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The paleosol in the Kerkom Sands near Pellenberg (Belgium) revisited

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Abstract

In an area east of Leuven (central Belgium), a buried sandy estuarine deposit of Oligocene age contains a dark colored organic layer of about 4 m thick. Our results suggests that the organic matter is an illuvial horizon, therefore warranting the hypothesis that the layer may qualify for a giant buried spodic horizon rather than a remainder of a Tertiary oil seepage as suggested by Van Riessen and Vandenberghe (1996). Of particular importance is the micro-morphological evidence, which reveals that the mainly monomorphous organic matter is present as ubiquitous coatings and concentrations around the quartz grains. These coatings show the for Podzols very typical polygonal cracked patterns. The geochemical signature (stable carbon isotope analysis) also gives strong indications for a continental origin of the organic carbon and therefore support the pedogenetic origin of the horizon. The paleopedological scene into which this soil has developed is inferred from the data.

Keywords: Paleopedology, Podzols, Micromorphology, Geochemistry

Introduction

Soils change spatially due to different paths of pedogenetic evolution on different lithologies in different topographical situations. Jenny's factors of climate and of time, are complicated by the effects of changing climates of variable duration (Jenny, 1941). Current soil cover is the result of a long pedogenetic history and in order to understand its geography, it is necessary to trace its present and past genesis. Paleosols are particularly important to provide insights in past pedogenesis, because they are a witness of former soil forming factors. This paper brings the case of a controversial paleosol, the so-called 'sable chocolaté' at the top of the Kerkom Sands, which can be seen in the Roelants sand quarry near Leuven (Belgium). It was originally interpreted as a relict Spodic B horizon from a fossil Giant Podzol, having an organic matter content of about 4.3% (Gullentops et al., 1988; Gullentops, 1990). A few years ago however, Van Riessen and Vandenberghe (1996) proposed that it is a fossil seepage from one of the North Sea oil deposits. The purpose of this paper is to reflect on the origin and formation of the 'chocolate-colored horizon' in the light of the present-day knowledge of pedogenesis of Podzols and based on new pedological data collected during a recent field research campaign.

Podzols have a horizon with accumulation of organic matter, aluminium and/or iron. Most show an albic E-horizon but this is not diagnostic. In Soil Taxonomy (Soil Survey Staff, 1999) Podzols are in principle part of the Spodosols, but not all soils that are considered to be Spodosols satisfy the criteria for a

Spodic horizon, diagnostic for a Podzol. In this paper the definitions of the World Reference Base for Soil Resources (WRB) (FAO/ISRIC/ISSS, 1998) will be used as a yardstick in the discussion. According to WRB, Podzols are soils having a Spodic horizon starting within 200 cm from the surface, underlying an albic, histic, umbric or ochric horizon, or an anthropedogenetic horizon less than 50 cm thick. The Spodic horizon is a dark colored subsurface horizon, which contains illuvial amorphous substances, composed of organic matter and aluminium, with or without iron.

Podzols are almost exclusively found in humid regions where precipitation exceeds evapo-transpiration. There appears to be no relationship between temperature and the occurrence of Podzols, although they occur almost exclusively in the boreal regions. Besides these zonal Podzols smaller occurrences of intrazonal Podzols, occur both in temperate and tropical regions (Driessen et al., 2001). In most of these cases a quartz-rich sandy parent material, poor in bases, a specific topography, a predominant superfluous precipitation and a low base content of the vegetation are the dominant pedogenetic factors. In many intrazonal Podzols, groundwater is the major soil-forming factor.

According to Retallack (1990), the first indications of podzolization appear in some Cambisols of Late Devonian age. The oldest indisputable Podzols are to be found at the end of the Eocene between the Sables de Beauchamps (Bartonian age) and the formation of Ezanville in the area near Paris (Retallack, 1986). A paleosol, which has an eluvial horizon was investigated by Buurman and Jongmans (1975) in Belgian and Dutch Limburg at the top of the Neerrepen Sands below the Lower Oligocene Henis Clay, and referred to as an Early Oligocene Podzol. Although the presence of a spodic B-horizon in this paleosol still remains questionable, the podzolization process has nevertheless been demonstrated.

The oil seepage hypothesis

Van Riessen & Vandenberghe (1996) suggested that the organic accumulation in the studied deposit is a Tertiary oil seepage. The possible oil impregnation is related to an important tectonic rearrangement, which started at the end of the Eocene and may have triggered migration of oil from traps in the southwest of the Netherlands to the Leuven area. The migrated oil may have generated a number of local oil seepages at the top of the early-Oligocene Kerkom Sands that occurred at the surface at that moment. Volatile and light components would have been evaporated during the aerial exposure, leaving the heavy components behind that consolidated and cemented the tar sands. The geochemical arguments for the oil-seepage hypothesis focused on the bitumen fraction. The bitumen is presumably relatively unchanged and is extractable in an apolar organic solvent. The geochemical fossils found in this fraction (pristane, phytane, steranes, dinosterone), which are frequently used in organic geochemistry to identify the origin of the organic material in oil exploration, indicate an environment that did not correspond to the local Oligocene environment, and hence it was concluded that they must be secondary geochemical fossils, produced elsewhere in a mature, marine, marly, Type II source rock of Mesozoic age. According to Van Riessen & Vandenberghe (1996) it is especially the maturity, which does not agree with the immature Kerkom Sands that leads to their interpretation of the chocolate horizon as an oil seepage.

Although it is a worthy hypothesis, it may not be justified to use the conventional geochemical tools, developed for the characterization of the origin of oils, and the geochemical fossils out of the bitumen fraction to research fossil Tertiary tar sands, which are furthermore almost completely humified. Although most of the organic matter in soils consists of humic-like compounds, mineral soils also contain up to 5% of the organic fraction that is soluble in apolar organic solvents. The question is how geochemical biomarkers behave and how their distribution is in (fossil) soils. Van Riessen & Vandenberghe have used organic matter of Chinese soil for comparison. Because organic matter chemistry in soils is quite variable, and differences between Podzols and other soils are major, this does not make much sense (Buurman et al., 1999). Therefore, Buurman et al. (1999) focussed on the humic acid type organic matter of both fossil and recent soils. They report on loss of polyphenols and an increase in long-chain aliphatics in fossil Podzols compared to Holocene Podzols. Although the chromatograms of the Holocene samples are not identical with those of the fossil ones, Buurman et al. (1999) recognized a genetic development sequence rather than a systematic difference between the two groups. In their reply, Van Riessen & Vandenberghe (1999) rightfully argue that Humic type organic matter is not solely restricted to the soil environment, and that a more profound genetic characterization of the humified fractions may be necessary for a more conclusive answer.

Geological profile

The sand quarry Roelants I, in which the buried profile was described and sampled is situated at Pellen-

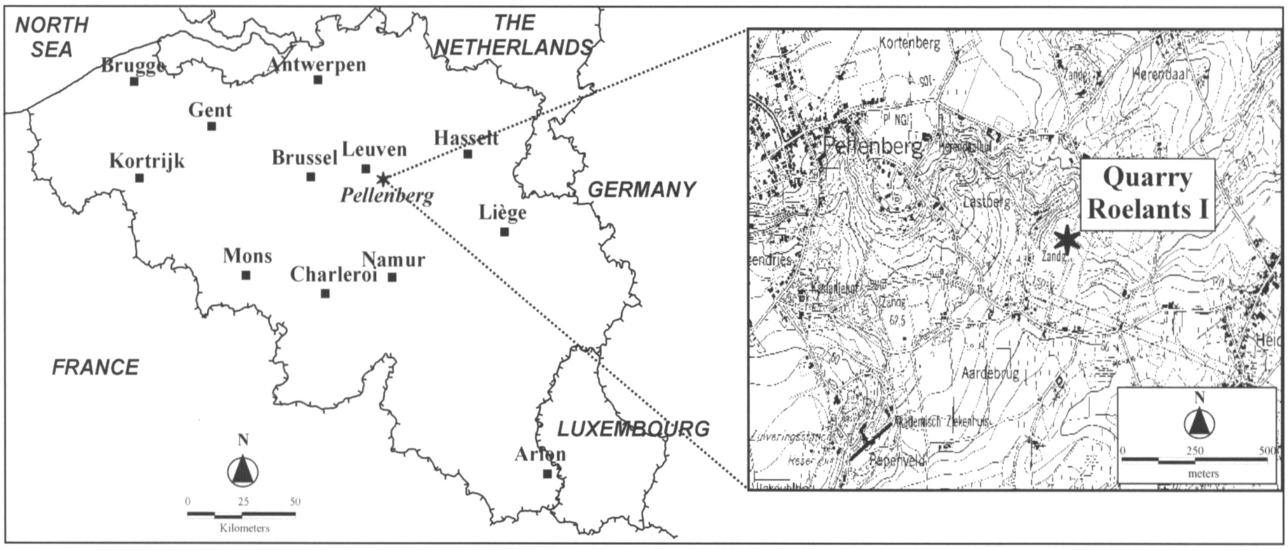

Fig. 1. Geographical location of the Roelants I quarry.

berg (Fig. 1), some 8 km east of Leuven and 4 km south-west of Lubbeek (coordinates 4°, 49′ E and 50° 52′ N).

Fig. 2 illustrates the overall setting of the different lithological units of the Belgian Tongerian and Rupelian. The wealth of facies and events allow identification of turning points from regression to transgression as local North Sea Stages, hence the Tongerian-Rupelian boundary and the stratigrafic position of the paleosol can be clearly identified (Gullentops, 1990). A schematic close-up of the stratigraphic succession in the Roelants I quarry is (partially) represented in Figure 2 and is as follows from the top down: (i) ± 1 m of Pleistocene löss (ii) Diest Sands (late Miocene) (iii) Boom Clay and Berg Sands (Rupelian – Oligocene) (iv) Marine Heide Sands (Oligocene) (v) Kerkom Sands, estuarine deposit (Oligocene).

The transition between (iv) and (v) is sharp and cliff structures are present. (iv) contains black rounded pebbles and irregular blocks, with the same color and texture as the underlying Kerkom Sand. The top 4 m of the Kerkom Sands has a dark color due to organic matter. The dark colored horizon is the subject of this study.

It is important to recall the paleogeographic evolution as deduced by Gullentops (1990). The phenomena observed in a very small area are indications for a rhythmic transgression of the Rupelian sea. A small regression allows the emersion of the estuarine Kerkom Sands and the installation of a wet-land vegetation responsible for a humic Podzol. Wave erosion on the advancing shore-face of the next transgressive pulse shaves off the soil to a remarkable cliff. The cohesive B_h allows even undercutting of the cliff and

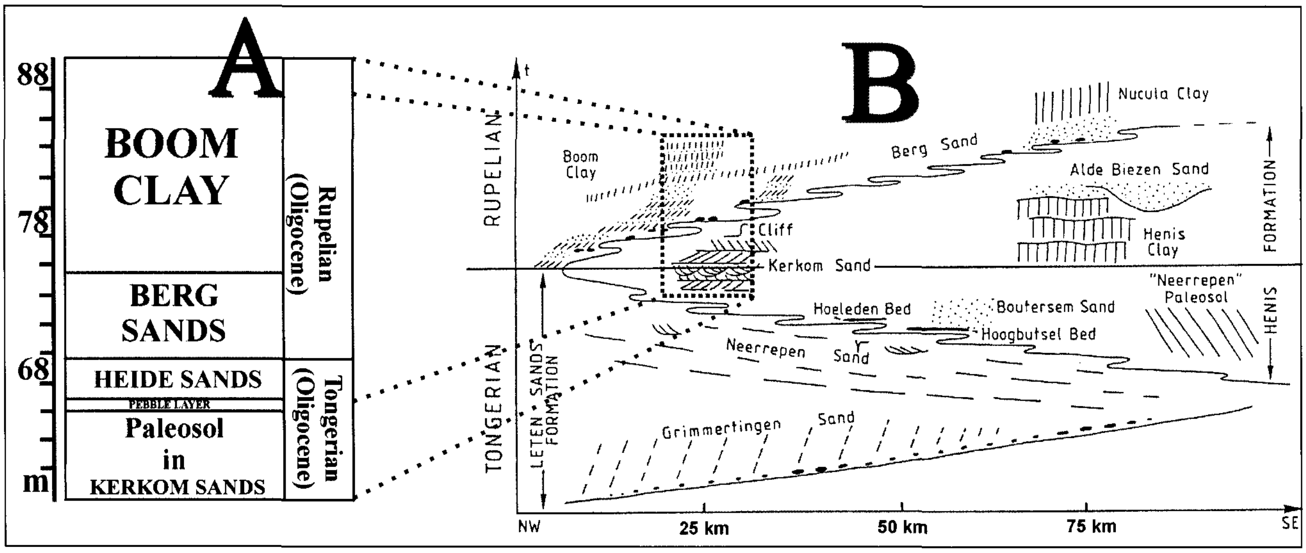

Fig. 2. Close-up (A) of the stratigraphic succession in the Roelants I quarry in the overall setting (B) of the different lithological units of the Belgian Tongerian and Rupelian and their cyclicity, adapted after Gullentops (1990).

rounding of the tumbled lumps. A new transgressive pulse brings in a second layer of the typical flat beach pebbles, about one meter higher. On the cliff it shaves off another part of the paleosol, certainly its eluvial horizon.

Methods

The soil profile was described according to guidelines for soil profile description (De Pauw, 1985). Thin sections for micromorphology were made out of undisturbed samples, petrified with 'Buehler epothin' low viscosity epoxy glue.

Granulometry of the soil samples was determined by laser diffraction analysis (Malvern Mastersizer S long bed) after removing carbonates (0.1M HCl), iron oxides (0.5% oxalic acid, boiling) and organic carbon (35% H_2O_2, 60°C) and applying a peptizing solution (10g/l sodium polyphosphate, boiling). Konert and Vandenberghe (1997) report good correspondence of the results from this technique with those from sieving and the pipette method, except for the (<2 μm) clay fraction. Using a higher grain size level for the clay fraction, when laser analysis is applied, enables comparison of the pipette results with the laser technique. The laser diffraction fraction <8 microns was believed to have a 1:1 correlation with pipette clay. Total organic carbon content was determined by the Amato method (Amato, 1983).

In order to elaborate on the origin of the organic carbon (pedogenetic versus oil seepage) a comparison was made of the isotopic (^{13}C / ^{12}C) composition with that of a well known oil seepage in Oklahoma, USA. The carbon isotopes were determined with a GSL/20-20 mass spectrometer both on powdered soil samples and on humic acids, extracted in 0.1 M NaOH, reprecipitated at pH 2, separated from the fulvic acids in the supernatant liquid by centrifugation, and finally redissolved in 0.1 M NaOH. Some extracts were freeze dried, others were purified by centrifugation of the extract in 'Millipore Tubes' (5000 MW) at 6000 rpm. Elemental composition of humic acids (C, H, N and S) was determined with an EA 1110 Elemental Analyzer, both on pulverized solid soil samples and on freeze dried and purified humic acids.

Results and discussion

Macromorphology

For the purpose of this paper a profile, situated on the northern flank of the Roelants I quarry, is described below (Table 1, Figs. 3 & 4). A comparable horizon pattern was found on the other side of the quarry, though the thickness of the different sub-horizons was rather variable.

The top of the profile coincides with the top of the Kerkom Sands and the total depth of the organically enriched horizon is about 4 m. The top of the Kerkom Sands is clearly erosional with cliff-structures and with both ordinary stony pebbles and black rounded pebbles and angular blocks of humic material derived from the humic horizon exposed in the overlying Heide Sands. There are some vertical white cracks and horizontal black bands present in the profile (Fig. 5).

Supposedly, the white cracks have formed after the Podzol, as a result of minor displacements. The white color is due to removal of organic matter. The black bands have a higher organic carbon content than the rest of the horizon, they do not extend throughout the whole profile width and are very variable in size. The profile is not very stable and frequently a part of the exposed wall collapses; only the black bands seem to have a greater cohesion.

Laterally the base of the overlying sands descends for nearly 1m abruptly over what is clearly a fossil cliff

Table 1: Profile-A, Roelants quarry, Pellenberg (Belgium), northern flank.

Bh1: 0-70 cm	dull brown (7.5 YR 5/3) loose, structureless, porous, organic-coated sand, with light brownish grey (7.5 YR 7/1) vertical cracks containing uncoated quartz grains; the cracks have sharp, irregular boundaries and extend into the underlying horizon; smooth boundary to:
Bh2: 70-293 cm	very dark brown (7.5 YR 2/3) loose, structureless, porous, organic coated sand, with vertical light brownish grey (7.5 YR 7/1) cracks containing uncoated quartz grains, the cracks have sharp, irregular boundaries; with black (7.5 YR 1.7/1) lamellae of variable thickness slightly more resistant and slightly harder than the matrix; smooth boundary to:
Bh3: 293-395 cm	brownish black (7.5 YR 3/1) loose, structureless, porous organic coated coarse sand, coarser below 355 cm, smooth boundary to:
C : > 395 cm	Greyish yellow (10 YR 5/2) soft, structureless, porous sand

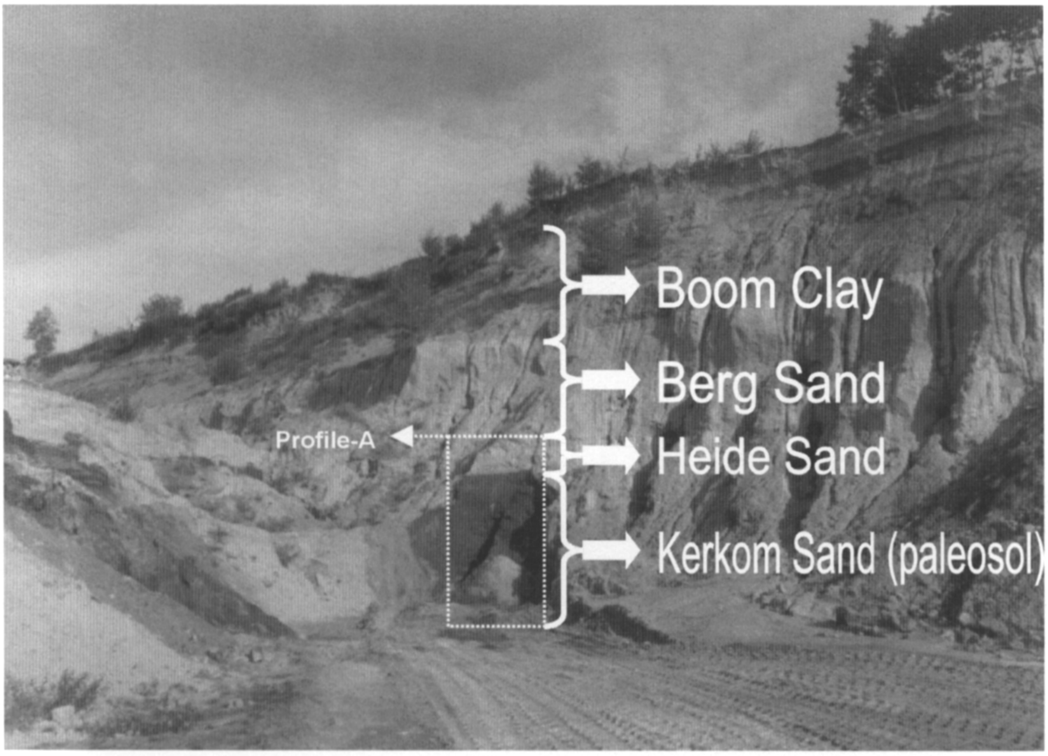

Fig. 3. General view of the quarry.

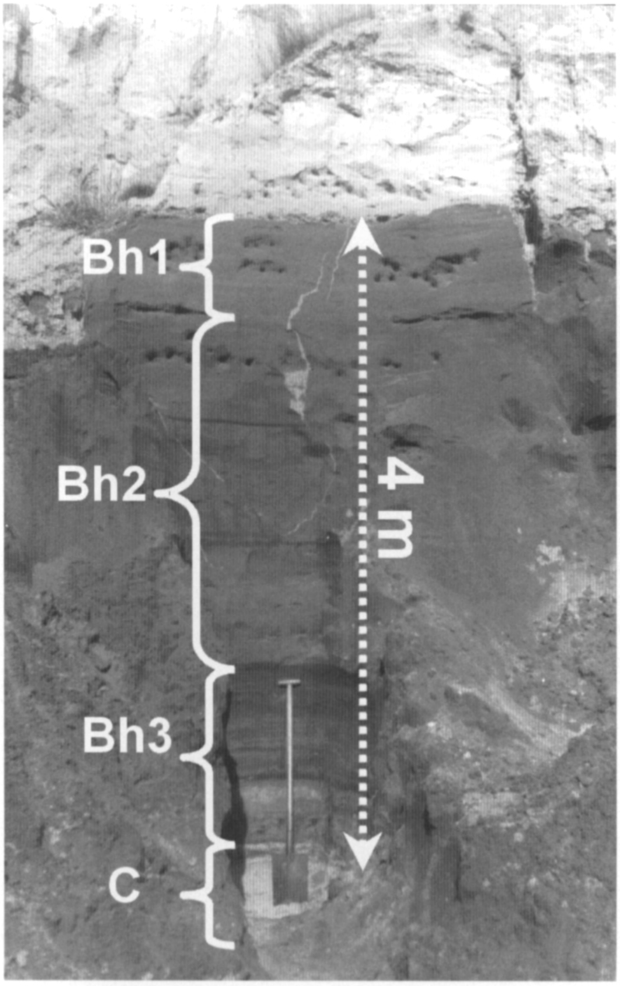

Fig. 4. Detailed view of profile A.

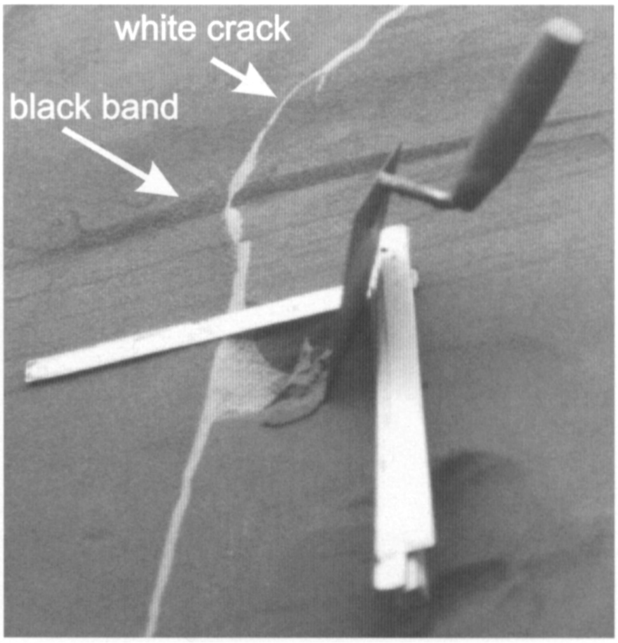

Fig. 5. Vertical white cracks without organic matter and horizontal black bands with a higher organic carbon content.

(Gullentops, 1990) (Fig. 6). At the base of the cliff, higher concentrations of humic pebbles, soil lumps and blocks can be found, which become smaller and more rounded by wave action with increasing distance from the cliff (Figs. 7 and 8).

These features (cliff-structures, humic blocks) indicate that the Spodic horizon was cemented at the time of the denudation of the profile by the erosive

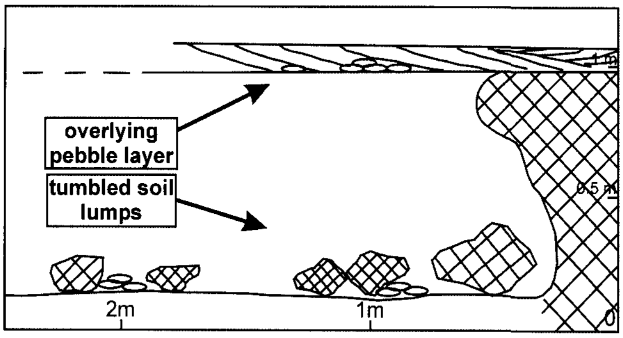

Fig. 6. Paleosol and Rupelian cliff (after Gullentops, 1990).

transgression. The latter is common in Podzols, where accumulated amorphous material frequently acts as a cementing agent. After burial, the horizon could have lost cohesion by partial decomposition of the organic matter (O.M.) and by changes in organic matter chemistry upon long burial and subsequent aeration as suggested by Buurman et al. (1999). The thickness of the Spodic horizon (at some places up to 4 m) suggests development under wet conditions. This is confirmed by the brown horizon's morphology (color, texture, and accumulation of O.M.), which is nearly identical to Spodic horizons of contemporary Carbic Podzols. A and E horizons and the upper part of the B horizon could have disappeared by the erosive power of later transgressions. The thickness is comparable to that of B horizons of groundwater Podzols in the northern and eastern U.S.A. (Daniels et al., 1975; Holzhey et al., 1975), which have no free Fe and contain small amounts of weatherable minerals favoring deep translocation of mobile organic constituents (DeConinck, 1983). The site may have been situated in a local depression in the landscape so that the organic carbon was not only coming from vertical but also from more elevated neighboring areas by lateral illuviation. Post-burial migration of the organic compounds is unlikely because it appears extremely difficult to remobilize the organic matter once it is precipitated. Conversely, further anaerobic degradation of the organic carbon is very likely to have happened after burial.

Micromorphology

The thin sections of the paleosol at Pellenberg (Fig. 9) were compared with others from a contemporary gleyic Podzol with monomorphic organic matter in the Belgian Campine (Fig. 10) and with Oklahoma tar sands (Fig. 11).

The resemblance in micro-morphological characteristics between the paleosol and the present-day Podzols is convincing. The mineral skeleton observed in thin sections from the organically enriched Kerkom Sands at Pellenberg, is composed mainly of quartz grains and a few feldspars. The mainly monomorphic organic matter is present as ubiquitous coatings and bridges. The coatings show the very typical polygonal cracked pattern for Podzols. This

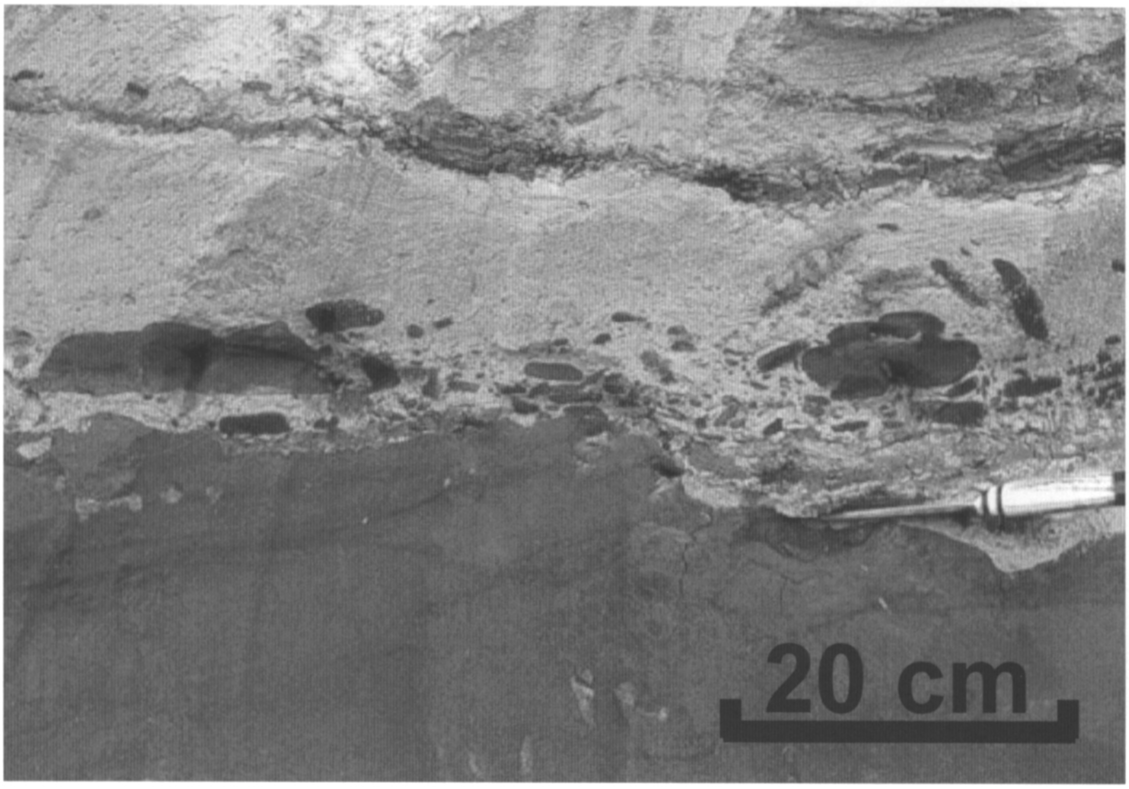

Fig. 7. Humic pebbles and blocks in the overlying Heide Sands.

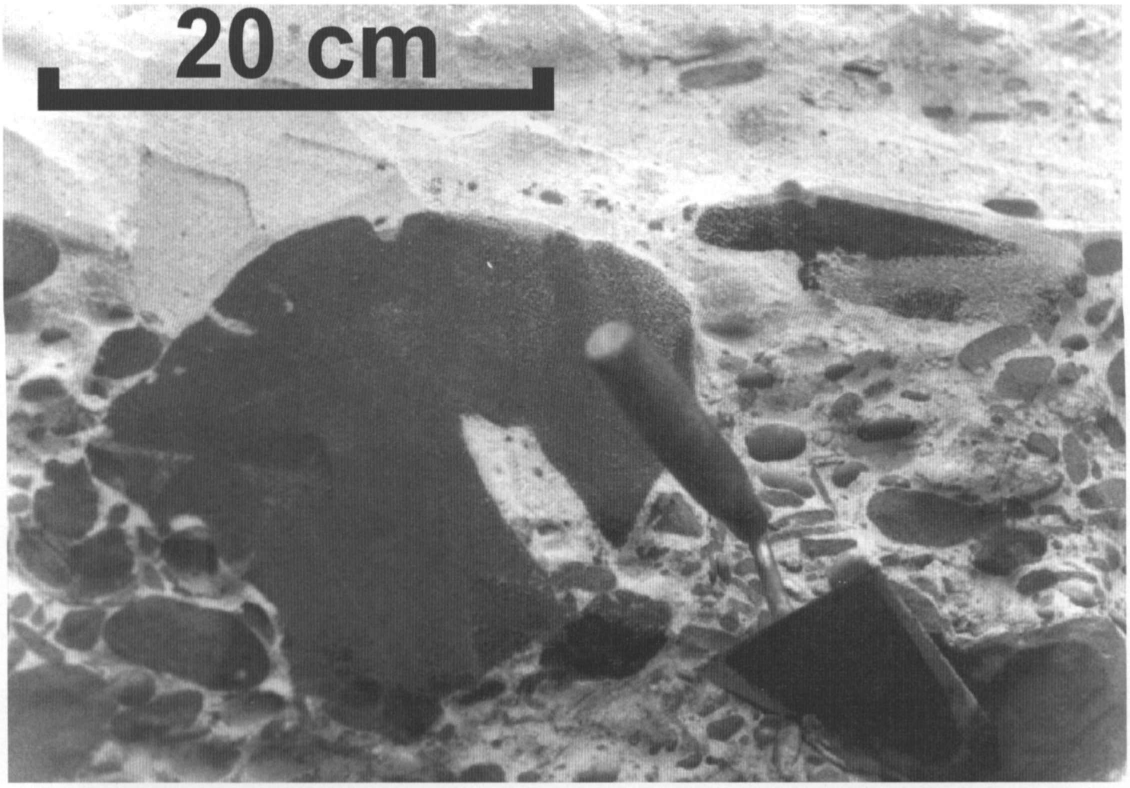

Fig. 8. Detail of humic pebbles and blocks in the overlying Heide Sands.

cracked pattern is related to the gel-like state of the organic matter when deposited in a spodic horizon (i.e., the organic constituents are surrounded by high amounts of hydration water). The transition to a solid state is accompanied by the loss of the majority of the hydration water, causing the strongly developed cracking pattern (DeConinck, 1980). Recognizable plant rests are absent.

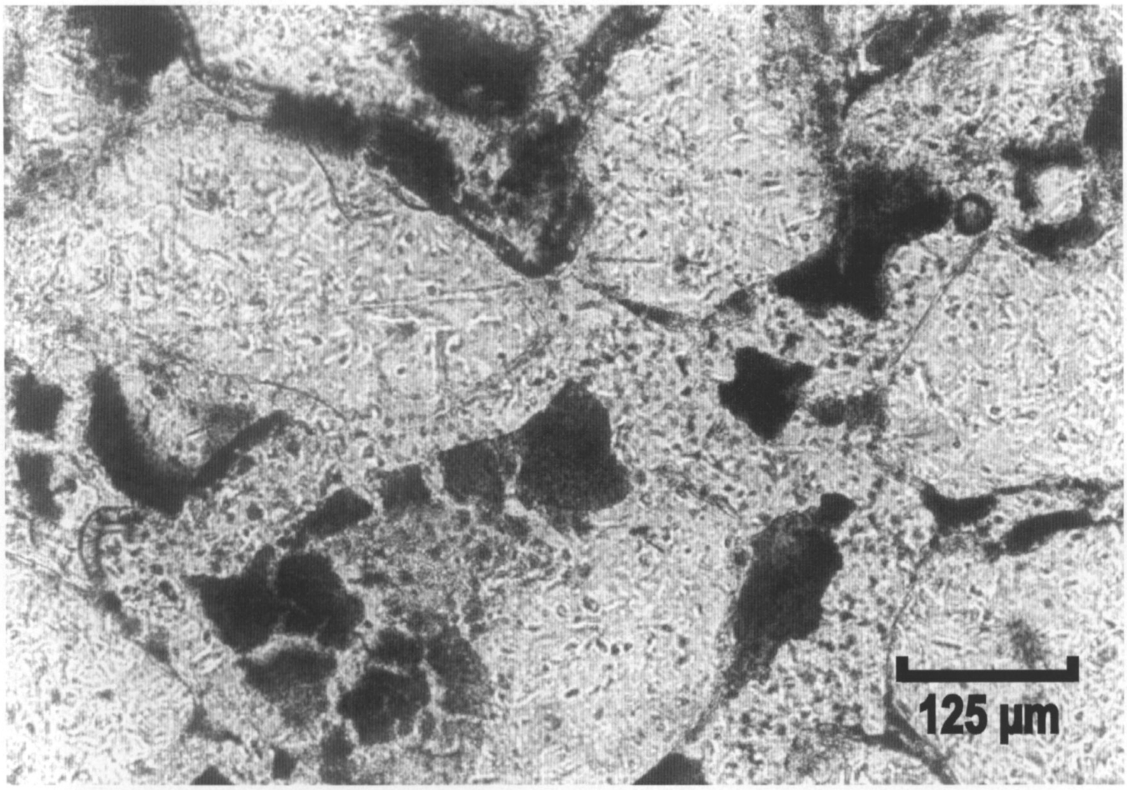

Fig. 9. Thin section of the paleosol with the cracked organic matter.

Fig. 10. Thin section of a present-day Podzol (Mol, Belgian Campine) with the cracked organic matter.

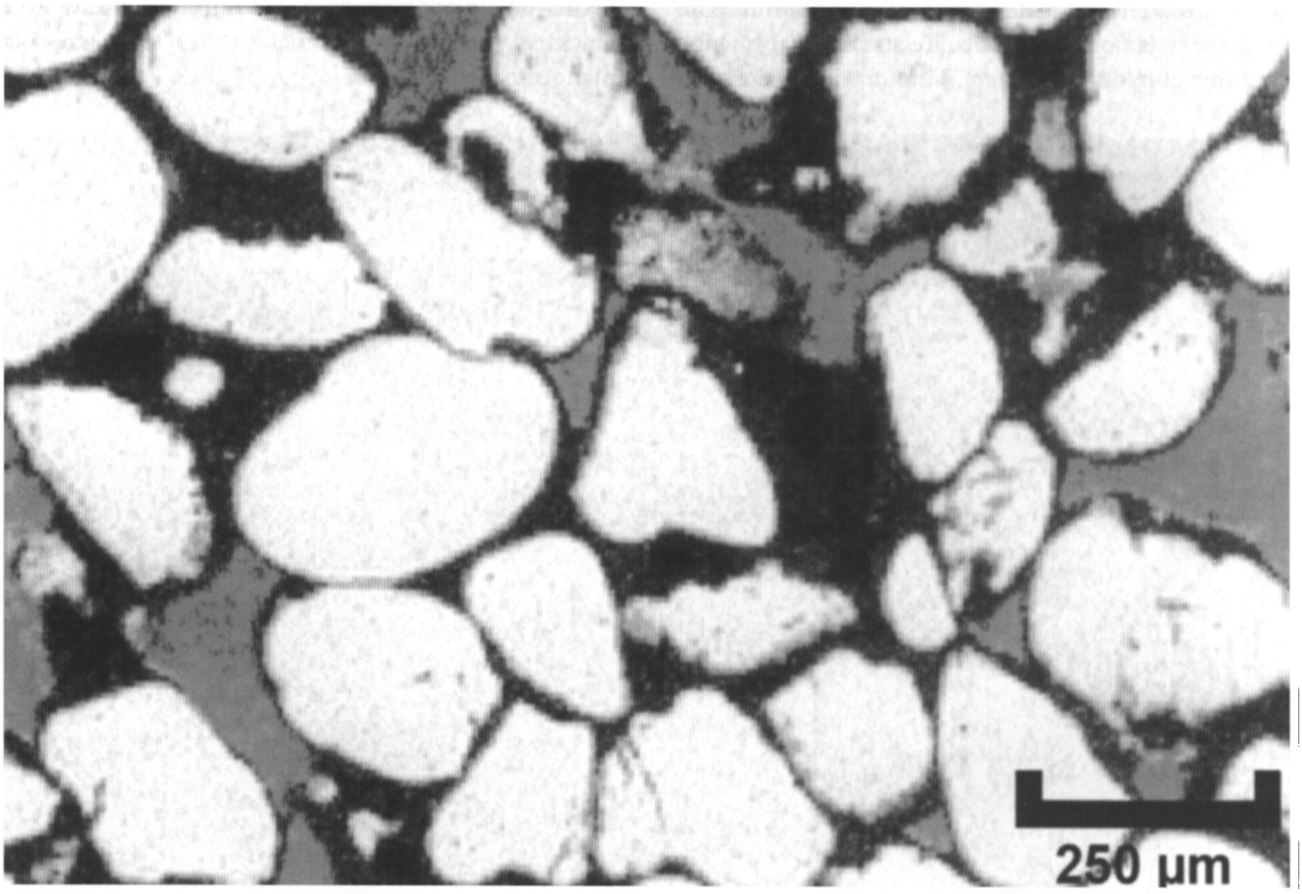

Fig. 11. Thin section of the Oklahoma tar sands (no cracked organic matter). Detail from plate 8 in the AAPG, 1997 Annuel Convention Guidebook Field Trip # 2: Petroleum Systems, Ardmore Basin and Arbuckle Mountains, Oklahoma, p 61.

In the Oklahoma tar sands the coatings are not cracked. Absence of cracked coatings in oil seepages is logical because their genesis does not have a hydration stage, which is essential to form the cracks upon dehydration.

The dark color of the horizon and the absence of uncoated quartz grains, due to an organic coating around all other constituents are typical field characteristics of monomorphic organic matter and are identical to present day Spodic horizons with monomorphic organic matter. The deep bleached cracks may also be due to the removal of the monomorphic organic matter, probably caused by increased water percolation and aeration along slight tectonic deformations.

Present day spodic horizons commonly have darker bands, identical to the bands in the studied paleosol. In hydromorphic Podzols they tend to have sharp, straight boundaries that are determined by sedimentary stratification. In well-drained Podzols, the bands are more irregular because they are related to penetration depth of rainfall events.

Granulometry and organic carbon content of the strata

The analytical data of the profile on the northern (profile A) and southern (profile B) flank of the Roelants I quarry are summarized in Table 2. The textural class is sand for all samples, but the distribution of the different sand fractions varies between the distinct sub-horizons. Down to approximately 3 m, the Kerkom Sands are well-sorted, almost symmetrical, intermediate to fine sands. The dark bands contain somewhat more clay than the rest of the horizon. Between 3 and 4 m, the Kerkom Sand coarsens considerably and become moderately sorted, very coarse to intermediate sands with a substantial admixture of finer material. Organic carbon was preserved in the Kerkom Sands since the above lying impermeable Boom Clay (Rupelian Stage) sealed this organic layer and provided a permanent anaerobic environment.

Geochemical signature of the humic compounds

The ^{13}C-values (Table 3) of the ground soil samples from the Kerkom Sands vary from δ^{13}C −23.23‰ to δ^{13}C −24.11‰. The extracted humic acids are isotopically somewhat heavier (up to δ^{13}C −22.11‰). In comparison, the Oklahoma oil seepage sample has a substantially lighter isotopic composition (δ^{13}C −31.15‰). Because photosynthesis is accompanied by isotopic fractionation of carbon and because not all living organisms fix CO_2 in the same way, the ^{13}C / ^{12}C values of the organic carbon in a sediment can provide information on the origin of this organic matter. Long preservation and slow decomposition may lead to change in isotopic composition (Bertram and Schleser, 1982; Buurman et al., 1998), so care should be taken when dealing with these results. Nevertheless, we can draw some conclusions (Table 3). Isotopic composition of the organic matter in the Kerkom Sands (δ^{13}C ± −23‰) is much heavier than known values for North Sea oil (δ^{13}C ± −29‰; Scholten, 1991). The values for the Kerkom Sands are also more than 7‰ heavier than known tar sands from Oklahoma and are much closer to those for ter-

Table 2: Selected physical and chemical properties of two profiles in the Roelants quarry, Pellenberg (Belgium): Profile-A, northern flank; Profile-B, southern flank.

Horizon	**Depth (m)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**C_t**
Profile-A	**Roelants quarry, Pellenberg (Belgium), northern flank**				
Heide Sand	−0.60 – 0.00	94.88	1.16	3.96	<0.01
Bh1	0.00 – 0.70	98.03	0.68	1.29	0.18
Bh2	0.70 – 2.93	99.41	0.14	0.45	0.22
Bh2(*)	1.50	97.18	0.49	2.33	1.27
Bh3	2.93 – 3.55	99.05	0.34	0.61	0.37
Bh3	3.55 – 3.95	98.81	0.42	0.77	0.11
C	3.95 – ...	97.78	0.50	1.72	<0.01
Profile-B	**Roelants quarry, Pellenberg (Belgium), southern flank**				
Heide Sand	−1.30 – 0.00	98.93	0.36	0.71	0.03
Humic block	−0.15	98.64	0.07	1.29	0.62
Bh1	0.00 – 0.50	98.71	0.26	1.00	0.53
Bh2	0.50 – 1.00	98.31	0.40	1.29	0.12
Bh3	1.00 – 1.37	96.03	1.11	2.86	0.28
Bh4	1.37 – ...	98.73	0.23	1.04	0.06

(*): Dark band in Bh2, sampled apart; C_t: total carbon content.

Table 3: Stable carbon isotope analysis of the organic impregnation in the Kerkom Sands at Pellenberg and of tar sands, Oklahoma, USA.

Horizon	Depth (m)	%C	$\delta^{13}C$ (PDB) in %
Profile-A	**Roelants quarry, Pellenberg (Belgium), northern flank**		
Bh2	0.70 – 2.93	0.24	–23.23
Bh2 (*)	1.50	1.41	–23.31
Bh2(*) (1)	1.50	17.26	–22.69
Bh2(*) (2)	1.50	39.27	–22.11
Profile-B	**Roelants quarry, Pellenberg (Belgium), southern flank**		
Humic block	–0.15	0.61	–23.74
Bh1	0.00 – 0.50	0.66	–24.11
Tar Sands, Oklahoma, USA			
Rock fragment	...	4.66	–31.15

(*): Dark band in Bh2, sampled apart; all samples are dried and ground samples except (1): a freeze-dried humic acid extract and (2): a purified humic acid extract.

restrial humic compounds (between $\delta^{13}C$ –24 and –27‰; Nissenbaum and Schallinger, 1974). Yet, since preserved organic fraction (aliphatics and aromatics) after burial generally tends to have a rather low $\delta^{13}C$, one would expect the values to be lower than the 27‰, rather than higher as found in the samples. Therefore, part of the carbon was probably derived from tropical C4-grasses, even though the great C4-grasses domination on earth actually takes place later, at the end of the Miocene (7 million to 8 million years ago).

Elemental analysis (Table 4) was conducted in order to explore the origin of the organic matter. Humic compounds of a terrestrial origin as observed in the paleosol, have relatively low N- en S-concentrations in comparison to marine humic acids, derived from planktonic material. The aromaticity of continental humic acids is, although partly dependent on the environmental conditions in which they are formed, in general much higher (up to 80%) than in marine environments (up to 20%) (Wilson, 1987) although recent research argues that this value could be overestimated and is almost exclusively related to organic matter fractions that contain considerable amounts of charred material (soot, charcoal) (Clapp and Hayes, 1999). Hence, low H/C ratios (i.e., lower than 0.8) are usually attributed to the coalification process (Van Krevelen, 1950; Yonebayashi and Hattori, 1988). Considering the long time of burial, some coalification would be quite logical and may explain the low H/C (0.24-0.82) ratios that are observed in the paleosol.

The authors of the oil seepage hypothesis are still facing the problem of a geochemical miss-match with the known West-Netherlands oils. Furthermore, there has never been any mention in geological literature of traces, remains or even indications of any oil movement along the proposed migration route, which was presumably more than 100 kilometers long.

Conclusions

In view of the discussed micro-morphological and geochemical data, we conclude that there is quite some evidence to confirm the hypothesis that the brown horizon at the top of the Kerkom Sands is a Spodic horizon from an Oligocene Humic Paleopodzol. The macro- and especially micro-morphologic features of the organic matter accumulation correspond to the morphology of present-day hydromorphic Podzols, both of temperate and of tropical regions. The geochemical characterization (^{13}C-isotopes) of the humic compounds provides evidence for a terrestrial origin of the organic matter and hence

Table 4: Elemental composition of the humic compounds of the organic impregnation in the Kerkom Sands, Pellenberg and their atomic ratios.

Horizon	Depth (m)	%C	%H	%N	%S	H/C	N/C	S/C
Profile-A	**Roelants quarry, Pellenberg (Belgium), northern flank**							
Bh2 (1)	0.70 – 2.93	13.28	0.27	0.05	#	0.24	<0.01	#
Bh2 (*)	1.50	1.76	0.12	0.03	#	0.82	0.015	#
Bh2(*) (1)	1.50	19.38	0.98	0.19	#	0.61	<0.01	#
Bh2(*) (2)	1.50	42.81	2.61	0.90	0.95	0.73	0.018	<0.01
Profile-B	**Roelants quarry, Pellenberg (Belgium), southern flank**							
Humic block (1)	–0.15	14.98	0.65	0.16	#	0.52	<0.01	#
Bh1 (1)	0.00 – 0.50	15.66	0.65	0.13	#	0.50	<0.01	#

(*): Dark band in Bh2, sampled apart; all samples are dried and ground samples except (1): a freeze-dried humic acid extract and (2): a purified humic acid extract; #: unreliable results.

seems to favor the Podzol hypothesis. Since the profile has been eroded and buried by the transgression that deposited the Berg Sands on top of the Kerkom Sands, the Podzol formation must have taken place before this marine phase in the Upper Tongerian.

Podzolization took place on the river deposits of the Kerkom River most likely on a low-laying terrace of the paleo-river. The very poor, quartz-rich and highly permeable Kerkom Sands certainly were conducive to podzolization. The spodic horizon formation probably occurred below the groundwater level with strong lateral humus transport. After the continental phase, the area was flooded by the limited transgression that deposited the Heide Sand. The A- and E-horizons would have been very loose and disappeared under the erosive power of the water. The top of the cemented Spodic horizon, which had a higher resistance, was broken into pieces resulting in cliff structures, humic pebbles or blocks, which are now found in between the deposited Heide Sands and the Kerkom Sands. Eventually, deposition of the Berg Sands followed and a part of the Heide Sand, with the humic pebbles, was reworked at the base of this formation. After deposition of the impermeable Boom Clay, all underlying sediments were sealed and protected against further weathering.

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