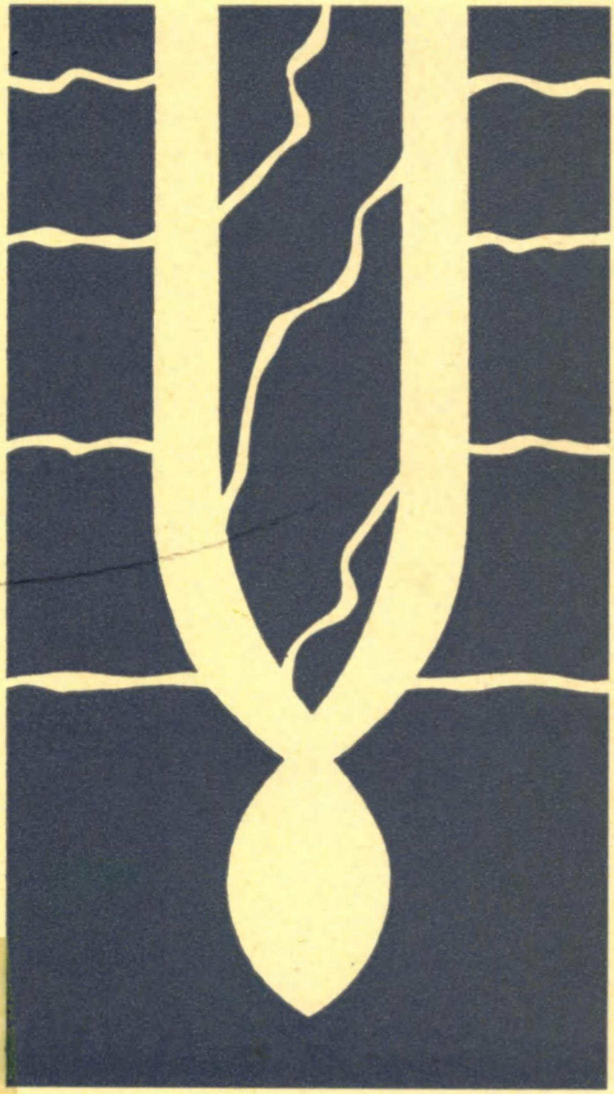
Survey Papers No. 3

THE LATE TERTIARY PENEPLAIN OF SOUTH LIMBURG (THE NETHERLANDS)



by J. M. M. van den Broek
and
L. van der Waals

Survey Institute, Wageningen

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Silicifications and fossil soils; a geological and pedological investigation

J. M. M. van den Broek
Soil Survey Institute, Wageningen

and

L. van der Waals
Geological Bureau, Heerlen

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. . . "fossil" soils may be encountered in stratigraphy, and a recognition of these materials and correct interpretation of their significance are essential to full unraveling of the geologic history of any area.

F. J. Pettijohn, Sedimentary Rocks, 1949, p. 373.

CONTENTS

Note. This paper is a report of lectures and an excursion held during the meeting of the Kon. Ned. Geol. Mijnbouwk. Genootschap, 23 and 24 April 1965 at Heerlen. It has also been published in Geologie en Mijnbouw vol. 45 (1967), p. 318-332.

SUMMARY

South Limburg formed the border-zone of a large West European peneplain during the Tertiary and the Late Tertiary. Thin local deposits of strongly weathered and corroded sand and gravel, strongly weathered outcrops of underlying formations, deep fossil soils and extensive surface silicifications are the characteristic features of this peneplain. Through a combined geological and pedological survey these features were found to be interrelated. They are the result of typical climatic circumstances and the associated vegetation acting on the earth surface. Such influences can leave their marks on the surface only during a period of geological calm: a period without any noticeable sedimentation or erosion. Such periods generally escape a geologist's observation; they are of utmost importance to the soil scientist.

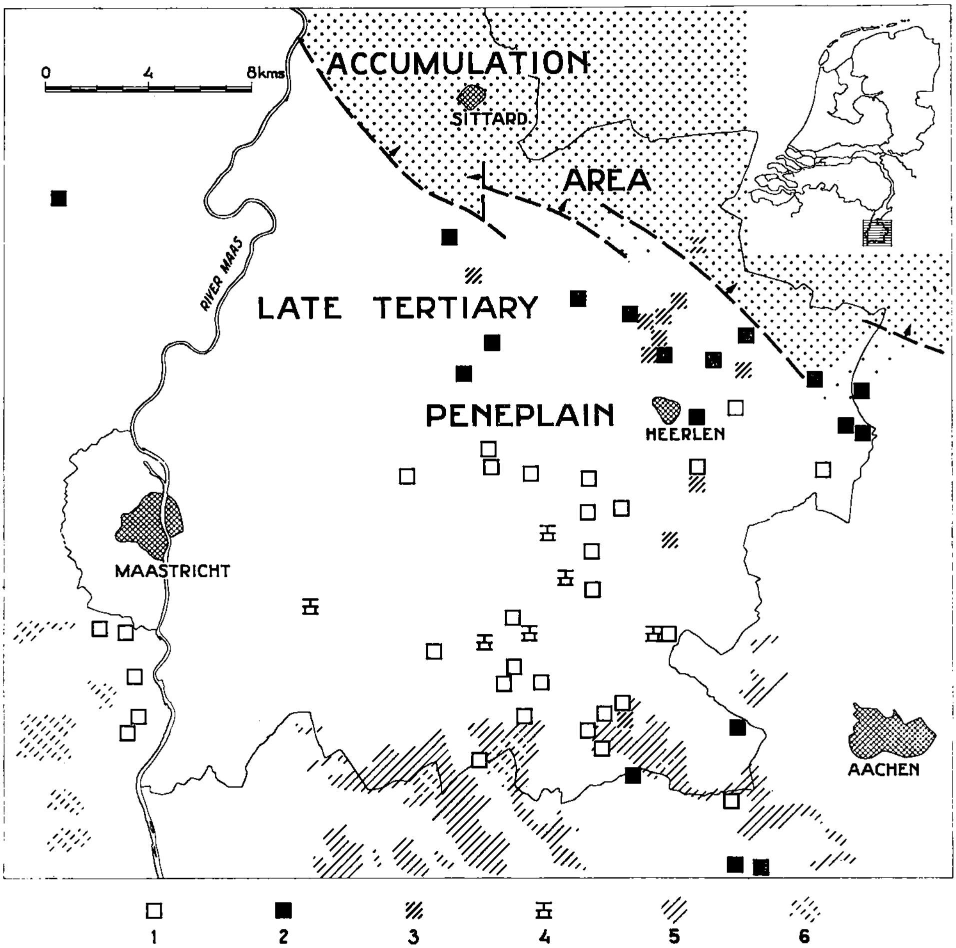
In South Limburg the Late Tertiary peneplain is partly covered by Pleistocene Maas deposits (in the western parts); the rest of this surface is dissected and remodeled during the Pleistocene (the eastern part).

From our systematic inventory a tentative description can be given of the important features of the environment during these times. In the long periods of geological calm a strong weathering developed as a result of a warm, humid climate with dry periods of several weeks. Erosion has been unimportant and restricted mainly to the strongly weathered surface material. This material has been shifted over short distances only. A thin discontinuous sheet of sediments developed on the peneplain, that has been named the Basal gravel complex. The deposits of the borders of the peneplain and of the contiguous graben are much thicker and easier to enravel stratigraphically. This fringe area has been called the accumulation region. Soil forming processes have

produced rather deep soils on the peneplain as well as in the deposits of the Basal gravel complex. Mobilisation of silica produced extensive surface silicification of limestones and in well drained clayless sands; these features compare favourably with the silcrete duricrusts in other parts of the world.

In South Limburg the peneplain is later transformed by erosion, furrowing, the influences of frost periods and the covering with younger sediments during the Pleistocene. In other parts of the world such fossil table lands are much better conserved because the climate became more arid.

Acknowledgment is made to Dr. L. VAN DER PLAS, Department of Geology and Mineralogy of the Agricultural University, Wageningen, for his critical comments and help with the translation of this paper. Mr. M. SNOEP carefully corrected the English text.



1. INTRODUCTION

For a rather long time South Limburg has been considered a peneplain on geomorphological evidence. According to some authors the surface of this peneplain was partly re-incized by rivers during the Pleistocene (Tesch, 1941; Oestreich, 1944; Hol, 1959).

The region must be considered as the relatively stable border zone of the stable Ardennes-Eifel tableland. Some observations, however, do not seem to confirm this view. First there is the occurrence of a number of not always clearly perceptible piedmont scarps around the Ardennes (Pissart, 1962; Alexandre, 1957-1958; Macar et Alexandre, 1957-1958) and secondly the type of faults and fault blocks, of which South Limburg is a part, along the northern flank of the Ardennes tableland. It has been possible to throw some new light on this problem through the results of a prolonged geological and pedological investigation of the surface rocks and the inherent pedological phenomena.

The region covered by our study is situated south of the larger faults bordering the Central graben (fig. 1). In this region we find a number of relatively flat pieces of land with a cover of loess deposits of varying thickness (Van den Broek, 1966). Besides these loess covers on many places outcrops of sandy and calcareous formations of Tertiary and Mesozoic age are found. Furthermore we find a discontinuous thin blanket of quartz-rich sands and gravels of a variable grain size on this dissected plateau, covering the Mesozoic and Tertiary formations. Van der Waals and Van den Broek et al. (1962) named this blanket the Basal gravel complex. On the peneplain itself this complex consists of local deposits. Moreover, these deposits are frequently reworked, partly removed or mixed with other components. In the accumulation area, north of the larger faults referred to above, these deposits form a formation of successive beds of considerable thickness.

From a petrographical point of view the deposits of the Basal gravel complex are characterized by sands, consisting almost exclusively of quartz. The heavy fraction is composed of only the so-called stable minerals. Whitened rock fragments and an abundance of quartz- and flintpebbles are found in the gravel. Symptoms of weathering, soil formation and silica accumulation are observed both in the Basal gravel complex and in the underlying older formations. These interrelated phenomena constitute a distinct feature of the Late Tertiary peneplain.

Fig. 1 (left). Distribution of silicifications and fossil soils of the Late Tertiary peneplain in South Limburg

LEGEND

1: dislocated boulders, silicifications of sand and gravel
2: silicifications in situ, Basal gravel complex, Miocene sand, Aachen quartz sand and Hervian green sand
3: strongly developed fossil soils
4: silicified chalk
5: silicified chalk, often with fossil soil: clay-with-flints ("Vuursteen eluvium")
6: silicified chalk and fossil soil under thin overburden

2. METHODS OF GEOLOGICAL AND PEDOLOGICAL INVESTIGATION

The methods of pedology and especially of soil survey were essential for a successful investigation of the Late Tertiary peneplain. Contrary to the geological methods, the inventory of a soil survey is mostly restricted to a few meters below the surface (BENNEMA, 1965). The differences in the objects of a study by a geologist or a soil scientist are of special interest for the investigation of the South Limburg peneplain. Generally, the geologist is interested in the periods of geogenetical processes, e.g. sedimentation, orogenesis and, to a lesser extent, denudation. The soil scientist directs his attention to processes of soil genesis and soil transformation (EDELMAN, 1939). These changes at the surface of our planet occur in those places and in those periods when from a geological point of view practically nothing happens, i.e. where sedimentation or erosion do not occur. Only during such periods is the surface of the earth's crust affected by the influences of a certain climate and vegetation. These mainly exogeneous influences produce a number of transformations in the surface layers, originating the formation of a soil. The soil forming processes and the factors at work in these processes are studied by the soil scientist. He begins his observations where those of geologists end. The occurrence of a fossil soil profile indicates an interruption in the process of sedimentation — a stratigraphical hiatus —; it carries information on the circumstances at the earth's surface during a period of geological calm.

But with regard to the object of study, the investigation methods of these two scientists are also different. In geology it is an important method to establish the correlation of sometimes rather deep profiles over long distances. The soil scientist studies surface or near surface phenomena and tries to extend these in a horizontal direction. Consequently, geology and soil science may complete each other in a number of cases. Especially the investigation of the Late Tertiary South Limburg peneplain has been unsuccessful in the past because only one of these two methods has been applied. The soil scientist cannot study the occurrence and the distribution of the buried fossil soils of the peneplain without the help of his geological colleague. Many of these fossil soils have been protected against later transformations, because they are covered by sheets of younger sediments. On the other hand, the geologist needs the help of a soil scientist for the explanation of the closely connected multifarious occurrences on the surface of the peneplain.

3. SOIL FORMING AND OTHER PROCESSES ON THE PENEPLAIN AND ALLIED PHENOMENA IN THE ACCUMULATION REGION

Large faults cut up the northern part of South Limburg in some blocks with a south-east north-west direction. A slight tilt makes these fault blocks dip to the north-west. The lower parts of these blocks in the north-west are covered with Pliocene sediments of an increasing thickness. An almost continuous series of sediments is found in these Late Tertiary *accumulation regions*. In the south-east *higher parts* of these blocks, being still a part of the South Limburg peneplain, are covered just as the peneplain itself with a very thin sheet of sands and gravels. This is clearly illustrated in fig. 2. During the Plio-Pleistocene an almost continuous sedimentation took place in the

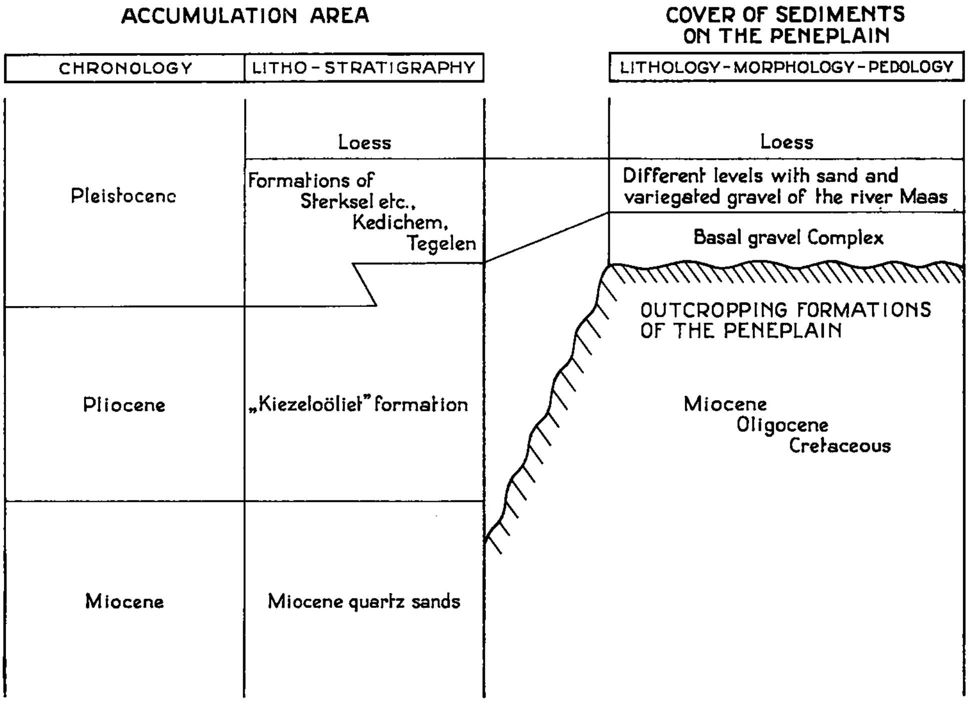


Fig. 2. Diagram of the stratigraphical sequence in the accumulation area and the peneplain in South Limburg

northern part; south of the large faults such a continuous sedimentation did not occur. The frontier between the accumulation region and the region with a slight and interrupted sedimentation shifted from block to block in an eastern direction (fig. 1).

The Plio-Pleistocene sequence of sediments in the *accumulation region* is made up of sands with a varying gravel content and intercalated clays. Paleontological investigations (ZAGWIJN, 1960) showed that a part of this sequence belongs to the Pliocene and the oldest Pleistocene (Praetiglian + Tiglian). This part used to be called the "Kiezeloöliet" formation on the basis of lithological characteristics. From a petrographical point of view the composition of the sand and the allied gravel of the "Kiezeloöliet" formation is very constant. An abundance of the so-called stable minerals characterizes the heavy fraction. The Pliocene gravel has the following composition: about 70 % of rounded or angular quartz (MAARLEVELD, 1956); flint fragments both rounded, angular or corroded and sometimes with a thick weathering crust or with a glistening waxy lustre; bleached fragments of sandstone or quarzite, sometimes still showing a red or green color in the core; silicified limestones (e.g. the so-called "Kiezeloöliet") and silicified fossils, shales and red iron-silica pebbles.

Secondary silica is found in most of the rock fragments; real limestones and fragments of volcanic rocks have not been found. The high quartz content has to be attributed to a strong chemical weathering during a warm and humid climate, c.f. CAILLEUX (1965). This material is thought to be the result of denudation and erosion of the strongly weathered Ardennes peneplain. Only at the end of the Pliocene period,

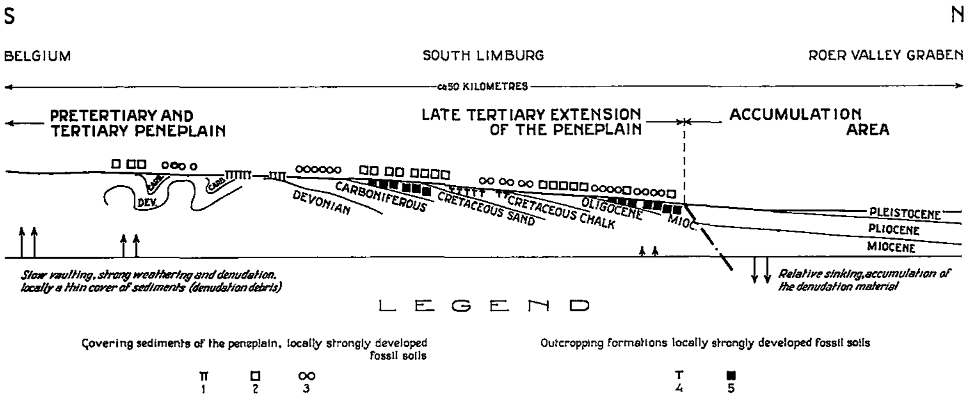


Fig. 3. Schematical south-north cross-section of the borderzone of the Ardennes-Eifel peneplain

LEGEND

1: silicifications of chalk (Upper Cretaceous); relics on the pre/lower Cretaceous peneplain
2: sands, locally silicified
3: gravels, locally silicified
4: chalk, locally silicified
5: sands, locally silicified

when the intensity of the weathering process decreased strongly because of lower temperatures, a gradually increasing amount of less stable minerals in the sand is found. This, however, did not lead to distinct sedimentological boundaries. The sequence of the younger Pleistocene sediments can be subdivided partly because of the introduction of material from the river Rhine.

It has already been argued that the sheet of sands and gravels on the more elevated parts of our region is rather thin (fig. 3). Here, the cover consists of layers with a varying thickness and a rather limited horizontal spread. The sequence is characterized by large lithological differences. The whole cover was given the name Basal gravel complex by Van der Waals and Van den Broek et al. (1962). The constituting lithological components are also found in parts of the Onx formation on the old Belgian geological maps. Just like the "Kiezelooliet" formation, the sediments of the Basal gravel complex have their heavy fraction, characterized by stable components; apparently gravel of both formations is rather similar. The large lithological variation within these gravels is rather striking, as can be seen from table 1. Moreover, these formations, referred to as denudation debris by Tesch (1941), are strongly different from the Oligocene and Miocene sediments because of the large gravel content. Hundreds of drillholes covering the whole region have shown that in South Limburg even small gravel deposits are rare in the Oligocene and Miocene sediments. Never we did find such large gravel deposits as in the so-called Basal gravel complex.

Apart from the lithological composition of the sands in the Basal gravel complex already discussed, it is not always easy to distinguish these sands from the underlying Tertiary sands. But the occurrence of silicification phenomena in this formation of sediments with strongly varying lithological characteristics and the occurrence of these sediments on the peneplain, make it clear that the Basal gravel complex should be considered as a separate unit.

Table 1. Silicifications in the peneplain area of South Limburg

A. *Silicifications in the Basal gravel complex (a cover of denudation debris on the peneplain)*

For the greater part isolated boulders, removed over short distance at the utmost. At many places the not silicified equivalents still in situ (the annotation on the old Belgian geological map is given between brackets):

a. Bleached fine and coarse white quartz gravel, locally with red impregnation of iron (Onx).

b. Fluviatile redeposition of clay-with-flints mixed with white quartz gravel, locally with red impregnation of iron.

c. Yellow, fine and coarse, weathered quartz sands, cross-bedded, sometimes with strings of fine gravel; locally some slight impregnation of iron (Ons).

d. White well-sorted quartz sands with silicified plant tissue and very rarely with shell imprints (Ong).

e. Coarse well-rounded flints or fine well-rounded flints with white quartz sand (Onp).

B. *Silicifications and concretionary silica concretions in outcropping formations at the peneplain.*

Miocene. Concretions only occurring in the permeable, white, bleached quartz sands, locally with imprints of Miocene seeds and leaves; on other places silicified roots and plant tissue of the peneplain vegetation. Intensity of concretionary silicifications decreasing with depth. In near-surface layers of lignite high concentration of amorphous silica.

Oligocene. Probably silicified shells can be found; not yet investigated thoroughly.

Upper Cretaceous. Chalk partly silicified and weathered to clay-with-flints and Terra rossa soil profile; top of the chalk formation for the greater part silicified to cherts; near the peneplain surface the carbonate is partly or totally replaced by micro-crystalline silica, small concretions of a fibrous chalcedony may occur.

Hervian green sand. Glauconitic sands. Locally silicified sands poor in clay but rich in glauconite; in clay-rich layers silicified shells, echinoids and belemnites.

Aachen quartz sand. Small concretions ranged on bedding planes; scattered lenses of silicified sands, sometimes with silicified wood in the core; locally silicified banks.

Some special phenomena occurring both in the thin deposits of the Basal gravel complex and in the underlying formations bear witness to the occurrence of surface processes in the past i.e. well-developed *soil profiles* and *silicification* of chalk, sands and gravels. Erosion and remodelling of the peneplain during the Pleistocene removed a part of the soils. In the western part of South Limburg they are in some places covered by Pleistocene deposits of the river Maas. The silicified components are also found as fragments in these deposits.

In the region under discussion the results of *silicification* are observed as sand and gravel concretions in the Basal gravel complex; such concretions are also found in the outcrops of the sands of the peneplain (fig. 3). Next to these concretions we often find silicified chalk and fossils (table 1). In most cases the intensity of the silicification process leads to a kind of silcrete, seldom to quarzitic sandstones. From the Basal gravel complex material, boulders of silicified sand, gravel and/or flint were formed, depending on the original components. Fig. 4 pictures such a concretion of sand. These

Fig. 4. Typical example of a boulder of silicified homogeneous fine sands. The botryoidal flow structure is characteristic of this type of sand concretion. In natural position the boulder is upside down, the flat side running parallel to the surface. (A dislocated boulder laying on its flat upperside; near Epen. Exposure nr. 62 D 181)

concretions still lie in large groups together in situ in most elevated areas of our region. VAN DEN BROECK (1901) and DELÉPINE (1925) already pointed to a comparable phenomenon occurring in the neighbouring Belgian and French regions. In the area around Heerlen we still find these concretions, laying in their original position in the enveloping not silicified material of the Basal gravel complex. In other places, among others in the southern part of our region, the enveloping not silicified material of the Basal gravel complex has been removed by erosion and the concretions are left behind, scattered around the area. Some of these boulders have slid along the slopes and are now found on the slopes and even on the valley floors.

These sand and gravel concretions can reach sizes of more than a cubic yard. They show lobate outlines and at least one clear plane face (fig. 4). The original joints are never silicified, a striking feature. With a special type of concretions, where bedding planes form top and bottom, these joint planes are the sides of the boulders. The surface of some of these boulders looks as if polished, being impermeable quartzitic, while the inside is permeable like a soft sandstone. Also the boulders composed of coarse components (quartz pebbles or flints) show this phenomenon of smooth and polished surfaces. There is no essential difference between the concretions of the Basal gravel complex and those of the Tertiary or older formations.

In outcrops of Miocene sands we find silicifications forming close continuous layers

Table 2. Soils of the Late Tertiary peneplain in South Limburg

Lithology of the parent material	Late Tertiary soil	Younger and recent soils on parts of the peneplain without younger cover (polycyclic soil profiles)
Limestones and chalk	Terra rossa; "Clay-with-flints"	Gray-Brown podzolic soil — Podzol
Sediments rich in clay	Red-Yellow Podzolic soil; Yellow Podzolic soil	(Grey-Brown Podzolic soil) — "brown soil"
Sediments poor in clay	Red-Yellow Latosol	"brown soil" — (Humus podzol)
Sediments free of clay	Humus podzol	— — Humus podzol

of cemented sand. They look like the so-called "duricrust" (LAMPLUGH, 1907), found and described in other parts of the world.

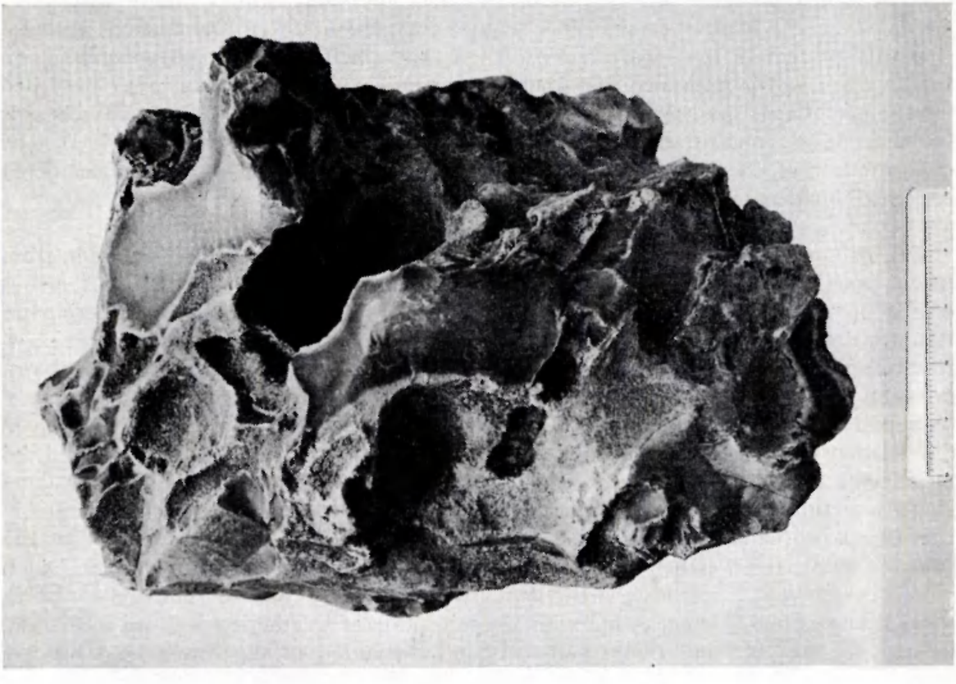
In the region under discussion they are well known as Nievelsteiner sandstones which are used as building material. A few friable sand concretions are here and there found below this silicified crust.

In the other sands not belonging to the Basal gravel complex, the silicifications may be found as concretionary forms (table 1). In limestones and chalk the carbonate is replaced by silicious material over a depth of a few meters. Such silicified limestones may be called porcellanites, considering the fact that this term is purely descriptive (among others: KOLODNY et al., 1965, sensu TALIAFERRO, 1934). The silicious material is mostly present in the form of crystobalite. The silicified limestone in combination with a fossil soil is indurated into chert-like material, which eventually may be called novaculite. The german term "hornstein" is rather confusing (cf. "hornfels"). Chert is found in large concentrations in the so-called "argile à silex" (clay-with-flints). The concentration of chert is highest in the surface part of the formation, at greater depth concentration decreases.

The *soil profiles* of the Late Tertiary peneplain (fig. 3) are quite different from recent West European soils (table 2). They may reasonably be compared with the soils of the present subhumid mediterranean climate. Next to an intensive weathering we found a downward movement of soil components in these fossil soils. They also show rubefaction, a process well known from tropical ferruginous soils. Haematite, responsible for the intensive red colour, is one of the most important iron compounds. Kaolinite is the main component of the clay fraction. On the deeply weathered chalk and limestones we find fossil soils of the *Terra rossa* type. These soils are coloured red and have a high kaolinite content. They are formed in the solution residue of the limestone, sometimes with a high content of flint or of silicified limestone (chert). The thickness of the profile can be as much as 5 meters. Because of the high content of flint and silicified chalk, this weathering product is called clay-with-flints (argile à silex; in Dutch "vuursteen-eluvium": "flintstone-eluvium"). Here we are dealing not only with a geological weathering process, but with a combination of weathering and soil formation, influencing the clay and flint residue also after solution of the limestone. The clay changed into a kaolinite. The flints were covered with a thick weathering crust; they also show corrosion phenomena (fig. 5). These flints can be so affected that even the core is thoroughly weathered. Such radically weathered fragments preferably occur in the top part of the soil profile. In places where the clay-with-flints profile is not covered with sediments of the Basal gravel complex or with Pleistocene sediments, the Terra rossa profile suffered the influences of younger soil forming processes of the Pleistocene or Holocene. The result is a polygenetic soil profile. The more recent influences caused brownish colours, found in the upper parts of the profile; these influences have not penetrated as deep as the older ones. The recent soil developed in this thoroughly weathered parent material is the podzol with an ashgrey toplayer.

The fossil soils on the other sediments of the peneplain are e.g. *Red-Yellow Podzolic soils, Red-Yellow Latosols* and *Podzol soils.* The *Red-Yellow Podzolic soils* are found almost exclusively on the clay-rich sediments. In the neighbouring German and Belgian regions we find comparable fossil soils, not only in Tertiary and Cretaceous formations, but also in the outcropping Palaeozoic sediments (MÜCKENHAUSEN, 1953; SCHMIDT and WOLTERS, 1952; MARÉCHAL, 1958). In Belgium these soil types are found in the weathered psammites (MARÉCHAL, 1958) and other clay-rich sediments. In the clay-rich sediments of the Basal gravel complex these soils are likewise found. Such soils are rather deeply developed. Some profiles may reach depths of over 3 metres, provided they have not been touched by erosion. They show a distinct illuvial or B horizon (a

Fig. 5. Weathered and strongly corroded flint from the clay-with-flints. (Exposure nr. 62 D 113)



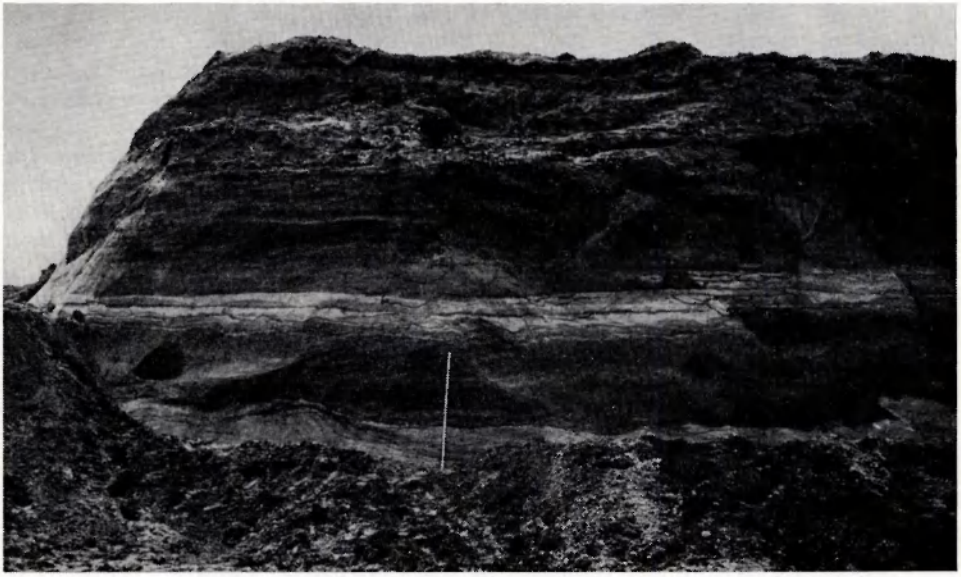


Fig. 6. Light textured sands of the Basal gravel complex with deep, strongly developed fossil soil profile showing two successive brightly coloured red and yellow bands. The fossil soil profile is covered by a thin layer of younger gravel and sand of the Basal gravel complex, not affected by soil formation and partly wedging into the fossil soil caused by frost action during Pleistocene. In top ca. 1 meter of loess. (Heerlerheide. Exposure nr. 60 D 48)

horizon characterized by clay accumulation washed down from the upper horizons). Bright coloured red B horizons are frequently observed, but yellow members are also found. These red horizons have long been noticed in various sediments of South Limburg (KLEIN, 1914), without having been ascribed, however, to soil forming processes, not to mention a fossil surface. The yellow members of the Red-Yellow Podzolic soils are tentatively attributed to influences of more humid atmospheric conditions than those prevailing during the formation of the predominant red members. In the region under consideration yellow B-horizons are sometimes found within the older red B horizons. One may suppose a change of climate to explain these subsequent yellow horizons. On the other hand, these yellow members are only clearly observed together with red ones, in less clay-rich strata (fig. 6). It seems as if the occurrence of yellow B horizons decreases with an increase of clay or other components liable to weathering. According to KREBS and TEDROW (1958) the processes of laterization and podzol formation are simultaneously at work in Red-Yellow Podzolic soils. They are absent in tropic regions proper. It may be concluded that the soils of the Late Tertiary peneplain of South Limburg originated during subhumid mediterranean or subtropical climatic conditions.

Soil profiles comparable with Red-Yellow Podzolic soils but developed in sediments with only a small amount of clay are known as *Red-Yellow Latosols* (BENNEMA, 1965). The occurrence of such profiles in the formations of the Basal gravel complex that are poor in clay may be seen in connection with a certain amount of weatherable components preventing the soil from undergoing a pure podzolization process.

In the quartz sands, without any clay material, *Podzols* have been developed. This white parent material is so poor that only humus has been displaced in the soil, and so-called *Humus Podzols* are formed. Illuvial humus has been found as purple coloured **B** horizons of variable thickness, sometimes at great depths in the profile accumulated in bands of a few tenths of a metre.

In places where a Pleistocene cover is missing, young soil formation phenomena are found both in the Red-Yellow Podzolic soils and in the Red-Yellow Latosols, just as has been described from the Terra rossa profiles. Here too we find the brown colours superimposed on the older red and yellow ones. Such polygenetic profiles have not been observed in podzols.

The Humus Podzols of the peneplain without a polygenetic horizon sequence can only be recognized as such if they are covered with Pleistocene sediments.

Fossil soils are not present in the accumulation region because of a continuous sedimentation and rather wet circumstances. Intensive soil forming processes could not occur during the short period in which strata of the "Kiezeloöliet" formation and other sediments formed the surface in this region. A faint reddish colouring, however, is known from drillholes in some parts of this specific region. It was found below the Praetiglian clays and may point to a restricted local soil forming process.

A combination of silicifications and fossil soils is frequently found, e.g. in the clay-with-flints. Even if such silicification phenomena are not found in situ, they are accompanied by the reddish traces of fossil laterization (Hamilton, 1964). In very poor, extremely drained parent material without a clay fraction, such as the Miocene sediments, silicification is found without these characteristic reddish colours. The red iron-silica pebbles (Van Straaten, 1946) occurring in the gravel of South Limburg are comparable with the ferriferous silica compounds of so-called ferricretes. In thin slides this typical kind of rock shows droplets of ironoxide within the authigenic quartz as described by Hamilton (1964). Besides, it is a well-known fact that mobilized silica can move over very great distances, vertically as well as horizontally. Its precipitation therefore often occurs very far from the zone where the iron is accumulating.

The frequent occurrence of root holes and imprints with silicified plant relics in the silicified material, as well as the occurrence of fossil soils and the intensity of silicifications decreasing with depth is ample proof that we deal with surface phenomena. The various components of the gravel of the "Kiezeloöliet" formation allow a clear picture of the silicified surface rocks once belonging to the different silcretes and ferricretes of the Ardennes peneplain.

A causal relation between the existing peneplain and the soil formation and kindred silicification has seldom been proposed. Consequently, the relevant descriptions of comparable phenomena are scattered in the literature. Other related observations pointed out in passing, and frequently noted in field descriptions of outcrops or profiles, again and again corroborate the above statement. The connection between these phenomena, however, has to be found almost exclusively in the properties of the climate and the allied environment. Such data are almost invariably missing.

4. CONDITIONS AND INFLUENCES ACTING ON THE PENEPLAIN DURING THE TERTIARY AND THE LATE TERTIARY

Observations of intensive soil formation, the movement of silica in the profile, and the occurrence of silicifications enable the reconstruction of conditions and influences acting on the peneplain during the Tertiary and the Late Tertiary. The observations just mentioned and the related processes point to a long and relatively quiet period in a geological sense. Only then can a vegetation establish itself and can a soil profile be formed.

The available evidence about the *morphology* of the peneplain does not point to the existence of a flat horizontal area in our region. The drainage of such areas is insufficient in most cases and the result is a type of weathering and soil formation different from those found on the South Limburg peneplain. Such conditions have been present in the neighbouring Eifel region, cf. MÜCKENHAUSEN (1953). Here, heavy, sticky, slowly permeable grey loams and clays are frequently found. Such waterlogged formations of heavy, mostly smectite clays are characteristic of flat, badly drained areas, rather irrespective of the nature of the parent material. The central parts of the peneplain are frequently covered with such a sheet of weathering products, whereas the borders show a different type of surface. South Limburg as well as the rest of the northern border of the Ardennes sloped slightly northwards. A number of rivers flowed through this area resulting in a region with a quiet relief and a drainage system of shallow valleys. This border zone with its great quantity of running water was possibly predisposed for concentration of silica. The shifting courses of the rivers caused local sedimentation restricted in time. Afterwards some of these deposits were partly removed. An intensive mixing of the material even with components from older deposits was the result. The sediments on a relatively stable peneplain are rather shallow and often deposited next to each other; this in contrast with the building up of an active sedimentation area where the formations are deposited on top of each other. On a peneplain both sedimentation and erosion are rather limited: erosion is rather shallow because of a vegetation cover and is restricted to the weathering sheet; deep incisions do not frequently occur.

Drastic erosion or a stronger sedimentation may locally occur through the movement of only one or some fault blocks of the faulted area. These processes die out, however, as soon as equilibrium is restored. Fig. 7 illustrates schematically with the help of only a few layers the pattern of sedimentation caused by local movements along the faulting zones of the northern peneplain border. In north-western direction, the same holds on a much larger horizontal scale for the Ardennes peneplain as a whole in regard of the formations found on it. For the long duration of this peneplain, sedimentation (e.g. of the Cretaceous limestones or chalk) or removal of thin layers of peneplain deposits towards the accumulation region could occur by transgressions and regressions, by a regional subsidence and by upheaval respectively. Situated between the accumulation area and the central part of the peneplain, the border zone was more sensitive to changes in sedimentation and vegetation caused by small vertical oscillations than the higher central part.

Direct information on the *climate* prevailing during the existence of the peneplain is not available. Judging from general information a warm, not arid climate seems to have been prevalent during the Tertiary. Disregarding short changes, it became gradually cooler during the Pleistocene, cf. ZAGWIJN (1960). The fossil Tertiary soils and the

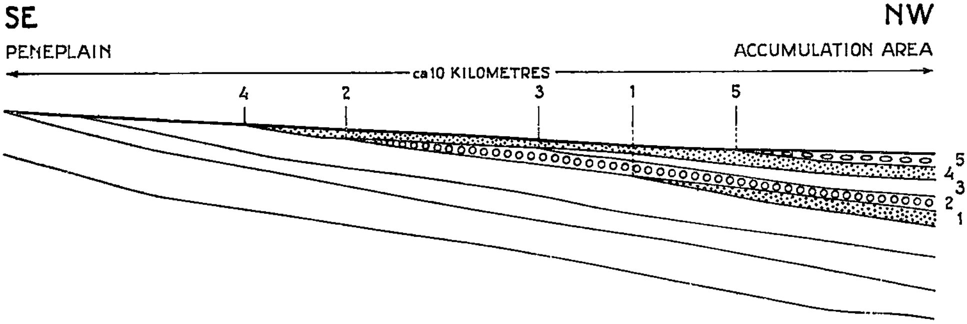


Fig. 7. Small scaled diagram of the transition from the accumulation area to the peneplain, along the SE-NW directed fault blocks. This transition moves on in time and passes from point 1 along point 2-3-4 to point 5

silicifications suggest a tropical to subtropical climate. The ubiquitous red colours in the soil profiles are caused by the formation of dehydrated ironhydroxides, a process now absent in Western Europe. Comparable recent to subrecent soils are found in Europe along the Mediterranean o.a., from Catalonia (Spain) towards Tuscany (Italy), on Corsica and in western Yugoslavia and Greece. A subhumid mediterranean climate with an average of 6-10 weeks of drought is characteristic for these regions. A strong weathering of the sediments, a breaking down of the minerals in these sediments and a mobilisation of silica also hint at circumstances inherent in humid subtropical to tropical environments. A climate with alternating dry and wet seasons and an annual precipitation of 2000 mm or more is now present in regions where such processes are operative. The dry season, however, has a monthly precipitation of less than 60 mm. Still, an exact description of the climate on the Late Tertiary peneplain is out of the question. For instance, the presence of yellow members next to the red members of the Red-Yellow Podzolic soils and the Red-Yellow Latosol may point to the existence of important variations in the climate. So much is certain, it has not been a desert region. From the available evidence it is clear that the enormous amounts of silica that have been on the move in this region can only have been made free during a humid tropical to subtropical period, cf. Woolnough (1927) and Cailleux (1965). Still, our knowledge of the mobilisation of silica and its precipitation, by which sand concretions and other silicifications are formed, is rather fragmentary. It seems plausible indeed, that for the formation of these silica-concretions a short period of climatic drought is responsible. A change in the pH of a solution rich in silica may also cause precipitation. As a cause of such drastic pH changes one may assume the introduction of seawater, cf. Grimm (1962). The last explanation, however, seems to have significance in a small number of cases only.

Relics of *vegetation* from the Tertiary are no longer present on the peneplain. Information concerning the vegetation covering the peneplain during the Miocene period has been gathered from the kaolinite-bearing contents of some sinkholes near Namur in Belgium.

Silicified root relics in various concretions of fine quartz sands are still found on the peneplain itself; a testimony of a Tertiary vegetation. It may be possible to obtain some insight on plant species by an anatomical determination of these root relics. On the other hand, the possibility exists to obtain information on the various plants growing during the Tertiary from the accumulation region. Lignite formations occur in the Oligocene and Miocene strata and pollen-rich clay beds are present in the Pliocene. An inventory of these formations presents a vegetation of rather dense forests of high trees.

It is quite certain, that a series of subsequent vegetations covered the Tertiary peneplain from the Senonian or even from some earlier time. Part of the soil material covering the borders of the peneplain has been washed down into the accumulation region. Consequently the changes of the vegetation covering these border regions can be inferred from the sedimentary formations in the accumulation region. This is especially the case because the intensive soil formation and the subhumid to humid warm climate must have caused both a luxuriant vegetation and an abundance of incoherent soil material at the cost of the formations on the surface of the peneplain.

The *parent material* of the fossil soils on the peneplain consists of two categories: the outcropping older formations and the complex of the abrasion and denudation sheet. Still, the soil profiles show a remarkable identity, as if a difference in parent material did not give rise to different soils. This feature may be explained by calling attention to the fact that especially the outcropping formations have been so altered by a period of exhaustive weathering that the soil profile observed now, represents the final phase of a cycle of soil-forming processes in a gradually impoverished parent material.

Both the "Kiezelooliet" formation and the Basal gravel complex are products of the exhausted materials of the peneplain formations. Thus, this material has more or less the same properties as the impoverished parent material discussed in the former section with regard to soil-forming processes. In this material we may expect the initial formation of a soil that represents the final equilibrium phase of the cycle assumed to have been formed in the outcropping strata. Consequently, the diversity, initially caused by differences in parent material is completely wiped out by the fact that at the end both parent material and soil profile reached a state of equilibrium by exhaustion or by the absence of material that could still be broken down.

The processes described before have been in operation for an extremely long period. It is possible to point out differences in duration of the processes occurring in certain parts of the peneplain. For instance, in some areas of the Basal gravel complex they did not influence the surface as long as in some of the older Tertiary or Mesozoic formations. The same holds true for some areas initially belonging to the accumulation area, that became part of the peneplain through upward novements. The age of the Ardennes peneplain is considerable, it dates back from the early Mesozoic at least. It is doubtful, however, whether influences as old as that are still to be observed in situ in the Tertiary features discussed in this paper. Especially the short periods during which these parts of the peneplain where at least to a larger extent covered by the sea have interrupted the continuousness of terrestrial influences. Such a period together with the deposition of marine sediments appeared among others during the Upper Cretaceous. During the Tertiary the influence of marine transgressions on this part of the peneplain gradually decreased, thus intensifying the continuous influences of weathering and soil formation. If we had based our hypothesis solely on the red colour of soils, such as the Red-Yellow Podzolic soils, one might object that such colours are characteristic not only of tropical or subtropical climates but may also be found as the results of extremely long periods of soil formation. This argument, put forward among others by BENNEMA

(1965), becomes important as soon as it is realized that at the end of the Pliocene changes brought about a more moderate type of climate. This argument, however, does not interfere with our conclusion that the period responsible for the features of the peneplain must have been considerably longer than the period that caused the recent West European soils.

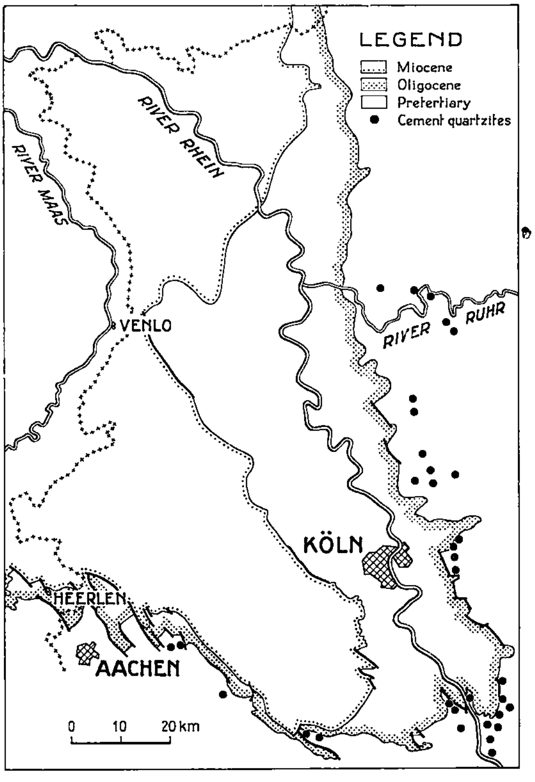
Throughout the Tertiary period silicification phenomena occurred. Some fluctuations in intensity, however, may be observed. For instance, in the clay-with-flints there is evidence that silicification started before or simultaneously with soil formation. The chert of these clay-with-flints profiles developed on limestone often shows silicified fossils. Soil formation in this parent material would have destroyed these fossils if silicification set in long after the start of the soil-forming processes. On the other hand, silicification is also apparent in sediments of the Basal gravel complex, covering the Terra rossa profiles and the clay-with-flints deposits in certain areas. It appears that the silicification process came to a stop in the Upper Pliocene (Reuverian).

5. CHANGES OF THE LANDSCAPE DURING THE PLEISTOCENE

The Pleistocene terraces of the river Maas slightly affected the Late Tertiary peneplain. The oldest members as defined by Brueren (1945), viz.: the Kosberg and Crapoel members, are rather comparable with the Basal gravel complex from a mineralogical and sedimentological point of view. In those two terrace members fossil soil profiles occur with the same properties as those of the peneplain. Younger terraces of the Pleistocene only occur on the western part of South Limburg. Observations of deeply situated outcrops and of drillholes reveal that on the average these deposits are situated on top of Basel gravel complex deposits, hardly affected by erosion beforehand. In one case we observed a fossil soil profile of the Late Tertiary peneplain covered with more than 7 m of sand and gravel belonging to the St. Geertruid-Berg member of Brueren (loc. cit.), part of the so-called Main-Terrace. Such phenomena are explained by the Pleistocene tilt of the Southern Limburg region. The area dipped towards the north-west causing the river Maas to shift gradually in a western direction.

The Pleistocene terrace deposits of the Maas and the sediments of the accumulation region belonging to the same period are both characterized by an increasing amount of less stable components, cf. Zonneveld (1955). It is assumed that this feature was caused by a complex of reasons, such as: a decreasing intensity of the weathering processes, an increasing erosion and a rejuvenation of the Ardennes tableland. Consequently the amount of nonweathered material of the Pleistocene sediments gradually increases. The eastern part of South Limburg only shows a dissection of the original level surface by the river Maas and its tributaries. As a result, we now find only remnants of the old peneplain. These remnants occur in the form of narrow ridges between two valleys or as flat-topped hills. The fossil soils as well as the silicified areas have been removed by erosion or by caving in and subsequent transport. In other parts of this area these soils and silicified strata are covered by a sheet of Pleistocene loess. Therefore their existence has been ascertained from drillholes or deep outcrops. Silicified blocks are strewn over the surface, along the slopes and on the valley floors. From the extremely large size of some of them, one may conclude that they have not been moved far from their original position (fig. 4).

Fig. 8. Cement quartzites in the border-zone of the Niederrheinische Bucht (according to Teichmüller, 1958)



6. DESCRIPTION OF COMPARABLE REGIONS

Silicification phenomena in combination with fossil red soils are by no means a special feature of this part of the Netherlands or even of Western Europe. Such features have been described from various places although the terminology varies. Near-surface silicifications have been described as:

— Sandstones: among others Van den Broeck (1901); Gulinck (1961), (Belgium).
— Zementquartzit: among others Teichmüller (1958), (Germany), cf. fig. 8.
— Pierres de Stonne, pierres de Beaumont, etc: among others Delépine (1925), (N. France).
— Argile à silex: among others Pomérol (1965).
— Boxstones: sarsens and greywethers: among others Evans and Stubblefield (1929), (England).
— Clay-with-flints: among others Jukes-Browne (1906); Loveday (1962), (England).
— Quartzite boulders: among others Hughes (1963), (N. America).

Table 3. Tentative diagram of peneplain history with changing climate

	Arid	Semi arid	Tropical to subtropical	Subhumid	Temporate
	Drying up (Australia, etc.) ←		Peneplain →	More humid and cooler (West Europe, etc.)	
Climate	Desert with intermittent showers	Rather dry with short wet seasons	Distinctly wet and dry seasons	Wet and rather dry seasons	Wet and cool
Humidity	Evaporation predominant		Periods with predominant precipitation	Precipitation predominant	
Weathering			Intensive chemical desintegration		
Silica migration	Nihil	Strongly decreasing	Maximal	Decreasing	
Silica mobilisation	Nihil	Strongly decreasing	Maximal	Strongly decreasing	
Products of chemical accumulation and concentration near the surface	Gypsum etc.	Carbonate (lime) calcrete caliche kunkar	Silica silcrete, porcellanite, novaculite Iron, predominantly haematite (red) Laterite Ferricrete	Iron (yellow)	Iron (brown)
Surface crusts		Duricrust s.l. "croûte calcaire" calcareous crust duripan	Duricrust s.s.		Sometimes iron hard pan
Physiographical development	Attack of duricrust by erosion and denudation with subsequent dissection of the peneplain		Peneplain maintained	Attack of duricrust by erosion, denudation and frost action. Only relics of the two preserved	
Denudation materials	Transported only for a minor part: silcrete rubble and gibber plains (Australia), viz. not removed, angular, broken parts of the duricrust		Locally transported on parts with some relief: components of the Basal gravel complex, "kiezeloöliet"-formation (South Limburg), viz. strongly weathered quartz sands and quartz-rich gravels	Transported far away into the accumulation area: Pleistocene fluviatile terrace deposits (West Europe), viz. removed, partly rounded debris of the peneplain mixed with unweathered components (in late Pleistocene the landscape of South Limburg was covered by loess deposits of varying thickness)	

— Surface quartzites, silcrete, etc.: among others LAMPLUGH (1907); FRANKEL (1952), (S. Africa).
— Surface quartzites, grey billy, gibber plain, silcrete rubble, etc: among others WOOLNOUGH (1927); RAGGAT (1938); WILLIAMSON (1957); LANGFORD-SMITH and DURY (1965), (Australia).

The close connection between silicification, tropical and subtropical soils and a peneplain has been pointed out by Australian colleagues, e.g. LITCHFIELD and MABBUTT (1962), LANGFORD-SMITH and DURY (1965), MABBUTT (1965) and WHITEHOUSE (1940). Petrographical descriptions of comparable phenomena from the regions bordering the Sahara have been given by MILLOT (1960). Silicification of sands and limestones of the Namib desert, S.W. Africa, have been reported by STORZ (1928). According to these reports the silicifications of sands and limestones in Southern Limburg and those of components in the Pliocene gravels described by VAN STRAATEN (1946) are almost identical with the phenomena described by MILLOT and STORZ (loc. cit.). In spite of the fact that the phenomena discussed in these papers are nowadays mainly found in arid or semiarid regions, it is generally assumed that one deals with fossil features. It is argued that they are the result of warm subhumid and humid climates with both wet and dry seasons. Climatic changes towards more arid circumstances created influences that enabled these duricrusts to persist up till the present time, cf. table 3. The changes of climate in Western Europe over the last thousands of years towards cool humid circumstances were able to obliterate partly the features of the Late Tertiary peneplain. Careful mapping may still produce an inventory of phenomena enabling reconstruction of this peneplain in West-Europe.

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