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Study of the iron forms occurring in the soils of a typical migmatite catena in the Taï region, south-west Côte d'Ivoire

by

Annemarie van der Velden

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Dept. of Soil Science and Geology
Agricultural University Wageningen

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ERRATA "STUDY OF THE IRON FORMS OCCURRING IN THE SOILS OF A TYPICAL MIGMATITE CATENA IN THE TAÏ REGION, SOUTH-WEST CôTE D'IVOIRE"

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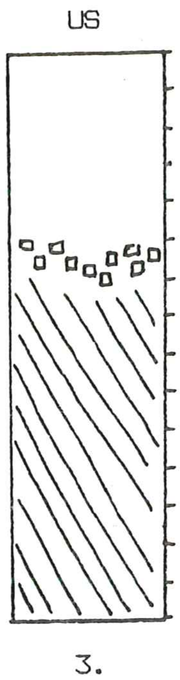

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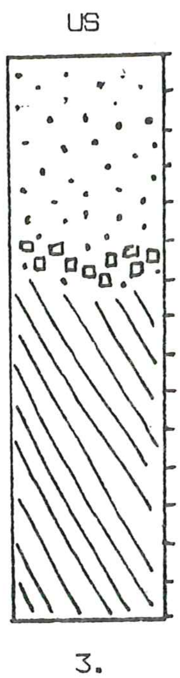

PREFACE

This study is done as part of the Soil Science programme of the Wageningen Agricultural University in the form of a graduation project. The project had a size of 840 sbu. These 840 sbu were spent as follows:

- participation in the First International Intensive Course on Soil Micromorphology, initiated by the ISSS subcommission B - 160 sbu;
- fieldwork in Côte d'Ivoire - 160 sbu;
- micromorphological study and other analyses, literature study, preparation of report and oral presentation - 520 sbu.

I would like to thank several people for their help in this study. First I want to thank my supervisors in Wageningen Wouter Blokhuis, Nico van Breemen and Rienk Miedema and my supervisor in Côte d'Ivoire Gerrit-Jan van Herwaarden.

I also want to thank Toine Jongmans and Tinie van Mensvoort for their useful suggestions.

Furthermore I thank Arie van Dijk for making the thin sections, Jan van Doesburg for his help with the X-ray powder diffraction and thermogravimetric analyses, Bram Kuyper for doing the X-ray fluorescence spectrometry and Barend van Lagen for carrying out the iron and aluminium analyses.

SUMMARY

This study concerns the forms in which iron occurs in the soils of a typical migmatite catena in the Taï region, south-west Côte d'Ivoire. Two occurrences of the typical migmatite catena are considered, known as "Marie catena" and "Theo catena".

In the migmatite catena iron occurs as:

a. remnants of a Tertiary ironstone crust, mostly as ironstone gravel ("pea-iron gravel") which has a shiny dark-purple surface and is very hard (can not be broken between fingers; when broken by force the gravel is purple on cross-section);
b. soft ironstone gravel, in three forms:
   - purple (tough to break between fingers);
   - uniform reddish-brown (easy to break between fingers);
   - mottled reddish-brown/light yellow (easy to break between fingers);
c. plinthite, soft and in various stages of hardening;
d. oxidation mottles in a gley-zone;
e. Fe-coated soil material giving the soil its red, brown or yellow matrix colour.

This study concentrates on the forms of iron mentioned under a., b. and c.

My first hypothesis, based on field observations, was that the different kinds of soft ironstone gravel are succeeding stages of weathering of the hard purple ironstone gravel: the first stage of weathering is the soft purple gravel, the second stage the uniform reddish-brown gravel and the third stage the reddish-brown/light yellow mottled gravel. This sequence is a sequence of decreasing hardness of the gravel (although the hardness of the uniform reddish-brown gravel and the reddish-brown/light yellow mottled gravel is the same) and "decreasing redness"[1] of the gravel in cross-section.

After conducting this study, it was concluded that in the Theo catena the soft purple ironstone gravel is a slightly weathered form of the hard purple ironstone gravel. The weathering expressed itself in the formation of yellow rims around the gravel, formation of irregular pores and the deposition of clay coatings in the pores. The hard- and soft purple ironstone gravel probably originate from an iron-impregnated metamorphic saprolite.

The uniform reddish brown- and light yellow/reddish brown ironstone gravel were found not to be related to the hard- and soft purple ironstone gravel. They originate from iron-impregnated soil material instead of a saprolite. Their occurrence in the Theo catena could not be explained very well.

In the soils of the Marie catena four types of gravel were distinguished in thin section. The first type originates from an iron-impregnated sedimentary rock. This type was only present in the crest position. The second type, present in alll gravel containing layers, corresponds with the hard- and soft purple ironstone gravel of the Theo catena. The third, also present in all gravel containing layers, type is similar to the second type, except that the third type has undergone more alterations:

1. Along the edges of the gravel and the edges of cracks in the gravel yellow rims (XPL) start to form. These are due

[1] With "decreasing redness" the change in colour from purple via reddish brown to yellow is meant.

to either depletion of iron or to hydration of hematite (Tardy et al., 1985). In these yellow rims the pseudomorphs are still distinct.

2. Existing pores and cracks widen, and their edges made more irregular by processes caused or started by the soil water that enters the pores.
3. Illuvial clay also invades into the gravel and is deposited in pores connected to the groundmass, as clay coatings.
4. Iron, either released from the gravel itself or brought into the ironstone gravel by soil water, is deposited in the pores in the form of goethite or hematite. Aluminium is deposited as gibbsite in the pores.
5. When the alterations, mentioned under 1 to 4 proceed (longer and/or more intensively), the portion yellow in the ironstone gravel becomes larger until the gravel is completely yellow and the pseudomorphs become less distinct. The infillings and coatings of the pores with goethite and hematite are still distinct, like the clay coatings (Plate 30).

The fourth type of ironstone gravel distinguished, was only observed in the profiles on the upper slope. This gravel are pieces broken off the plinthite lying directly under the horizon in which the fourth type of gravel occurs, due to weathering.

My second hypothesis implied that the hardened plinthite found in upper slope positions of the Marie catena is fossil instead of recently formed, as assumed by De Rouw et al. (1990).

The micromorphological observations confirm this hypothesis: the strongly iron-impregnated part of the plinthite contains pseudomorphs, while the iron-poor part of the plinthite does not contain pseudomorphs, indicating that the iron-poor part of the hardened plinthite had time to get affected by weathering. Other indications that strengthen this conclusion are the absence of iron mottles in the rest of the profile, the fact that no pseudomorphs are present in the horizon above the plinthite and the drainage conditions of the upper slope (well-drained).

This plinthite, which is now considered fossil, was formed in positions influenced by the groundwater which later became upper slope- and crest positions after uplifting and dissection of the (pene)plain in which it was formed.

Apart from the ironstone gravel and plinthite, also some attention is paid to features related to other aspects of soil formation in the soils of the Marie catena, as detected by micromorphology and as observed in the field.

In short we can say that the slope on which the Marie catena is situated exists of a core of saprolite/bedrock of migmatite, which is covered by various layers of colluvium. In the valley bottom also alluvial deposits are present. The connection and continuation of the layers is not clear in all cases.

Charcoal, probably originating from the burning of vegetation by man or by nature, was found in all profiles of the Marie catena except for the profile in the valley bottom.

Traces of current translocation of clay was found in the crest and upper slope positions of the Marie catena.

Actual plinthite formation is taking place in the Marie catena in the middle and lower slope positions.

In conclusion a remark can be made with relation to the application of generally used methods of analysis, like thermogravimetric analysis and iron extraction by dithionite, oxalate and pyrophosphate, on ironstone gravel. In this study it appeared that the above mentioned analysis are not very well applicable on ironstone gravel: several discrepancies between the results were found.

CONTENTS

1. INTRODUCTION

1.1 General introduction

This study concerns the soils of a typical migmatite catena[1] in the Taï region, south-west Côte d'Ivoire. The study is performed using micromorphology, X-ray powder diffraction, X-ray fluorescence spectrometry, thermogravimetric- and chemical analyses. It is focused on the forms in which iron occurs in these soils. Also attention is given to the micromorphological characteristics concerning the general soil genesis aspects of this catena.

In the Taï region research is being conducted within the framework of the programme "Analysis and design of land-use systems in the Taï region, Côte d'Ivoire" of the Wageningen Agricultural University. The soil science research is being done within two projects:
- project 6.: Soil inventarisation and land evaluation;
- project 7.: Nutrient cycling in different types of land-use.

This study fits in both projects. Within project 6. the soil genesis on a typical migmatite catena is studied with special attention to the different forms in which iron occurs in the catena. On a representative toposequence of this catena ("Marie catena", see below) field trials were done within the framework of project 7. to define the production capacity of the different soils. Together with soil chemical- and soil physical data from the same toposequence a quantitative physical evaluation of the soils in the Taï region can be done.

Two occurrences of the typical migmatite catena are considered, known as "Marie catena" and "Theo catena". The Marie catena is described by Van Herwaarden (in prep.). The Theo catena is described by Hooyer (1991). Except for the valley bottoms, which were under forest, both catena's were under cultivation. On the Marie catena maize was cultivated. The Theo catena was under plantation of coffee and rubber.

In the migmatite catena iron occurs as:

a. remnants of a Tertiary ironstone crust, mostly as ironstone gravel ("pea-iron gravel") which has a shiny dark-purple surface and is very hard (can not be broken between fingers; when broken by force the gravel is purple on cross-section);
b. soft ironstone gravel, in three forms:
   - purple (tough to break between fingers);
   - uniform reddish-brown (easy to break between fingers);
   - mottled reddish-brown/light yellow (easy to break between fingers);
c. plinthite, soft and in various stages of hardening;
d. oxidation mottles in a gley-zone;
e. Fe-coated soil material giving the soil its red, brown or yellow matrix colour.

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[1] The catena concept as used in this report: a succession of soils along a slope, formed from the same parent rock over the same period of time and under the same climatic conditions, that are different due to differences in drainage and due to differences in parent material: soils downslope may have received material from higher positions. (Remark the differentiation that is made here between parent rock and parent material!) Vegetation is seen as a derivation of drainage and not as a independent soil forming factor.

This study concentrates on the forms of iron mentioned under a., b. and c.

1.2 Laterite

McFarlane (1976) gives a historical review of the concepts that have been developed about laterite[2] genesis and landscape evolution. The first models of laterite formation proposed marine or volcanic origin or even termite activity as the cause of laterite formation. These models were soon dismissed (Oldham, 1893).

More generally accepted were the concepts of laterite as a residuum respectively laterite as a precipitate. In the "residuum" concept the accumulations are caused by relative accumulation due to the immobility of the constituents. The "precipitate" concept resulted from the recognition of the fact that pallid zones[3] typically underlie laterites and of the increasing understanding of the several ways in which iron and alumina can be mobilized. The source of the concentration of iron and aluminium was believed to be essentially the underlying pallid zone, but more distant sources were also considered possible if not probable. Two mechanisms were suggested for this enrichment of the laterite horizon: capillarity and the seasonal fluctuation of the watertable. Capillarity, as a major factor, has been generally given up since capillary action is restricted to a hight of less than 2 meter (Sivarajasingham et al., 1962; Baver, 1956). Also, there is a growing awareness that a fluctuating watertable as a mechanism must be treated with reserve:

- fresh groundwater floats on the underlying solutions thus presenting a barrier to the rise of solutions enriched with iron etc. (Goudie, 1973; Sivarajasingham et al., 1962);
- the scale of many laterites is so large that seasonal variations far more extreme than those occurring at present have to be assumed (Walther, 1916);
- the concept of laterite enrichment and pallid zone depletion as synchronous and complementary processes is faced with the not uncommon occurrence of laterite directly on fresh rock, the occurrence of laterite over extremely thin leached horizons and the fact that even the deepest pallid zones ate quantitatively inadequate to account for the concentration in the crust (Trendall, 1962);
- many laterites occur on surfaces of relatively high relief, some of which is explained by modifications of the original laterite surface, but some of which is original.

A third mechanism for the enrichment of the laterite horizon, whereby ionic diffusion may remove rock alteration products from deep within the weathering profile (Lelong, 1966), remains unproven.

According to McFarlane (1976) two other kinds of models of laterite formation have received more attention: detrital models and those which combine the above mentioned concept of laterite as a residuum and the concept of laterite as a pre-

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[2] McFarlane's definition of laterite: "highly weathered material (1) rich in secondary forms of iron, aluminium or both; (2) poor in humus; (3) depleted of bases and combined silica; (4) with or without non-diagnostic substances such as quartz, limited amounts of weatherable primary minerals or silicate clays; and (5) either hard or subject to hardening upon exposure to alternate wetting and drying."

[3] Pallid zone: pale coloured horizon due to leaching of iron (McFarlane, 1976).

cipitate. The detrital model suggests laterite formation with contributions from topographically higher positions (Figure 1.1). This theory can only apply to all laterites if laterites that are now situated on high positions once were low-level laterites and became high-level laterite after relief inversion or dissection of the landscape.

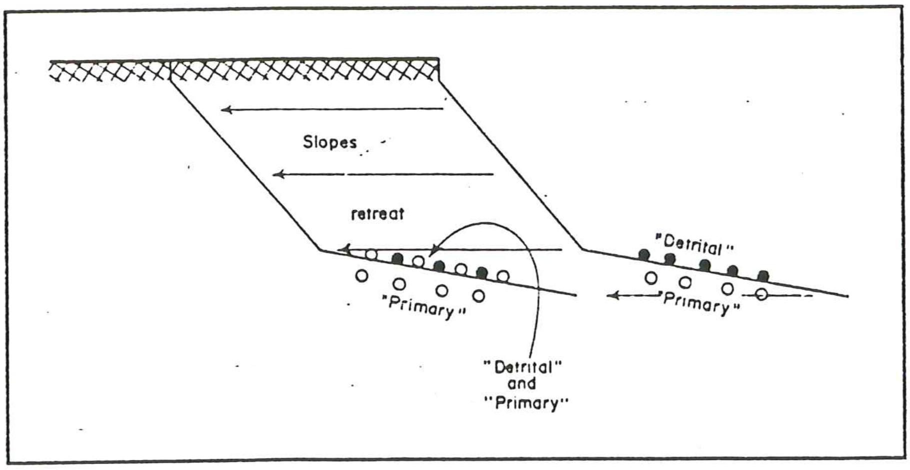

Figure 1.1 Primary laterite development on pediments in association with detrital accumulations.
With parallel slope retreat, primary laterite developed within the profile of a pediment is incorporated into the surface detrital layers (source: McFarlane, 1976).

The "residuum-precipitate" models assume a mixture of both ideas that all have their own share in the models. These models too leave a lot of questions unanswered.

The term laterite has been used in literature to describe a number of different materials (Ahn, 1970; McFarlane, 1976). Ahn (1970) suggests to use more accurate alternative words instead of laterite. He suggests the following alternatives:
- "ironstone" or "iron pan" for rock-like sheets of indurated iron-rich material, where pan refers to a hardened horizon;
- "ironstone concretions" for iron-rich concretions in the soil;
- "slightly or moderately indurated" or "soft or hard plinthite" for mottled iron-rich horizons.

The ironstone gravel mentioned in section 1.1 under a. (p.1) is thought to be a remnant of the ironstone crust that once covered the area (see section 2.1.4, p.9). Therefore it is not right to call the gravel "ironstone concretions" after Ahn, since the word concretions implies bodies formed independent from each other. That is not the case with the bodies meant here: they were once part of the same ironstone crust. For this reason the term "ironstone gravel" is used in this report for the gravel mentioned in section 1.1 under a. (p.1).

1.3 Plinthite

The fact that plinthite is only one form of what in literature is often described as laterite, becomes obvious when one compares the definition of laterite by McFarlane (section 1.2, note 2) and the definition of plinthite in the Legend of the Soil Map of the World (FAO, 1974):

"an iron-rich, humus-poor mixture of clay with quartz and other dilutents, which commonly occurs as red mottles, usually in platy, polygonal or reticulate patterns, and which changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying. In a moist soil, plinthite is usually firm but it can be cut with a spade. When irreversibly hardened, the material is no longer considered plinthite but is called ironstone."

Sys (1968) suggested to call the irreversibly hardened plinthite "petroplinthite". The terms "soft and hard plinthite" were mentioned in section 1.2 (p.3) as more accurate terms than laterite for a mottled iron-rich horizon, after Ahn (1970).

In this report chosen is to speak of "soft or hard plinthite" after Ahn (1970), although hard plinthite is a contradiction because per definition plinthite is soft! The terms hard and soft plinthite are preferred because they describe the plinthite as it is observed in the field and don't not make a statement about the formation of plinthite.

According to De Rouw et al. (1990) plinthite formation is a process similar to the gleying process as it is known in the temperate zones. The reduction of solid iron (Fe^{3+}) to ferrous iron (Fe^{2+}), that is a principal sub-process in the gleying process, can take place in a water-saturated soil. The water-saturation can be caused by a fluctuating groundwater-table, or by water-stagnation over an impermeable layer. This gleying process is much more intensive in the tropical zones. Plinthite usually occurs in lower slope positions were the watertable fluctuates and which receives ferrous iron from higher-lying sites.

1.4 Summary of terms used

So far, a number of definitions of terms used in this report were given. The following list enumerates these definitions, together with definitions of other terms frequently used in this report. This list is restricted to terms that are often used in literature with various meanings.

Catena - a succession of soils along a slope, formed from the same parent rock over the same period of time and under the same climatic conditions, that are different due to differences in drainage and due to differences in parent material: soils downslope may have received material from higher positions. (Remark the differentiation that is made here between parent rock and parent material!) Vegetation is seen as a derivation of drainage and not as a independent soil forming factor.

Laterite - A collective noun for several substances that have in common that they consist of highly weathered material that is: (1) rich in secondary forms of iron, aluminium or both; (2) poor in humus; (3) depleted of bases and combined silica; (4) with or without non-diagnostic substances such as quartz, limited amounts of weatherable primary minerals or silicate clays; and (5) either hard or subject to hardening upon exposure to alternate wetting and drying (McFarlane, 1976).

Ironstone crust - A sheet of the material as described under laterite at the soil surface.

Ironstone gravel - Pieces of the material as described under laterite with a diameter between 2 mm and 20 mm.

Hard ironstone gravel - Ironstone gravel that is not breakable between fingers.

Soft ironstone gravel - Ironstone gravel that is tough to easy to break between fingers.

Plinthite - Material described under laterite that is formed under alternating reducing and oxidizing conditions, usually caused by a fluctuating groundwater-table or water stagnation over an impermeable layer.

Hard plinthite - Plinthite that is hardened through exposure, not breakable by hand.

Soft plinthite - Plinthite that is breakable by hand.

1.5 Formulation of research subjects

On the crest of the above mentioned Theo catena the hard ironstone gravel and the three distinguished forms of soft ironstone gravel (see section 1.1, p.1) were sampled. The first research question was the origin/formation of the soft ironstone gravel and the relation to the hard purple ironstone gravel.

The plinthite mentioned under c. (section 1.1, p.1) occurs in middle- and upper slope positions. One would not expect recent plinthite formation due to fluctuating groundwater on the middle- and upper slope positions. The second research question was the explanation for the occurrence of plinthite in these positions.

Next to this, some attention is paid to features related to other aspects of soil formation in the soils of the Marie catena, as detected by micromorphology and as observed in the field.

In the sections 1.2 and 1.3 an review of literature on laterite and plinthite was given. More detailed literature on these subjects is used in the discussion (chapter 5) at the appropriate places in the text.

2. SITE DESCRIPTION AND HYPOTHESES

2.1 Site description

2.1.1 Location

The migmatite catena studied is situated in south-west Côte d'Ivoire close to the village of Taï and to the Cavally River, which forms the border with Liberia (Figure 2.1). Taï has the following coordinates: latitude 5°53' North, longitude 7°27' West.

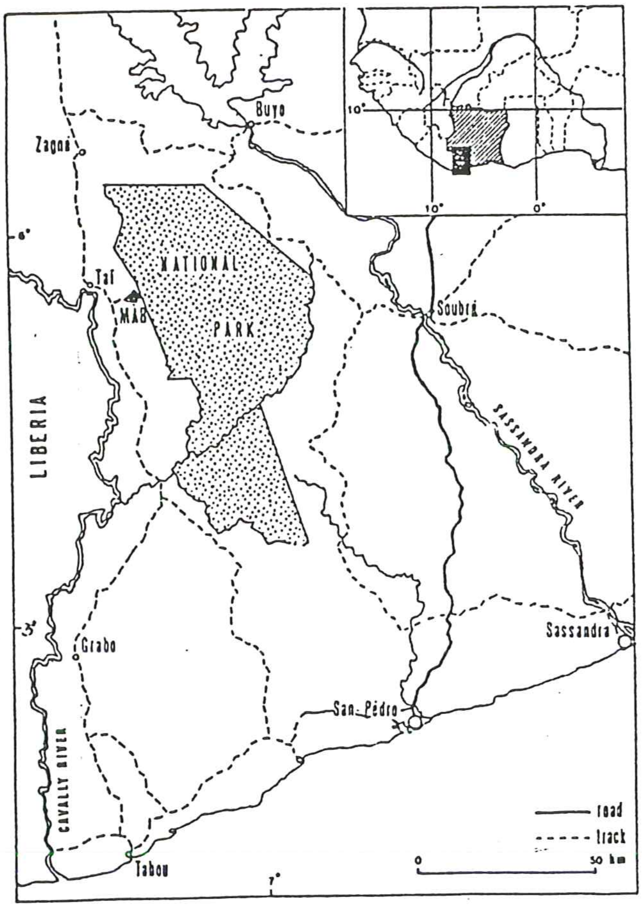

Figure 2.1 South-west Côte d'Ivoire
(source: Fraters, 1986)

In Figure 2.2 the location of the Theo- and Marie catena are indicated.

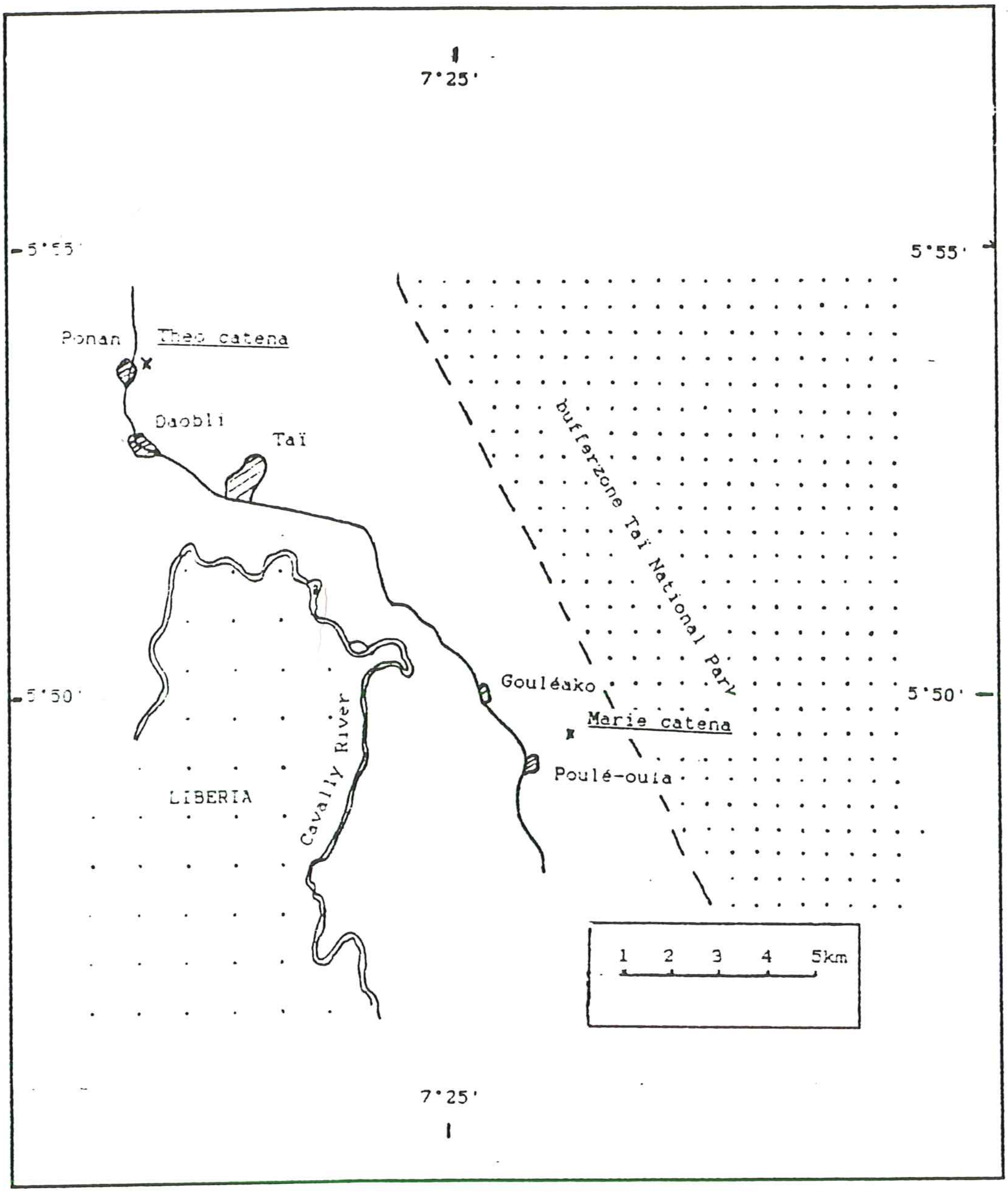

Figure 2.2 Location of the Theo- and Marie catena, Taï region, Côte d'Ivoire.

2.1.2 Climate

The Taï Region has an Aw climate, according to Köppen's system: a tropical rainy season with a mean temperature in the coldest month >18°C and a distinct rainy season. Four seasons are distinguished:

- a long rainy season from March to July, which accounts for almost 45 % of the rain;
- a short dry season from July to September;
- a short rainy season from September to November, which accounts for almost 30 % of the rain;
- a long dry season from November to March.

(De Rouw et al., 1990).

The mean annual temperature is 26.2°C, with monthly means between 24.7°C and 27.4°C, and an annual monthly mean minimum of 21.2° and a maximum of 31.1°C. See Table 2.1 for climatic data.

Table 2.1 Climatic data as recorded at the Taï meteorological station (source: Fraters, 1986).

	Jan	Feb	Mar	Apr	May	Jun	Jul
T av (°C)	26.1	27.1	27.3	27.4	26.8	25.7	24.7
T min (°C)	20.2	21.4	21.5	21.8	22.0	21.6	20.8
T max (°C)	31.9	32.8	33.0	32.9	31.6	29.7	28.5
Prec. (mm)	21	65	148	170	216	269	124

	Aug	Sept	Oct	Nov	Dec	Mean/Total
T av (°C)	25.3	25.9	26.5	26.2	25.3	26.2
T min (°C)	20.9	21.4	21.8	21.1	20.3	21.2
T max (°C)	29.6	30.3	31.1	31.2	30.3	31.1
Prec. (mm)	132	293	240	108	47	1833

2.1.3 Geology

In south-west Côte d'Ivoire the rocks belong to the Precambrian Basement Complex that consists of orogenic formations of the Libérien and Eburnéen systems in this area. Their age is 3.0-2.3 milliard years BP and 2.3-1.7 milliard years BP respectively. Both formations have a rectilinear structure of parallel bands with a northeast-southwest orientation (Fig. 2.2.) (Fraters, 1986).

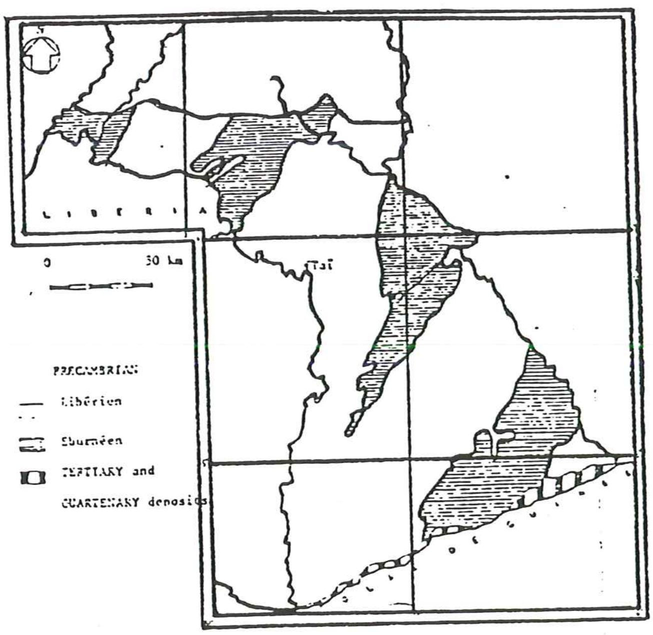

Figure 2.3 Simplified Geological Map of south-west Côte d'Ivoire (source: Fraters, 1986).

The Libérien system covers the Taï region. The principal rock type is migmatite: a rock that results from the introduction of material with more or less granitic characteristics into a pre-existing metamorphic rock (De Rouw et al., 1990).

The migmatite as it was observed in an inselberg in the Taï National Forest had a banded structure, with bands varying in thickness from several cm to dm.

2.1.4 Geomorphology

The Taï region consists of uplands with an undulating to rolling relief. The average difference in elevation between summits and valley bottoms is about 20 to 25 meter. The elevation of the summits is 150-200 meter above sea level.

According to Ahn (1970) a landscape like this was formed in three stages:

1. A hilly landscape undergoes erosion which, if sufficiently prolonged, reduces it to a near flat, peneplain.
2. Old and highly weathered soils, often rich in iron, mantle the peneplain.
3. The rivers on the peneplain rejuvenate, usually by a rise of the land relative to sea level, and new valleys are rapidly cut into the old landscape.

The result is a landscape in which the original peneplain surface is represented only by the relatively flat summit areas of occasional hills. The highly weathered peneplain soils survived on these summits, though perhaps in modified form, and constitute the oldest soil materials in the area. The valley slopes and floors are associated with younger soils, though these younger soils may incorporate some of the older material, like ironstone gravel.

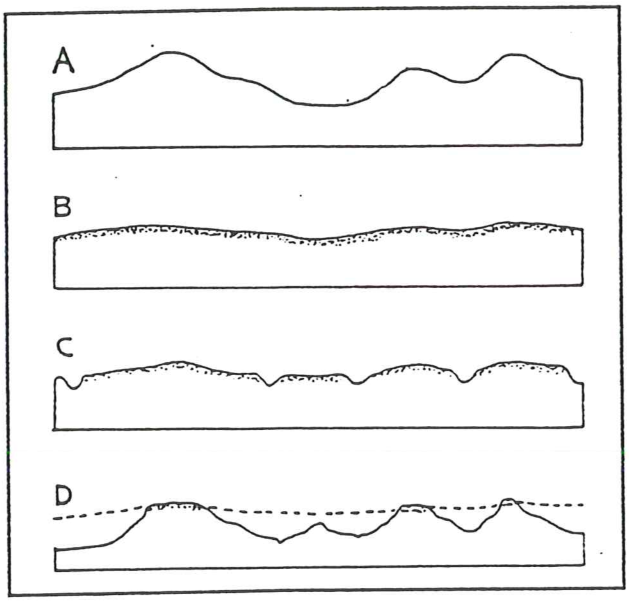

Figure 2.4 Stages in the dissection of the landscape (after: Ahn, 1970); Diagram A: a hilly landscape under erosion; diagram B: peneplain mantled with highly weathered soils (shaded); diagram C: rejuvenation of the rivers on the peneplain; diagram D: new valleys while highly weathered peneplain soils (shaded) survive on the summits.

2.1.5 Soil formation

As mentioned in section 2.1.4 (p.9) the landscape consists of a dissected peneplain with remnants of an ironstone crust on the now highest terrain positions, the crests. The soils in such a landscape can be described by a typical catena. Within the catena five positions are distinguished: crest (C), upper- (US), middle- (MS) and lower slope (LS), valley bottom (VB). Soils on crest, upper- and middle slope are usually developed "in situ" and are subject to soil erosion. The ironstone gravel on the surface or at shallow depth in crest and upper slope soils is probably the remnant of the Tertiary ironstone crusts. Lower slope soils have developed in colluvial material that was eroded from the higher positions. Valley bottom soils have developed in a mixture of colluvial and alluvial material.

The five prominent soil forming processes in catena's in the Taï region are (adapted from De Rouw et al. (1990)):

1. After dissection of the peneplain that was covered with ironstone crusts and ironstone gravel soil formation "in situ" started in crest, upper- and middle slope positions that were freely drained. These soils are now strongly weathered, depleted of bases and have high contents of sesquioxides.
2. The clay contents of the soils that have formed "in situ" increase with depth. Two causes are possible:
   - vertical migration of clay in suspension, mainly lateral, but - except for the crest - with a lateral component;
   - selective transport by termites and worms. (Termites and worms can bring clay-rich material to the surface, as nests and casts respectively, that is taken away by surface erosion and thus creating a relatively sandy top soil (C.A.M. Nooren, 1991).);
   - weathering of clay.
3. In soil profiles or sections thereof that are subject to water saturation gleying will take place. If the gley mottles harden upon periodic or continuous drying, this material is called plinthite. Plinthite is not only found in positions where there is actual influence of the ground water (e.g. valley bottom and lower slope positions), but also in middle-, upper slope and crest positions (see section 2.2, p.14).
4. Upon weathering migmatite rocks produce reddish clayey soils or yellowish brown loamy soils, depending on its composition. Quartz fragments and fine quartz gravel are often present; they are derived from quartz veins in the original rock;
5. Soils in a catena are strongly related, each soil receives compounds from soils in higher positions and loses compounds to lower positions on the slope. The major processes causing these translocations of material are;
   - lateral movement of water with suspended matter and soluble compounds, including ferrous iron;
   - erosion at higher positions and sedimentation on lower slope sites and in the valley bottom.

2.1.6 Description of the soils of the migmatite catena

A schematic cross-section of the Marie catena and position of the soil pits is given in Figure 2.5. The pits in the Marie catena will be referred to as Marie 1, Marie 2, etc. (ditto for Theo catena).

Within the catena studied five physiographic positions were distinguished (section 2.1.5, p.9). With exception of the upper slope, where two soil pits were made, one soil pit was made on each of the physiographic positions of the Marie catena (see Appendix A for physiographic soil map of the Marie catena); six soil pits in total. On the Theo catena six soil pits were made: one on the crest, upper slope, lower slope and valley bottom and two pits on the middle slope.

Soil profile descriptions of the soil pits of the Marie- and Theo catena, according to the FAO Guidelines (FAO, 1977) and using the Munsell Soil Colour Charts, were already available (Van Herwaarden, in prep.; Hooyer, 1991)(Appendix B and C respectively).

In this section a comprehensive description of the soils on the Marie catena will be given, since these have a central role in this study.

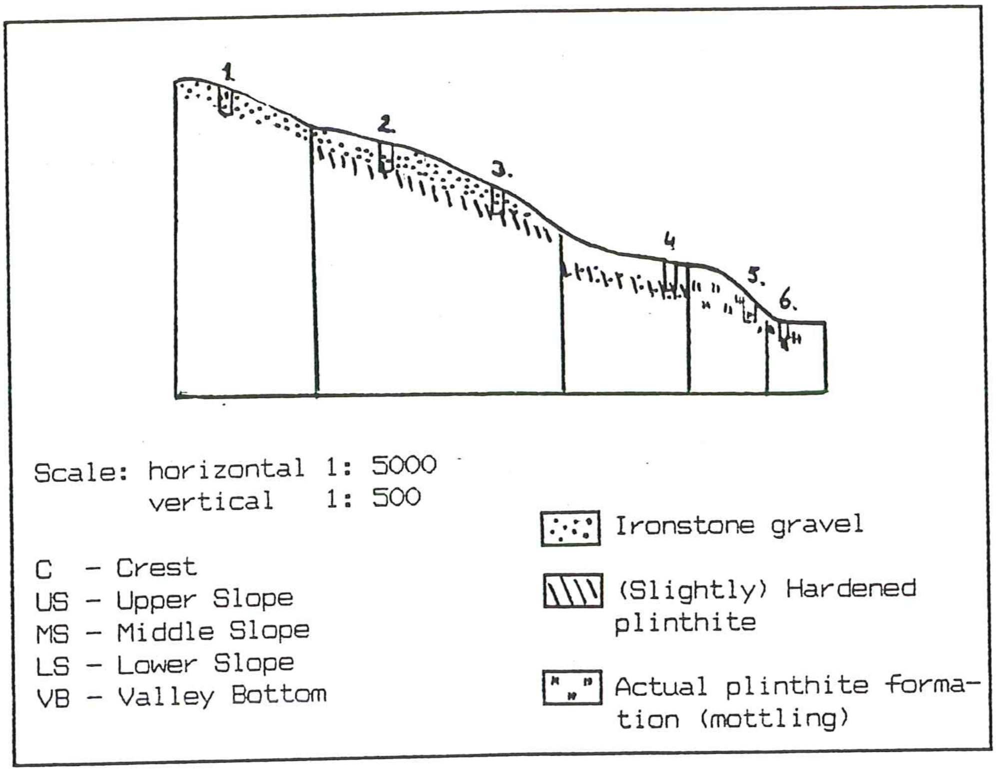

Figure 2.5 Schematic cross-section of the Marie catena. (after: Van Herwaarden, in prep.)

The soils of the Marie catena were classified as presented in Table 2.2.

Table 2.2 Classification of the soils of the Marie catena according to the FAO-Unesco classification (source: Van Herwaarden, in prep.).

Marie 1 - Ferric Acrisol
Marie 2 - Plinthic Acrisol
Marie 3 - Plinthic Acrisol
Marie 4 - Plinthic Acrisol
Marie 5 - Plinthic Acrisol
Marie 6 - Dystric Gleysol

Of the profile on the crest, Marie 1, the upper 75 cm of the profile contains much gravel. Most of the gravel is hard ironstone gravel, but with increasing depth, the proportion soft ironstone gravel increases. Occasionally quartz fragments are found. The surface soil is a brown to dark brown (7.5YR4/4) sandy loam. Below this sandy loam the colour changes downwards from yellowish red (5YR5/6) to red (2.5YR5/6-4/7) and the texture changes from clay loam to clay.
Marie 2, on the upper slope, has a shallow (0-5 cm) non-

gravelly brown to dark brown (10YR4/3) layer of loam at the surface. Below this non-gravelly layer gravel appears to a depth of approximately 90 cm. This gravel-containing layer overlies plinthite that becomes more dense with increasing depth. The colour changes with depth from strong brown (7.5YR5/6) to yellowish red (5YR5/7). The texture is loam of the profile below 5 cm is sandy clay loam until a depth of 25 cm and clay loam below 25 cm.

In the second profile on the upper slope, Marie 3, gravel appears directly on the surface and continues until a depth of 70 cm. Below 70 cm, plinthite is present. The texture grades with depth from sandy clay loam to sandy clay, while the colour changes downwards from dark brown (10YR4/3) to yellowish red (5YR5/6). A broken up quartz vein is present above the plinthite.

Ironstone gravel is almost absent in the middle slope profile. In Marie 4 the surface soil is a brown to dark brown (10YR4/3) loamy sand. The subsoil changes from a yellowish brown (10YR5/4) sandy loam to a brownish yellow (10YR6/6) sandy clay loam. Yellowish red (5YR5/6) mottles are present between 100 and 120 cm. Ironstone gravel is found in this profile below 100 cm.

In the profile on the lower slope, Marie 5, a broken up quartz vein is present between 25 and 60 cm. The surface soil is a brown (10YR5/3) sandy clay. Downwards the profile the soil changes from a light yellowish brown (10YR6/4) sandy clay loam, via a very pale brown (10YR4/7) sandy clay to a white (5Y8/1) sandy clay. Brownish yellow (10YR6/8) mottles are present below 90 cm.

In Marie 6, the profile in the valley-bottom, the surface soil is a very dark grayish brown (10YR3/2) clay loam. The subsoil is a light gray to gray (10YR6/1) clay to a depth of 110 cm. Below 110 cm the colour remains the same but the structure changes from a sandy clay to a loamy coarse sand. Mottles appear at 5 cm and are strong brown (7.5YR5/6).

Hard purple ironstone gravel was found in Marie 1, 2, 3 and 4. Soft ironstone gravel was observed in Marie 1 and 2 in the lower part of the gravel-containing horizon (see Figure 2.6).

In all six profiles of the Theo catena hard purple ironstone gravel was found, soft ironstone gravel was found in profiles 1-5. Van Herwaarden (in prep.) determined four types of gravel and their amounts (in percentages of total gravel) in the horizons of the Marie catena (see Appendix E). His "type 2-gravel"[4] corresponds with the soft uniform reddish-brown and the reddish-brown/yellow mottled ironstone gravel. His data also show an increasing proportion of his "type 2-gravel" ironstone gravel with depth in Marie 1 and 2. He also found soft ironstone gravel in Marie 3, where the proportion decreased with depth.

A schematic representation of the profiles described above is given in Figure 2.6. A more detailed description is made by Van Herwaarden (in prep.)(see Appendix B).

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[4] "moderately hard, irregular, ironstone nodules, without a coating" (Van Herwaarden, in prep.)

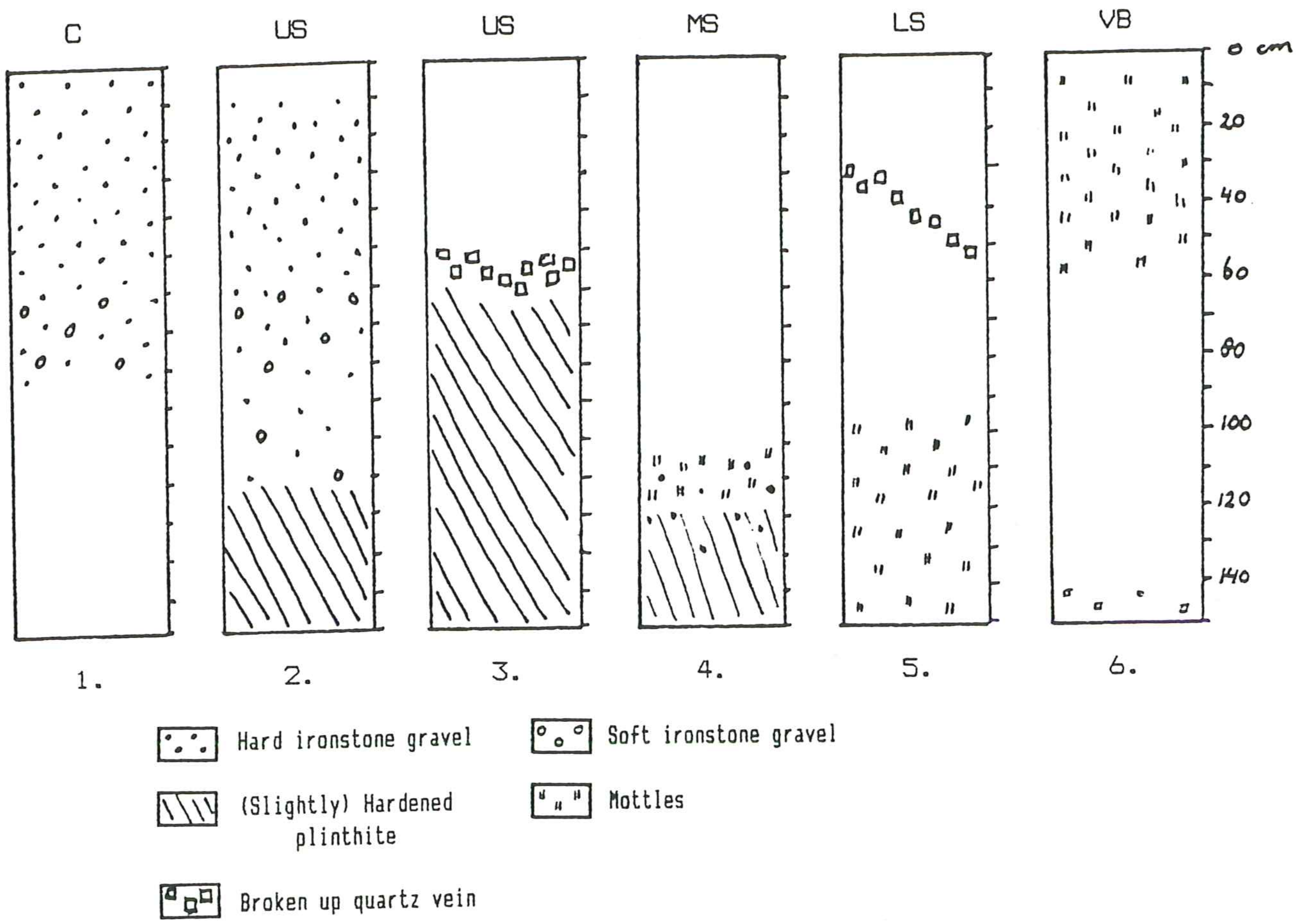

Figure 2.6 A schematic representation of the profiles of the Marie catena.

A set of analyses (pH, P-total, P-Olsen, % C, grain size distribution, C.E.C. and base saturation) of Marie 1-6 was done in the framework of project 7. The complete set of data are presented in Appendix D.

In general the pH in the soils of the Marie catena are low (4.7-6.9). The general trend in the pH-H_2O and pH-KCl in the different profiles is a decreasing pH with depth.

The pH-KCl is everywhere lower than pH-H_2O but the difference is never more than 1.0 unit.

The percentage organic carbon decreases with depth in all profiles except in Marie 3, where the Bws3 increases relative to the overlying horizon. The percentage organic carbon does not exceed 2.3 %.

The C.E.C. (cmol(+)/kg), which is low in these soils, decreases with depth in Marie 1 and 4 (5.5-3.2 and 5.1-3.4 respectively), in Marie 2, 3 and 5 does not show any pattern: 3.5-3.8-3.0-4.2, 7.2-2.9-5.4-6.6 and 6.8-3.4-3.7-5.0-4.7 respectively.

2.2 Hypotheses

My first hypothesis, based on field observations, was that the different kinds of soft ironstone gravel are succeeding stages of weathering of the hard purple ironstone gravel: the first stage of weathering is the soft purple gravel, the second stage the uniform reddish-brown gravel and the third stage the reddish-brown/light yellow mottled gravel. This sequence is a sequence of decreasing hardness of the gravel (although the hardness of the uniform reddish-brown gravel and the reddish-brown/light yellow mottled gravel is the same) and "decreasing redness"[5] of the gravel in cross-section. This hypothesis is based on the following observations:

1. Since the soft ironstone gravel was always found together with the hard ironstone gravel within one and the same horizon it seemed reasonable to assume there was a relationship between the two.
2. The gravel had abrupt boundaries with the soil matrix. The suggestion of the sequence being a sequence of "in situ" formation, instead of a sequence of weathering, was dismissed on this ground, since "in situ" formation would give bodies like mottles with a diffuse and irregular boundary with the soil matrix. Also the absence of any visual iron precipitation like mottles and the absence of long-lasting alternating oxidation and reduction conditions as e.g. caused by a fluctuating watertable and/or by an impermeable layer in the subsoil that causes water stagnation (Van Herwaarden, in prep.), were extra reasons for dismissing the idea of "in situ" formation.

The "decrease in redness" of the gravel in the weathering sequence suggests a decrease in ironoxides like hematite (that gives the soil matrix a reddish colour) and an increase in ironoxides like goethite and amorphous Fe^{3+}-oxides (that give the soil matrix a yellowish brown to brown colour) (Scheffer et al., 1979).

In thin section, all stages of weathering of the gravel are expected to show the same matrix or only small differences (due to weathering), since they were all supposed to originate from the same material.

The hypothesis is tested by determining whether or not goethite and hematite are present (by X-ray powder diffraction) and if so, whether there is a decreasing ratio hematite:goethite in the presumed weathering sequence. Together with micromorphological observations this should provide some answers.

The amount of goethite and hematite present can be determined by subtracting the amount of iron present as goethite (Fe-goethite) from the total amount of iron present in crystalline ironoxides (Fe-total,cryst.). Fe-goethite can be determined by thermogravimetric analysis. Fe-total,cryst. can be determined by subtracting the amount of oxalate-extractable iron (Fe-oxalate) from the amount of dithionite-extractable iron (Fe-dithionite).

$$\text{Fe-hematite} = \{\text{Fe-dithion.} - \text{Fe-oxalate}\} - \text{Fe-goethite} \quad (1)$$

It is assumed that oxalate-extractable iron includes amorphous and organically bound iron and dithionite-extractable iron includes amorphous, organically bound and crystalline iron (see section 3.4, p.17).

My second hypothesis is that the horizons of hardened plinthite found in the upper slope positions have not been formed recently as assumed by De Rouw et al. (1990), since there is no fluctuating watertable and no evidence of an impermeable layer in the subsoil that can cause water stagnation (Van Herwaarden, in prep.). The plinthite found in this position is

[5] With "decreasing redness" the change in colour from purple via reddish brown to yellow is meant.

presumably fossil.

To test this hypothesis the thin sections of the plinthite in Marie 2 and 3 will be examined. In case the boundary between the plinthite and the surrounding groundmass is diffuse and not sharp this indicates that the plinthite was formed "in situ".

When traces can be seen that the surrounding groundmass of around the plinthite has been more exposed to weathering than the groundmass of the plinthite it can be concluded that the plinthite is fossil. This because the impregnation with iron of the plinthite has worked as a "protective shield".

3. MATERIALS AND METHODS

3.1 The samples and the analyses done

Of the wall of Theo 1 samples were taken of the hard purple and of the soft ironstone gravel. The soft ironstone gravel was sorted in the field in three fractions, by colour of the cross-section after breaking them between fingers: a. purple, b. uniform reddish-brown, c. mottled reddish-brown/light yellow. The samples were washed and dried.

Bulk samples were taken of each of the horizons described in the profile descriptions of the Marie catena (total 32 samples). The samples were air-dried in the laboratory. Of all samples the fine earth fraction was separated from the gravel fraction by sieving the sample through a 2 mm sieve.

Also samples were taken of plinthite and saprolite in the following pits of the Marie catena:

- Marie 3, depth 60 to 120 cm: plinthite, purple;
- Marie 3, depth 60 to 120 cm: plinthite, yellow and red;
- Marie 4, depth 120 to 130 cm: plinthite;
- Marie 5, depth 120 to 130 cm: white/brown soft saprolite;
- Marie 5, depth 130 to 140 cm: purple semi-hard saprolite[6];
- Marie 5, depth 160 to 170 cm: white-brown saprolite (auger sample).

Additionally a piece of migmatite was cut of an inselberg in Taï National Park.

3.2 Mineralogy

To establish which minerals are present, X-ray powder diffraction (XRD) using a diffractometer was performed on the hard and soft ironstone gravel sampled in the Theo catena, on the plinthite and on the saprolite samples of the Marie catena. Also XRD was done on the fine earth samples of the horizons of which the above mentioned plinthite and saprolite samples were taken. Before XRD was performed all samples were dried and ground to a very fine powder. Of the soft reddish-brown/light yellow mottled gravel the reddish-brown and light yellow parts were treated separately. Co$K\alpha$ radiation (40 kV, 32 mA) was used with a scan speed of 3°/min.

The results of the XRD of the uniform reddish-brown ironstone gravel and the uniform reddish-brown gravel were very similar. Therefor it was assumed that the reddish-brown part was similar to the uniform reddish-brown ironstone gravel and only the uniform reddish-brown gravel was analyzed in the different analyses.

3.3 Total analyses

X-ray fluorescence spectrometry (XRFS) was used to obtain a total analysis of the major elements in the 32 fine earth fractions of the bulk samples of the Marie catena (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, BaO). Also gravel fractions of the hard and soft ironstone gravel samples of the Theo catena were analyzed by XRFS. To obtain some more information about the parent material of the catena the piece of migmatite cut from the inselberg was also analyzed by XRFS. The samples were ground and 600 mg sample was melted together

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[6] Van Herwaarden (in prep.) describes this as soft ironstone gravel.

with 2400 mg Litiumtribromide into a bead at high temperature (1200°C). The XRFS was done using a Philips PW-1404 spectrometer with a Scandium anode.

3.4 Iron- and aluminium analyses

According to soil analysis procedures of ISRIC (ISRIC, 1987) amounts of dithionite-extractable, oxalate-extractable and pyrophosphate-extractable iron and aluminium were determined in seven selected fine earth samples, in the hard purple ironstone gravel, in the soft purple ironstone gravel, in the soft uniform reddish-brown ironstone gravel and the yellow part of the reddish-brown/light yellow mottled ironstone gravel.

According to Stucki et al. (1988) the iron compounds dissolved by dithionite "are primarily iron oxides of varying crystallinity" although the dithionite-extract would also contain "the comparatively small fractions of water-soluble, exchangeable, and organically-bound Fe". By extracting with oxalate the amorphous and organically bound iron can be dissolved (Stucki et al., 1988). Pyrophosphate-extraction is often used to estimate organically bound iron and aluminium. According Stucki et al. (1988) the nature of the pyrophosphate-extractable iron is obscure and reproducibility poor. Still, in the absence of better techniques, the pyrophosphate-extraction technique is often used to determine organically bound iron.

3.5 Thermogravimetric analyses

The amount of goethite and kaolinite present in the hard purple and soft purple, uniform reddish-brown and light yellow part of the reddish-brown/light yellow mottled ironstone gravel was determined by thermogravimetric analysis.

The ironstone gravel was ground to a powder before the analysis was done. A Thermal Analyzer (Dupont 1090) coupled to a Thermalgravimetric Analyzer (Dupont 951) was used. The heating rate was 10°C/min and an air flow of 50 ml/min was let over the sample.

3.6 Micromorphology

Micromorphological samples had been taken previously, by Gerrit-Jan van Herwaarden, from fresh walls of the soil pits in the Marie catena. The 7 x 7 cm samples had been air-dried, impregnated with epoxy resin and cut into thin sections.

The thin sections were examined using a petrographic microscope. The types of ironstone gravel present in the thin sections, were described and the amount present per type/sub-type determined. The latter was done by counting all gravel present in a thin section and determining for each of them what type/sub-type it belonged to. Micromorphological terminology used in this report, concerning micromorphological descriptions, is partly the terminology of Bullock et al. (1985).

Also thin sections were made of the ironstone gravel sampled in the Theo catena. Micromorphological descriptions of this ironstone gravel were made too.

A thin section was made of a piece of migmatite taken from the inselberg in the Taï National park. The minerals present in the rock were determined by observing their optical properties.

3.7 Summary

A summary of the analyses done per sample is given in Table 3.1

Table 3.1 Summary of the analyses[7] done per sample of the Theo- and Marie catena.

Theo catena	XRD	XRFS	dithionite-extraction	oxalate-extraction	pyrophosphate-extraction	thermogr. analysis	micromorphology
hard purple ironst.grav.	x	x	x	x	x	x	x
soft purple ironst.grav.	x	x	x	x	x	x	x
unif.red.brown ironst.g.	x	x	x	x	x	x	x
mottled ironst.grav.	x	x	x	x	x	x	x

Marie catena	XRD	XRFS	dithionite-extraction	oxalate-extraction	pyrophosphate-extraction	thermogr. analysis	micromorphology
undisturbed samples of: all horizons described	-	-	-	-	-	-	x
fine earth fraction of: all horizons described	-	x	-	-	-	-	-
fine earth fractions of:							
Marie 1, Ah, 0-7 cm	-	-	x	x	x	-	-
Marie 1, Bws3, 75-150 cm	-	-	x	x	x	-	-
Marie 3, Bws1, 8-30 cm	-	-	x	x	x	-	-
Marie 3, Bms3, 70-150 cm	x	-	x	x	x	-	-
Marie 4, Bws3, 120-150 cm	x	-	x	x	x	-	-
Marie 5, Bws2, 60-100 cm	-	-	x	x	x	-	-
Marie 5, Bws3, 100-150 cm	-	-	x	x	x	-	-
Marie 6, 2Cg, 140-150 cm	-	-	x	x	x	-	-
plinthite of:							
Marie 3, Bms2, 60-120 cm (purple)	x	-	-	-	-	-	-
Marie 3, Bms2, 60-120 cm (yellow/red)	x	-	-	-	-	-	-
Marie 4, Bws3, 120-130 cm (varied)	x	-	-	-	-	-	-
saprolite:							
Marie 5, Bws3, 120-130 cm (white/brown)	x	-	-	-	-	-	-
Marie 5, Bws3, 130-140 cm (purple)	x	-	-	-	-	-	-
Marie 5, Bws3, 160-170 cm (white/brown)	x	-	-	-	-		-

[7] For convenience micromorphology is seen as an "analysis" too.

4. RESULTS

4.1 Introduction

One of the assumptions made at the beginning of this study was that the gravel sampled in the Theo catena was similar to the gravel of the Marie catena. **After studying the thin sections of the Marie catena and thin sections made of the gravel samples of the Theo catena it appeared that the gravel of the catenas was not similar in every respect!** The types of gravel present in the Marie catena are described in section 4.3.3.1 (p.20), the gravel types present in the Theo catena are described in section 4.4.6 (p.33).

By the time the difference between the gravel in both catenas was discovered, the chemical analyses were already performed on basis of the assumption that the gravel was similar! For this reason, from now on the two catena's and the matching results of the analyses will be dealt with separately.

First the observations done on the thin section of the piece of migmatite, taken from the inselberg in Taï National Park, will be described.

4.2 The migmatite

Of the piece of migmatite taken from the inselberg a thin section was made. The migmatite observed showed a combination of minerals similar to the minerals in a granite (A.G. Jongmans, pers. comm.). The minerals present in this thin section were: quartz, alkali-feldspars, biotite and hornblende. Quartz and alkali-feldspars were the most frequently occurring minerals. See Plate 1.

4.3 Marie catena

4.3.1 Mineralogy

Table 4.1 Results of X-ray powder diffraction of selected plinthite, fine earth fractions and saprolite samples of the Marie catena[8].

Prof.nr.	Hor.code	depth (cm)	colour	quartz	kaolinite	goethite	hematite
				plinthite			
3	Bms2	60-120	purple	+	+	+	+
3	Bms2	60-120	yellow/red	+	+	+	+
4	Bws3	120-130	varied	+	+	+	+
				fine earth fraction			
3	Bms3	70-150		+	+	+	?
4	Bws3	120-150		+	+	+	-
				saprolite			
5	Bws3	120-130	white/brown	+	+	+	?
5	Bws3	130-140	purple	+	+	+	+
5	Bws3	160-170	white/brown	+	+	+	-

[8] + present
- not present
? could be present

Results of the XRD done on plinthite and saprolite sampled in he Marie catena, and on the fine earth fractions of the horizons in which the plinthite samples were taken, are presented in Table 4.1. Quartz, kaolinite and goethite were, without exception, present in all samples.

Hematite was present in the plinthite samples and in the purple saprolite sample. In the other samples hematite was either not present or could not definitely be detected[9].

4.3.2 Total analyses and iron- and aluminium extraction analyses

The complete set of results of the total analysis of the fine earth samples of the soil horizons of all six profiles of the Marie catena and of the migmatite, obtained by XRFS, and the results of the iron- and aluminium extraction analyses of selected soil horizons of the Marie catena, are presented in Appendix F.

Weight percentages of SiO_2 with depth, and the percentages of Al_2O_3 and Fe_2O_3 increase with depth in all profiles except Marie 6. Marie 6 had constant percentages of SiO_2 and Fe_2O_3 and a variable percentage Al_2O_3. Marie 6 had a much lower percentage Fe_2O_3 than all other profiles.

TiO_2 percentages were uniform throughout the profiles (around 1 %). Percentages MnO, MgO, CaO, Na_2O, K_2O, P_2O_5 and BaO were very low, often below the detection limit.

There was little variation in the amounts of iron and aluminium extractable by oxalate and pyrophosphate in the selected horizons of the Marie catena: 0.0 to 0.2 %. The only exception was the Fe-pyrophosphate in the Bws1 horizon of Marie 3 with a percentage of 0.8.

4.3.3 Micromorphology

Three aspects were studied in the thin sections of the Marie catena: a. the ironstone gravel, b. the plinthite and c. features related to other aspects of soil formation. These three aspects will be dealt with separately in this section.

4.3.3.1 The ironstone gravel

Description of the different types of ironstone gravel

In the thin sections the ironstone gravel was clearly visible in the groundmass: the boundary between gravel and groundmass was abrupt and the gravel had a colour different from the colour of the surrounding groundmass.

Four main types and six sub-types of gravel could be distinguished in the thin sections of the Marie catena. These types were distinguished on a basis of their probable origin and mutual relationships.

Type 1: Gravel completely consisting of alternating layers, which are light and dark yellowish brown to brown in crossed polarized light (XPL). The iron-impregnated groundmass of this type of gravel consists of fine

[9] Possible peaks characteristic for hematite were very low and might have been irregularities in the baseline of the diffractogram.

material, with rare quartz grains. This type of gravel is rounded. See Plate 2.

Type 2: Gravel not at all, or not completely consisting of alternating layers, with an iron-impregnated groundmass of fine material, in which quartz grains and pseudomorphs of minerals are present in various amounts. The pseudomorphs of minerals are distinct, and can be recognized without rotating the stage of the microscope. The colour of the gravel is determined by the degree of iron-impregnation. In plain polarized light (PPL) the colour is dark red to black, in XPL it is red to dark red. This type of gravel is rounded.

Type 2a: Gravel of type 2, of which the edge, or part of it, is yellow in XPL. See Plate 3.

Type 2b: Gravel of type 2, of which the edge, or part of it, consists of alternating light and dark yellow/yellowish brown layers in XPL. See Plate 4.

Type 2c: Gravel of type 2, which has none of the characteristics mentioned under type 2a and 2b. See Plate 5.

Type 3: Gravel not at all, or not completely consisting of alternating layers, with a groundmass of fine material, in which occasional quartz grains are present. Pseudomorphs of minerals are not distinct, and can only be observed at high magnification (63x, 100x) when the stage of the microscope is rotated. The degree of iron-impregnation varies between and within the gravel, but there are no areas that are not iron-impregnated. The colour of the gravel is determined by the degree of iron impregnation and can vary between yellow and red (XPL). This type of gravel is rounded.

Type 3a: Gravel of type 3, which has a predominantly yellow colour in XPL. Although the major part of this gravel does not show any structure, a minor part shows a concentric structure. See Plate 6. and 7.

Type 3b: Gravel of type 3, which has a predominantly red colour in XPL. See Plate 8.

Type 3c: Gravel of type 3, which has for about 50 % a red colour and for about 50 % a yellow colour in XPL. See Plate 9.

Type 4: Gravel not consisting of alternating layers, with a groundmass of fine material, in which quartz grains and pseudomorphs of mineral grains are present. The groundmass is not completely impregnated with iron: some areas are not impregnated. These non-impregnated areas are gray (PPL) and yellowish green (XPL). The iron-impregnated areas are dark red to black (PPL) and red to dark red (XPL). This type of gravel is angular. See Plate 10. and 11.

Apart from these main types and sub-types, combinations of the types 2 and 3 within one gravel existed ("remainder" in Table 4.2).

To make this report easier to read the terms "type 1", "type 2", "sub-type 2a" etc. will be replaced or used together with more descriptive terms. The latter anticipate the discussion in chapter 5, but in spite of this, using the more descriptive terms will improve the readableness of this report. The terms are:

- type 1: *sediment gravel*;
- type 2: *metamorphic gravel*;
  - sub-type 2a: *yellow-rimmed*[10] *metamorphic gravel*;
  - sub-type 2b: *layered-rimmed metamorphic gravel*;
  - sub-type 2c: *not-rimmed metamorphic gravel*;
- type 3: *altered metamorphic gravel*;
  - sub-type 3a: *yellow altered metamorphic gravel*;
  - sub-type 3b: *red altered metamorphic gravel*;
  - sub-type 3c: *yellow/red metamorphic gravel;*
- type 4: *plinthite gravel.*

One has to keep in mind that we are dealing with <u>ironstone gravel</u> here, although e.g. a term like *sediment gravel* seems to imply something else!!

<u>Micromorphological features in the different kinds of ironstone gravel</u>

The *sediment gravel* (type 1) is very dense, except for some pores on the edges. An occasional crack is filled with a reddish (XPL) material, which is interpreted as hematite.

Two different sets of pseudomorphs could be observed within the *metamorphic gravel* (type 2) in the thin sections:
1. gravel with relatively small (20 - 150 µm), white and yellow coloured (XPL) pseudomorphs (see Plate 5.);
2. gravel with relatively large (50 - 500 µm), grayish white coloured (XPL) pseudomorphs (see Plate 6.).

In an occasional *metamorphic gravel* (type 2), bands of both sets of pseudomorphs were found together.

Along the edges of the gravel (Plate 3.) and pores (Plate 12.) in the *metamorphic gravel* yellow rims (XPL) could be found. (The gravel with a yellow (XPL) rim is the *yellow-rimmed metamorphic gravel* as it was described in the section above.) In these yellow rims the pseudomorphs were distinct. Some of the *metamorphic gravel* had large yellow (XPL) parts in which the pseudomorphs were visible, but less distinct than in the yellow rims mentioned above.

Many pores were present in the *metamorphic gravel*, often with irregular edges (Plate 13.). Yellow and red (XPL) coatings and infillings of the pores were sometimes observed (Plate 14. and 15.). The yellow infilling/coatings are interpreted as goethite, the red ones as hematite. These infillings/coatings could be found in the red part of the ironstone gravel but also in the yellow parts mentioned above (Plate 6. and 16.). Each kind of infilling/coating could be found alone in a pore, but the yellow and red (XPL) coatings were also observed superimposed on each other, in any sequence.

In some pores of the *metamorphic gravel* bright white (XPL) crystals, interpreted as gibbsite (Plate 17.), are observed.

Orange (XPL) clay coatings were occasionally present in pores.

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[10] Rimmed: having a rim.

In the groundmass of *altered metamorphic gravel* pseudomorphs were not very distinct and not as often present as they were in the *metamorphic gravel* but they could frequently be recognized when the gravel was (type 2) studied at high magnification (63 x or 100 x) and the stage of the microscope was rotated.

In the type 3 gravel occasionally parts were observed that were similar to the *metamorphic gravel* (Plate 18.). These parts were lying in the centre of the ironstone gravel as well as on the outer side. Also some of the *altered metamorphic gravel* had an edge with alternating light and dark yellow/-yellowish brown layers, similar to that of the *layered-rimmed metamorphic gravel*.

In most of the *altered metamorphic gravel* the pores were as frequent as they were in the *metamorphic gravel*. The edges of the pores were also irregular. In some *altered metamorphic gravel* the groundmass had less pores and therefore was more dense.

The same coatings and infillings of pores with material interpreted as goethite and hematite, as described for the *metamorphic gravel*, could be seen in the *altered metamorphic gravel* (Plate 16. and 18.).

(Fragments of) clay coatings could be frequently observed in the *altered metamorphic gravel*.

In the *plinthite gravel* the boundary between the iron-poor and iron impregnated areas is diffuse. The iron-poor areas are often situated on the edge of the gravel. In these areas cracks have clay coatings and iron impregnation occurs along the cracks. In the iron-impregnated areas impregnated and not impregnated clay coatings can be observed in cracks.

In an occasional gravel bow-like features are observed. The bows are alternating red (XPL; black, PPL) and grey (XPL; yellowish green, PPL) (Plate 19. and 20.). Yellow (XPL) infillings are observed in cracks perpendicular on the bows.

Amounts and types of ironstone gravel in the thin sections

The amount of gravel was counted per main type and sub-type, in each thin section. See Tables 4.2, 4.3 and 4.4. The thin sections of horizons containing no ironstone gravel were left out of these tables.

Table 4.2 Amount of gravel in the thin sections of the Marie catena, per main type, expressed as percentage of the total gravel in the thin section, and the ratio type 2/type 3.

Prof. nr.	Hor. code	depth (cm)	n[11]	*sediment gravel* (type 1)	*metamorphic gravel* (type 2)	*altered metamorphic gravel* (type 3)	*plinthite gravel* (type 4)	remainder	type 2/ type 3
1	Ah	0- 8	88	7.0	44.9	47.7	0.0	1.1	0.9
	AB	10- 18	103	4.9	45.6	46.6	0.0	2.9	1.0
	AB/Bws1	20- 28	105	5.7	44.7	40.1	0.0	9.5	1.1
	Bws1	34- 42	81	4.9	39.6	51.9	0.0	3.7	0.8
	Bws2	46- 54	86	1.2	43.0	54.7	0.0	1.2	0.8
	Bws2	60- 68	68	1.5	36.8	57.4	0.0	4.5	0.6
	Bws3	76- 84	20	0.0	45.0	55.0	0.0	0.0	0.8
	Bws3	88- 96	36	0.0	38.9	58.3	0.0	2.8	0.7
	Bws3	100-108	11	0.0	63.6	36.4	0.0	0.0	1.8
	Bws3	112-120	10	0.0	60.0	40.0	0.0	0.0	1.5
2	Ah/AB	2- 10	41	0.0	56.1	43.9	0.0	0.0	1.3
	AB	13- 21	57	0.0	61.4	36.8	0.0	1.8	1.7
	Bws1	27- 35	100	0.0	75.0	18.0	0.0	7.0	4.2
	Bws1	38- 46	130	0.8	70.1	26.9	0.0	2.3	2.6
	Bws1	52- 60	151	0.0	80.8	15.3	0.0	4.0	5.3
	Bws21	64- 72	123	0.0	67.5	21.1	0.0	11.4	3.2
	Bws21	82- 90	55	0.0	74.5	12.7	0.0	12.7	5.9
	Bws22	96-104	73	0.0	78.0	13.7	0.0	8.2	6.0
	Bws3	116-124	10	0.0	70.0	30.0	0.0	0.0	2.3
3	Ah	3- 11	85	0.0	77.6	20.0	0.0	2.4	3.9
	Bws1	15- 21	60	0.0	80.0	16.7	0.0	3.3	4.8
	Bws2	42- 47	62	0.0	74.2	22.6	0.0	3.2	3.3
	Bws2	50- 55	104	0.0	36.5	7.7	53.8	1.0	4.7
	Bws2	55- 62	73	0.0	26.0	9.6	64.4	0.0	2.7
	Bws2	67- 70	35	0.0	14.3	0.0	85.7	0.0	∞
4	Bws2	108-116	90	0.0	37.7	57.8	0.0	4.4	0.7
	Bws3	126-134	32	3.1	31.3	62.5	0.0	3.1	0.5

When one considers the figures given in Table 4.2 (taking into account that the percentages given of thin sections with relatively low amounts of gravel have to be viewed with a certain caution), one can see that:

- in most cases >90 % of the gravel can be allotted to one of the four main types (see table);
- in Marie 1 the gravel layer contains *sediment gravel* (type 1) until a depth of 70 cm (the amount of *sediment gravel* decreases with depth), below 70 cm *sediment gravel* does not occur any more;
- in Marie 2 *sediment gravel* only occurs in one thin section (0.8 %), in Marie 3 *sediment gravel* does not occur, in Marie 4 *sediment gravel* (type 1) only occurs in one thin section (3.1 %);
- in Marie 3 change can be observed below a depth of 50 cm: *metamorphic gravel* suddenly halves as well as *altered metamorphic gravel* and *plinthite gravel* (type 4) suddenly appears and the amount increases with depth;

[11] Number of gravel in thin section.

- in Marie 1 the ratio type 2:type 3 is about 1, in Marie 2 and 3 this ratio shifts in favour of *metamorphic gravel* (type 2), in Marie 4 it shifts in favour of *altered metamorphic gravel*;

In Tables 4.3 and 4.4 the amounts of gravel are given per sub-type, expressed as percentage of the total amount of gravel within the appropriate main type.

Table 4.3 The amounts of gravel in the thin sections of the Marie catena, per sub-type of the *metamorphic gravel*, expressed as percentage of the total amount of *metamorphic gravel* (type 2).

Prof. nr.	Hor. code	depth (cm)	n[12]	*yellow-rimmed metam. gravel* (sub-type 2a)	*layered-rimmed metam. gravel* (sub-type 2b)	*not-rimmed metam. gravel* (sub-type 2c)
1	Ah	0- 8	39	35.9	20.5	43.6
	AB	10- 18	47	40.4	25.5	34.0
	AB/Bws1	20- 28	47	34.0	12.8	53.2
	Bws1	34- 42	32	50.0	3.1	50.0
	Bws2	46- 54	37	40.5	2.7	56.8
	Bws2	60- 68	25	20.0	4.0	76.0
	Bws3	76- 84	9	22.2	0.0	77.8
	Bws3	88- 96	14	28.6	0.0	71.4
	Bws3	100-108	7	0.0	0.0	100.0
	Bws3	112-120	5	0.0	0.0	100.0
2	Ah/AB	2- 10	23	8.7	0.0	91.3
	AB	13- 21	35	17.1	5.7	77.1
	Bws1	27- 35	75	36.0	0.0	64.0
	Bws1	38- 46	81	33.3	1.2	77.8
	Bws1	52- 60	122	17.2	0.8	82.0
	Bws21	64- 72	83	45.8	2.4	51.8
	Bws21	82- 90	41	25.0	0.0	68.2
	Bws22	96-104	57	40.4	56.1	3.5
	Bws3	116-124	7	14.3	0.0	85.7
3	Ah	3- 11	66	60.6	0.0	39.4
	Bws1	15- 21	48	54.2	0.0	45.8
	Bws2	42- 47	46	26.1	2.2	71.7
	Bws2	50- 55	38	34.2	0.0	65.8
	Bws2	55- 62	19	36.8	0.0	63.2
	Bws2	67- 70	5	20.0	0.0	80.0
4	Bws2	108-116	34	88.2	11.8	0.0
	Bws3	126-134	10	60.0	10.0	30.0

When one considers the figures in Table 4.3, (taking into account that the percentages given of thin sections with relatively low amounts of gravel have to be viewed with a certain caution), one can see that:
- only small quantities of *layered-rimmed metamorphic gravel* compared to the *yellow-rimmed metamorphic gravel* and *not-rimmed metamorphic gravel* are present in Marie 1, 2, 3 and 4 (with one exception: Marie 2, Bws22, 96-104 cm);
- in Marie 1, 2 and 3 the percentage of *not-rimmed metamorphic*

[12] Number of type 2 gravel in thin section.

gravel seems to exceed the percentage of *yellow-rimmed metamorphic gravel*, except for the upper part of Marie 3, in Marie 4 the percentage *yellow-rimmed metamorphic gravel* and *layered-rimmed metamorphic gravel* exceed that of the *not-rimmed metamorphic gravel*;

- in Marie 1 at 55 cm there is a sudden change in amount of *yellow-rimmed metamorphic gravel*: from ± 40 % to ± 23 %;
- in Marie 2 there is no clear trend with depth of any of the sub-types of the *metamorphic gravel*;
- in Marie 3 there is a sudden change in amounts of *yellow-rimmed metamorphic gravel* and *not-rimmed metamorphic gravel*: between 20 and 40 cm the amount of *yellow-rimmed metamorphic gravel* halves from 50-60 % to 30 %, and the amount of *not-rimmed metamorphic gravel* increases from ± 40 % to 60-80 %;
- in Marie 4 based on only two thin sections nothing can be said about the trends with depth.

Table 4.4 The amounts of gravel, in the thin sections of the Marie catena, per sub-type of *altered metamorphic gravel*, expressed as percentage of the total amount of *altered metamorphic gravel*.

Prof. nr.	Hor. code	depth (cm)	n[13]	*yellow altered metam. gravel* (sub-type 3a)	*red altered metam. gravel* (sub-type 3b)	*yell./red altered metam. gravel* (sub-type 3c)
1	Ah	0- 8	42	35.7	47.6	16.7
	AB	10- 18	48	37.5	50.0	12.5
	AB/Bws1	20- 28	42	31.0	52.4	16.7
	Bws1	34- 42	42	45.2	28.6	26.2
	Bws2	46- 54	47	42.6	44.7	12.8
	Bws2	60- 68	39	17.9	61.5	20.5
	Bws3	76- 84	11	27.3	36.4	36.4
	Bws3	88- 96	21	33.3	57.1	9.5
	Bws3	100-108	4	0.0	100.0	0.0
	Bws3	112-120	5	20.0	60.0	20.0
2	Ah/AB	2- 10	18	5.6	72.2	22.2
	AB	13- 21	21	9.5	38.1	52.4
	Bws1	27- 35	18	16.7	33.3	50.0
	Bws1	38- 46	35	31.4	54.3	14.3
	Bws1	52- 60	23	4.3	95.6	0.0
	Bws21	64- 72	26	11.5	73.1	15.4
	Bws21	82- 90	7	14.3	85.7	0.0
	Bws22	96-104	10	0.0	80.0	20.0
	Bws3	116-124	3	33.3	66.7	0.0
3	Ah	3- 11	17	29.4	38.8	11.8
	Bws1	15- 21	10	60.0	40.0	0.0
	Bws2	42- 47	14	14.3	57.1	28.6
	Bws2	50- 55	8	37.5	62.5	0.0
	Bws2	55- 62	7	0.0	57.1	42.9
	Bws2	67- 70	0	0.0	0.0	0.0
4	Bws2	108-116	52	28.8	63.5	7.7
	Bws3	126-134	20	20.0	75.0	5.0

[13] Number of type 3 gravel in thin section.

When one considers the figures in Table 4.4 (taking into account that the percentages given of thin sections with relatively low amounts of gravel have to be viewed with a certain caution), one can see that:

- only small quantities of *yellow/red metamorphic gravel* compared to *yellow-altered metamorphic gravel* and sub-*red altered metamorphic gravel* are present in most thin sections of Marie 1;
- sub-*red altered metamorphic gravel* seems to occur slightly more often than *yellow-altered metamorphic gravel* in Marie 1;
- in Marie 2 the percentage sub-*red altered metamorphic gravel* increases with depth, while *yellow-altered metamorphic gravel* and *yellow/red metamorphic gravel* are variable;
- in Marie 3 sub-*red altered metamorphic gravel* seems to occur more often than *yellow-altered metamorphic gravel* and *yellow/red metamorphic gravel*, the percentages *yellow-altered metamorphic gravel* and *yellow/red altered metamorphic gravel* are variable, the percentage sub-*red altered metamorphic gravel* increases with depth;
- in the two thin sections of Marie 4 sub-*red altered metamorphic gravel* occurs more often than *yellow-altered metamorphic gravel* and *yellow/red metamorphic gravel*.

4.3.3.2 The plinthite

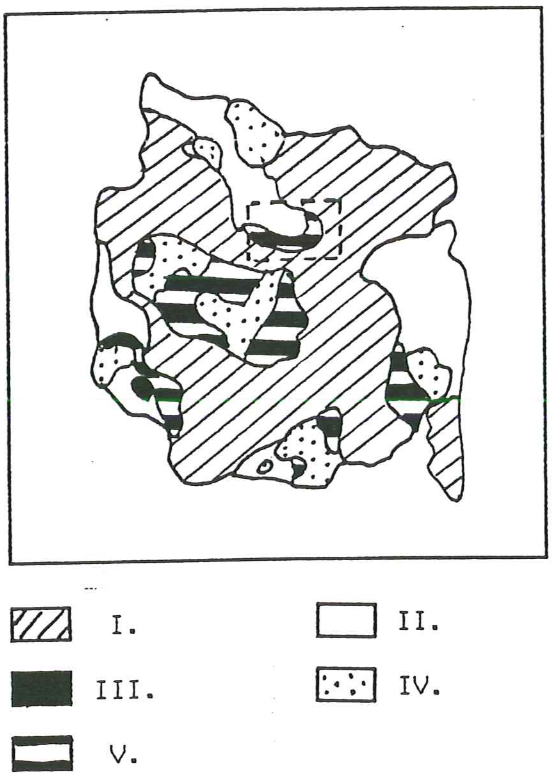


Figure 4.1 Schematic representation of the hardened plinthite in Marie 3 (Bms3, 87-92 cm) in thin section (the square indicates the location where Plate 21. and 22. were taken). See text for description of the types of material indicated.

The thin section of the hardened plinthite sampled in Marie 3 showed a complex composition of five different types of material. A schematic representation of the thin section is given in Figure 4.1. The different types of material are numbered I to V.

The number I material was striking since it formed a "framework" in and around which the other four types of matrix were situated.

A micromorphological description of the five types of material distinguished is given below.

Type I: Fine groundmass with quartz grains and other mineral grains (or pseudomorphs thereof), strongly impregnated with iron. The colour is dark red to black in PPL and red to dark red in XPL. Pores are present. Clay coatings, which are impregnated as well, are often present along the pores.

Type II: An iron-poor fine groundmass with quartz grains, which is yellow in PPL and gray in XPL. In the pores and cracks, clay coatings are present. Hypocoatings along the pores make that part of the clay coatings are iron-impregnated.

Type III: This is a *yellow-rimmed metamorphic gravel* ironstone gravel which is embedded in the plinthite.

Type IV: Fine groundmass with quartz grains, not impregnated with iron. In PPL the colour is yellowish brown, in XPL it is grayish brown. Pores are present. No clay coatings were observed.

Type V: Fine groundmass with quartz grains, slightly impregnated with iron. In PPL the colour is orange, in XPL it is yellowish brown. Clay coatings along the pores are also impregnated.

Remarkable were the diffuse boundaries between types I and II and between types IV and V. The other boundaries are often abrupt.

In Marie 4 below 90 cm iron-hypocoatings around voids started to occur. With increasing depth the amount of hypocoatings increased until whole areas of the soil matrix were impregnated. Below 126 cm some areas are strongly impregnated with iron and are red in XPL (dark red in PPL). Pseudomorphs of minerals did not occur in these strongly impregnated areas, nor in any other part of the groundmass of this profile.
In Marie 5 from 20 cm depth downwards the amount of hypocoatings of iron around voids in creased grading into whole areas of the soil matrix that were iron-impregnated. Below ± 60 cm areas strongly impregnated with iron occurred. Also below 60 cm the amount of pseudomorphs after mica increased. These pseudomorphs were especially present in the iron-impregnated areas. The size of the pseudomorphs regularly exceeded 1500 µm.

4.3.3.3 Features related to other aspects of soil formation

The thin sections were studied for the occurrence of phenomena that could presumably give information about the soil forming processes in the Marie catena, such as charcoal, worm channels, droppings, casts and clay coatings. The observations are described in the following section. (See Figure 2.5 for a schematic representation of the profiles of the Marie catena.)

In Marie 1 charcoal was observed in the upper 30 cm of the profile. Very few worm channels were found (only around a depth of 50 cm), no droppings or casts were seen. The occurrence of clay coatings in voids and around mineral grains, and of fragmented clay coatings was occasional in the gravel-containing part of the profile, and increased with depth below the gravelly part of the profile.

In the gravel-containing part of the profile the coarse grains in the groundmass were all quartz grains. Below the gravel-containing part more grains other than quartz were present.

In Marie 2 charcoal was present in the thin sections of the upper 60 cm of the profile. A few worm channels as well as some droppings of soil fauna (40 - 110 µm, spherical and elliptical) were observed in the surface soil (0 - 20 cm) which is non-gravelly. Occasional clay coatings in voids and around mineral grains and fragmented clay coatings started to occur below ± 40 cm.

The mineral grains of the groundmass consisted of quartz throughout the whole profile.

In Marie 3 too, charcoal was present in the thin sections of the upper 50 cm of the profile. No worm channels or casts were observed in the profile, except for the alternating red (XPL) and grey (XPL) bow-like features in the *plinthite gravel* (type 4) as discussed in section 4.3.3.1 (p.23).

Clay coatings in voids and around mineral grains were absent above 55 cm, but below 55 cm they rare to occasional.

In Marie 4 charcoal was observed throughout the whole profile. Traces of faunal activity were present in the form of coalescent spheres consisting of organic matter in a cavity at 11-15 cm depth. Infillings of channels with soil material that was more brown (PPL) than the surrounding soil matrix were present to a depth of 90 cm.

Clay coatings of voids were few throughout the profile except for the areas that where iron-impregnated. In these iron-impregnated areas many clay coatings were present. The clay coatings were either impregnated with iron or not impregnated.

In the thin sections of Marie 5 charcoal was observed in the upper 65 cm of the profile. Many organ and tissue residues were present in the surface soil. The amount rapidly decreased with depth. In the upper 10 cm rare organo-mineral excrements (200-300 µm, spherical and cylindrical) were present. Infillings with material more rich in organic matter were observed till a depth of 60 cm.

Rare clay coatings were seen at 12-20 cm depth.

Of Marie 6 only two thin sections were taken from 0-5 and 18-23 cm depth. Charcoal was present in both thin sections. In the upper thin section many organ and tissue residues were present as well as occasional hypocoatings of iron around pores. Only rare spherical organic excrements (30-50 µm) were seen inside organ residues.

In the lower thin section few organ and tissue residues were present. Occasional hypocoatings of iron were present around pores. No droppings.

4.4 Theo catena

4.4.1 Introduction

In the Theo catena four types of gravel were distinguished in the field:

a. hard ironstone gravel which was purple at cross-section, could not be broken between fingers;
b. soft ironstone gravel which was purple at cross-section, tough to break between fingers;
c. soft ironstone gravel which was uniform reddishbrown at cross-section, easy to break between fingers;
d. soft ironstone gravel which was reddish-brown/light yellow mottled at cross-section, easy to break between fingers.

These for types were sampled and analyzed, the results are given in the following sections.

4.4.2 Mineralogy

There was little variation in the minerals found in the gravel samples of the Theo catena by X-ray powder diffraction. Quartz, kaolinite and goethite occurred in all samples.

Hematite was definitely present in the hard purple-, soft purple-, soft uniform reddish-brown- and the reddish-brown part of the reddish-brown/light yellow mottled ironstone gravel. In the yellow part of the soft reddish-brown/light yellow mottled ironstone gravel it was not clear whether hematite was present or not[14]. See Table 4.5.

Table 4.5 Results of X-ray powder diffraction of the hard and soft ironstone gravel samples of the Theo catena[15].

Type of gravel	quartz	kaolinite	goethite	hematite
a. hard purple	+	+	+	+
b. soft purple	+	+	+	+
c. uniform reddish-brown	+	+	+	+
d. red. brown/l. yellow mottled:				
reddish-brown part	+	+	+	+
l. yellow part	+	+	+	?

The diffraction patterns of the uniform reddish-brown ironstone gravel and the reddish-brown part of the reddish-brown/-light yellow mottled ironstone gravel were very similar: the same minerals were present and they had the same peak intensities. The micromorphological observations also indicated a resemblance between uniform reddish brown and l.yell./-unif.reddish brown mottled ironstone gravel except for the size of the iron-poor areas. Therefore, from now on the red-

[14] Possible peaks characteristic for hematite were very low and might have been irregularities in the baseline of the diffractogram.

[15] + present
- not present
? could be present

dish part of the reddishbrown/light yellow ironstone gravel will be assumed similar to the uniform reddish-brown ironstone gravel.

4.4.3 Total analyses

The results of the total analysis by XRFS of the hard and soft (all three forms) ironstone gravel of the Theo catena are presented in Table 4.6

The amounts of SiO_2 and Al_2O_3 increased from hard purple to reddish-brown/light yellow soft ironstone gravel. The percentage TiO_2 is low, around 1 % in all types of gravel.

The percentage Fe_2O_3 decreases from hard purple- to soft mottled ironstone gravel. Remarkable is the low percentage (8.55 %) in the light yellow part of the mottled ironstone gravel.

In the gravel the amounts of MgO, CaO, Na_2O, K_2O and BaO were below the detection limit, except for the amount of K_2O in the light yellow part of the mottled gravel where it was 0.08 %.

The percentage of MnO in all gravel was below 0.1. In the soft purple gravel it was 2.5 times higher, while in the uniform reddish-brown and light yellow part it was 3.2 respectively 5.3 times lower. The loss on ignition is around 10 % in all gravel.

Table 4.6 Total amounts, in weight percentages, of major elements in the hard and soft ironstone gravel of the Theo catena, obtained by X-ray fluorescence spectrometry.

Type of gravel	SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO[16] %	CaO[17] %
a. hard purple	23.76	1.00	16.97	46.66	0.08	<0.03	<0.01
b. soft purple	32.04	1.16	17.61	38.92	0.04	<0.03	<0.01
c. uniform red. brown	40.86	0.96	24.67	22.54	0.02	<0.03	<0.01
d. light yell. part of mottled gravel	51.94	0.90	27.26	8.55	0.01	<0.03	<0.01

Type of gravel	Na_2O %	K_2O[18] %	P_2O_5 %	BaO[19] %	M.L.I.[20] %	sum %
a. hard purple	<0.04	<0.003	0.16	<0.03	10.35	98.55
b. soft purple	<0.04	<0.003	0.40	<0.03	11.03	100.74
c. uniform red. brown	<0.04	<0.003	0.05	<0.03	10.83	99.49
d. light yell. part of mottled gravel	<0.04	0.08	0.03	<0.03	11.27	99.59

16 Values <0.03 % are below detection limit.

17 Values <0.01 % are below detection limit.

18 Values <0.003 % are below detection limit.

19 Values <0.03 % are below detection limit.

20 M.L.I. - Mass Loss on Ignition: the sample is heated at 900 °C for at least four hours.

Knowing that the only minerals present in the gravel are kaolinite, quartz, goethite and hematite, one can calculate the weight percentages of these minerals present with the figures given in Table 4.6. One has to make the following assumptions:

- all Al_2O_3 is present in kaolinite - no substitution of Al^{3+} for Fe^{3+} in goethite or hematite is present;
- all water (M.L.I.) is present in kaolinite and goethite;
- no substitution of Fe^{3+} for Al^{3+} in kaolinite is present.

The percentages Al_2O_3, Fe_2O_3, SiO_2 and H_2O in the different minerals are:

	Al_2O_3	Fe_2O_3	SiO_2	H_2O
kaolinite	39.50 %		46.54 %	13.96 %
quartz			100 %	
goethite		89.86 %		10.14 %
hematite		100 %		

The calculation is done as follows: first all Al_2O_3 is combined with SiO_2 and H_2O to form kaolinite. The SiO_2 left over is ascribed to quartz, the H_2O left over is combined with Fe_2O_3 to form goethite. The Fe_2O_3 left, is ascribed to hematite.

For the hard purple ironstone gravel the amounts of kaolinite, quartz, goethite and hematite calculated are:

kaolinite	42.96 %
quartz	3.77 %
goethite	42.92 %
hematite	8.09 %
sum	97.74 %

For the soft purple ironstone gravel the calculation stops after combining the Al_2O_3 with SiO_2 and H_2O to form kaolinite, since there is not enough Fe_2O_3 to form goethite with all the water left. The same is true for the yellow part of the mottled ironstone gravel.

The results of the calculations for the uniform reddish brown ironstone gravel are:

kaolinite	62.46 %
quartz	11.79 %
goethite	20.82 %
hematite	3.83 %
sum	98.90 %

4.4.4 Iron- and aluminium analyses

In the hard and soft ironstone gravel the amounts of oxalate- and pyrophosphate-extractable iron and aluminium were very low (0.0 - 0.2 %), much lower than the dithionite-extractable iron and aluminium. This was especially true for iron, were the amount of dithionite-extractable iron lies between 4.4 and 12.0 %. See Table 4.7.

Table 4.7 Percentages dithionite-, oxalate- and pyrophosphate-extractable iron and aluminium in the hard and soft ironstone gravel of the Theo catena.

%	a. hard purple	b. soft purple	c. unif.reddish-brown	d. l. yellow part of mottled gravel
Fe-dithion.	7.3	12.0	10.3	4.4
Fe-oxalate	0.2	0.2	0.0	0.2
Fe-pyroph.	0.0	0.0	0.0	0.0
Al-dithion.	0.4	0.4	0.7	0.4
Al-oxalate	0.1	0.1	0.1	0.2
Al-pyroph.	0.0	0.0	0.0	0.0

4.4.5 Thermogravimetric analyses

The results of the X-ray powder diffraction of the gravel sampled in the Theo catena showed that the only minerals present which contained water in their crystal structure were goethite and kaolinite. Therefor these were the only minerals which were able to lose water during heating, and thus the only minerals of which the amount present could be determined by thermogravimetric analysis. The diagrams produced by thermogravimetric analysis are presented in Appendix G.

According to Blazek (1972) goethite loses its water between 300-400 °C and kaolinite around 600 °C. In the diagrams made, weight loss occurred from 230 to 325 °C and from 325 to 600 °C. Assumed is that the first weight loss corresponds with goethite and the second with kaolinite. Calculations of weight percentages goethite and kaolinite can be found in Appendix H, the results are given in Table 4.8.

Table 4.8 Weight percentages of goethite and kaolinite in the hard and soft ironstone gravel of the Theo catena obtained by thermogravimetric analysis.

Type of gravel	goethite (%)	kaolinite (%)
a. hard purple	31.3	25.5
b. soft purple	17.2	34.7
c. uniform red. brown	19.8	60.2
d. l. yellow part of mottled gravel	19.4	52.4

4.4.6 Micromorphology

Of the four types of ironstone gravel (a, b, c and d) one thin section was made of a few gravel of each type. A micromorphological description of the four types of gravel is given below.

Type a: Gravel with a groundmass of fine material, impregnated with iron, in which there are pseudomorphs present (consisting of kaolinite according to the results of X-ray diffraction, see section 4.4.2, p.30). The amount of quartz grains varies; some gravel have little or no quartz grains, others have many quartz grains. The colour is determined by the degree of the impregnation with iron. In PPL the colour is dark red to black, in XPL it is red to dark red. See Plate 23. and 24.

Type b: Gravel with a groundmass of fine material, impregnated with iron, in which there are areas with only quartz grains and areas with only pseudomorphs within one gravel.The colour is determined by the degree of the impregnation with iron. In PPL the colour is dark red to black, in XPL it is red to dark red. In an occasional gravel yellowish orange (XPL) clay coatings were observed around quartz grains. See Plate 25.

Type c: Gravel with a groundmass of fine material, containing randomly dispersed quartz grains and other mineral grains. Small iron-poor areas (yellowish green, PPL; gray, XPL) can be observed next to areas strongly impregnated with iron. See Plate 26. and 27.

Type d: Gravel with a groundmass of fine material, containing randomly dispersed quartz grains and other mineral grains. The groundmass is yellowish green in PPL and gray in XPL), while around the pores and cracks impregnation with iron (red, XPL) occurs. See Plate 28. and 29.

<u>Micromorphological features in the different kinds of ironstone gravel</u>

In type a (hard purple) ironstone gravel, pores with irregular edges, similar to those mentioned in section 4.3.3.1 (p.22) in the *metamorphic gravel* and *altered metamorphic gravel* of the Marie catena, were observed in all of the hard purple ironstone gravel. Also a yellow band plus a yellow rim was observed in one of the ironstone gravel in the thin section of the hard purple ironstone gravel. This band and rim were also similar to those mentioned in section 4.3.3.1 (p.22) in the *metamorphic gravel* of the Marie catena.

Pores with irregular edges were also seen in the type b (soft purple) ironstone gravel. A yellow rim was observed at one of the soft purple ironstone gravel in the thin section. Clay coatings were seen around quartz grains in one of the soft purple ironstone gravel. These clay coatings were not impregnated with iron. They were yellowish orange (XPL) in the thin section.

In the groundmass of the uniform reddish ironstone gravel (type c) clay coatings were present. These coatings were both impregnated and not impregnated. The boundary between the iron-poor and iron-impregnated areas was diffuse. Within the iron-impregnated areas the degree of impregnation varied.

The groundmass of type d (reddish-brown and light yellowish red mottled) ironstone gravel showed larger iron-poor areas than uniform reddish brown ironstone gravel. The iron impregnation was concentrated around the pores and cracks. Like uniform reddish brown ironstone gravel the groundmass contained impregnated and not impregnated clay coatings.

Plate 1.

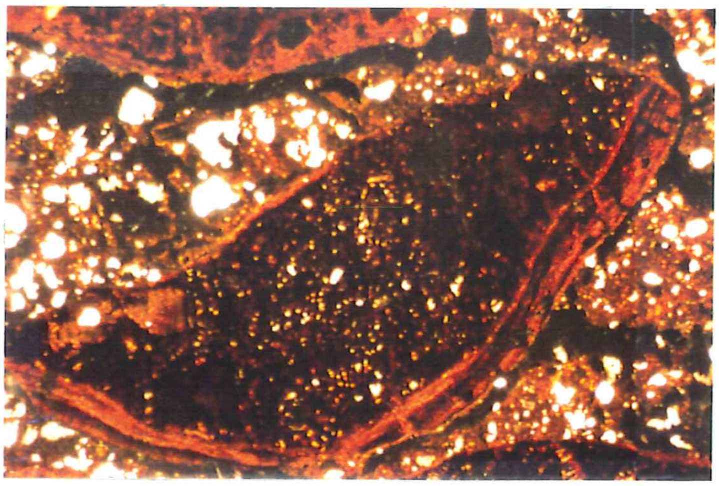


Plate 4.

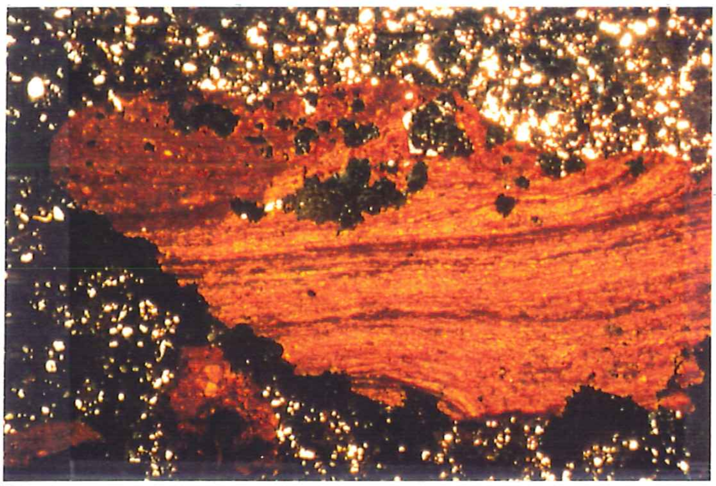
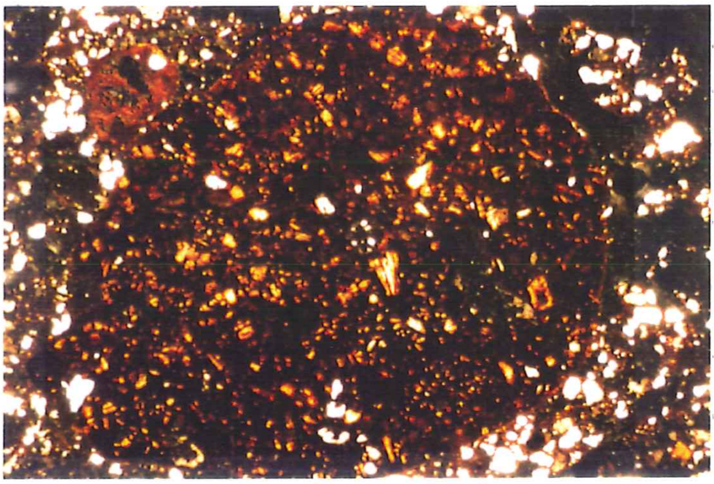


Plate 2.



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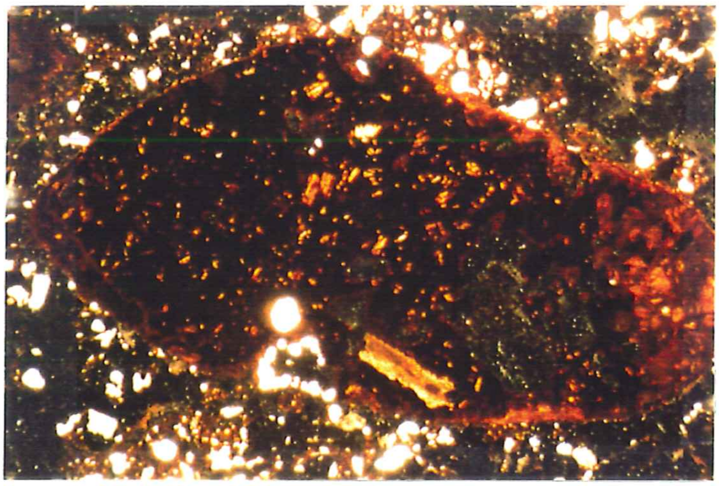

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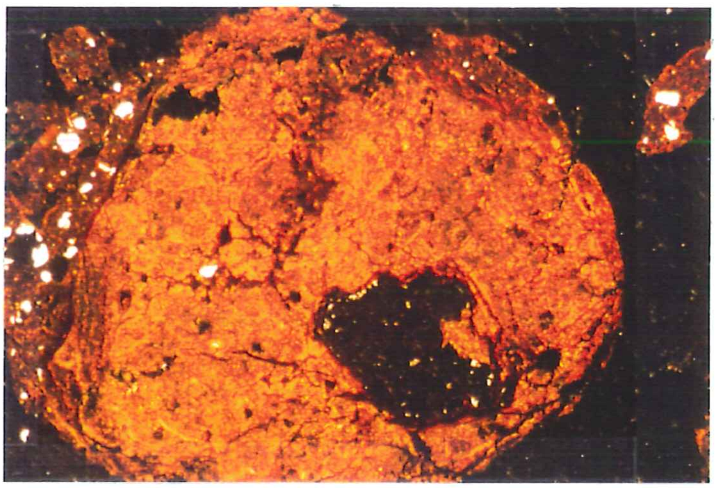


Plate 6.

Plate 1. Migmatite containing quartz, alkali-feldspars, biotite and hornblende (framelength 3.2 mm, XPL).

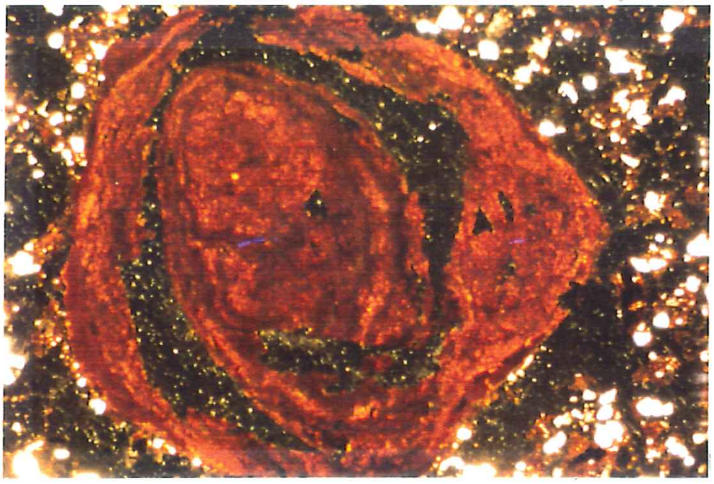
Plate 2. Type 1 ironstone gravel, Marie catena (framelength 8.1 mm, XPL).

Plate 3. Type 2a ironstone gravel containing relatively large grayish white pseudomorphs (50 - 500 μm), Marie catena (framelenght 3.6 mm, XPL).

Plate 4. Type 2b ironstone gravel, Marie catena (framelength 3.6 mm, XPL).

Plate 5. Type 2c ironstone gravel containing relatively small white and yellow pseudomorphs (20 - 150 μm), Marie catena (framelength 4.4 mm, XPL).

Plate 6. Type 3a ironstone gravel showing hematite in cracks, Marie catena (framelength 3.6 mm, XPL).



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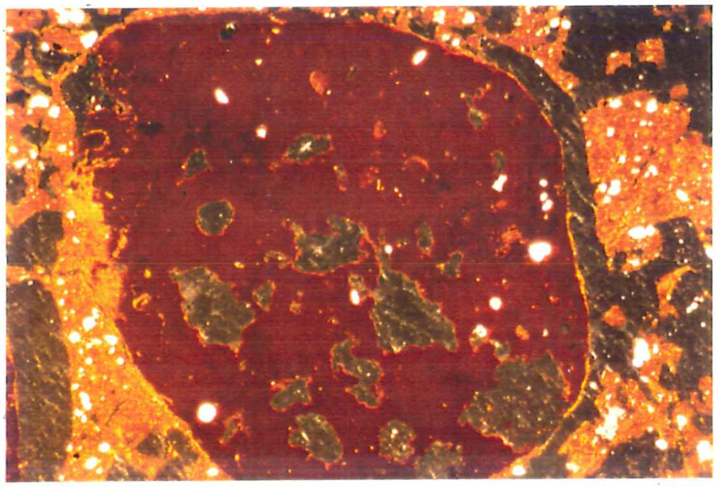

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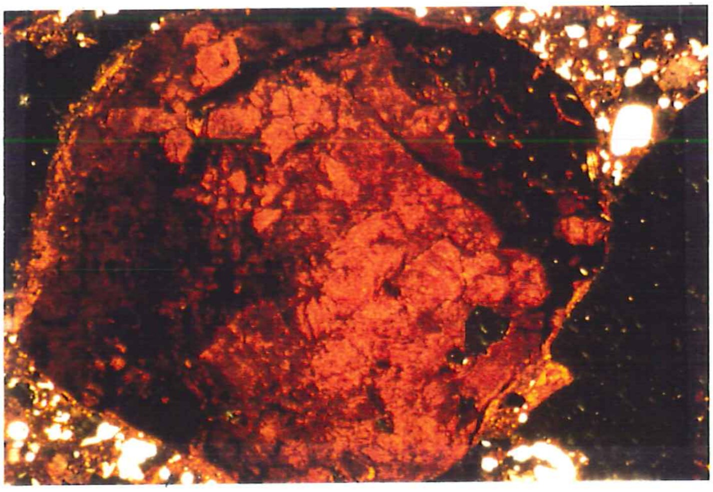

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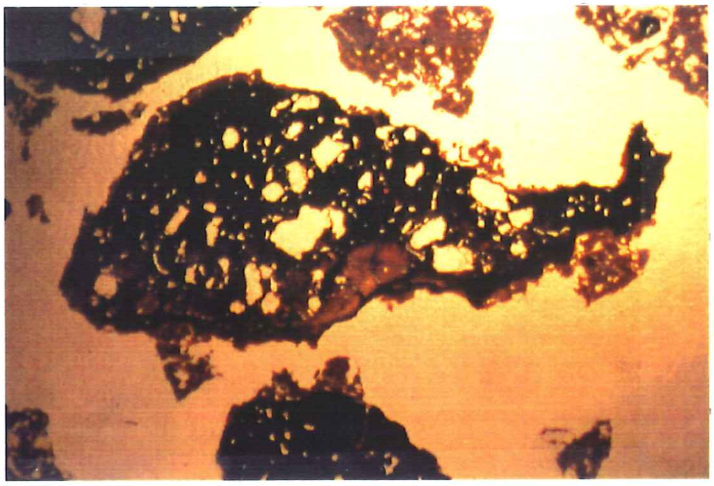

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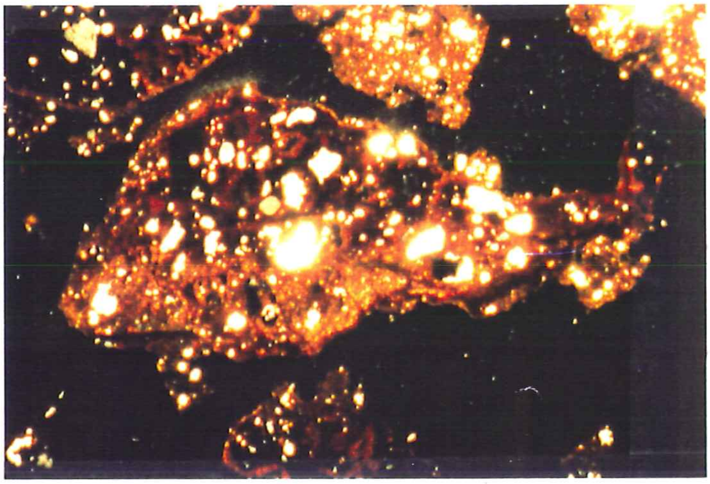

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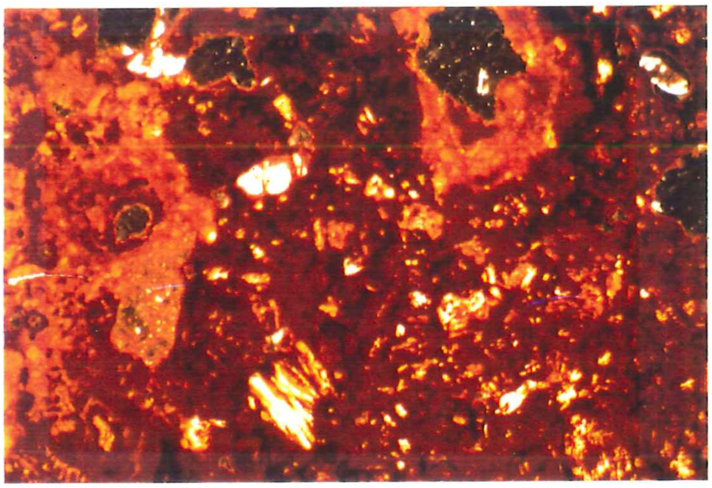


Plate 12.

Plate 7. Type 3a ironstone gravel with a concentric structure, Marie catena (framelength 3.6 mm, XPL).

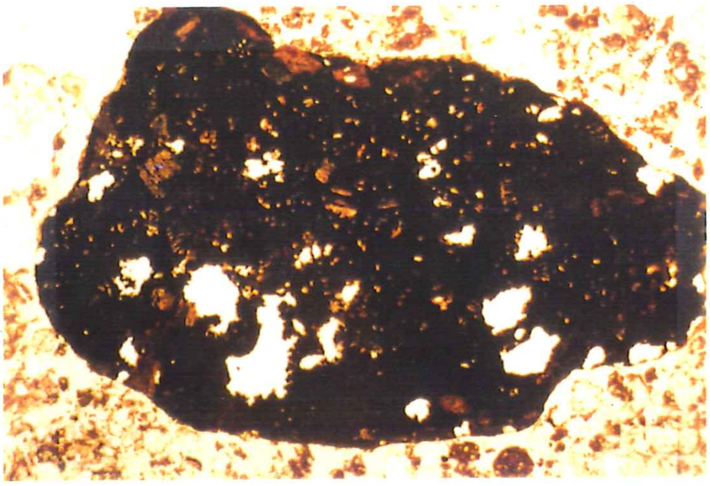
Plate 8. Type 3b ironstone gravel, Marie catena (framelength 3.6 mm, XPL).

Plate 9. Type 3c ironstone gravel, Marie catena (framelength 3.6 mm, XPL).

Plate 10. Type 4 ironstone gravel, Marie catena (framelength 6.9 mm, PPL).

Plate 11. Type 4 ironstone gravel, Marie catena (framelength 6.9 mm, XPL).

Plate 12. Type 2 ironstone gravel showing depletion of iron along a pore (above, right of middle) and re-impregnation with hematite (left, middle), Marie catena (framelength 1.8 mm, XPL).



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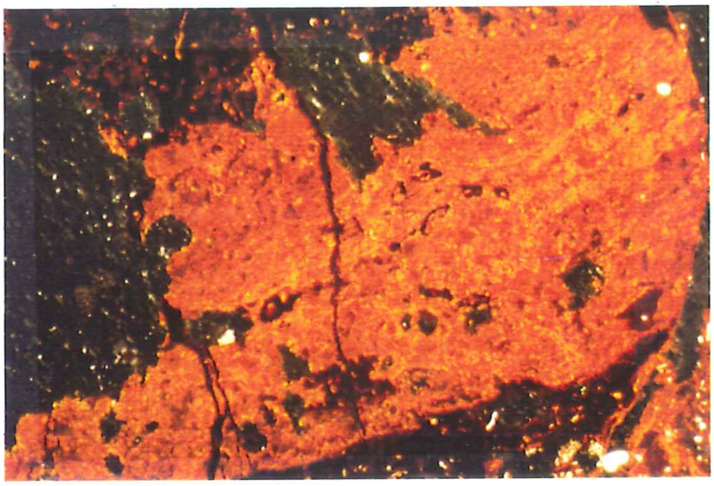

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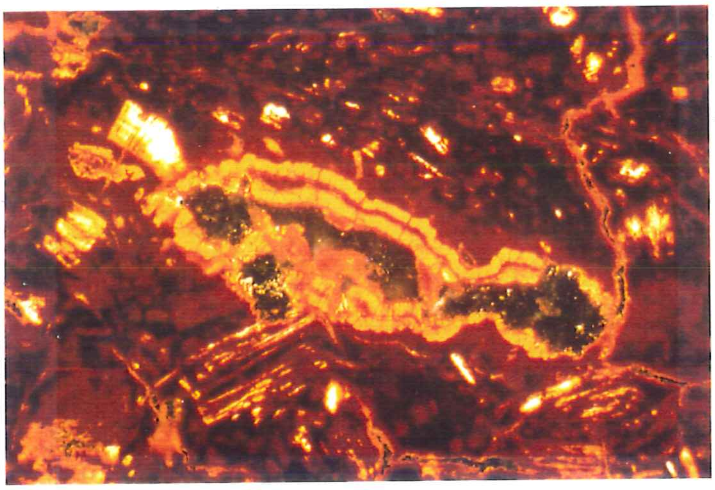

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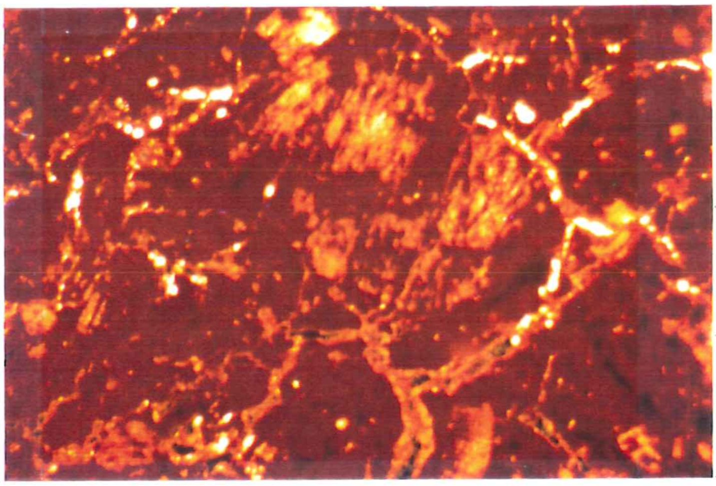

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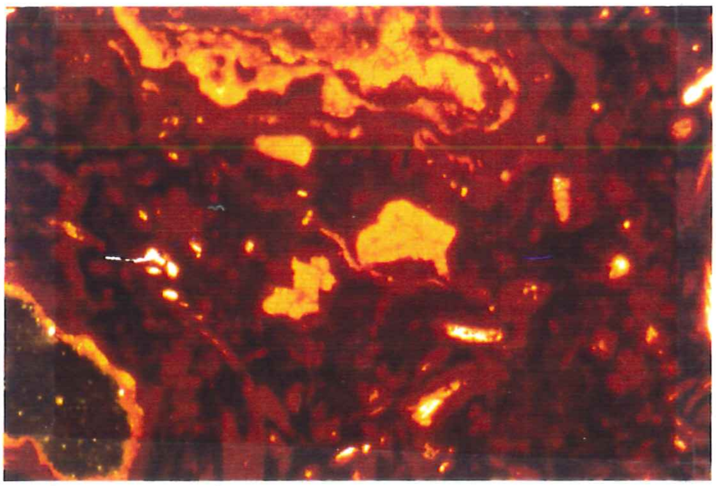

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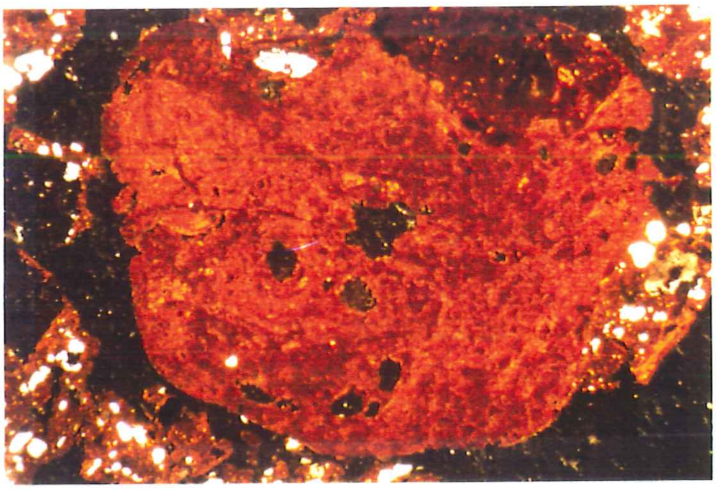


Plate 18.

Plate 13. Type 2 ironstone gravel showing pores with irregular edges (framelength 4.2 mm, PPL).

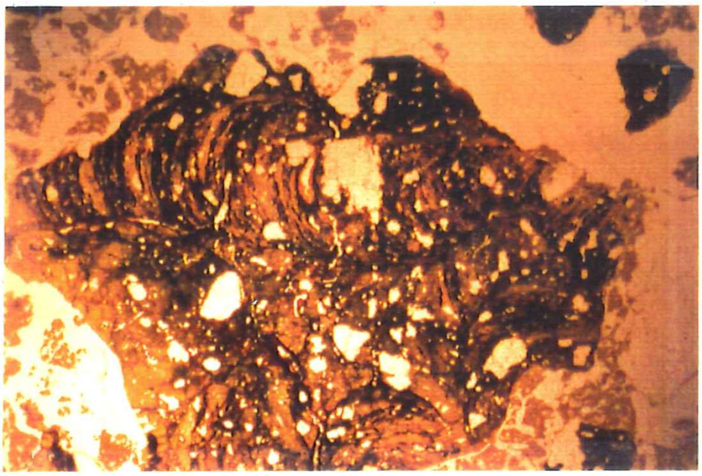
Plate 14. Type 2 ironstone gravel showing a coating of alternating goethite and hematite, Marie catena (framelength 1.0 mm, XPL).

Plate 15. Type 2 ironstone gravel showing infillings of goethite and hematite, Marie catena (framelength 0.65 mm, XPL).

Plate 16. Type 3 ironstone gravel showing hematite in cracks and infillings with hematite and goethite, Marie catena (framelength 1.3 mm, XPL).

Plate 17. Type 2 ironstone gravel showing clay coatings of pores and gibbsite crystals in pores, Marie catena (framelength 1.3 mm, XPL).

Plate 18. Type 3 ironstone gravel showing a little piece of type 2 ironstone gravel, Marie catena (framelength 4.0 mm, XPL).



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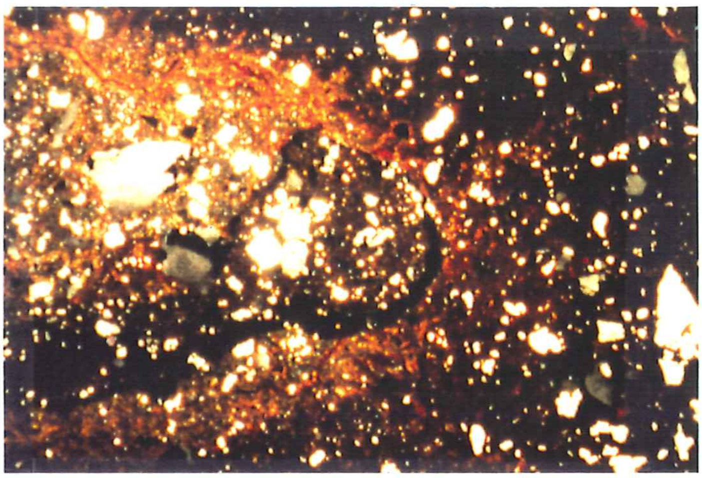

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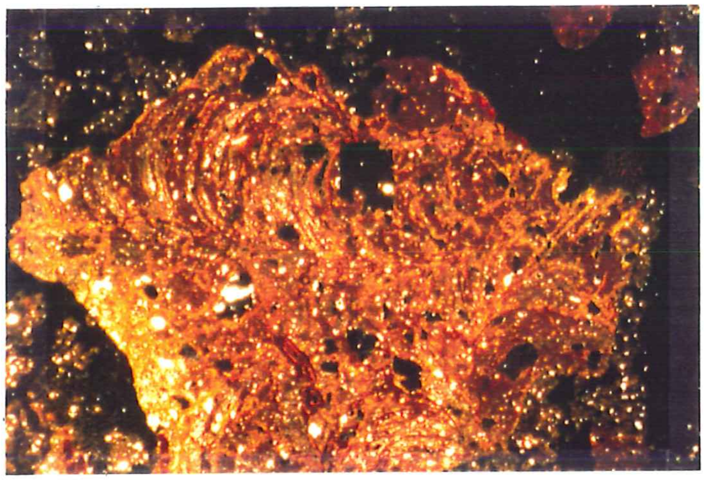

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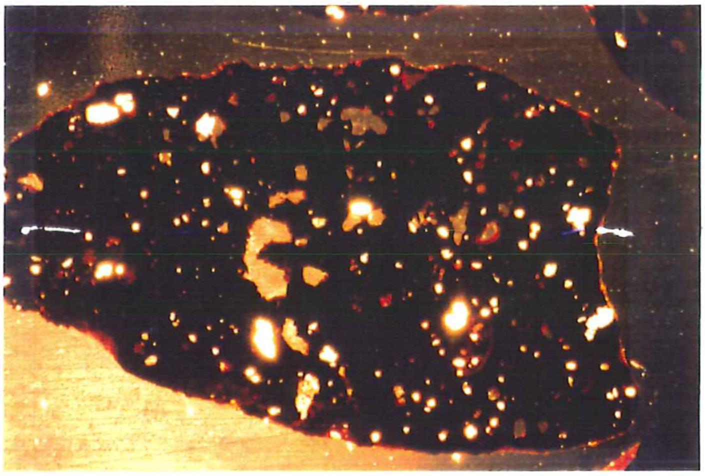

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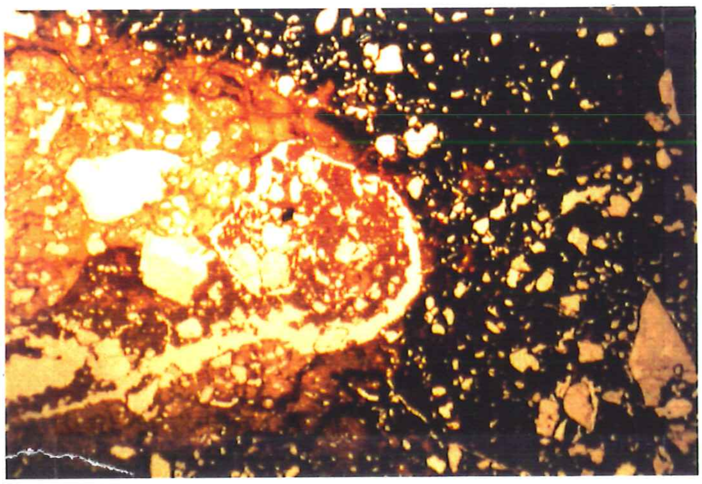

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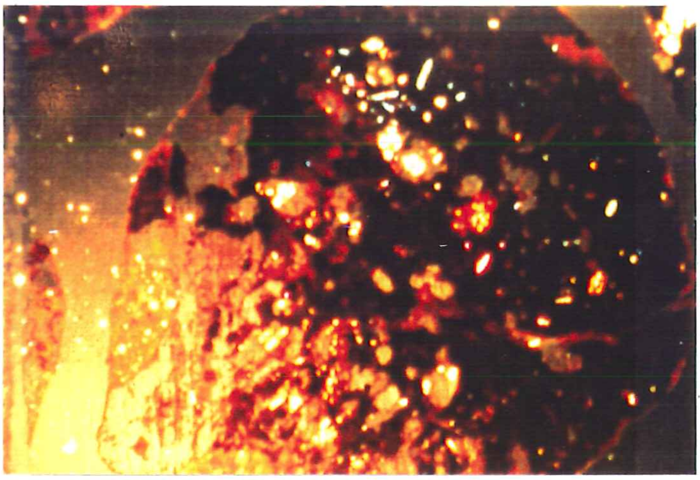


Plate24.

Plate 19. Bow-like feature in a type 4 ironstone gravel, Marie catena (framelength 7.2 mm, PPL).

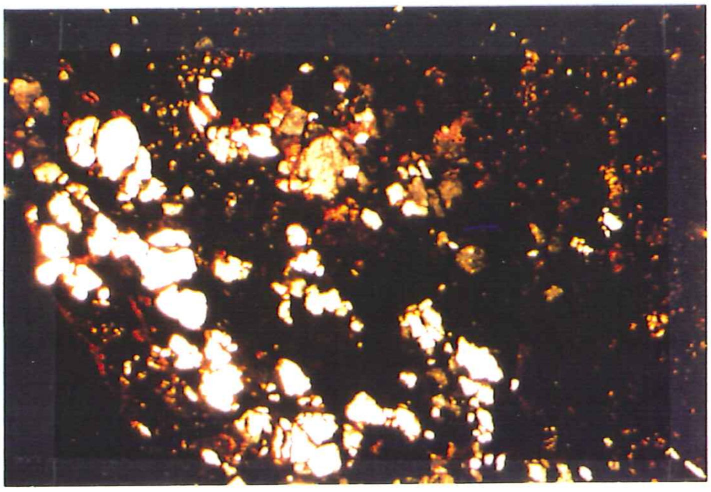
Plate 20. Bow-like feature in a type 4 ironstone gravel, Marie catena (framelength 7.2 mm, XPL).

Plate 21. Section of the hardened plinthite from Marie 3 showing the type I, II and V material (framelength 7.2 mm, XPL).

Plate 22. Section of the hardened plinthite from Marie 3 showing the type I, II and V material (framelength 7.2 mm, PPL).

Plate 23. Hard purple ironstone gravel, Theo catena (framelength 7.2 mm, XPL).

Plate 24. Hard purple ironstone gravel, Theo catena (framelength 7.2 mm, XPL).



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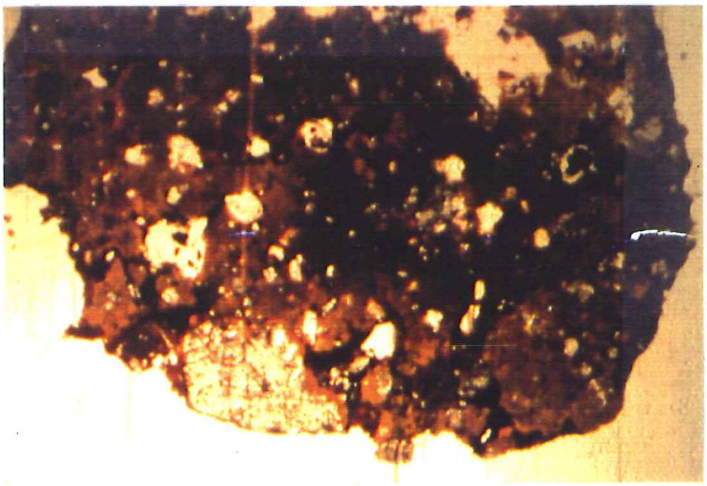

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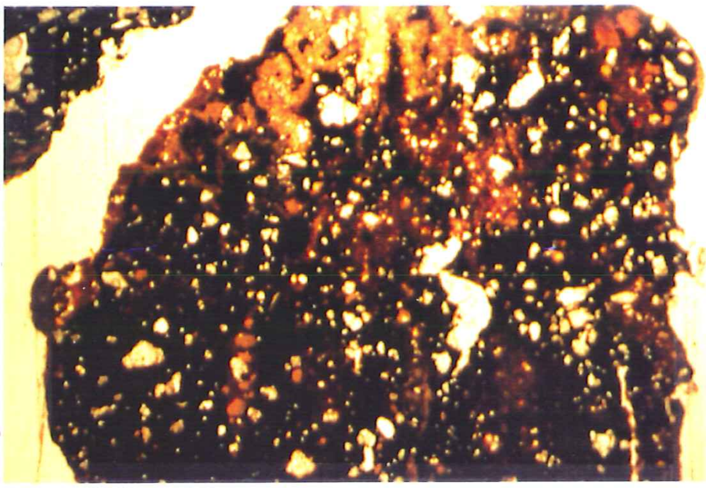

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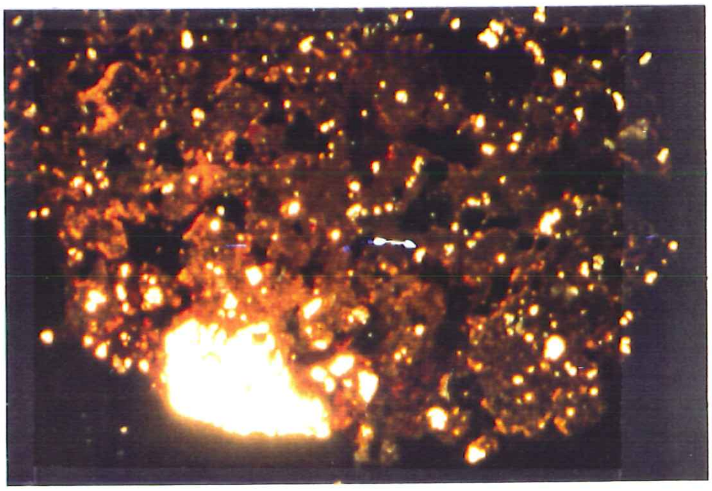

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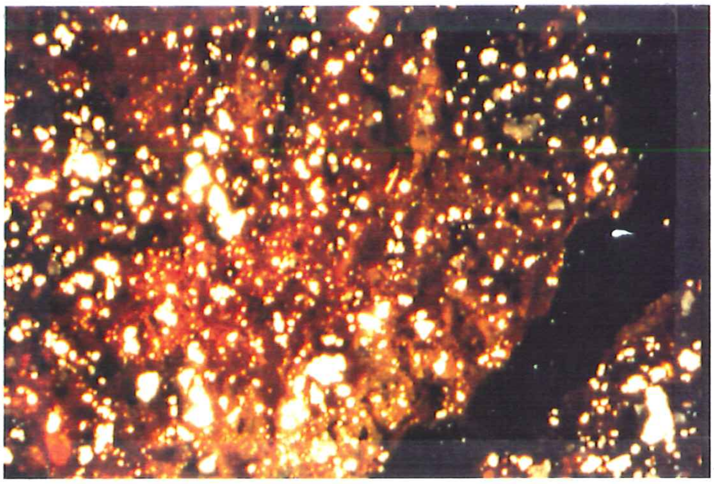


Plate 27.

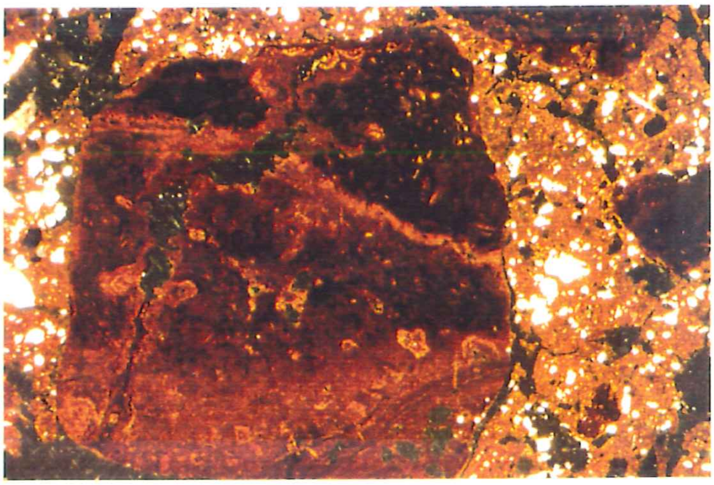


Plate 30.

Plate 25. Soft purple ironstone gravel showing clay coatings (upper middle), Theo catena (framelength 3.6 mm, XPL).

Plate 26. Uniform reddish brown ironstone gravel, Theo catena (framelength 8.1 mm, PPL).

Plate 27. Uniform reddish brown ironstone gravel, Theo catena (framelength 8.1 mm, XPL).

Plate 28. Mottled ironstone gravel showing iron impregnation around the pores, Theo catena (framelength 6.9 mm, XPL).

Plate 29. Mottled ironstone gravel showing iron impregnation around the pores, Theo catena (framelength 6.9 mm, PPL).

Plate 30. Type 2 ironstone gravel gradually changing into a type 3 gravel, showing infillings with goethite and a band which is depleted with iron, Marie catena (framelength 5.4 mm, XPL).

5. DISCUSSION

5.1 Introduction

In this chapter the results as they are presented in chapter 4 will be discussed and put in a broader perspective. The Marie catena and Theo catena will be, in principal, dealt with separately (section 5.2 and 5.3 respectively), but in the discussion of the Theo catena relationships with the Marie catena will be dealt with too.

5.2 The Marie catena

5.2.1 The ironstone gravel

Discussion in connection with the micromorphological observations of the ironstone gravel

From the micromorphological observations the following conclusions were drawn with relation to the origin of the ironstone gravel and the changes that are taking place within the ironstone gravel in its present position.

The *sediment gravel* is composed of alternating layers. This, and the fact that the gravel is ironstone gravel indicates that the *sediment gravel* was formed as follows: a saprolite of a sedimentary rock has been impregnated with iron (plinthization). After exposure, the iron-impregnated saprolite hardened, thus becoming ironstone. The exact formation of the ironstone will not be discussed here, since this is a very complicated matter and many different suggestions have been made about the formation, but the presence of hematite as the principal form of ironoxide in the ironstone is observed by many authors (e.g. Schmidt-Lorenz, 1964; Tardy et al., 1985; Muller et al., 1986; Muller et al., 1990).

When the ironstone broke up, it formed the *sediment gravel*. Since the gravel is rounded it must have been transported, over an considerable distance, before is ended up in the Marie catena studied here.

The only alterations that have taken place in the *sediment gravel* (type 1) in its present position, are the infilling of cracks with a red material which is interpreted as hematite and the formation of pores on the edges of the gravel. This gravel forms only a minor part of the total gravel (see Table 4.1).

The *metamorphic gravel* contains pseudomorphs, indicating that this type was formed from a saprolite. The saprolite was a saprolite of a metamorphic rock with bands of different composition: an occasional gravel showed bands containing different pseudomorphs. The formation and the transportation of the *metamorphic gravel* is similar to that of the *sediment gravel*.

The *altered metamorphic gravel* is similar to the *metamorphic gravel*, except that it has undergone/is undergoing alterations due to weathering. These alterations are various:

1. Along the edges of the gravel and the edges of cracks in the gravel yellow rims (XPL) start to form. These are due to either depletion of iron or to hydration of hematite (Tardy et al., 1985). In these yellow rims the pseudomorphs are still distinct.

2. Existing pores and cracks widen, and their edges made more irregular by processes caused or started by the soil water that enters the pores.
3. Illuvial clay also invades into the gravel and is deposited in pores connected to the groundmass, as clay coatings.
4. Iron, either released from the gravel itself or brought into the ironstone gravel by soil water, is deposited in the pores in the form of goethite or hematite. Aluminium is deposited as gibbsite in the pores.
5. When the alterations, mentioned under 1 to 4 proceed (longer and/or more intensively), the portion yellow in the ironstone gravel becomes larger until the gravel is completely yellow and the pseudomorphs become less distinct. The infillings and coatings of the pores with goethite and hematite are still distinct, like the clay coatings (Plate 30).

The fact that within a single gravel different forms of iron-oxides were deposited close to each other and even on top of each other in various sequences, can be explained by the existence of different micro-environments in the gravel in space and time. Different micro-environments can be caused e.g. by the direction of the exit of the pore: a pore with an inlet to the upper side of the gravel, might be filled with soil water more often than a pore with an inlet to the lower side of the gravel if the gravel does not lie within the influence of the groundwater.

Another explanation of the presence of different forms of ironoxides close to each other is given by Tardy et al. (-1983). They proposed that an aqueous solution at saturation with respect to a given mineral in a pore with a given size, can be oversaturated in a pore with a smaller size and not saturated in a pore with a larger size.

The fact that the pseudomorphs become less distinct in the ironstone gravel that has turned yellow can be explained when one considers that the pseudomorphs consist of kaolinite. This clay can go into suspension and be transported. This makes that the kaolinite of the pseudomorphs does not retain its original orientation. It is this orientation of the kaolinite retaining the original mineral structure that makes the identification as pseudomorphs possible. When the clay loses its orientation, the visibility disappears. It is not longer possible to identify the pseudomorphs. The loss of orientation only occurs in the ironstone gravel that has turned yellow, apparently the state in which the gravel is red coloured is a kind of preservative state.

The not-rimmed metamorphic gravel is the ironstone gravel which has undergone no other alteration than the formation of pores with an irregular edge. Then the edges and cracks are started to be affected by loss or recrystallization of iron and yellow-rimmed *metamorphic gravel* is formed. (The *layered-rimmed metamorphic gravel* can not by placed in this order and will be discussed below.) In *yellow-altered metamorphic gravel*, *red altered metamorphic gravel* and *yellow/red metamorphic gravel* the alterations have progressed so far that the pseudomorphs have disappeared for the greater part. In *red altered metamorphic gravel* in some cases re-impregnation with iron has taken place which gives the gravel the red colour, in other cases the iron was never completely removed.

Based on the above described relationships between *metamorphic gravel* and *altered metamorphic gravel*, one would expect an increase with depth of the least weathered gravel and a decrease of the very weathered gravel, due to a more intense weathering close to the surface compared to deeper in the profile caused by a higher and more fluctuating soil temperature. The few trends with depth observed confirm this: an increase of the, least weathered, *not-rimmed metamorphic gravel*, with depth in Marie 1 and 3, and a decrease of the *yellow-rimmed metamorphic gravel* in Marie 1 and 3.

The different stages of progressive alteration within one profile can be attributed to the fact that the ironstone gravel, when it arrived at its present position, did not all have the same degree of iron impregnation. Gravel that had a lesser degree of impregnation is now in a further stage of alteration.

Layered-rimmed metamorphic gravel, the type of ironstone gravel with a red to dark red colour (XPL), pseudomorphs of minerals and a layered edge, has not been discussed in this section yet.

The *layered-rimmed metamorphic gravel* undergoes the same alterations as discussed above (development of yellow rims around the pores, widening of pores, infillings of pores, etc.). In that respect the *layered-rimmed metamorphic gravel* is not different from *not-rimmed metamorphic gravel*. The difference is in the presence of a yellow layered edge.

Nahon (1976) studied lateritic crusts and calcareous crusts in Senegal and Mauritania. In the upper parts of the profiles, and downslope he observed the common occurrence of layered ochre rings around ironstone gravel. The ochre rings consisted of goethite that were apparently formed at the expense of the core of the gravel, that consisted of hematite. All stages between gravel with a thin ring of layers of goethite and a large hematite core, via a thick ring of goethite and a small hematite core, to a concentric gravel that consists of goethite only, were observed by Nahon. An explanation for this conversion of the core of hematite to a layered ring of goethite is not provided by Nahon.

The ironstone gravel classified as *layered-rimmed metamorphic gravel* in this study does not have complete rings of yellow layers, it is often only partly surrounded by such layers. The stages of the conversion of hematite to goethite as described by Nahon were observed in this study too. The end stage of the concentric gravel was classified as *yellow altered metamorphic gravel*.

Layered-rimmed metamorphic gravel occurs in Marie 1, 2 and 4. In Marie 3 this sub-type is absent. In Marie 1 the amount of *layered-rimmed metamorphic gravel* decreases with depth, similar to what Nahon observed, but in Marie 2 the amount varies with depth. The trend Nahon indicated, that downslope the occurrence of the rings of goethite was more common, can not be confirmed nor contradicted by the observations done in this study, because ironstone gravel is absent in Marie 5 and 6. Still in Marie 4 the percentage *layered-rimmed metamorphic gravel* is 10-11 % against percentages below 6 % in Marie 2 (except for one horizon which has 56.1%).

The question how the layered edge is formed, and why it is not formed around all gravel, remains unanswered.

Nahon's observation that the amount of gravel with a layered edge was common in the upper parts of the profiles and downslope seems to confirm the above mentioned suggestion that the weathering of the ironstone gravel is more intense closer to the surface.

The *plinthite gravel*, with its iron-poor and iron-impregnated areas, is likely to originate from the hardened plinthite lying directly under the gravel. When one compares the description of the *plinthite gravel* (section 4.3.3.1, p.21), type 4) with the description of type I and II material of the plinthite (section 4.3.3.2, p.28) they are remarkably similar. Probably the *plinthite gravel* are pieces of the hardened plinthite broken off due to weathering.

The idea that *plinthite gravel* (type 4) is plinthite that never coalesced to form a plinthite-horizon can be rejected by the fact the gravel has a abrupt boundary. It would not have a abrupt, but a gradual boundary with the groundmass when it had been formed "in situ".

The *plinthite gravel* is not very hard. This is demonstrated by the bow-like features that can be observed in an occasional gravel. These imply faunal activity after the formation of *plinthite gravel*, because the bows were alternating red and gray (XPL) thus indicating that the material that passed the stomach of the animal already had the red and gray colours.

5.2.2 The plinthite

When we want to discuss the plinthite in the Marie catena we have to separate the hardened plinthite in Marie 2 and 3 (described in section 4.3.3.2, p.27) from the hardened plinthite in Marie 4 and the soft plinthite in Marie 5 (also described in section 4.3.3.2, p.28). Already in section 2.1.6, Figure 2.4 (p.9) we could see that these two occurrences of hardened plinthite were not connected.

In the thin section of the hardened-plinthite-containing horizon of Marie 3 (Bms3, 87-92 cm) five types of material were distinguished. Type I material forms a "framework" and together with the type II and V material it forms the real plinthite. Type I is the material to which the iron of the type II material was transported due to oxidizing and reducing conditions. The type V material that got only partly impregnated with iron.

In the type II and V material only quartz grains were present as coarse grains while in the type I material also (pseudomorphs of) other minerals besides quartz were present. This difference is ascribed to the preservative power of the iron impregnation: in the type II and V material (pseudomorphs of) minerals are thought to have been present too like in the type I material, but due to weathering these (pseudomorphs of) minerals disappeared.

The type III material is an ironstone gravel of the *yellow-rimmed metamorphic gravel*.

The type IV material is similar to the groundmass of the horizons higher in the profile. It probably got into the hardened plinthite horizon due to faunal activity. The soil fauna had access to the plinthite because the type II and V material was softer than the type I material since these materials were iron-poor and slightly iron-impregnated. Proof of this is provided by the occasional *plinthite gravel* which contained bow-like features resembling the passage of an earthworm.

Only one single ironstone gravel was observed in the plinthite, thus suggesting that the part of the profile in which the plinthite is situated is different from the overlying gravel-containing part. The single *yellow-rimmed metamorphic gravel* probably came into the plinthite with the type IV material due to faunal activity.

In Marie 2 and 3 no mottles were observed that could indicate actual movement and deposition of iron. This, and the fact that (pseudomorphs of) other minerals besides quartz are present in the type I material, while they are absent in the type II and V material, indicates that the hardened plinthite in the Marie 3 (and in Marie 2) is fossil: the type II and V material have had the time to get affected by weathering, leading to disappearance of the (pseudomorphs of) minerals.

The fossil plinthite can only have formed in the upper slope position were it is present now, if the upper slope has once been in the influence of the groundwater. This is possible when one considers that what is now the crest and upper slope of the Marie catena was once part of a (pene)plain before uplifting and dissection of the landscape took place. In that situation the plinthite could be formed in what now are the crest and upper slope positions (see Figure 5.1).

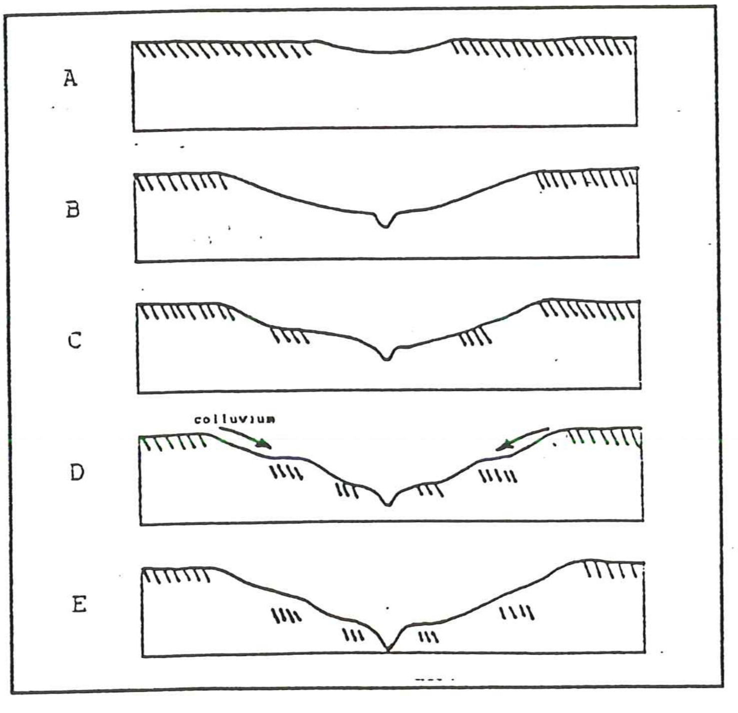


Figure 5.1 Stages in the formation of plinthite in a landscape that is uplifted and dissected.
In diagram A an ironstone crust is formed under influence of the ground water. In B dissection of the landscape takes place due to a lowering of the erosion base. Plinthite is formed downslope which hardens due to exposure (C). The hardened plinthite is covered by colluvium in diagram D. Again dissection takes place and formation of plinthite starts further downslope (diagram E).

In Marie 4 the hardened plinthite is clearly coupled to the mottles present: with increasing depth the amount of hypocoatings increase, as well as the degree of the iron impregnation until the iron-impregnated areas fuse and form hardened plinthite. The hardened plinthite does not contain pseudomorphs of minerals nor does the surrounding groundmass and the boundary between the iron-impregnated areas and the surrounding groundmass is diffuse. On these grounds we can speak of actual plinthite formation.

The same is true for Marie 5 as could be seen in the thin sections. The difference is that at a depth of 60 cm in this profile a saprolite is present in which the plinthite was formed, while the plinthite in Marie 4 was formed in soil material. This can be seen by the increase of pseudomorphs after mica below this depth. In the soft plinthite the pseudomorphs are most clearly present. This is ascribed again to the preservative power of the iron-impregnation. Van Herwaarden (in prep.) did not use the word plinthite in the description of Marie 5, but he used the words "soft dusky red ironstone nodules" instead. Neither did he draw the plinthite in Figure 2.4. Probably Van Herwaarden, when he made the soil profile description, was influenced by the image of the ironstone gravel present in Marie 4, which was had the same colour as the plinthite in Marie 5. Saprolite was not mentioned in the profile description of Marie 5.

The fact that the actual plinthite in Marie 4 is strongly cemented, while the plinthite in Marie 5 is soft can be explained by the fluctuation of the watertable. In Marie 4 the fluctuation will be larger than the fluctuation in Marie 5 which lies lower on the slope, closer to the stream in the valley bottom.

In Marie 6 no plinthite formation was described by Van Herwaarden (in prep.), but hypocoatings of iron of voids were present.

We know now that the purple saprolite (Marie 5, 130-140 cm) indicated as "purple saprolite" in section 3.1 (p.16) is in fact hardened plinthite. Knowing this it is easy to understand the occurrence of hematite in the "purple saprolite". It agrees with the statement that hematite is the principal form of ironoxide in ironstone, mentioned in section 5.2.1 (p.35).

5.2.3 Features related to other aspects of soil formation

This section is put together from the results of field observations, the profile descriptions and the study of thin sections.

Soil faunal- and human activity

The traces of human activities are present in Marie 1 to 5 in the form of the charcoal. The charcoal probably originates from the burning of the vegetation when the land was taken into use and/or from forest fires.

Traces of faunal activities are few in Marie 1 to 3. This can probably ascribed to the presence of the ironstone gravel which presents physical obstacles for at least the soil macrofauna. The only traces of faunal activity can be seen in Marie 2 in the non-gravelly top soil. Field observations showed termite activity in the upper part of this profile, in the form of cavities (diameter 10 cm) containing remnants of termite nests. In the thin sections of the upper part of Marie 2 some worm (or termite ?) channels and casts of soil fauna were observed.

In Marie 4, where ironstone gravel was only present at greater depth (below 100 cm), the faunal activity was more accentuated than in any of the other (higher lying) profiles: worm (or termite ?) channels were observed even as the remnants of a termite nest in a cavity.

In Marie 5 and 6 where many organ and tissue residues were present, little faunal activity was noticed. The only traces of soil fauna were rare organo-mineral excrements on Marie 5 and rare organic excrements in Marie 6.

Translocation of clay

Translocation of clay is currently taking place in Marie 1 as well as in Marie 2, as can be concluded from the presence of non-fragmented clay coatings in the profiles. Still, some of the clay coatings in these two profiles were fragmented due to movement of the coatings. In Marie 2 movement of clay takes place below 40 cm as can be concluded from the presence of clay coatings. In Marie 3 no traces of translocation of clay were observed.

Movement of clay is indicated by clay coatings in Marie 4 throughout the whole profile, but clay coating were dominantly present in the lower part of the profile where impregnation with iron was taking place.

Rare traces of translocation of clay were observed in Marie 5 and none in Marie 6.

Van Herwaarden classified Marie 1 to 5 as Acrisols (see Table 2.2, p.11): soils having a argic B horizon. This classification becomes dubious for Marie 5 knowing that only rare clay coatings were observed. On the other hand, according to the Revised Legend of the Soil Map of the World (FAO, 1988) the textural differentiation does not have to be caused by illuvial accumulation of clay, but may also be due to destruction of clay in the surface horizon, to biological processes, to selective surface erosion of clay or to a combination of some of these processes.

De Rouw et al. (1990) classify most of the soils in the Taï region as Ferralsols, not as Acrisols (some Cambisols and Regosols distinguished too). Their argument for doing so is that although the diagnostic horizon only meets nine out of ten properties characteristic for the ferallic B horizon, it fits well into the concept of the ferralic B horizon.

Construction of the profiles from different layers

The ironstone-gravel-containing layer of Marie 1 (0-75 cm) is a colluvial layer that overlies a gravel-free layer, which contains more different mineral grains in the groundmass apart from quartz, than the colluvial layer. The largest part of the profile of Marie 2 and Marie 3 lies in the same colluvial layer as the top part of Marie 1: the colluvium contains ironstone gravel and the mineral grains are quartz grains. In the lower part of the profiles lies a gravel-free layer in which the fossil plinthite developed (see section 5.2.2, p.39).

The occurrence of a thin gravel-free horizon covering Marie 2 is ascribed to termite activity (C.A.M. Nooren, 1991).

In Marie 4 an ironstone gravel-containing layer is present below a depth of 100 cm, in which actual plinthite formation and hardening of this plinthite takes places. This gravel-containing layer is overlain by another layer: a gravel-free layer with a sandy texture (sandy loam, sandy clay loam and sandy clay). Figure 2.4, section 2.1.6 (p.9), shows the results of a study along the slope of the Marie catena where a set of augerings were done to a depth of ± 120 cm. What lies below is unknown and is left blank in Figure 2.4. What we do see is that between profiles 3 and 4 (on the boundary of upper- and middle slope) the two gravel layers do not connect. It could be that the gravel layer of the mid-slope continues in the upper slope.

In Marie 5 no gravel is present. The upper part of the profile is a gravel-free soil, with a texture similar to that of the upper part of Marie 4: sandy clay loam, sandy clay. This indicates the continuation downslope of the layer that formed the upper part of the profile of Marie 4. Below 60 cm a saprolite is present. At the transition of the sandy soil to the saprolite actual plinthite formation was taking place.

Marie 6 is situated in a soil in a alluvial/colluvial deposit. This can be concluded from the fact that the texture, especially in the lower part of the profile, varies strongly from one horizon to the other. Probably this profile has also received material from the higher positions.

5.3 Theo catena

Discussion in connection with the micromorphological observations of the ironstone gravel

Type a and b (hard purple- respectively soft purple-) ironstone gravel of the Theo catena are related. Soft purple ironstone gravel (tough to break between fingers) is the slightly weathered version of hard purple ironstone gravel (not breakable between fingers). This statement is not only based on the colour of the gravel at cross-section (purple) but also on the similar micromorphological characteristics of the two types (similar groundmass impregnated with iron, containing quartz and pseudomorphs). The weathering of soft purple ironstone gravel expresses itself, apart from being breakable between fingers, in the presence of clay coatings around quartz grains in the gravel.

Types a and b ironstone gravel show remarkable resemblance with the *metamorphic gravel* of the Marie catena (compare micromorphological descriptions in sections 4.3.3.1 (p.21) and 4.4.6 (p.33), Plates 3., 5. and 23., 24., 25.). It is therefore reasonable to assume that hard- and soft purple ironstone gravel also originate from an iron-impregnated saprolite, like the *metamorphic gravel* (type 2) from the Marie catena (section 5.2.1, p.35). Like the *metamorphic gravel*, types a and b gravel do not originate from the migmatite studied in thin section (section 4.2, p.19 and Plate 1.) but either from a saprolite of a migmatite with a different composition or from a saprolite from another kind of rock.

It is not difficult to imagine that the gravel was formed from a saprolite of another migmatite or other kind of rock, at considerable distance from its present location. Due to transportation the gravel finally ended up in the migmatite catena studied here. The transportation would account for the roundness of the gravel.

Within the *metamorphic gravel* of the Marie catena clay coatings were found just like they were observed in the soft purple ironstone gravel. Of the soft purple ironstone gravel we know that it is breakable between fingers, probably some of the *metamorphic gravel* is breakable between fingers too.

Differences in quartz- and pseudomorph content between the *metamorphic gravel* and the hard- and soft purple ironstone gravel (and within the hard- and soft purple ironstone gravel) can be explained when one assumes that the saprolite of origin had a varying composition.

The hard- and soft purple ironstone gravel ironstone gravel found in the Theo catena is thought to be similar to the *metamorphic gravel* (type 2) in the Marie catena. When the *altered metamorphic gravel* is a weathered form of the *metamorphic gravel* as assumed in section 5.2.1 (p.35) one would expect "*altered metamorphic*-like" gravel in the Theo catena as well. So far no "*altered metamorphic*-like" gravel was found in the Theo catena. To be certain of the absence of "*altered metamorphic*-like" gravel in the Theo catena, thin section should be made of the soil horizons of the Theo catena.

The uniform reddish brown and l.yell./unif.reddish brown mottled ironstone gravel of the Theo catena are totally different from the hard- and soft purple ironstone gravel: they give the impression to be formed from soil material (e.g. presence of iron-impregnated clay coatings in groundmass).

Especially the l.yell./unif.reddish brown mottled ironstone gravel, but in a lesser degree the uniform reddish brown ironstone gravel too, have areas which are iron-poor. This, together with the red (XRD) iron impregnation around pores and cracks, resembles the process known as gleying. The presence of this gravel with an appearance coupled to gleying or plinthization is puzzling since the gravel was sampled on a crest. According to the profile descriptions of the Theo catena by Hooyer (1991), the gravel is not only present in the profile on the crest but in all profiles except for the profile in the valley bottom. See Figure 5.2. Theo 1 to 4 are well drained, Theo 5 is moderately well drained (Hooyer, 1991). Under these drainage conditions one does not expect plinthization.

In Figure 5.2 another reason to reject the idea of the gravel being formed by recent plinthization, apart from the above mentioned drainage conditions, can be seen: when recent plinthization is the cause of the formation of the uniform reddish brown and l.yell./unif.reddish brown mottled ironstone gravel one would expect mottles to be present in all parts of the profiles were the uniform reddish brown and l.yell./-unif.reddish brown mottled ironstone gravel is present. This is not the case in Theo 1, 2, 4 and 5.

Furthermore the reason why the uniform reddish brown and unif. reddish brown ironstone gravel was noticed in the first place was that it was lying distinct in the soil matrix, if they were the product of "in situ" plinthization it would rather have a diffuse and irregular than a distinct boundary (see section 2.2, p.15).

An explanation for the occurrence of uniform reddish brown and l.yell./unif.reddish brown mottled ironstone gravel in the Theo catena can not be supplied by the data gathered in this study. Possibly the uniform reddish brown and l.yell./-unif.reddish brown mottled ironstone gravel is inherited like the hard ironstone gravel present in the catena (see Figure 5.2). The gravel is now easy to break between fingers, but it is most likely that in this state it would not have survived transportation. Therefore we have to assume that the gravel was more firm when it was transported and is now subject to softening. That the uniform reddish brown and l.yell./unif.reddish brown mottled ironstone gravel is more soft than the hard- and soft purple ironstone gravel can be related to the degree of impregnation: gravel with a lesser degree of impregnation is sooner subjected to softening than gravel with a high degree of impregnation.

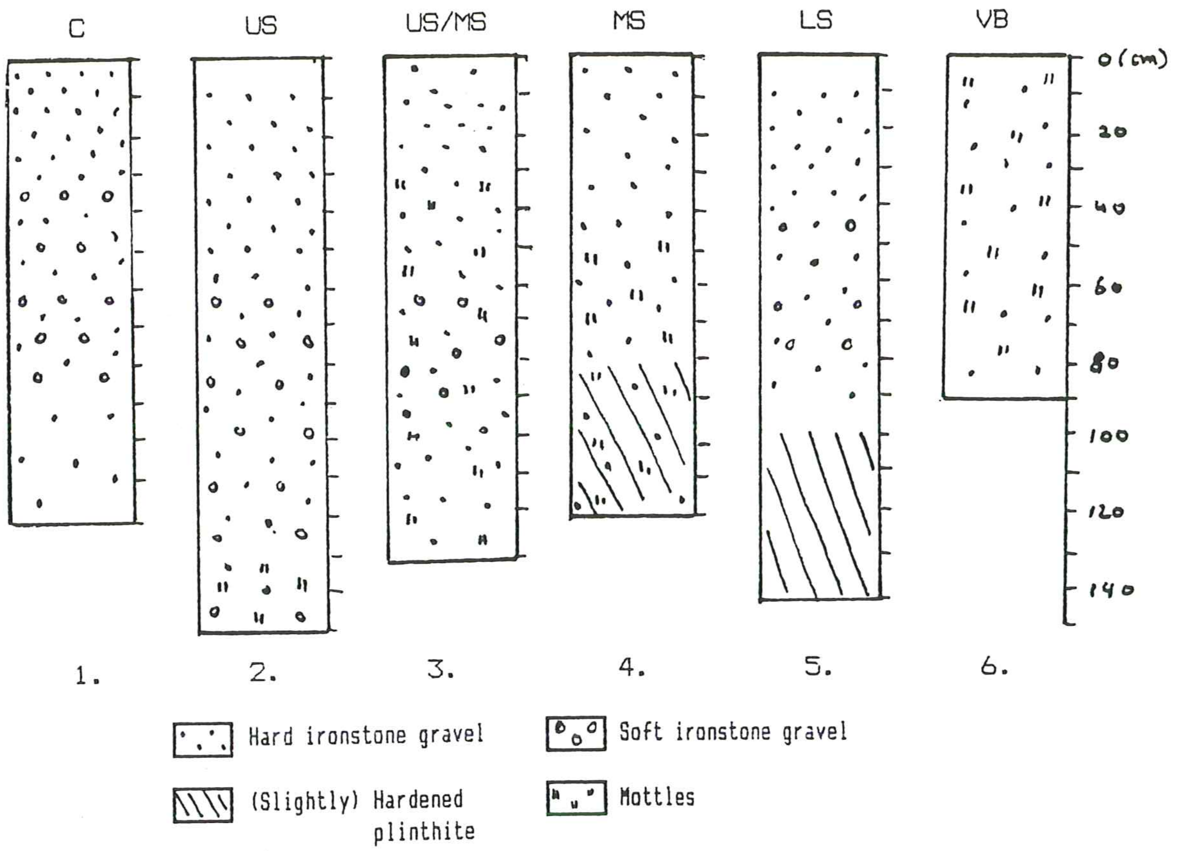


Figure 5.2 A schematic representation of the profiles of the Theo catena.

Discussion in connection with the analyses done on the ironstone gravel

Hematite was detected in the hard-, soft purple ironstone gravel and uniform reddish brown ironstone gravel but hematite was not unambiguously detected in the light yellow part of the mottled ironstone gravel. This is in agreement with the expectations based on the light yellow colour (see section 2.2, p.14).

Of the results of the total analyses by XRFS (section 4.4.3, p.31) the percentages SiO_2, Al_2O_3 and Fe_2O_3 are most interesting, the other major elements measured show little or no difference between the different forms of ironstone gravel characterized.

The amounts of SiO_2 and Al_2O_3 are higher in the three kinds of soft purple ironstone gravel compared to the hard purple ironstone gravel, while the amount of Fe_2O_3 is lower in the three kinds of soft gravel. The differences in amounts of SiO_2, Al_2O_3 and Fe_2O_3 between the different types of ironstone gravel can be relative and can be caused due to differences in amounts of these elements in the parent material of the gravel. Remarkable is the low amount of Fe_2O_3 in the light yellowish part of the mottled gravel. This confirms the micromorphological description of the gravel (section 4.4.6, p.34) where iron-poor areas were described.

The calculation done in section 4.4.3 (p.32) to determine the weight percentages of kaolinite, quartz, goethite and hematite present in the gravel, from the amounts of Al_2O_3, Fe_2O_3, SiO_2 and H_2O measured by XRFS, could only be completed for the hard purple- and the uniform reddish brown ironstone gravel. Apparently the assumptions made (no Al^{3+} or Fe^{3+} substitution, all water present in kaolinite and goethite), were not valid. This is not completely surprising when one knows that Al^{3+} substitution for Fe^{3+} in hematite can be up to 15 % mole fraction of the Fe_2O_3, and up to 33 % mole fraction of the FeO(OH) (Tardy et al., 1985). Fe^{3+} substitution for Al^{3+} in kaolinite can be up to 3 % mole fraction of the kaolinite (Tardy et al., 1985).

A summary of the iron analyses done on the gravel is given in Table 5.1. The results of the XRFS were given in percentages Fe_2O_3 (section 4.4.3, p.31), in Table 5.1 this is recalculated to percentage Fe. The results of the thermogravimetric analyses were given in weight percentage goethite (section 4.4.5, p.33), in Table 5.1 this is recalculated to weight percentage Fe that was present in the form of goethite.

Table 5.1 Summary of the iron analyses performed on the ironstone gravel sampled in the Theo catena.

Type of gravel	% Fe-dithion. (extraction)	% Fe-total (XRFS)	% Fe-goethite (TGA)
a. hard purple	7.3	32.6	19.7
b. soft purple	12.0	27.2	10.8
c. unif. red. brown	10.3	15.8	12.4
d. l. yell. part mottled gravel	4.4	6.0	12.2

Table 5.1 shows remarkable differences between the results of the different analyses.

1. The amount of iron present in goethite in the light yellow part of the mottled ironstone gravel is higher than the total amount of iron determined by XRFS.

   This indicates that the thermogravimetric method for determining the amount of goethite present is not a correct method. Probably one of the assumptions done within this method was wrong (see section 4.4.5, p.33).

2. The total amount of iron present in ironoxides (determined by dithionite-extraction) is, in three out of four determinations, lower than the percentage iron present in goethite.

   Apparently one or maybe both methods do not work well. It was already indicated under point 1. that the thermogravimetric analysis did not meet the expectations, but also remarks can be made about the dithionite-extraction method.

   See Table 5.2 for the ratio % Fe-dithion. to % Fe-total.

Table 5.2 Ratio % Fe-dithion. to % Fe-total measured on the ironstone gravel sampled in the Theo catena.

Type of gravel	ratio % Fe-dithionite to % Fe-total
a. hard purple	0.22
b. soft purple	0.44
c. unif. red. brown	0.65
d. l. yell. part mottled gravel	0.73

As can be seen in Table 5.2 the amount of iron measured by extraction with dithionite approaches the amount of iron measured by XRFS more and more going from the hard purple- to the light yellow part of the mottled ironstone gravel. Apparently the iron is present in the hard purple ironstone in such a way that it can not be extracted well by dithionite. In the soft purple ironstone gravel the ratio % Fe-ditionite to % Fe-total is twice as high as in the hard purple gravel. *This indicates that something has happened in the gravel during weathering that makes that more iron can be extracted by dithionite.*

Since pyrophosphate and oxalate are weaker means of extraction than dithionite, it is likely that they too are not good means of extraction where the hard and soft purple ironstone are concerned.

In the uniform reddish-brown ironstone gravel and light yellow part of the mottled ironstone gravel the amount of iron extracted by dithionite approaches the amount of iron determined by XRFS even more than the soft purple ironstone gravel. Probably the forms in which iron is present is well extractable by dithionite. One has to keep in mind that the Fe-total also includes the iron present in kaolinite as substitute for aluminium (this is never more than 3 % mole fraction of the kaolinite; Tardy et al., 1985), so the Fe-dithionite and Fe-total will never be completely equal.

The initial thought was to calculate the amount of hematite in the different types of ironstone gravel by subtracting the amount of iron present in the goethite from the total amount of iron present in crystalline ironoxides (see section 2.2, formula 1, p.14). That this it not possible will be clear in the light of the discussion above.

An alternative method to calculate the amount of hematite present in the gravel is to subtract Fe-goethite from Fe-total, while assuming that Fe-total does not include large amounts of amorphous ironoxides or iron substituted in kaolinite. This method is not applicable either since in the light yellow part of the mottled ironstone gravel the amount of Fe-goethite is larger than the amount of Fe-total.

When one assumes that all the aluminium measured by XRFS can be ascribed to kaolinite, one can calculate the amount of kaolinite that should be present. In Table 5.3 the results of that calculation are given as well as the results of the amount of kaolinite determined by TGA.

Table 5.3 Comparison between the amount of kaolinite determined by TGA and recalculation of the amount of Al_2O_3 determined by XRFS.

Type of gravel	% kaolinite (TGA)	% kaolinite (XRFS)
a. hard purple	25.5	43.0
b. soft purple	34.7	44.6
c. unif. red. brown	60.2	62.5
d. l. yell. part mottled gravel	52.4	69.0

Table 5.3 shows that the amount of kaolinite measured by TGA is always lower than the amount of kaolinite calculated from the results of XRFS. Two explanations are possible:

1. the assumption that kaolinite looses all its water between 375-600 °C is not right;
2. not all of the Al_2O_3 measured by XRFS can be ascribed to kaolinite, aluminium can be present as substitute for iron in e.g. goethite up to 33 % mole fraction of the FeO(OH) (Tardy et al., 1985).

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

In this chapter first the answers with respect to the hypotheses described in section 2.2 (p.13) will be discussed, after that the soil formation on the Marie catena will be dealt with. Finally, other conclusions which can be drawn from this study and recommendations for further research will be given.

The first hypothesis was that the soft purple-, the uniform reddish-brown- and the mottled ironstone gravel, seen in both the Theo and the Marie catena, are progressive stages of alterations of the hard purple ironstone gravel. In the Marie catena four types of ironstone gravel were distinguished in the thin sections. Type 1 gravel, *sediment gravel*, is thought to originate from a saprolite of a sedimentary rock that was impregnated with iron by plinthization. The second type, the *metamorphic gravel* is thought to originate from a saprolite of a metamorphic rock which was impregnated with iron as well. This second type is turning into the third type (*altered metamorphic gravel*) of ironstone gravel distinguished, due to progressive alterations that take place in the ironstone gravel. Those progressive alterations are:

1. Along the edges of the gravel and cracks in the gravel yellow rims (XPL) start to form.
2. Existing pores and cracks widen, and their edges made more irregular.
3. Illuvial clay is transported into the gravel and deposited in the pores as clay coatings.
4. Iron, either released from the gravel itself or brought into the ironstone gravel by soil water, is deposited in the pores in the form of goethite or hematite. The same happens with aluminium.
5. When the alterations, mentioned under 1 to 4 proceed (longer and/or more intensively), the portion yellow in the ironstone gravel becomes larger until the gravel is completely yellow and the pseudomorphs become less distinct. The infillings and coatings of the pores with goethite and hematite are still distinct, even as the clay coatings which are still distinct.

The *plinthite gravel* (type 4) originates from the breaking up of the hardened plinthite which can be found below the horizon were the *plinthite gravel* was found.

The relationship between the four types of ironstone gravel distinguished in the thin sections and the hard purple-, soft purple-, uniform reddish-brown- and mottled ironstone gravel, as they were observed in the field, can not be made because no samples of these types of gravel were taken in the Marie catena.

Instead samples of the hard purple-, soft purple-, uniform reddish-brown- and mottled ironstone gravel were taken in the Theo catena. After studying a small part of these gravel types in thin section it turned out that only the hard and soft purple ironstone gravel could be seen in the thin sections of the Marie catena as well, namely as type 2; the *metamorphic gravel*.

The *sediment gravel* and *metamorphic gravel* in the Marie catena and the hard and soft purple ironstone gravel in the Theo catena, do not originate from the migmatite as it was present as an inselberg in Taï National Park. This can be concluded from the study of a thin section made of the piece of rock taken from the inselberg. The saprolite present in

Marie 5 did show pseudomorphs like the large grayish white pseudomorphs described in section 4.3.3.1 (p.22), except that they are larger (at least three times) and wider. Probably the ironstone gravel was formed from a saprolite at some distance and was transported to its present location, which would explain the roundness of the ironstone gravel.

The reddish-brown- and mottled ironstone gravel in the Theo catena were different from any of the types of ironstone gravel seen in the Marie catena. These two types of gravel originate from a soilmass that got impregnated with iron, was transported to its present location and now is subject to softening due to weathering.

A remark to be made here is that in this study the importance of the rule of thumb, that all samples necessary in a soil science study have to be taken in one and the same site or series of sites, is confirmed again.

The second hypothesis implied that the hardened plinthite found in upper slope positions is fossil instead of recently formed, as assumed by De Rouw et al. (1990).

The micromorphological observations confirm this hypothesis: the strongly iron-impregnated part of the plinthite contains pseudomorphs, while the iron-poor part of the plinthite does not contain pseudomorphs, indicating that the iron-poor part of the hardened plinthite had time to get affected by weathering. Other indications that strengthen this conclusion are the absence of iron mottles in the rest of the profile, the fact that no pseudomorphs are present in the horizon above the plinthite and the drainage conditions of the upper slope (well-drained).

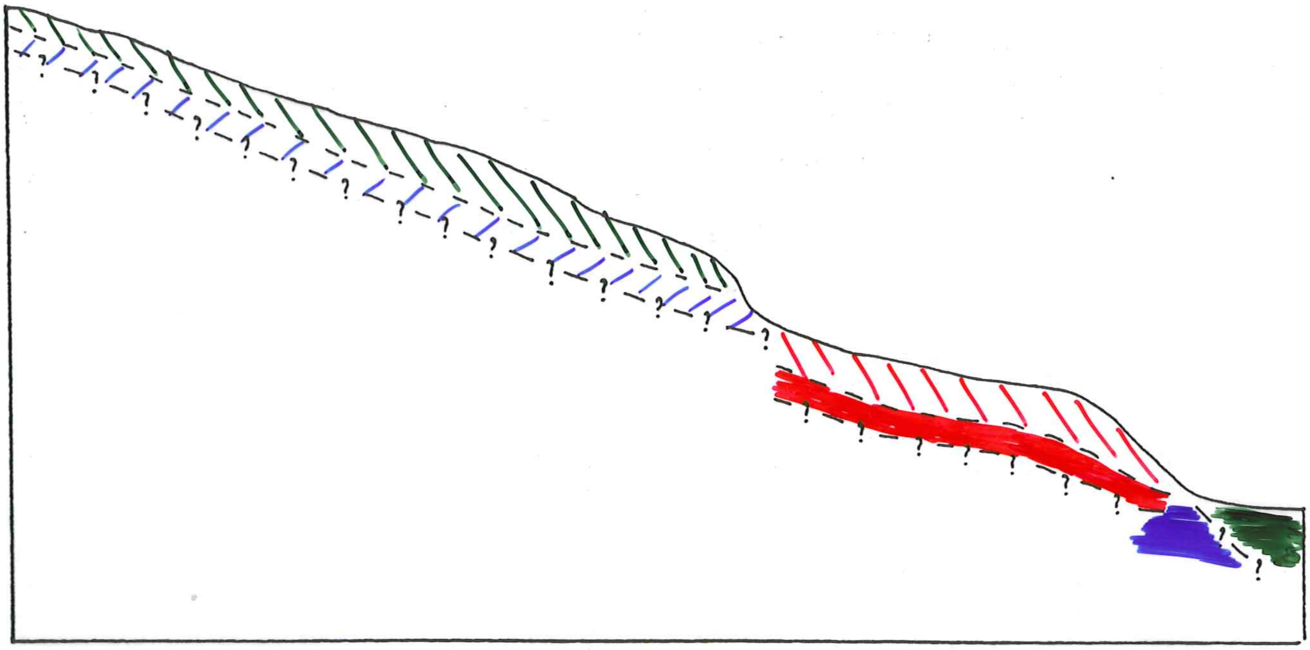
This plinthite, which is now considered fossil, was formed in positions influenced by the groundwater which later became upper slope- and crest positions after uplifting and dissection of the (pene)plain in which it was formed.

From the macro- and micromorphological observations the Figure 2.4 after Van Herwaarden (in prep.) can be adapted on the following aspects:

- the mottles indicated on the lower slope are actual plinthite formation;
- a differentiation can be made between the fossil hardened plinthite on the upper slope and the actual plinthite on the middle and lower slope;
- mottles present in the profile on the middle slope and valley bottom are absent in Figure 2.4, but should be represented;
- saprolite can be indicated in Marie 5.

In Figure 6.1 these adaptations are made. On the transparent overlay of Figure 6.1 the different layers, as they were distinguished and discussed in section 5.2.2 (p.38), are indicated.

In short we can say that the slope on which the Marie catena is situated exists of a core of saprolite/bedrock of migmatite, which is covered by various layers of colluvium. In the valley bottom also alluvial deposits are present. The layers are represented on the overlay of Figure 6.1. The connection and continuation of the layers is not clear in all cases.



contains gravel, only quartz grains in coarse fraction groundmass

gravel-free, quartz grains and other minerals in coarse fraction groundmass

gravel-free, only quartz grains in coarse fraction groundmass

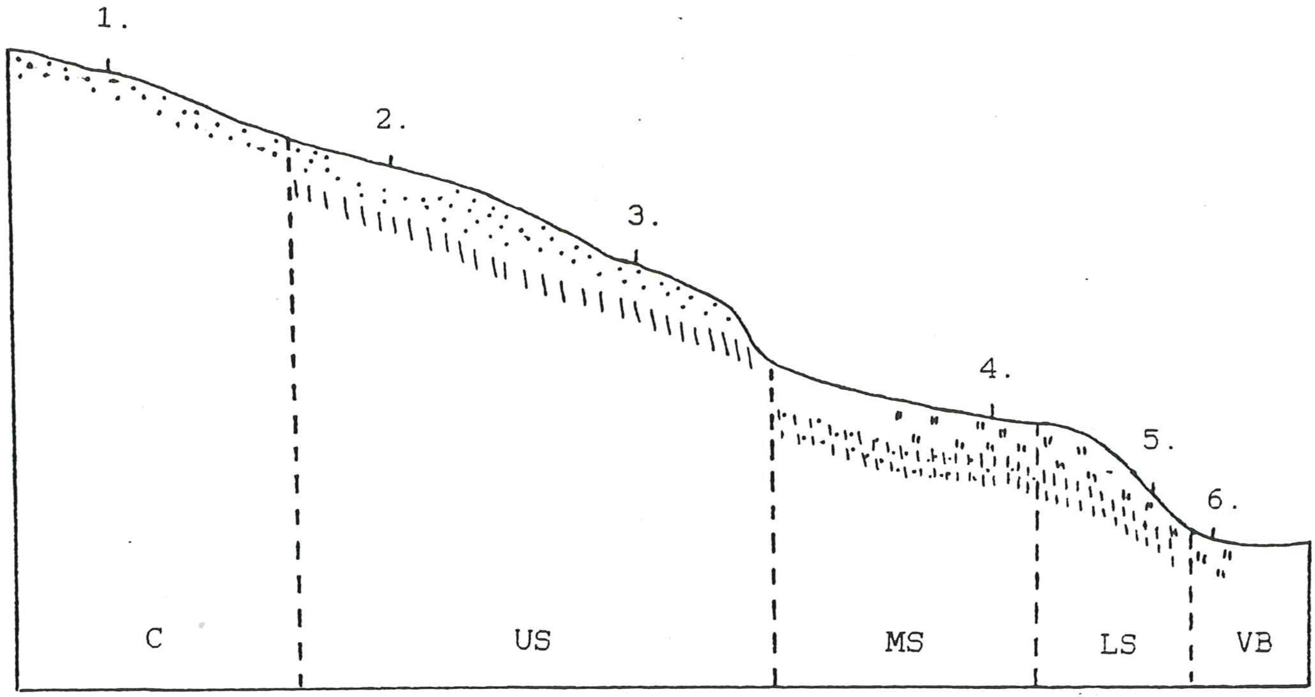
contains gravel, only quartz grains in coarse fraction groundmass

saprolite

alluvial deposit

boundary

uncertain boundary



Scale: horizontal 1: 2500
vertical 1: 250

C - Crest
US - Upper Slope
MS - Middle Slope
LS - Lower Slope
VB - Valley Bottom

Ironstone gravel

Fossil plinthite

Actual plinthite

Mottles

Figure 6.1 A schematic representation of the Marie catena showing the resence of ironstone gravel, fossil and actual plinthite an mottles. On the transparent overlay the different layers di tinguished are shown.

The application of generally used methods of analysis, like dithionite extraction and thermogravimetric analysis, turn out not to be very well applicable on the ironstone gravel: several discrepancies in the results were found.

The above mentioned conclusion brings us right to the recommendations for further research. It is interesting to study the reason why iron can not be extracted from the ironstone as it can be from soil samples. In what form is the iron present, in what way is it different from the iron in soil material? Is there a correlation between the degree of hardness/-impregnation with the amount of iron extractable, as indicated by the results of this study? This could be done by taking samples of ironstone and measuring the force necessary to

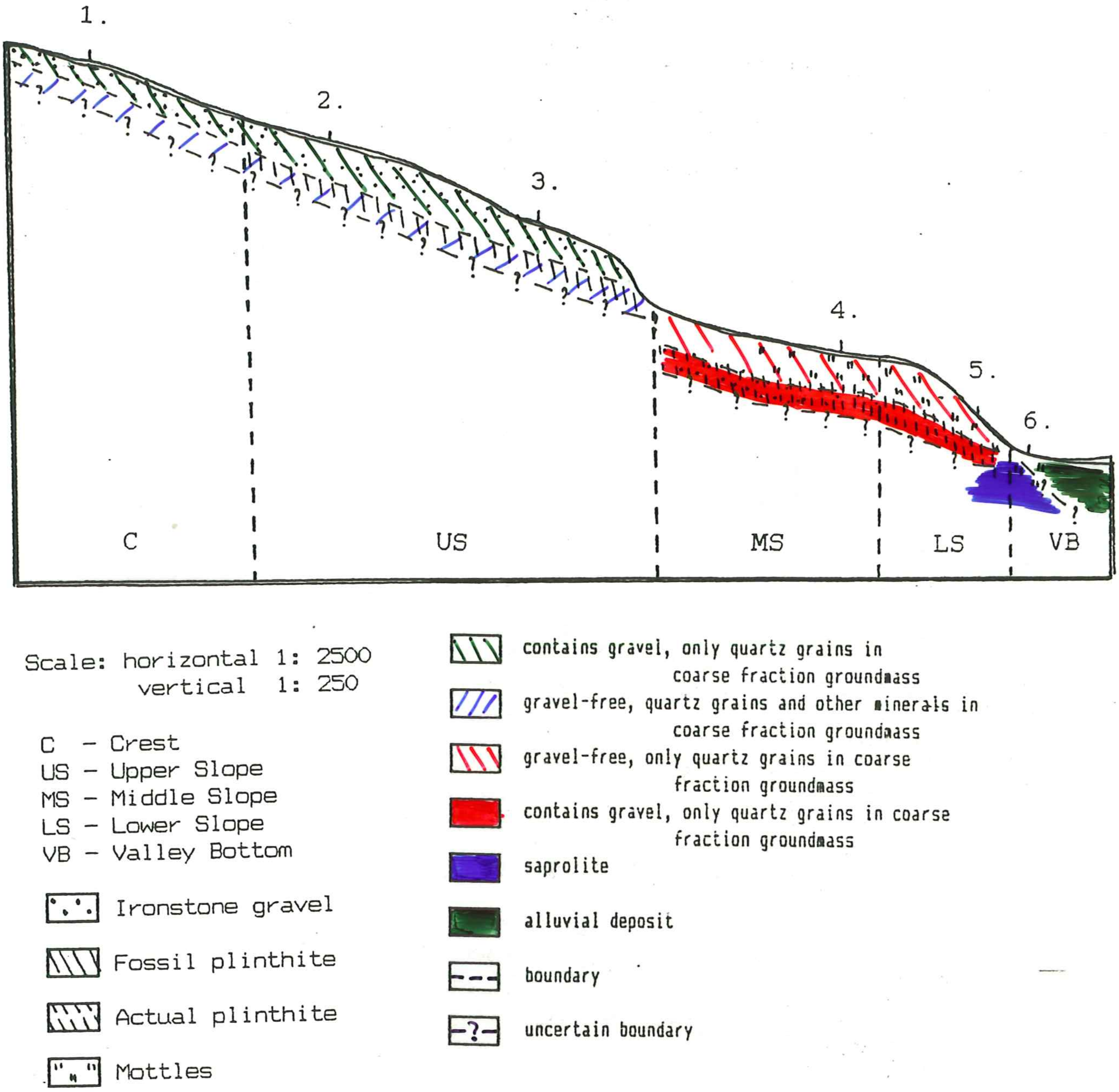


Figure 6.1 A schematic representation of the Marie catena showing the resence of ironstone gravel, fossil and actual plinthite an mottles. On the transparent overlay the different layers di tinguished are shown.

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Further more I want to recommend to take samples of the core and the yellow rim of the *yellow-rimmed metamorphic gravel* ironstone gravel, by micro-drilling, to determine by XRD whether the rim is formed by depletion of iron or recrystallization.

Also I want to recommend to take samples, by micro-drilling, of the material interpreted as hematite and goethite and of the crystals interpreted as gibbsite to confirm these interpretations by XRD.

Although at this moment it does not seem likely that soil science research will be done in Côte d'Ivoire by the Wageningen Agricultural University in the near future, I want to recommend that samples of the soft ironstone gravel in the Marie catena will be taken and that an intensive study is done to try to connect the different layers distinguished. The latter could be done by augering along the hill until the saprolite/bedrock is found. This could be at considerable depth so pits should be dug to solve the problem of the short augers.

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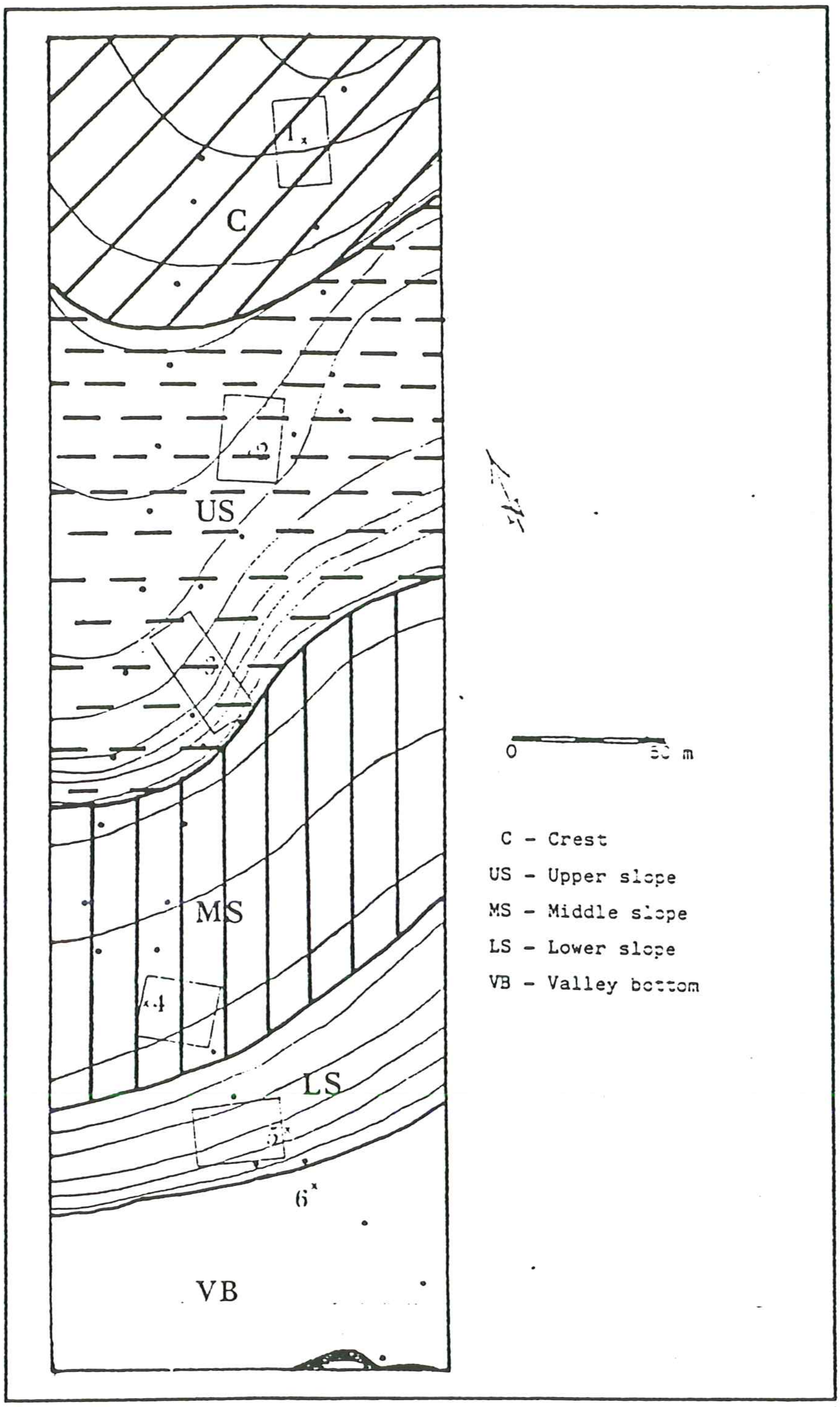
Appendix A Physiographic soil map Marie catena



(source: Van Herwaarden, in prep.)

Appendix B Soil profile descriptions Marie-catena

source: Van Herwaarden (in prep.)

Marie 1

Author: G.J. van Herwaarden
Physiographic position: crest
Location: latitude 5°49'33.3", longitude 7°23'25,7"
Relative altitude[1]: +17.3 m

Ah	0- 7 cm	Brown to dark brown (7.5YR4/4), moist, very gravelly sandy loam; structure determined by gravel; very friable when moist, non-sticky and non-plastic when wet; common pores; few, angular, large and small, fresh quartz fragments; frequent, spherical, medium (1 cm), hard, ironstone nodules; very frequent, very fine to coarse roots; gradual, smooth boundary.
AB	7- 25 cm	Yellowish red (5YR5/6), moist, very gravelly clay loam; structure determined by gravel; very friable when moist, slightly sticky and slightly plastic when wet; common pores; frequent, angular, large and small, fresh quartz fragments; frequent, spherical, medium (1 cm), hard, ironstone nodules; few, fine roots; smooth boundary.
Bws1	25- 45 cm	Yellowish red (5YR5/6), moist, very gravelly clay loam; structure determined by gravel; friable when moist, slightly sticky and slightly plastic when wet; common pores; frequent, angular, large and small, fresh quartz fragments; frequent, spherical, medium (1 cm), hard, ironstone nodules; few, very fine roots; clear smooth boundary.
Bws2	45- 75 cm	Red (2.5YR5/6), moist, gravelly clay; structure determined by gravel; firm when moist, sticky and plastic when wet; few pores; few, angular, large and small, fresh quartz fragments; few, spherical, medium (1 cm), hard, ironstone nodules; few, very fine roots; clear, wavy boundary.
Bws3	75-150+ cm	Red (2.5YR4/7), moist, non-gravelly clay; weak, medium, subangular blocky; firm when moist, sticky and plastic when wet; few pores; very few, spherical, small (<1 cm), hard, ironstone nodules; very few roots.

[1] Altitude relative to Marie 6.

Marie 2

Author: G.J. van Herwaarden
Physiographic position: upper slope
Location: latitude 5°49'30.4", longitude 7°23'27.4"
Relative altitude[2]: +13.6 m

Ah	0- 5 cm	Brown to dark brown (10YR4/3), moist, non-gravelly loam; weak, fine and medium, subangular blocky; very friable when moist, slightly sticky and non-plastic when wet; common pores; many roots; clear, smooth boundary.
AB	5- 25 cm	Strong brown (7.5YR5/6), moist,slightly gravelly sandy clay loam; weak medium, subangular blocky; very friable when moist, slightly sticky and slightly plastic when wet; common pores; few, spherical, large and small, hard, ironstone nodules; common roots; wavy boundary.
Bws1	25- 60 cm	Strong brown (7.5YR5/6), moist, very gravelly clay loam; structure determined by gravel; friable when moist, slightly sticky and plastic when wet; common pores; frequent, angular, large and small, fresh quartz fragments; very frequent, irregular, large (>1 cm), hard, ironstone nodules; few roots; gradual, wavy boundary.
Bws21	60- 90 cm	Strong brown (7.5YR5/6), moist, gravelly clay loam; few, distinct, clear, brownish yellow mottles; structure determined by gravel; friable when moist, slightly sticky and slightly plastic when wet; few pores; few, angular, large and small fresh quartz fragments; very frequent, irregular, medium (1 cm), soft and hard, ironstone nodules; few roots; gradual, irregular boundary.
Bws22	90-110 cm	Yellowish red (5YR5/7), moist, slightly gravelly clay loam; common, medium, distinct, clear, brownish yellow (10YR4/6) mottles; weak, medium, subangular blocky; firm when moist, slightly sticky and slightly plastic when wet; few pores; frequent, irregular, medium (1 cm) soft and hard, ironstone nodules; weakly cemented, discontinuous plinthite; few roots; gradual, smooth boundary.
Bws3	110-150+ cm	Yellowish red (5YR5/7), moist, slightly gravelly clay loam; many, heterogeneous, prominent, clear, dark yellowish brown (10YR4/6) mottles and many heterogeneous, prominent, clear, red (2.5YR4/7) mottles; weak, medium, angular blocky; firm when moist, sticky and plastic when wet; few pores; few, irregular, medium (1 cm), hard, ironstone nodules; weakly cemented, continuous plinthite; few roots.

Remark: frequent termite holes/nests.

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[2] Altitude relative to Marie 6.

Marie 3

Author: G.J. van Herwaarden
Physiographic position: upper slope
Location: latitude 5°49'28.3", longitude 7°23'23.0"
Relative altitude[3]: +11.8 m

Ah	0- 8 cm	Dark brown (10YR4/3), moist, very gravelly, sandy clay loam; structure determined by gravel; very friable when moist, slightly sticky and slightly plastic when wet; common pores; frequent, irregular, large (>1 cm), hard ironstone nodules; common roots; gradual, smooth boundary.
Bws1	8- 30 cm	Strong brown (7.5YR4/6), moist, very gravelly, sandy clay loam; structure determined by gravel; friable when moist, sticky and slightly plastic when wet; few pores; diffuse, wavy boundary.
Bws2	30- 70 cm	Yellowish red (5YR5/6), moist, very gravelly, sandy clay; structure determined by gravel; firm when moist, sticky and plastic when wet; few pores; few, angular, large and small, fresh quartz fragments; frequent, spherical, medium (1 cm), hard, ironstone nodules; few roots; abrupt, wavy boundary.
Bms3	70-150+ cm	Strong brown (7.5YR5/6), moist, gravelly clay; many coarse, prominent, clear, red (10YR4/6) mottles; structure determined by gravel; very firm when moist, sticky and plastic when wet; cemented, continuous plinthite.

[3] Altitude relative to Marie 6.

Marie 4

Author: G.J. van Herwaarden
Physiographic position: middle slope
Location: latitude 5°49'25.1", longitude 7°23'29.3"
Relative altitude[4]: +5.3 m

Ah	0- 6 cm	Brown to dark brown (10YR4/3), moist, non-gravelly loamy sand; weak, fine, subangular blocky; very friable when moist, non-sticky and non-plastic when wet; common pores; many roots; clear, smooth boundary.
AB	6- 40 cm	Yellowish brown (10YR5/4), moist, non-gravelly sandy loam; moderate, fine and medium subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; common pores; common roots; gradual, smooth boundary.
Bws11	40- 70 cm	Yellowish brown (10YR5/5), moist, non-gravelly sandy clay loam; moderate, medium subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; common pores; common roots; gradual, smooth boundary.
Bws12	70-100 cm	Brownish yellow (10YR6/6), moist, non-gravelly sandy clay loam; common, fine distinct, clear, strong brown (7.5YR5/6) mottles; moderate, medium, subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; common pores; common roots; abrupt, smooth boundary.
Bws2	100-120 cm	Brownish yellow (10YR6/6), moist, gravelly sandy clay loam; common, medium, distinct, diffuse, yellowish red (5YR5/6) mottles; structure determined by gravel; friable when moist, slightly sticky and slightly plastic when wet; few pores; few, angular, medium (1 cm), fresh quartz fragments; frequent spherical, medium (1 cm), hard, ironstone nodules; few roots; clear, wavy boundary.
Bws3	120-150+ cm	Brownish yellow (10YR6/7), moist, slightly gravelly sandy clay; many, medium to coarse, prominent, sharp, red (10YR4/8) mottles; firm when moist, sticky and plastic when wet; very few pores; frequent, spherical, medium (1 cm), hard, ironstone nodules; strongly cemented, continuous plinthite; very few roots.

Remark: Very frequent termite holes/nests.

[4] Altitude relative to Marie 6.

Marie 5

Author: G.J. van Herwaarden
Physiographic position: lower slope
Location: latitude 5°49'23.6", longitude 7°23'29.5"
Relative altitude[5] : +1.3 m

Ah	0- 10 cm	Brown (10YR5/3), moist, non-gravelly sandy clay; moderate, fine, subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; many pores; very frequent roots; gradual, smooth boundary.
AB	10- 30 cm	Light yellowish brown (10YR6/4), moist, non-gravelly sandy clay loam; moderate, fine, subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; few pores; common roots; gradual, wavy boundary.
Bws1	30- 60 cm	Light yellowish brown (10YR6/4), moist, non-gravelly sandy clay loam; common, fine, faint, clear, yellowish brown (10YR5/6) mottles; moderate, medium, subangular blocky; few pores; friable when moist, slightly sticky and slightly plastic when wet; few angular small (<1 cm), fresh quartz fragments; common roots; few charcoal; diffuse wavy boundary.
Bws2	60-100 cm	Very pale brown (10YR7/4), moist, non-gravelly sandy clay; many, fine, faint, clear, brownish yellow (10YR6/8) mottles; moderate, medium, subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; few pores; frequent, angular, large and small, fresh quartz fragments; frequent, irregular, small (<1 cm), soft, dusky red (10R3/4), ironstone nodules; few pores; common roots; diffuse, irregular boundary.
Bws3	100-150+ cm	White (5Y8/1), moist, non-gravelly, sandy clay; many, medium, faint, clear, brownish yellow (10YR6/8) mottles; weak, fine and medium, subangular blocky; friable when moist, slightly sticky and slightly plastic when wet; few pores; few, angular, large and small, fresh quartz fragments; very frequent, irregular, large and small, soft, dusky red (10R3/4) ironstone nodules; few roots.

Remark: Gravel layer (stone line) with a thickness of ± 5 cm consisting of angular, large and small, fresh quartz fragments is present between 25 and 60 cm depth.

[5] Altitude relative to Marie 6.

Marie 6

Author: G.J. van Herwaarden
Physiographic position: valley bottom
Location: latitude 5°49'22.6", longitude 7°23'28.2"
Altitude: 0 m[6]

Ah	0- 5 cm	Very dark grayish brown (10YR3/2), moist, non-gravelly clay loam; weak, fine, subangular blocky; very friable when moist, slightly sticky and slightly plastic when wet; many pores; abundant roots; clear, irregular boundary.
ACg	5- 30 cm	Light gray to gray (10YR6/1), wet, non-gravelly clay; common, medium, distinct, clear, strong brown (7.5YR5/6) mottles; very weak, medium, subangular blocky; slightly sticky and slightly plastic when wet; few pores; frequent roots; gradual, wavy boundary.
C11g	30- 60 cm	Light gray to gray (2.5YR6/1), wet, non-gravelly clay; common, medium and coarse, distinct, clear, strong brown (7.5YR5/6) mottles; massive; sticky and slightly when wet; few pores; few roots; gradual, irregular boundary.
C12g	60-110 cm	Light gray to gray (5YR6/1), wet, non-gravelly clay; few, medium, faint mottles; massive; sticky and plastic when wet; very few pores; very few, angular, large and small, fresh quartz fragments; very few roots; diffuse, wavy boundary.
C13g	110-140 cm	Light gray to gray (5YR6/1), wet, non-gravelly sandy clay; massive; sticky and plastic when wet; very few pores; very few, angular, large and small, fresh quartz fragments; very few roots; diffuse wavy boundary.
2Cg	140-150+ cm	Light gray to gray (5Y6/1), slightly gravelly loamy coarse sand; massive, slightly sticky and non-plastic when wet; few, angular, large and small, fresh quartz fragments.

Remark 1: In 2Cg horizon also discontinuous thin layers consisting of sandy clay and clay are present.
Remark 2: Augering from 150 cm depth downwards to 200 cm depth shows no differences from 2Cg horizon in the subsoil.

[6] Reference point of altitude.

Appendix C Soil profile descriptions Theo catena

(source: Hooyer, 1991)

Theo 1, plantation café

Topographie: ondulé
Position physiographique: sommet
Roche-mère: migmatite
Drainage: normal
Par: A.A. Hooyer

Ah 0- 5 cm Brun foncé (7.5YR3/4), limon sableux, peu graveleux, structure faible, polyédrique angulaire moyenne; fraible à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins; peu nombreux nodules spheriques, mediums, ferrugineux, durs, grises/rouges; nombreuses racines très fines et fines, nombreuses racines moyennes, très peu grosses racines; carbon; transition distinctes et ondulée; pH 6.43;

AB 5- 25 cm Brun rougâtre foncé (5YR3/4), limon argilo sableux, très graveleux; structure déterminée par le gravier; friable à l'état frais, peu collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; très nombreux nodules spheriques, mediums, ferrugineux, durs, grises/rouges; assez nombreuses racines très fines et fines, peu nombreuses racines moyennes, très peu grosses racines; transition graduelle et irregulière; pH 6.09;

Bws1 25- 55 cm Rouge jaunâtre (5YR4/6), limon argilo sableux, très graveleux; structure déterminée par le gravier; friable à l'état frais, peu collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; très nombreux nodules arrondis, mediums, ferrugineux, durs et tendres, grises/rouges; peu nombreuses racines très fines et fines, très peu nombreuses racines moyennes; transition diffuses et ondulée; pH 5.57;

Bws2 55- 90 cm Rouge jaunâtre (5YR5/6), argile sableuse, graveleuse; assez nombreuses panachures, moyennes, distinctes, assez nette, rouge (2.5YR4/8), peu nombreuse panachures fines, distinctes, assez nettes jaune (10YR7/8); structure faible, polyédrique, angulaire moyenne; friable à l'état frais, collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; nombreux nodules arrondis, mediums, ferrugineux, durs et tendres, grises/rouges; peu nombreuses racines très fines et fines, très peu nombreuses racines moyennes; transition graduelle et ondulée; pH 5.22;

Continuation du Theo 1:

Bws3 90-120+ cm Rouge (2.5YR4/8), argile, peu graveleuse; peu nombreuses panachures, moyennes, distinctes, assez nettes, rouges (10R3/3), peu nombreuses panachures moyennes, fort, assez nettes, jaunes (10YR8/8); structure moyenne, polyédrique angulaire grossière; ferme à l'état frais, collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; peu nombreux fragments anguleux de quartz peu altérée, blocs; peu nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; peu nombreuses racines très fines et fines, très peu nombreuses racines moyennes; pH 5.46.

Remarque: Veine de Quartz peu altérée (épaisseur 10 cm) à 90 cm de profondeur.

Theo 2, plantation café

Topographie: ondulé
Position physiographique: haut de versant
Roche-mère: migmatite
Drainage: normal
Par: A.A. Hooyer

Ah	0- 10 cm	Brun rougâtre à rouge jaunâtre (5YR4/5), limon argilo sableux, non graveleux; structure faible, polyédrique subangulaire moyenne; fraible à l'état frais, peu collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; nombreuses racines moyennes; charbon; transition distinctes et ondulée; pH 5.16;
AB	10- 40 cm	Rouge jaunâtre (5YR4/6), argile sableuse; très graveleuse; structure déterminée par le gravier; très friable à l'état frais, collant et plastique à l'état humide; assez nombreux pores très fins et fins, peu nombreux pores moyens et larges; très nombreux nodules spheriques, petits et medium, ferrugineux, durs, grises/rouges; peu nombreuses racines très fines; transition diffuse et ondulée; pH 4.91;
Bws1	40-100 cm	Rouge jaunâtre (5YR5/6), argile sableuse; très graveleuse; structure déterminée par le gravier; très friable à l'état frais, collant et plastique à l'état humide; assez nombreux pores très fins et fins; très peu nombreux fragments anguleux de quartz frais, graviers; très nombreux nodules arrondis, mediums, ferrugineux, durs et assez tendres, grises/rouges; très peu nombreuses racines très fines; transition graduelle et irrégulière; pH 5.12;
Bws2	100-125 cm	Rouge jaunâtre (5YR5/6), limon argilo sableux, graveleux; structure faible, polyédrique angulaire moyenne; fraible à l'état frais, peu collant et plastique à l'état humide; peu nombreux pores très fins et fins; nombreux nodules arrondis, petits, ferrugineux, assez tendres, grises/rouges; très peu nombreuses racines très fines; transition graduelle et ondulée; pH 4.84;
Bws3	125-150+ cm	Rouge jaunâtre (5YR5/6), limon argilo sableux, peu graveleux; nombreuses panachures, moyennes, vagues, assez nettes, rouges (2.5YR4/7), peu nombreuses panachures fines, distinctes, assez nettes, jaune (10YR7/8); structure moyenne, polyédrique angulaire moyenne; fraible à l'état frais, peu collant et plastique à l'état humide; peu nombreux pores très fins; peu nombreux fragments anguleux de quartz peu altérée, gravier; peu nombreux nodules arrondis, petits, ferrugineux, assez tendres, grises/rouges; très peu nombreuses racines très fines; pH 4.85.

Theo 3, plantation caoutchouc

Topographie: ondulé
Position physiographique: haut de versant/mi-versant
Roche-mère: migmatite
Drainage: normal
Par: A.A. Hooyer

Ah 0- 5 cm Brun foncé (7.5YR3/4), limon argilo sableux, peu graveleux; structure faible, polyédrique subangulaire moyenne; très fraible à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins; peu nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; nombreuses racines très fines et fines; charbon; transition distinctes et ondulée; pH 5.82;

AB 5- 30 cm Brun jaunâtre foncé (5YR3/4), limon argilo sableux, très graveleux; structure déterminée par le gravier; fraible à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins, peu nombreux pores moyens; très peu nombreux fragments anguleux de quartz frais, graviers; très nombreux nodules spheriques, medium, ferrugineux, durs, grises/rouges; assez nombreuses racines très fines et fines peu nombreuses racines moyennes; transition graduelle et ondulée; pH 4.78;

Bws1 30- 60 cm Brun rougâtre à rouge jaunâtre (5YR4/5), argile sableuse, très graveleux; peu nombreux panachures, moyennes, distinctes, assez nettes, bruns jaunâtres foncés (10YR3/6); structure déterminée par le gravier; fraible à l'état frais, collant et peu plastique à l'état humide; nombreux pores très fins et fins, peu nombreux pores moyens; très peu nombreux fragments anguleux de quartz frais, graviers et cailloux; très nombreux nodules arrondis, petits et mediums, ferrugineux, durs, grises/rouges; peu nombreuses racines très fines et fines; transition diffuse et ondulée; pH 4.81;

Bws2 60-100 cm Rouge jaunâtre (5YR4/6), argile, très graveleuse; peu nombreux panachures, moyennes, distinctes, assez nettes, bruns jaunâtre foncé (10YR3/6); structure determinée par le gravier; fraible à l'état frais, collant et plastique à l'état humide; assez nombreux pores très fins et fins; très peu nombreux fragments anguleux de quartz frais, graviers; très nombreux nodules spheriques, mediums, ferrugineux, durs et tendres, grises/rouges; très peu nombreuses racines très fines et fines; transition graduelle et ondulée; pH 4.75;

Bws3 100-130+ cm Rouge jaunâtre (5YR5/6), argile, graveleuse; structure moyenne, polyédrique subangulaire moyenne; ferme à l'état frais, collant et peu plastique à l'état humide; peu nombreux pores très fins; nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; plinthite peu cimentée, bariolée; très peu nombreuses racines très fines; pH 4.63.

Remarque: Panachures probablement nodules fortement alterés et desintegrés.

Theo 4, plantation caoutchouc

Topographie: ondulé
Position physiographique: mi-versant
Roche-mère: migmatite
Drainage: normal
Par: A.A. Hooyer

Ah 0- 5 cm Brun jaunâtre foncé (10YR3/4), limon sableux, peu graveleux; structure faible, polyédrique subangulaire moyenne; très friable à l'état frais, peu collant et peu plastique à l'état humide; très nombreux pores très fins et fins; peu nombreux nodules spheriques, mediums, ferrugineux, durs, grises/rouges; très nombreuses racines très fines et fines, assez nombreuses racines moyennes, très peu grosses racines; charbon; transition distinctes et ondulée; pH 6.43;

AB 5- 20 cm Brun jaunâtre foncé (10YR3/6), limon argilo sableux, graveleux; structure faible, polyédrique subangulaire moyenne; friable à l'état frais, collant et peu plastique à l'état humide; nombreux pores très fins et fins, peu nombreux pores moyens; nombreux nodules spheriques, mediums et grands, ferrugineux, durs, grises/rouges; nombreuses racines très fines et fines, peu nombreuses racines moyennes, très peu grosses racines; transition graduelle et ondulée; pH 5.33;

Bws1 20- 40 cm Brun jaunâtre foncé (10YR4/6), argile sableuse, très graveleuse; structure déterminée par le gravier; friable à l'état frais, collant et plastique à l'état humide; nombreux pores très fins et fins, peu nombreux pores moyens; très peu nombreux fragments anguleux de quartz peu alterée, graviers; très nombreux nodules irrégulières, mediums et grands, ferrugineux, durs et tendres, grises/rouges; assez nombreuses racines très fines et fines, très peu nombreuses racines moyennes; transition graduelle et ondulée; pH 5.00;

Bws2 40- 70 cm Brun vif (7.5YR5/7), argile sableuse, très graveleuse; peu nombreuses panachures, moyennes, distinctes, assez nettes, bruns rougâtres (2.5YR4/4); structure déterminée par le gravier; friable à l'état frais, collant et plastique à l'état humide; assez nombreux pores très fins et fins, peu nombreux pores moyens; très nombreux nodules irrégulières, mediums et grands, ferrugineux, durs et tendres, grises/rouges; peu nombreuses racines très fines et fines; transition distinctes et ondulée; pH 5.08;

B3 70-125+ cm Brun vif (7.5YR5/6), argile sableuse, peu graveleuse; nombreuses panachures, grands, vagues, assez nettes, rouges (2.5YR4/6), assez nombreuses panachures moyennes, distinctes, assez nettes, jaune brunâtre (10YR6/8), assez nombreuses panachures moyennes, distinctes, assez nettes, rouges foncés (10R3/6); massive; ferme à l'état frais, collant et peu plastique à l'état humide; assez nombreux pores très fins; très peu nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; plinthite cimentée, bariolée; peu nombreuses racines très fines; pH 5.02.

Theo 5, plantation caoutchouc

Topographie: ondulé
Position physiographique: bas de versant
Roche-mère: migmatite
Drainage: modéré
Par: A.A. Hooyer

Ah	0- 10 cm	Brun jaunâtre foncé (10YR3/6), limon sableux, non graveleux; structure faible, polyédrique angulaire moyenne; fraible à l'état frais, très peu collant et très peu plastique à l'état humide; nombreux pores très fins et fins, assez nombreux pores moyens; nombreuses racines très fines et fines, peu nombreuses racines moyennes; charbon; transition distinctes et ondulée; pH 4.77;
AB	10- 30 cm	Brun jaunâtre foncé (10YR4/6), limon argilo sableux, peu graveleux; structure faible, polyédrique angulaire grossière; fraible à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins, peu nombreux pores moyens; très peu nombreux nodules arrondis, petits ferrugineux, durs, grises/rouges; assez nombreuses racines très fines et fines, peu nombreuses racines moyennes, très peu nombreuses grosses racines; charbon; transition distinctes et ondulée; pH 4.48;
B1	30- 90 cm	Brun jaunâtre (10YR5/8), argile sableuse, peu graveleuse; structure faible, polyédrique angulaire grossière; fraible à l'état frais, collant et peu plastique à l'état humide; nombreux pores très fins et fins; très peu nombreux nodules arrondis, petits, ferrugineux, durs et tendres, grises/rouges; assez nombreuses racines très fines et fines, très peu nombreuses racines moyennes; transition distinctes et ondulée; pH 4.52;
B3	90-135+ cm	Brun jaunâtre (10YR5/8), argile sableuse, peu graveleuse; nombreuses panachures, grandes, vagues, assez nettes, rouges (2.5YR4/6), assez nombreuses panachures moyennes, distinctes, assez nettes, jaunes rougâtre (7.5YR6/8); structure moyenne, polyédrique angulaire moyenne; fraible à l'état frais, collant et peu plastique à l'état humide; assez nombreux pores très fins et fins; peu nombreux fragments anguleux de quartz assez alterée, graviers; très peu nombreux nodules arrondis, petits, ferrugineux, durs et tendres, grises/rouges; plinthite cimentée, bariolée; peu nombreuses racines très fines et fins; pH 4.69.

Remarque: Près de la fosse cailloux de quartz.

Theo 6, forêt

Topographie: ondulé
Position physiographique: bas-fond
Roche-mère: migmatite
Drainage: pauvre (nappe phreatique à 25 cm)
Par: A.A. Hooyer

Ah 0- 10 cm Brun jaunâtre foncé (10YR3/4), limon sableux, non graveleux; assez nombreuses panachures, fines, vagues, assez nettes, bruns à bruns jaunâtre (7.5YR4/4); structure faible, polyédrique angulaire grossière; friable à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins; nombreuses racines très fines et fines, peu nombreuses racines moyennes, très peu grosses racines; transition distinctes et irrégulière; pH 4.61;

AC 10- 45 cm Jaune brunâtre à brun jaunâtre clair (10YR6/5), limon argilo sableux, peu graveleux; nombreux panachures, bariolées; structure faible, polyédrique angulaire grossière; friable à l'état frais, collant et peu plastique à l'état humide; nombreux pores très fins et fins, très peu nombreux pores moyens; peu nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; assez nombreuses racines très fines et fines, peu nombreuses racines moyennes, très peu grosses racines; transition graduelle et ondulée; pH 5.45;

C 45- 95+ cm Gris à gris clair (5Y6/1), sable limoneux, graveleux; nombreux panachures, grandes, distinctes, assez nettes, bruns jaunâtres (10YR5/6); structure faible, polyédrique angulair moyenne; friable à l'état frais, peu collant et peu plastique à l'état humide; nombreux pores très fins et fins; nombreux fragments anguleux de quartz frais, graviers; peu nombreux nodules arrondis, petits, ferrugineux, durs, grises/rouges; peu nombreuses racines très fines et fines, très peu nombreuses racines moyennes; pH 5.54.

Remarque: A cause du faible profondeur de la nappe phréatique l'approfondissement était impossible.

Appendix D Data analysis Marie catena

Prof. nr.	depth (cm)	$pH-H_2O$	pH-KCl	phosphate (mgP/kg) total	phosphate (mgP/kg) Olsen	carbon % Kurmies[1]
1	0- 7	6.9	6.2	190	0.2	1.4
	7- 20	6.6	5.6	205	0.4	1.0
	20- 45	5.8	4.9	159	0.2	0.8
	45- 70	5.2	4.7	229	0.1	0.7
	70-140	5.1	4.8	270	0.0	0.7
2	0- 5	5.5	4.4	138	2.4	1.4
	5- 20	5.0	4.2	135	3.2	1.1
	20- 60	4.9	4.4	160	1.4	0.9
	60- 90	4.8	4.4	158	0.2	0.7
	90-110	4.7	4.4	183	0.0	0.7
	110-150	4.8	4.5	196	0.0	0.7
3	0- 8	5.8	4.7	200	1.9	2.3
	8- 40	4.8	4.3	140	8.4	0.7
	40- 85	5.0	4.2	195	0.1	0.8
	85-150	4.9	4.1	183	0.2	1.3
4	0- 6	5.1	4.1	100	2.8	1.5
	6- 40	4.9	4.2	70	1.2	0.9
	40- 75	4.9	4.2	73	0.4	0.8
	75-105	4.7	4.2	65	0.4	0.6
	105-125	4.8	4.3	66	3.6	0.6
	125-150	4.7	4.3	80	0.0	0.6
5	0- 10	6.2	5.5	119	1.9	1.9
	10- 40	4.9	4.2	71	1.0	0.9
	40- 70	5.1	4.2	75	0.1	0.8
	70- 90	5.1	4.3	88	0.1	0.6
	90-150	5.1	4.5	150	0.1	0.6
6	0- 5	5.1	4.1	338	1.2	6.1
	5- 30	5.1	3.9	142	0.3	2.1
	30- 60	5.0	3.7	62	0.1	1.4
	60-110	5.1	3.8	98	0.0	1.3
	110-150	5.1	4.0	75	0.0	0.8

[1] The Kurmies method is based on oxidizing the soil organic matter in a strong sulphuric acid medium. See Houba, V.J.G. and J.J. van der Lee, I. Novozamsky and I. Walinga, 1988. Soil Analysis Procedures. Part 5 in the series: Soil and Plant Analysis, a series of syllabi.Dept. of Soil Sci. and Plant Nutrition, Wageningen, Agricultural University, The Netherlands.

Prof. nr.	depth (cm)	grain size distribution (%) >250µm	50-250µm	2-50µm	<2µm
1	0- 7	37.6	31.3	11.1	18.5
	7- 20	33.4	31.7	13.0	22.4
	20- 45	34.4	22.7	11.9	31.9
	45- 70	33.5	14.4	12.3	42.2
	70-140	17.8	15.8	15.2	52.7
2	0- 5	40.1	32.9	10.4	16.2
	5- 20	40.7	28.7	10.3	21.6
	20- 60	38.8	23.9	9.4	29.6
	60- 90	34.2	18.3	10.3	40.4
	90-110	26.8	27.6	11.8	34.7
	110-150	29.6	30.2	12.7	30.3
3	0- 8	30.5	29.6	11.0	26.2
	8- 40	37.3	33.4	13.5	17.7
	40- 85	28.1	14.9	8.5	50.1
	85-150	22.9	20.0	10.0	47.6
4	0- 6	47.8	22.5	8.5	17.2
	6- 40	42.2	25.6	9.5	24.2
	40- 75	37.5	23.4	7.5	32.9
	75-105	40.0	16.7	6.3	38.6
	105-125	28.8	20.1	14.4	38.3
	125-150	33.2	18.9	13.0	37.3
5	0- 10	50.0	24.3	7.3	16.2
	10- 40	39.8	22.3	7.6	30.6
	40- 70	34.8	15.6	12.0	38.0
	70- 90	28.5	11.8	21.8	40.9
	90-150	27.1	17.8	33.2	25.2
			>50µm		
6	0- 6	-	36.5	25.8	26.8
	6- 30	-	44.6	22.2	31.9
	30- 60	-	49.2	22.0	29.3
	60-110	-	35.4	27.7	38.5
	110-150	-	72.4	14.0	15.6

Continuation Appendix D: Data analysis Marie catena

Prof. nr.	depth (cm)	Ammonium-acetate method (cmol(+)/kg) C.E.C.	Na	K	Mg	Ca	Al^{3+}	Mn
1	0- 7	5.5	0.09	0.16	0.74	6.22	0.00	0.01
	7- 20	3.7	0.02	0.06	0.49	3.07	0.00	0.01
	20- 45	3.4	0.04	0.07	0.41	1.85	0.00	0.01
	45- 70	3.2	0.02	0.08	0.29	1.12	2.02	0.01
	70-140	3.6	0.02	0.11	0.08	0.47	0.00	0.00
2	0- 5	3.5	0.02	0.04	0.21	2.40	0.00	0.02
	5- 20	3.4	0.07	0.03	0.08	2.30	0.00	0.01
	20- 60	3.8	0.07	0.03	0.04	1.57	0.58	0.01
	60- 90	3.0	0.02	0.03	0.00	1.02	0.11	0.01
	90-110	4.2	0.17	0.03	0.00	0.87	0.01	0.01
	110-150	3.8	0.02	0.03	0.00	2.95	0.01	0.01
3	0- 8	7.2	0.24	0.15	1.11	4.27	0.02	0.02
	8- 40	2.9	0.04	0.11	0.62	4.04	0.02	0.01
	40- 85	5.4	0.04	0.26	0.16	0.75	0.04	0.01
	85-150	6.6	0.09	0.17	0.37	1.40	0.02	0.01
4	0- 6	5.1	0.15	0.03	0.12	1.52	0.05	0.03
	6- 40	3.7	0.59	0.03	0.00	1.82	0.07	0.02
	40- 75	3.1	0.37	0.01	0.04	1.90	0.13	0.02
	75-105	3.6	0.09	0.03	0.04	1.45	0.17	0.01
	105-125	3.5	0.07	0.06	0.16	0.22	0.27	0.01
	125-150	3.4	0.07	0.04	0.08	0.47	0.47	0.01
5	0- 10	6.8	0.07	0.21	0.82	4.27	0.73	0.01
	10- 40	3.4	0.00	0.02	0.00	1.45	1.08	0.01
	40- 70	3.7	0.04	0.04	0.00	0.07	1.91	0.01
	70- 90	5.0	0.13	0.04	0.00	1.57	3.20	0.01
	90-150	4.7	0.15	0.07	0.12	0.17	5.47	0.01
6	0- 5	16.55	0.10	0.26	1.31	4.74	0.06	0.10
	5- 30	5.21	0.10	0.05	0.57	1.45	0.01	0.07
	30- 60	3.62	0.10	0.04	0.41	1.13	0.00	0.05
	60-110	4.29	0.05	0.04	0.63	2.42	0.02	0.03
	110-150	2.81	0.13	0.05	0.31	0.78	0.00	0.03

Appendix E Gravel contents Marie catena

Gravel contents Marie catena at different depths. Total gravel content is expressed as percentage of the dry soil, gravel types[1] are expressed as percentage of the total gravel content (source Van Herwaarden, in prep.).

Prof. nr.	Hor. code	depth (cm)	total	type 1a	type 1b	type 2	type 3	undefined
1	Ah	0- 7	70.8	89	7	1	2	3
	AB	7- 25	67.6	58	28	2	1	11
	Bws1	25- 45	68.1	53	21	5	3	19
	Bws2	45- 75	42.7	55	7	33	6	0
	Bws3	75-150	13.8	41	19	34	5	0
2	Ah	0- 5	2.7	12	15	56	17	0
	AB	5- 25	59.8	73	26	0	2	0
	Bws1	25- 60	69.9	40	6	35	11	10
	Bws21	60- 90	57.4	17	2	69	7	4
	Bws22	90-110	26.8	13	3	84	1	0
	Bws3	110-150	28.6	28	1	71	1	0
3	Ah	0- 8	70.6	61	3	34	1	1
	Bws1	8- 30	75.3	60	2	21	3	14
	Bws2	30- 70	68.9	48	21	19	2	11
	Bms	70-150	55.2	1	1	98	0	0
4	Ah	0- 6	1.8	0	0	0	98	0
	AB	6- 40	1.2	43	0	0	57	0
	Bws11	40- 70	2.9	27	10	13	50	0
	Bws12	70-100	2.3	9	5	4	66	16
	Bws2	100-120	63.9	53	4	42	1	0
5	Ah	0- 10	1.0	0	0	0	100	0
	AB	10- 30	1.8	0	0	0	100	0
	Bws1	30- 60	4.1	0	0	0	100	0
	Bws2	60-100	5.0	0	0	0	100	0
	Bws3	100-150	9.2	0	0	0	100	0
6	Ah	0- 5	0.5	0	0	0	100	0
	ACg	5- 30	0.0	-	-	-	-	-
	C11g	30- 60	0.0	-	-	-	-	-
	C12g	60-110	0.4	0	0	0	100	0
	2Cg	40-150	11.7	0	0	0	100	0

[1] Type 1a: hard, spherical, ironstone nodules, completely coated (dark patina);
Type 1b: hard, spherical, ironstone nodules, broken and incompletely coated;
Type 2: moderately hard, irregular, ironstone nodules, without a coating;
Type 3: hard, angular, mineral fragments (mainly quartz);
Type 4: undefined gravel, difficult to assign to any of the classes above.

Appendix F Results XRFS of soils Marie catena

Total amounts, in percentages, of major elements in the fine earth fraction of the horizons of the soil pits in the Marie catena, obtained by X-ray fluorescence spectrometry.

Prof. nr.	Hor. code	depth (cm)	SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO[1] %	CaO[2] %
1	Ah	0- 7	82.24	0.85	6.44	4.81	0.05	0.07	0.08
	AB	7- 25	72.58	0.86	10.46	8.49	0.04	0.05	<0.01
	Bws1	25- 45	57.40	1.15	21.02	11.39	0.04	<0.03	<0.01
	Bws2	45- 75	61.63	1.02	17.55	10.19	0.04	0.05	<0.01
	Bws3	75-150	66.76	0.99	14.91	10.58	0.04	<0.03	<0.01
2	Ah	0- 5	87.37	0.70	5.37	3.33	0.05	0.07	0.01
	AB	5- 25	81.42	0.82	6.02	4.62	0.04	0.07	<0.01
	Bws1	25- 60	77.65	0.80	9.76	5.06	0.03	0.06	<0.01
	Bws21	60- 90	69.71	0.85	13.84	8.06	0.04	<0.03	<0.01
	Bws22	90-110	59.45	1.05	19.72	9.85	0.04	<0.03	<0.01
	Bws3	110-150	56.50	1.12	20.94	10.81	0.04	<0.03	<0.01
3	Ah	0- 8	74.32	1.17	8.52	5.99	0.07	0.36	0.77
	Bws1	8- 30	65.68	1.08	14.95	8.80	0.05	0.13	<0.01
	Bws2	30- 70	58.71	1.13	18.94	10.85	0.05	<0.03	<0.01
	Bms3	70-150	57.96	1.05	19.98	11.84	0.04	<0.03	<0.01
4	Ah	0- 6	82.85	0.53	8.12	2.38	0.02	0.06	<0.01
	AB	6- 40	81.98	0.60	8.92	2.36	0.02	0.05	<0.01
	Bws11	40- 70	82.00	0.57	8.87	2.40	0.01	0.07	<0.01
	Bws12	70-100	79.93	0.56	10.96	2.77	0.01	0.06	<0.01
	Bws2	100-120	67.28	0.71	15.64	7.80	0.02	<0.03	<0.01
	Bws3	120-150	70.48	0.65	15.02	5.55	0.01	0.04	<0.01
5	Ah	0- 10	79.93	0.59	10.94	2.39	0.01	0.04	<0.01
	AB	10- 30	79.25	0.59	10.77	2.37	0.01	<0.03	<0.01
	Bws1	30- 60	71.96	0.65	15.51	3.48	0.01	<0.03	<0.01
	Bws2	60-100	51.37	0.85	21.32	16.20	0.01	<0.03	<0.01
	Bws3	100-150	52.95	0.76	20.25	16.28	0.01	<0.03	<0.01
6	Ah	0- 5	73.29	0.85	11.10	1.58	0.02	0.07	0.13
	ACg	5- 30	78.39	0.81	11.39	1.14	0.02	0.06	0.03
	C11g	30- 60	80.29	0.77	10.49	1.41	0.02	0.05	0.02
	C12g	60-110	75.43	0.91	14.21	1.40	0.02	0.05	0.02
	2Cg	140-150	86.84	0.76	6.82	1.04	0.03	0.07	0.03
migmatite			70.62	0.54	14.37	4.45	0.04	1.69	2.46

[1] Values <0.03 % are below detection limit.

[2] Values <0.01 % are below detection limit.

Continuation Appendix F: Total amounts, in percentages, of major elements in the fine earth fraction of the horizons of the soil pits in the Marie catena, obtained by X-ray fluorescence spectrometry.

Prof. nr.	Hor. code	depth (cm)	Na_2O[3] %	K_2O %	P_2O_5[4] %	BaO[5] %	M.L.I[6] %	sum %
1	Ah	0- 7	<0.04	0.14	0.05	<0.03	4.92	99.33
	AB	7- 25	<0.04	0.10	0.06	<0.03	5.71	98.21
	Bws1	25- 45	<0.04	0.01	0.08	<0.03	9.61	100.32
	Bws2	45- 75	<0.04	0.04	0.07	<0.03	8.42	98.68
	Bws3	75-150	<0.04	0.06	0.07	<0.03	7.37	100.46
2	Ah	0- 5	<0.04	0.01	0.04	<0.03	4.89	101.48
	AB	5- 25	<0.04	0.01	0.04	<0.03	4.86	99.51
	Bws1	25- 60	<0.04	0.00	0.04	<0.03	5.46	98.49
	Bws21	60- 90	<0.04	0.00	0.05	<0.03	6.81	98.97
	Bws22	90-110	<0.04	0.00	0.06	<0.03	9.01	98.81
	Bws3	110-150	<0.04	0.00	0.06	<0.03	9.32	98.38
3	Ah	0- 8	<0.04	0.01	0.08	<0.03	7.49	98.44
	Bws1	8- 30	<0.04	0.00	0.05	<0.03	8.25	98.66
	Bws2	30- 70	<0.04	0.00	0.06	<0.03	9.53	98.45
	Bms	70-150	<0.04	0.01	0.05	<0.03	9.83	100.40
4	Ah	0- 6	<0.04	0.00	0.03	<0.03	5.47	99.07
	AB	6- 40	<0.04	0.00	0.02	<0.03	4.89	98.47
	Bws11	40- 70	<0.04	0.00	<0.01	<0.03	4.59	98.11
	Bws12	70-100	<0.04	0.00	0.02	<0.03	5.07	98.99
	Bws2	100-120	<0.04	0.00	0.02	<0.03	7.13	98.21
	Bws3	120-150	<0.04	0.00	0.02	<0.03	6.76	98.15
5	Ah	0- 10	<0.04	0.01	0.02	<0.03	4.49	98.01
	AB	10- 30	<0.04	0.01	0.02	<0.03	5.54	98.18
	Bws1	30- 60	<0.04	0.01	0.02	<0.03	7.15	98.45
	Bws2	60-100	<0.04	0.00	0.04	<0.03	10.82	100.16
	Bws3	100-150	<0.04	0.00	0.05	<0.03	10.04	99.89
6	Ah	0- 5	<0.04	0.57	0.09	<0.03	13.48	101.04
	ACg	5- 30	<0.04	0.57	0.04	<0.03	6.14	98.42
	C11g	30- 60	<0.04	0.56	0.02	<0.03	4.60	98.06
	C12g	60-110	<0.04	0.57	0.03	<0.03	5.81	98.26
	2Cg	140-150	<0.04	0.54	0.02	<0.03	2.74	98.71
	migmatite		3.18	2.14	0.16	0.06	0.86	100.56

[3] Values <0.04 % are below detection limit.

[4] Values <0.01 % are below detection limit.

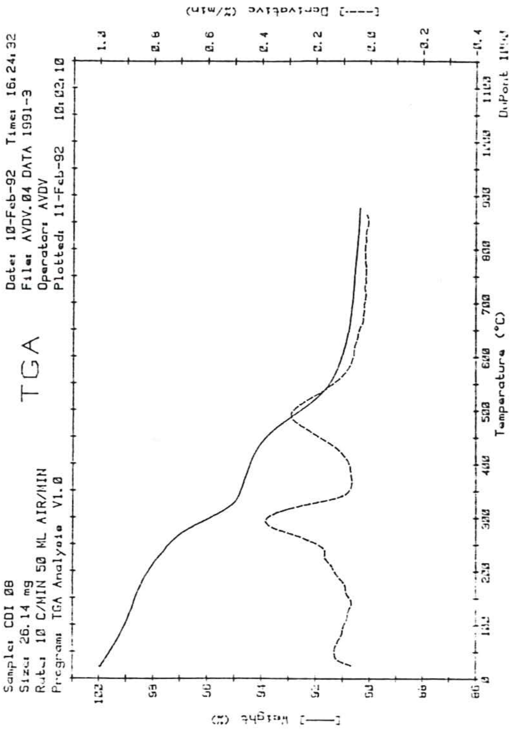
[5] Values <0.03 % are below detection limit.

[6] M.L.I. - Mass Loss on Ignition the sample is put away at 900 °C for at least four hours.

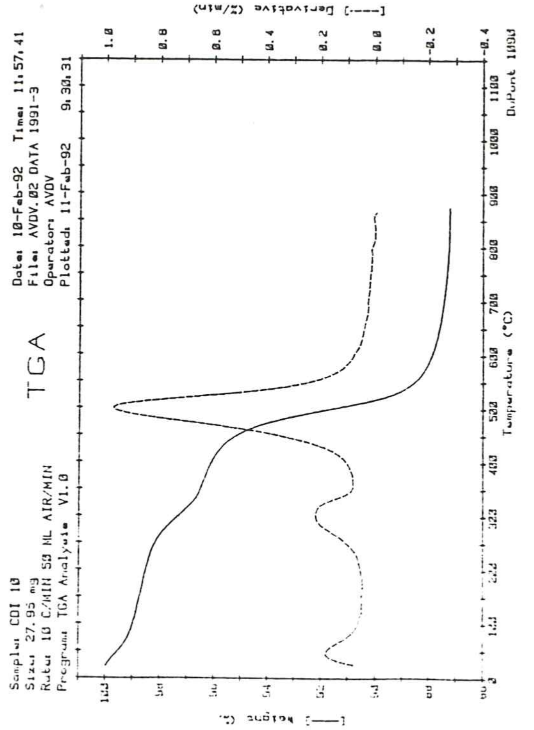
Continuation Appendix F: Weight percentages dithionite-, oxalate- and pyrophosphate-extractable iron and aluminium in selected horizons of the soils on the Marie catena.

Prof. nr.	1	1	3	3	4	5	5	6
Hor. code	Ah	Bws3	Bws1	Bms3	Bws3	Bws2	Bws3	2Cg
depth (cm)	0-7	75-150	8-30	70-150	120-150	60-100	100-150	140-150
%								
Fe-dithion.	2.3	4.8	4.1	5.9	3.2	8.7	7.1	0.1
Fe-oxalate	0.1	0.1	0.1	0.1	0.0	0.2	0.1	0.0
Fe-pyroph.	0.2	0.1	0.8	0.2	0.0	0.0	0.0	0.0
Al-dithion.	0.3	0.6	0.6	0.7	0.4	0.6	0.4	0.0
Al-oxalate	0.0	0.1	0.1	0.1	0.1	0.2	0.1	0.0
Al-pyroph.	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0

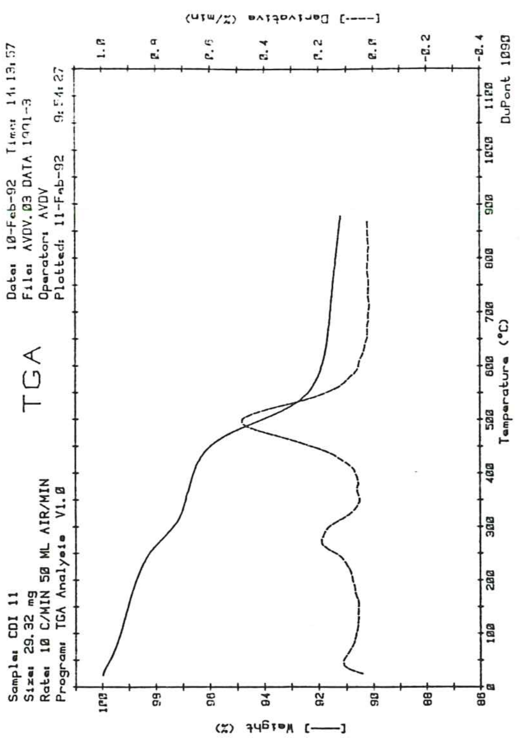
Appendix G Diagrams of thermogravimetric analyses ironstone gravel Theo catena



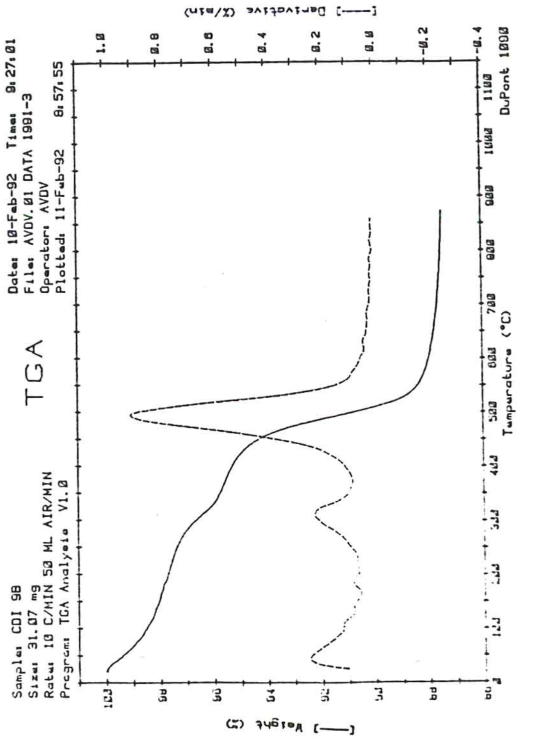
a. hard purple ironstone gravel



c. uniform reddish brown ironstone gravel



b. soft purple ironstone gravel



d. light yellowish part of the mottled ironstone gravel

Appendix H Calculations weight percentages goethite and kaolinite from data thermogravimetric analyses

To calculate the weight percentage water in goethite respectively kaolinite, the following formula were used:

$$\textit{weight \% goethite} = \frac{b - c}{10.14 * a} * 10^3$$

$$\textit{weight \% kaolinite} = \frac{c - d}{13.96 * a} * 10^3$$

in which:

a = weight sample before heating
b = weight sample at 230 °C
c = weight sample at 375 °C
d = weight sample at 600 °C

10.14 = weight % water in goethite
13.96 = weight % water in kaolinite

Hard ironstone gravel

a = 26.14 mg
b = 25.56 mg
c = 24.73 mg
d = 23.80 mg

weight % goethite = 31.3
weight % kaolinite = 25.5

Soft purple ironstone gravel

a = 29.32 mg
b = 28.88 mg
c = 28.37 mg
d = 26.95 mg

weight % goethite = 17.2
weight % kaolinite = 34.7

Soft uniform reddish brown ironstone gravel

a = 27.95 mg
b = 27.48 mg
c = 26.92 mg
d = 24.57 mg

weight % goethite = 19.8
weight % kaolinite = 60.2

Light yellow part of soft reddish brown/light yellow ironstone gravel

a = 31.07 mg
b = 30.31 mg
c = 29.70 mg
d = 27.34 mg

weight % goethite = 19.38
weight % kaolinite = 52.4