains (50-200 microns), aggregates, and discontinuous bands up to several mm thick. Weathered glauconite has a changing (flecked) orientation pattern (type *e*). Iron compounds occur as ferric papules (type *f*) of amorphous or crystalline habit.

In sandy parts, the individual sand grains are covered by clay cutans 20-100 microns thick with a continuous orientation pattern, similar to the cutans found in weathered flint (type *b*). Thick cutans along voids, with a continuous orientation pattern, are common throughout the samples. Clay papules with a high birefringence (type *c* and *d*), 100-500 microns across, occur throughout the groundmass in a clustered distribution pattern. The papules are derived from the thick cutans and may envelop ferric papules (type *f*).

The samples from CBR, Lixhe (84072-74) clearly illustrate the transition form dissolving chalk to eluvial accumulation. The chalk is very porous and contains sporadic small (<50 microns) quartz grains and sand-size (up to 200 microns) glauconite grains. Clusters of quartz grains (Tertiary sand) are found on top of the chalk; such clusters contain free-grain argillans (clay cutans).

Minute accumulations of illuviated fine clay with strong orientation are found in all fine pores of the dissolving chalk. Thick clay cutans (0.1-2 mm thick) with a continuous orientation pattern are found in the larger dissolution voids. Many of these cutans are broken and form papules comparable to types *c* and *d* of the Ulvend profile. The clayey residue on top of the chalk consists almost exclusively of fine clay with a continuous orientation pattern, which becomes stronger when more removed from the chalk. The birefringence of the clay is irregular, due to a clustering of clay from fine



a


b

Fig. 4. Massive clay accumulation with irregular birefringence. No skeleton grains visible. a. plain light; b. crossed polarizers. Section 78087.

and from coarser pores. The mineralogy of these clay accumulations is similar to that of the non-carbonate residue in the chalk, and distinct from that of the overlying loess. It consists predominantly of smectite clay.

The dissolution-pipe filling from Schiepersberg (78087) has similar features. Its groundmass consists of fine clay with a strong continuous orientation pattern and very irregular birefringence. Thick clay cutans with a strong continuous orientation pattern and regular birefringence are again found in larger dissolution voids (Fig. 4ab).

3. Eluvia below a cover of Tertiary sand

The three samples from the CPL quarry, Halembaye (84069-71) have very similar features, which strongly contrast with those of eluvia without sand cover. The samples have a groundmass of clayey material, which is strongly impregnated with iron compounds and many voids are partly filled with amorphous or crystalline iron accumulations (type *f*). The samples do *not* contain features of clay transport such as clay cutans and derived papules.

The dissolution-pipe infilling from the Curfs quarry (84080) has a groundmass consisting of a mixture of uniform quartz grains (Tertiary sand) and glauconite fragments. The groundmass is strongly impregnated with iron and many voids are partly filled with amorphous or crystalline iron accumulations. The glauconite may have a flecked orientation pattern when weathered. Features of clay transport are absent.

4. Chemical analysis of clay cutans, papules, ferric papules, and glauconite

In order to compare clay papules with in-situ clay cutans, chemical analyses were made of cutans and papules from various locations. Changes in composition of glauconite, in relation to development of birefringence, were also investigated. Mean values of a number of analyses are reported in Table 2. In the analyses of clay papules and cutans, standard deviations are small and the populations are clearly separated, especially with respect to Si/Al ratios.

There is a distinct weathering sequence recognizable in the chemical composition of clay cutans and papules. This sequence is reflected in MgO, Al_2O_3

Table 2. Semi-quantitative analysis of oriented clay papules and other micromorphological features (weight %).

Oxide	Clay Papules				Glauconite weathering					Ferric papules
	A	B	C	D	E	F	G	H	I	J
MgO	1.2	1.2	1.7	1.6	2.6	0.6	1.2	1.1	2.0	0.2
Al_2O_3	27.8	28.1	22.9	21.5	6.3	4.3	7.8	7.5	15.8	2.1
SiO_2	44.0	48.6	45.9	49.9	49.7	34.5	49.6	32.5	55.4	2.5
P_2O_5	0.2	0.2	0.2	n.d.	0.2	0.4	0.8	1.3	n.d.	3.5
SO_2	0.2	0.2	0.2	n.d.	0.1	0.2	0.3	0.3	n.d.	0.5
Cl	0.1	0.1	0.1	n.d.	0.1	0.1	0.2	0.3	n.d.	0.3
K2O	1.8	2.6	3.5	3.6	9.8	0.7	1.3	1.3	3.8	0.3
CaO	1.7	0.3	2.2	2.4	0.8	2.7	2.6	1.8	1.7	2.0
$Ti0_2$	1.5	1.3	1.8	1.4	0.4	0.8	0.5	0.6	1.0	0.4
Fe_20_3	21.8	17.7	21.1	19.5	30.1	55.8	35.8	53.3	20.3	88.3
Si/Al atomic ratio	1.41	1.53	1.77	2.05	7.0	7.0	5.6	3.8	3.1	

nd= not determined. A. 6 papules from Ulvend, sections 83167 and 83170; B. 2 papules from Vylener Bos, section 84077; C. 4 coatings from dissolution pipe material, section 78087; D. 4 samples of oriented clay from contact chalk, Halembaye, sections 84067,73,72,74; E. Unweathered glauconite grain, 2 analyses, Curfs, section 84080; F. Glauconite sheet, weathered with little birefringence, Curfs, section 84080, 2 samples; G. Glauconite with weak flecked orientation, 2 samples, Curfs, section 84080; H. Glauconite with strong flecked orientation, 1 sample, Curfs, section 84080; I. Glauconitic material with weak flecked orientation, 2 samples, section 84067; J. Ferric papules, 4 samples, Halembaye, sections 84071, 84068.

and K_2O contents, but more clearly in the Si/Al atomic ratio. In the samples that are in direct contact with the chalk, the Si/Al ratio is close to 2, which reflects the dominance of 2:1 minerals, mainly smectite. The ratio is lower in the pipe fillings and in the Vylener Bossen samples, and lowest in the Ulvend samples (1.4). The latter were taken from the top layers of the eluvium, while those of the Vylener Bossen were from deeper layers. The changes reflect a shift towards 1:1 clay minerals. The cause is a loss of silica rather than an accumulation of aluminium. CaO contents vary and probably reflect impurities. Chemical analyses of the matrix material are not reported in the table. They always had higher Si/Al ratios, between 2 and 4.5, which is probably due to the presence of silt-size quartz fragments and flint weathering remains. Matrix material always had lower iron contents than cutans and papules. Fresh glauconite and weathered glauconite with a flecked orientation pattern have chemical compositions which are very distinct from the foregoing. The fresh glauconite grain stands out with a very high K_2O content. Iron contents and Si/Al ratios are much higher in the weathered glauconite than in the clay papules, but the composition of glauconitic weathering products is quite variable. Iron papules, whether amorphous or crystalline, have approximately the same composition and contain some phosphate next to predominant iron compounds.

Interpretation

1. Sequence of processes

The differences in properties between residues present below a cover of Tertiary sand and residues that have direct contact with the atmosphere are striking. Below a sand cover, residual clay and other detritic material may accumulate, but features connected with clay movement are absent. A strong accumulation of iron compounds of amorphous or crystalline habit is typical, which is probably connected either with periodic saturation of the material with water or with preferent drainage channels. Broken up, the iron accumulations give rise to iron papules (type *f*). Glauconite may weather and develop a flecked orientation pattern. Residues that have direct contact with the atmosphere are characterized by transport of clay, and accumulation in oriented, birefringent fillings of voids. The following sequence of events is derived from micromorphological evidence and refers to the eluvia without sand cover.

- The oldest features of weathering are ferric papules (type *f*). They never envelop other pedogenic features. Only below a sand cover are these iron concentrations related to actual voids, and they should therefore be ascribed to subsurface weathering.
- The oldest features of soil formation are type *c* and *d* papules. Such papules appear to be common in limestone weathering residues. They were described by Bullock & Murphy (1979) from clay-with-flints in England and attributed to a fossil phase of clay translocation. Verstraten & Sevink (1979b) described similar papules from a *Kleefaarde* on Kunrade Chalk (Maastricht Formation) from South Limburg without drawing conclusions as to their origin. Our samples of weathering residues in direct contact with the chalk indicate that such papules are broken remains of the thick, continuous coatings that form in larger pores of the dissolving chalk. In subaerial weathering of the chalk, these coatings are the first stage of accumulation. Formerly, layers with high amounts of birefringent clay overlying carbonate-rich material were referred to as *beta*-horizons (Bartelli & Odell 1960a,b) and were supposed to be secondary accumulation horizons of clay originating from the overlying deposit (e.g. loess). Oriented clay in such *beta*-horizons may account for more than 50% of the soil volume and mainly occur in the form of papules (Ducloux 1973, 1978). Ducloux explained the predominance of papules by fractionation of cutans due to freezing, but such fractionation could also be due to irregular subsidence due to dissolution of underlying rock. We have to conclude that in the present case the clay accumulation on top of the chalk is a primary accumulation of weathering residue, because its mineral composition is similar to that

of the chalk and not to that of overlying deposits. The papules are not inert with respect to weathering. Chemical analyses indicate a gradual loss of silica as their mineralogy changes from predominantly smectitic to partly kaolinitic.

- The rounded bodies of matrix material (type *g*) contain papules *c* and *d* and iron papules (*f*) and are therefore younger than these. The presence of the matrix bodies suggests horizontal movement of material, probably under periglacial conditions.
- Type *a* clay illuviation coatings are encountered in present voids. They may surround the matrix bodies described above, or the clay and iron papules. The formation of these clay illuviation coatings is therefore a younger phase of soil formation. Its local alternation with illuviation of fine matrix material, which is common in the overlying loess (Van Schuylenborgh et al. 1970) indicates that it is derived from the loess cover. They should therefore be of a Late Pleistocene to recent age.
- The most recent phenomenon in the Ulvend profile is the partial reduction and removal of iron from water-transporting channels, the so-called pseudogley. This process leads to the formation of bleached, grey channels in the brown matrix. In the channels, clay illuviation cutans of the preceding phase are partly dissolved and loose their birefringence. This leads to a greasy appearance (Brinkman et al. 1973). Chemical analyses of the bleached coatings (not reported in the Table) indicate that Mg, K, and Al are removed from the lattice, leaving a skeleton of amorphous silica which still retains part of the clay orientation.

This sequence of processes leads to the following dynamic model for the genesis of the flint eluvium.

2. A model for the genesis of the flint eluvium

a. As long as the chalk is covered with a considerable deposit of undisturbed Tertiary sands, dissolution leads to residues with grey colours that may locally contain strong accumulations of iron. Clayey residues do not have birefringence that is due to orientation. Glauconite will gradually weather to clay, and such weathered glauconite grains or sheets develop an irregular birefringence. This weathering also occurs during the following stages. Such residues may already have formed before removal of the sand cover and will be modified by later soil formation.
b. Soil forming processes start to act upon the chalk as soon as the sediment cover is reduced or removed. In the present case, the sediment cover consists of Early Oligocene sands, and removal may date from the Late Oligocene or later.
c. Dissolution of calcium carbonate sets free non-calcareous material such as flints, siliceous skeletons, glauconite and clay. The clay is transported over short distances and fills pores in the underlying chalk, forming birefringent pockets. In normal pores, such pockets are small, but they become more than a millimetre thick in dissolution channels, where clay may form continuous coatings.
d. Upon continuing dissolution of the chalk, larger and smaller pockets of oriented clay are agglomerated, resulting in a clayey residue consisting of very large to very small bodies of oriented clay, alternating with other residual material. Below this residue, dissolution of chalk proceeds as under c.
e. Depending on the relative amounts of flints and finer residue, residual material may envelop flint, or fill part of the space between the residual flints. If there is little fine residue, overlying deposits may be washed down into the residue.
f. Continuing dissolution results in gradual subsidence of the surface. This subsidence is not homogeneous, because dissolution of the chalk surface is irregular. The weathering front is in continuous movement and this results in a frequent shift of void systems and in a break-up of clay cutans, of clayeyfied glauconite, and of iron accumulations of stage *a*, resulting in scattering of fragments of birefringent clays and iron papules all through the weathering residue.

g. This continued and irregular movement, together with shrinking and swelling of the predominantly smectitic residue, explains the incorporation of overlying sediments (sand, loess) in the weathering residue. Clay may move into sandy pockets and form cutans on sand grains and bridges between grains.

h. During the dissolution process, flints are set free from the chalk. Partly silicified fringes of flints are freed of calcite, and protruding silica skeletons are set free. Cryptocrystalline parts of the flint may dissolve and result in the formation of cavities in the flint. Such cavities are filled with illuvial clay and show birefringent linings similar to the lining of voids in the fine residue. The cavities in flint do not callapse upon subsidence of the residue, but connections between illuvial clay in the flint cavities and that in the fine residue are severed by subsidence. Part of the flints is covered by secondary accumulation of silica. The source of this silica should be sought in the dissolution of siliceous skeletons, the dissolution of other parts of the flint, or in the weathering of clays.

i. The clay mineral assemblage of the weathering residue predominantly consists of smectite (montmorillonite) with small amounts of mica minerals. Weathering of glauconite adds to the mica fraction, and further weathering of both smectite and mica will increase the kaolinite content. The smectite content will always be highest near the contact with the chalk, while in undisturbed profiles, the kaolinite content may increase upwards in the profile. The papules of oriented clay undergo the same weathering and become more kaolinitic with time.

j. There are no indications of changes in weathering type during the Tertiary, and the weathering front may still behave as it did during the onset of weathering. Changes in the upper part of the weathering residue are related to climatic changes during the Pleistocene and to the presence of a loess cover. The presence of matrix balls suggests a periglacial distortion of the residue, expressed in lateral movement. The younger phase of clay transport is related to the loess cover and has penetrated the eluvium. This phase is easily separated from the earlier clay translocation. Channels with loessic material in the eluvia have illuviation of both clay and matrix material and are frequently accentuated by bleaching due to pseudogley.

Processes b through i should be regarded as simultaneous as soon as one or two decimetres of residual material have accumulated. The continuous 'internal' movements in the flint eluvium imply that it is very difficult to distinguish between in-situ and reworked material, unless foreign material is incorporated. The sequence of processes is also valid for eluvia described from France (Mathieu 1971, Stoops & Mathieu 1970) and England (Thorez et al. 1971) which have similar micromorphological properties.

Comparison of flint eluvium and *kleefaarde*

Micromorphological features of plateau *kleefaarde* as described by Verstraten & Sevink (1979b) are similar to those of the flint eluvia without sand cover, and the same stages of soil formation can be distinguished. It is therefore likely that the *kleefaarde* is a lateral equivalent to the flint eluvia, which developed on chalk poor in flints. Verstraten & Sevink (1979a) supposed that such weathering residues are of Late Tertiary or Early Pleistocene age. This dating was based on the occurrence of concentrations of cryptocrystalline quartz aggregates which these authors identified as phytoliths, or siliceous remains of plant tissue. The sequence of events we encountered in weathered flints strongly suggests that these 'phytoliths' are in fact siliceous marine microfossils and are a weathering residue of flint or partly silicified chalk. Concentrations of these microfossils are frequently found in the weathering mantle of flints. This implies that a minimum age for the residue cannot be based on the assumed 1 million years necessary for the transition of biogenic opal to chalcedony. There is no reason to suppose that soil formation in the *kleefaarde* should be younger than that in the flint eluvium. An Eemian age, attributed by Buurman (1972) to similar soils on Carboniferous limestones in the Belgian Condroz and extrapolated to the *kleefaarde* is therefore not valid for the latter. In the following discussion, the *kleefaarde* on plateaus will be considered as lateral equivalents of the flint eluvium. Soil residues on valley sides which are younger than the Late Tertiary peneplain are not discussed here.

The role of silicified chalk of 'tridymite', or better opal-CT mineralogy is still unclear. The material was described by Buurman & Van der Plas (1968, sample 110) and by Buurman (1972, samples 110,139,140) from the Osebos near Gulpen and from the Platte Bossen near Simpelveld, and is also reported to occur in *kleefaarde* by Verstraten & Sevink (1979a). This material and its genesis will be dealt with in a forthcoming paper.

Stratigraphic conclusions

Eluvial layers below a Tertiary sand cover are essentially different from eluvia without sand cover. Only exposed eluvia have characteristics of soil formation, whereas eluvia below a sand cover result from subsurface weathering. The latter may be associated with accumulations of halloysite and gibbsite (Buurman et al. 1975). Absence or considerable reduction of the sand cover is necessary for the formation of pedogenic properties. The Tertiary sands of Halembaye were placed in the Early Oligocene (Klimmen Deposit) by Felder (1983), and the Holset Sands, covering the eluvia of the Vylener Bossen, were placed in the Early Oligocene by Buurman & Janssen (1983). This sand cover originally formed a continuum and covered all investigated localities. Therefore, pedogenic properties have necessarily formed after the removal of this Early Oligocene sand. This agrees with the opinion of Albers & Felder (1979) who suggested a post-Oligocene age. The residue below the sand cover is not necessarily of the same age and as the two types have strongly contrasting properties, they should not be presented as a continuous phase in geological cross sections. Eluviation below the sand cover may have started soon after regression of the Early Oligocene sea, and before the onset of soil formation. Our investigations, however, suggest that formation of both types of residues still continues at the weathering front. The upper layers of the exposed eluvia have been altered by the loess cover and by changed hydrological conditions. At present, flint eluvia with characteristics of pre-Oligocene soil formation have not been encountered in South Limburg. This leaves a long period of regression and terrestric environment unaccounted for, which covers most of the Paleocene and all of the Eocene. Residues from this period would probably have properties similar to those of the post-Oligocene eluvia, with slightly stronger weathering (loss of silica) and redder colours. Descriptions by Mathieu (1971) and by Pomerol & Riveline-Bauer (1967) of Paleocene and Eocene eluvia from France point in this direction. It is unlikely that such residues would show a strong resemblance to the kaolinitic basal clays of lignite depositis, as was suggested by Albers & Felder (1979).

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