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The Veldwezelt site (province of Limburg, Belgium): environmental and stratigraphical interpretations*

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Abstract

Uphill and drainage line environments reveal many hiatuses or discordances, because of truncation by erosion. In downslope position accumulation often prevailed outside the drainage lines and prevented erosion, even during unstable periods. Consequently, downslope sections yield the most detailed environmental data, but often lack contact with uphill series. However, for stratigraphical correlation the contact between downslope and uphill series is essential. In the Veldwezelt loess sequence this contact is intact, which provides additional data on transitional processes. In view of these special palaeoenvironmental conditions, exhibiting a transition between downslope and uphill areas and a south-east trending stream, an extraordinarily detailed Late Saalian, Eemian and Weichselian loess sequence could be reconstructed. The Veldwezelt series furnished important pedological, sedimentological, faunal, tephrochronological and cryogenic data, on the basis of which palaeoenvironmental conclusions could be drawn and six types of pedo-sedimentological cycles distinguished. A stratigraphical overview was obtained by correlating the Veldwezelt section with other west European loess frameworks and tephra sequences; the sedimentary series at Harmignies (Mons Basin, southern Belgium) and the Greenland GRIP ice core.

Keywords: loess, pedology, palaeoenvironment, stratigraphy, sedimentology, cryogenesis, Belgium, Pleistocene

Introduction

In the study area, the European loess belt is merely 30 km in width, being situated between the cover sands of the northern Campine area (Kempen, northeast Belgium) and the Palaeozoic basement rocks of the southern Ardennes (southeast Belgium). Near its northern margin, the Veldwezelt loess pit, situated near the bottom and along the western bank of the Hezerwater valley, was exploited between 1990 and 2000 (Fig. 1). Since the construction of the Albert Canal (around 1930), the water of the Hezerwater stream flows into this canal some 300 metres further to the southwest. The Albert Canal also lowered the groundwater table, so the exploitation of this brickyard-pit was not hampered by water.

Both banks of the Albert Canal were widened between 1980 and 1990. In an intensive, 10-year field survey the outcropping sediments, palaeosols and cryogenic features were recorded by the late Werner M. Felder and Peter W. Bosch, in co-operation with the author. These data were of immense value for our understanding of the geomorphology and the stratigraphy of this area.

At the Veldwezelt quarry, the ancient Hezerwater stream had a southeasterly course from the Late Saalian to the Holocene (Fig. 2). Therefore it was possible to study the complete Weichselian infilling process of aeolian and loess-derived slope deposits. Similar to this loess pit, other loess quarries in the neighbourhood did not yield any pollen data. Organic remains such as molluscs and micro- and macrofauna are confined to the calcareous sediments of the penultimate and ultimate ice age (except for the Belvédère loess/gravel pit, now defunct). Especially for the older sediments (i.e., prior to MIS-4) there are no widely accepted chronological data, because the different dating methods are still under development.

Along the widened Albert Canal, in neighbouring loess quarries and also in the Veldwezelt pit samples were taken for heavy mineral analysis and tephra research, on the basis of

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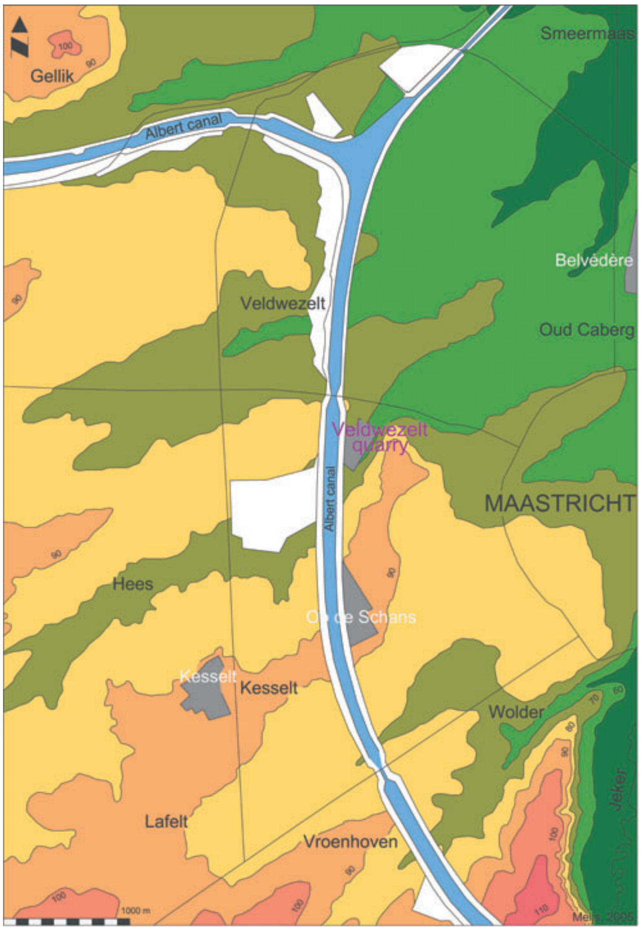
which a chronostratigraphical model was developed for this region from MIS-16 to the present day (Meijs, 2002, 2006).

The main objective of the present paper is to supply a description and interpretation of the Veldwezelt series and its correlation with regional and global palaeoclimatic records, with the emphasis on the Eemian and Weichselian periods.



Description

Unit 4

Below a 7-8 metre high cliff slope derived sediment was deposited on a basement of Cenozoic sands, consisting of red brown luvisol and dark brown humic soil lumps (unit 4; see Fig. 3). These infillings incorporate crumbly and gritty sediment (grit-bed material), humus lenses, grey sandy clay, gravels (up to 3 cm diameter) and sesquioxides. The grit-bed material consists of red brown and dark brown angular soil aggregates in secondary context (diameter varies between 2 and 4 mm). The dark brown humus lenses may attain widths and thicknesses of up to 8 and 2 cm, respectively.

Unit 5

Nearby these slope deposits change into thick fluvial Hezerwater sediments (unit 5; see Fig. 3). They consist of sorted river-washed sand and gravel (about 2-3 cm), elements above 4 cm are exceptional (maximum diameter 25 cm). In places where decalcification did not occur after sedimentation (i.e., between 35 and 50 m in Fig. 3), Cenozoic marine shells are abundant. These are characteristic of the Hezerwater fluvial deposits, whose drainage basin extensively coincided with the Cenozoic sandy subsoil. At 50 m (see Fig. 3), a large cryoturbatic sand convolution is present with an amplitude of 150 cm.

Units 6-7

More to the cliff, a gravel layer tapers out towards the valley floor, its upper surface sloping down 35% (unit 6; see Fig. 3). The gravel elements are disordered, without layering or visible preferential arrangement of the long axes. This deposit is also

Fig. 1. Location of the Veldwezelt loess quarry.

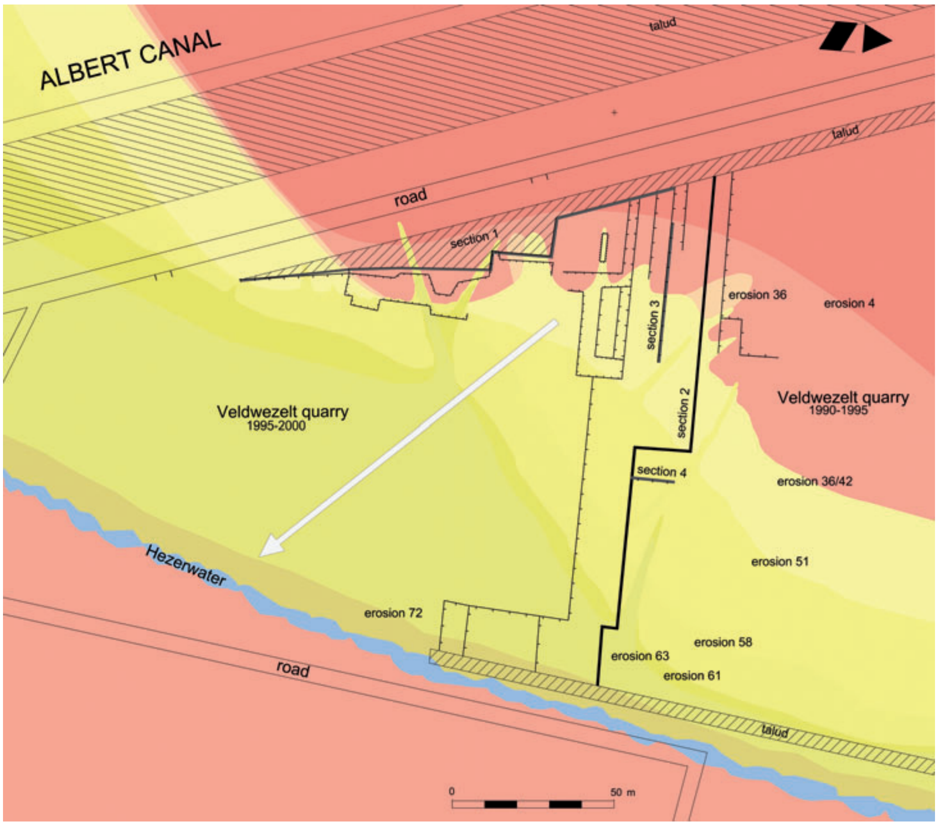


Fig. 2. Southeasterly migration of the Hezerwater stream and the location of loess sections 1 to 4 at the Veldwezelt loess quarry.

contemporaneous with the fluvial sandy gravels of the Hezerwater stream (unit 5) and consists of three individual cycles of slope transport. The lower cycle (unit 6) is cut by the upper two cycles (unit 7), which interline downslope with the fluvial sands of unit 5. The slope deposits of units 6 and 7 contain rusty brown coloured gravel, with a coarse sand matrix (mean diameter 2.5 cm; maximum diameter 40 cm).

Unit 8

The gravelly slope deposits are covered by yellow-brown, homogeneous, slightly sandy silt, without coarse elements and with a rather constant thickness over 5 metres of slope (unit 8; see Fig. 3). In this sediment only one tundrasol is present, the uppermost three centimetres of which have a grey-green to bluish-grey appearance. This tundrasol is more clayey than the parent material, has a weak platy structure and shows a moderate amount of biopores. Underneath a 20-30 cm thick rusty horizon is present, due to iron enrichment from the overlying tundrasol.

Units 9-10

The lower boundary of unit 9 is erosive, showing gritty layers, small gravels and reworked sesquioxides. Unit 9 consists of laminated silty loam, with fine-layered yellow-brown silt. It contains little clay and root pores, shows some sporadic small frost cracks and has a platy structure (see Fig. 3). On the valley wall, the bottom of unit 10 is also erosive, with pocket-like structures and some filled ice-wedges (see Fig. 3). Its fine layered sandy loam shows an alternation of yellow-brown and grey to light yellow silt layers. The sediment is poor in clay, contains few biopores, has a coarse platy structure and shows some cryoturbatic phenomena. Some scattered thin lenses of medium-fine sand are present (1 mm thick). The veneers of yellowish fine aeolian sand become thicker and better delineated towards the Hezerwater valley bottom.

On the valley floor this sediment passes laterally into stratified loams and sands, showing an alternation of yellow-brown to beige-grey silt layers and yellow-whitish layers with medium-fine aeolian sand (unit 10). The yellow-brown silt lamina are clayey, while the beige-grey are poor in clay. The individual layers have a thickness varying from 1 mm to 3.5 cm. The stratification is subhorizontal or weakly dipping and shows wavy borders, with some scattered mini-gullies (at most 15 cm wide and 3.5 cm deep). In the upper part of this sequence (at 100 m in Fig. 3), a larger, 5 m wide, gully was active, draining water in a northeasterly direction. At the floor of this gully system, some small gravels are present (up to 5 mm in diameter). Otherwise, the entire unit is free of gravels.

The structure is platy, without any pores or clay coatings. Where the sediment is calcareous (between 35 and 50 m in Fig. 3), tiny remains of Cenozoic marine shells are present, probably originating from outcropping sands of this age in the neighbourhood. From the top of this unit a polygonal network descends into the subsoil (diameter 1-1.5 m; depth 1-1.5 m),

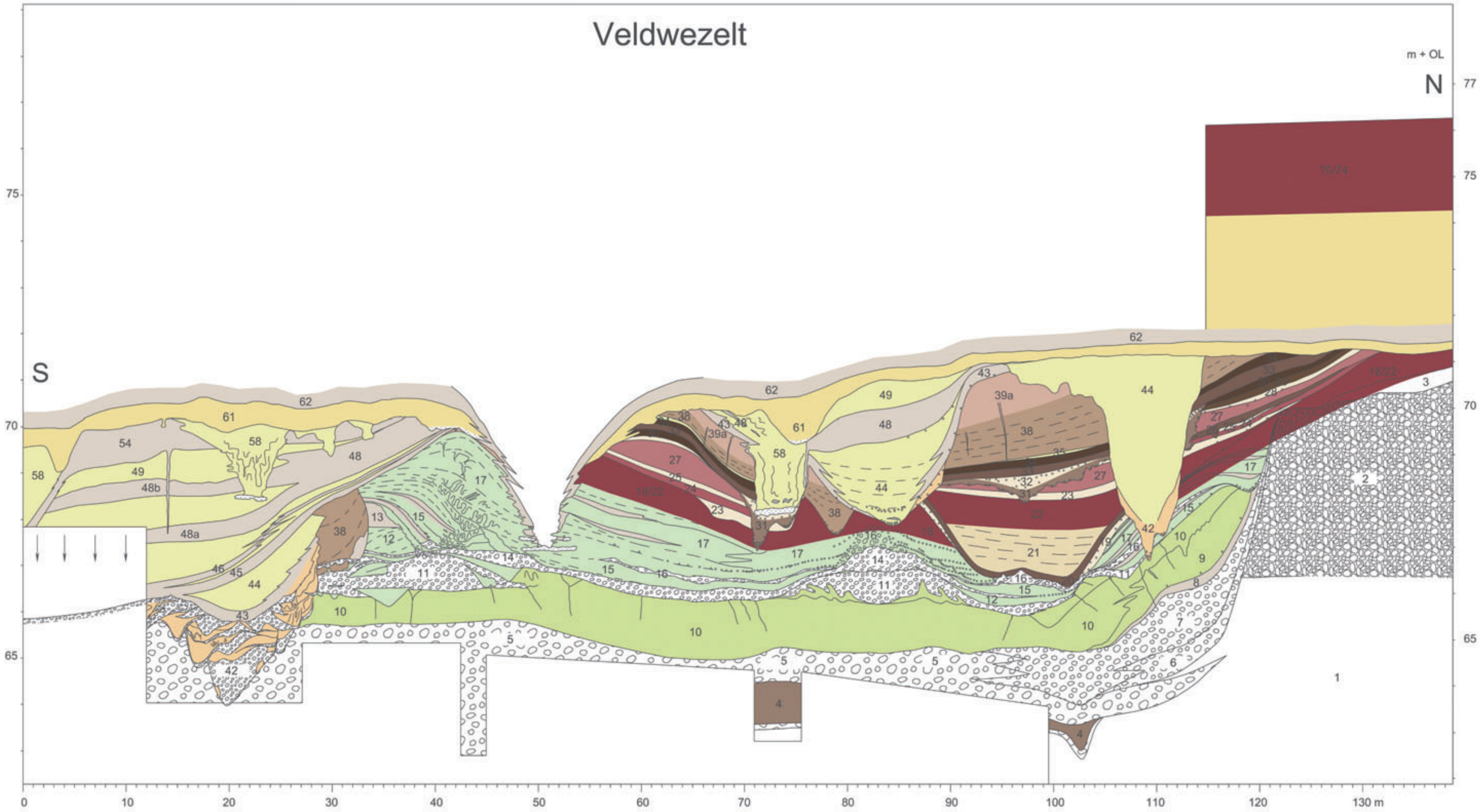


Fig. 3. Veldwezelt north-south loess section 1. The heavy mineral samples for green amphibole percentages in the fraction 30-63 µm were taken at 115 m in unit 8 (13.5%), unit 9 (8%), unit 17 (5.5%), unit 18 (4.5%) and unit 27 (5%; see also Meijs, 2002); for location of the Veldwezelt north-south loess section 1, see Fig. 2.

showing narrow and long frost cracks. Sometimes upheaval structures are visible within these polygons. In some places the stratified loams and sands of unit 10 pass laterally into aeolian sand bodies of medium- to fine sand (occasionally up to 1 m thick).

Units 11-17

This period starts with a strong erosional unconformity, causing a basal gravel lag (unit 11; see Fig. 3). It erodes the underlying stratified loams and sands of unit 10 and cuts off the characteristic polygonal network. In total three gravelly erosion discordances were observed (units 11, 14 and 16), with intervening loam lenses (units 12, 15a and 17a) and tundrasols (units 13, 15b, 17b). Locally the erosion discordances appear as slope fans or gravel slumps.

Between 90-100 m in Fig. 3, the finely stratified sediment of unit 15 (former name ZNB) is totally reduced and contains some very thin, mm-thick fine sand layers. Its structure is fine platy with many vertical pores (0.5 mm wide), which are covered by iron and manganese coatings. At the top of this unit some fresh, 'in situ-like' human flint artefacts were recovered (Bringmans et al., 2006). The intervening loam strata consist of weakly to strongly laminated greyish to grey-yellowish silt.

The stratification is made up by an alternation of lamina pairs, each pair containing a brownish layer (slightly clayey and sandy) and a yellowish pure silt layer, devoid of any clay (thickness varying from 0.1 to 1 cm). Sometimes clusters of predominantly brownish lamina occur, with only very thin intermediate yellowish lamina and vice versa. The lamination is horizontal to subhorizontal, with some scattered small and shallow mini-gullies (maximum 7 cm wide and 1 cm deep). These mini-gullies are totally filled up with either brownish or yellowish silt. Periods of tundrasol formation alternate with cryoturbation convolution zones and ice-wedge generations (amplitude 10-40 cm, ice-wedge casts 10-20 cm wide and 15-30 cm deep).

Worth mentioning is a strong humic tundrasol (unit 13), which developed in the upper part of unit 12. This intensely homogenised palaeosol has a weak humic and greyish appearance, contains iron and manganese speckles and shows pores with iron coatings on the ped surfaces. It also contains many molluscan shells and calcareous concretions ('loess dolls', maximum thickness 10 cm). Especially the so-called shrub snail (*Arianta arbustorum*) is characteristic of its malacological assemblage (Kuijper, 2003).

Units 18-29

At the beginning of this period the climate suddenly ameliorated and a deep interglacial luvisol developed in the underlying loams (unit 18; see Fig. 3). The upper part is very clayey and more rusty brown, with numerous grey gley speckles. It shows an angular to polyedric soil structure, with brown clay coatings on the ped surfaces. A study into the organic carbon content indisputably determined that it concerns an independent palaeosol (Schirmer, 2003). From the top of this brown luvisol, vertical worm channels penetrate into the subsoil. They are covered and filled with dark brown humic clay coatings and worm excrements. Some scattered digging channels (krotowinas) are present, filled with a typical white-greyish sediment material.

After this warm period a climatic deterioration caused erosion of the underlying luvisol and sediment. Locally (at 100 m in Fig. 3) it formed a new steep side-gully of the Hezerwater stream with valley slopes of 35% and only sparse gravels (1-3 cm) were left on its basal erosion line (unit 19: former name VLL). The worm channels belonging to unit 18 are clearly cut by this erosion. In this period even the gravel cliff became partially exposed. On top of this basal erosion line loamy, white greyish slope-derived sediment is present, with some dispersed gravels. At the bottom of the side-valley these sediments have a reduced green-grey appearance. Numerous human 'in situ-like' flint artefacts were recovered from this level (Bringmans et al., 2006).

In this geliflucted sediment a thin humic, partly syngenetical, palaeosol developed on the gully floor as well on the steep gully slopes (unit 20: former name VLB). It has a yellow-brownish colour, with many light grey irregular mottles (diameter up to 2 cm) and it shows a massive soil structure. Very characteristic is the presence of charcoal particles, frequently in the form of an elongated string, approximately in the middle of this palaeosol (especially *Pinus sylvestris*; see F. Damblon *in* Bringmans, 2006). This means that possibly younger homogenisation processes did not influence the original position of these charcoal particles. The charcoal is present from the gully floor to the top of the cliff, where the Maas gravel was still outcropping. At the same level as the charcoal, various concentrations of 'in situ-like' human flint artefacts were found, together with some large boulders (approximately 20 cm; Bringmans et al., 2006). Halfway on the south facing slope a 150-cm deep digging hole starts from the surface of this palaeosol. The access to the hole is small (diameter 10 cm), but downwards it becomes 30-40 cm wide. Only very occasionally an isolated rodent digging channel (krotowina) was observed.

On top of this palaeosol a bed is present with an alternation of gritty lamina, consisting of washed sesquioxides (in particular manganese), sand layers, washed silt, veneers of gravel (up to 0.5 cm) and more silty-clayey lamina (unit 21). Especially on the gully floor the underlying palaeosol (unit 20) was partially eroded by this gelicolluvium. Upwards the silt component increases ('fining-upwards sequence'), but it still remains strongly stratified, with some scattered sand layers and very small gravels.

After this first interglacial luvisol cycle (18-21) the process of luvisol pedogenesis, erosion, accumulation of white-greyish slope derived material, frost action, humic (syngenetical) pedogenesis and gelicolluviation repeated another three times (22-23, 24-26 and 27-29; see Fig. 3). In these cycles polygonal ice-wedge networks developed in cold and rather humid climatic conditions, just after the erosion but before the drier humic pedogenesis (diameter 50-75 cm, depth 50-175 cm, width 3-7 cm; unit 23, 25 and 28). Later on due to the moist conditions within these fossil ice-wedge casts, the adjoining material and sub horizontal branches became reduced by gley processes (pseudogley). The palaeosol of unit 27 (former name VBLB) has a grey-brown Greysem appearance and shows in the middle part concentrations of 'in situ-like' human flint artefacts, including some scattered charcoal particles (*Betula* sp.; see F. Damblon *in* Bringmans, 2006). In most parts of the palaeolandscape, however, no accumulation of gelicolluvium sediments occurred between units 18 and 27, leading to a complex polygenetical luvisol 18-22, 18-24 or even 18-27.

Units 30-33

After the four foregoing luvisol cycles (18-21, 22-23, 24-26 and 27-29), now the overall climate became so cold and dry that Chernosem-like cycles could develop (30-33 and 34-36; see Fig. 3). While cycles 18-21, 22-23, 24-26 and 27-29 started with luvisol-type of palaeosols, cycles 30-33 and 34-36 start with a Chernosem palaeosol-type (unit 30: Greysem-Chernosem and unit 34: Chernosem). The four luvisol-type palaeosols show clay illuviation with yellow-brownish clay coatings, while in the Greysem-Chernosem palaeosol of unit 30 dark brownish humic clay coatings are present. In the Chernosem of unit 34 no clay coatings could be observed at all. In the time span between these six cycles the overall climate steadily became colder and drier, at last resulting in more mixed grassland vegetation types with Chernosem-like palaeosols.

On top of the Greysem-Chernosem of unit 30 many charcoal particles are present (especially *Pinus sylvestris*; see F. Damblon *in* Bringmans, 2006) and this level also represents the maximum concentration of the Rocourt tephra, containing the characteristic Enstatite minerals (Mees & Meijs, 1984). A serious and vigorous linear erosion phase followed with humic mud and gravel flows. In the field this erosional unconformity was detected at the transition of the gully infillings and their neighbouring palaeosol sequences. Here the charcoal particles, which rest on top of the Greysem-Chernosem palaeosol of unit 30, were taken by erosion and deposited on the floor of the gully systems. This means that the gully erosion occurred immediately after the formation of the palaeosol of unit 30 and the deposition of the Rocourt tephra and charcoal pieces. This downcutting erosion must have started after a change to a more open and sparse vegetation cover. In the beginning, the gullies were rapidly filled with half-frozen Greysem-Chernosem lumps and other truncated sediment and palaeosol material (unit 31). Synchronously, with the gully infilling process intense worm, rodent and beetle activity took place, which is responsible for the numerous channels, starting from the top and lower-lying levels into the subsoil (worm/beetle channels 4-6 mm; rodent channels 4-10 cm). Some worm channels are filled with dark brown humic clay coatings and worm excrements. At last the chaotic gully filling was followed by white-greyish slope derived material with some gravels (unit 32a) and a syngenetical humic pedogenesis (unit 32b). Probably in this time span the characteristic marmorisation took place in moist parts of the palaeolandscape ('Pantherfleckung' according to Bibus et al., 1996).

The next slow aeolian loess deposition and minor syngenetical humic pedogenesis caused a light-brown humic marker loess (unit 33; first marker loess). Especially units 31, 32 and 33 are characterised by the presence of innumerable krotowinas (rodent digging channels; diameter 4-10 cm), which indicate climatic circumstances that were apparently ideal for digging rodents.

Units 34-36

Chernosem cycles 34-36 starts with humic pedogenesis (unit 34). In the dark brown humic Chernosem of unit 34 no (humic) clay coatings could be observed. The upper part of this Chernosem shows some irregular, light grey reduction areas in a dark brown matrix with spread rust spots. On top of this humic palaeosol of unit 34 a shallow frost network with a diameter of 50 cm is present. The individual incipient ice-wedges are 4-5 cm wide at the upper part and penetrate only 25 cm deep into the subsoil. This humic palaeosol (unit 34) was followed by aeolian loess deposition, devoid of any humus (unit 35; second marker loess). Apparently, the digging activity of rodents stopped in this marker loess accumulation period.

After this second marker loess a very important and widespread erosion and gelicolluviation period started, during which the underlying sediments and palaeosols were cleared over large areas (unit 36). From Fig. 4 it becomes clear that in the beginning this erosion was very rigorous and truncated the underlying sediments. It formed a steep side valley in the east-facing valley wall of the Hezerwater stream (height 6 metres, slope 25%). Erosion must have taken place in a cold climate envelope, with little vegetation and probably permafrost in the subsoil.

On the Hezerwater valley floor a sediment series is present, with an alternation of fine to coarse 'grit beds', gravel layers and strongly washed veneers of yellow-greyish sand and silt, with some larger lumps of Bt and humic material, displaced human flint artefacts and gravels (unit 36). Microscopic research has revealed the presence of the Rocourt tephra with the characteristic Enstatite minerals within the humic lumps (determination: E.P.M. Meijs). Especially at the bottom of this sequence the different sediment layers show 'cut and fill'

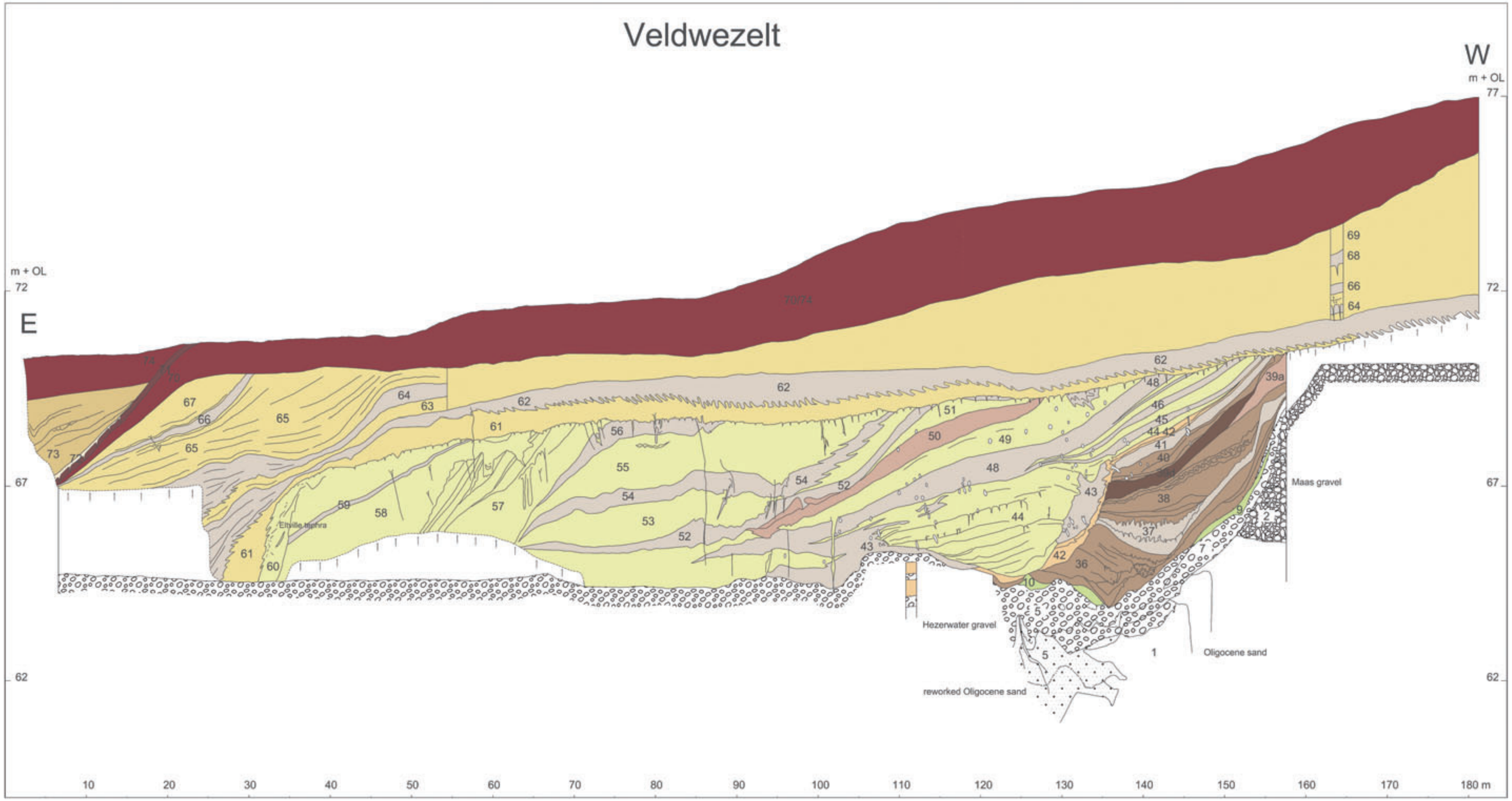


Fig. 4. Veldwezelt west-east loess section 2; for location see Fig. 2.

structures. It is clear that a broad system of always moving subgullies maintained an alternation of deposition and erosion. Individual gullies are about 20-100 cm wide and 5-25 cm deep. These so-called 'grit bed' layers mainly consist of rounded, packed soil pieces (2-10 mm, with incidentally larger lumps of 5-10 cm diameter). Between these sediment infillings some strong cryoturbatic convolutions (amplitude 20-30 cm) and ice-segregation structures are present, indicating cold permafrost circumstances. If the speed of these mud flows decreased below the slope a part of the sediment was deposited. Frozen palaeosol or humic lumps were occasionally taken into these grit bed flows by gullying or undercutting processes. Grit beds are confined to drainage lines, while in the other down slope environments gelicolluviation sediments prevail.

The gelicolluvium beds consist of strongly laminated silty sediment, with an alternation of grey-yellowish, fine sandy to coarse silty loam layers (overland flow/sheet wash) and grey-brownish clayey, sometimes humic loam layers (gelifluction). In view of the fact that upslope outcropping Chernosems and luvisols were eroded by these denudation processes, the gelicolluvium incorporates dark brown humic Chernosem, crumbly red brown luvisol lamina, intercalated yellowish, whitish or greyish silt layers and some spread layers with washed sesquioxides. They resemble the so-called 'Lehmbrockelsande' or pellet sands (LBS sediment; Demek & Kukla, 1969).

Units 37a-38

Upwards the stratified LBS sediment of unit 36 gradually becomes more and more influenced by pedogenetic processes, leading to the formation of a complex syngenetic grey-brown tundrasol, which is the beginning of the next (humic) tundrasol cycle (units 37a-38). On the floor of a side gully of the Hezerwater stream this palaeosol is divided into two subsoils, the upper one (unit 37b) being more humic than the lower (unit 37a). From the lower palaeosol vertical worm channels penetrate 75 cm deep into the subsoil. They have a diameter of 6-8 mm and occasionally are filled with worm excrements. Between these two subsoils stratified yellow-brownish sediment is present. Upwards this laminated sediment becomes more and more homogenised and at last transforms into a humic, grey-brownish tundrasol (unit 37b). Here too fossil worm channels are present, but fewer than in the underlying palaeosol. Both in the stratified sediment under the lower subsoil 37a and above the upper subsoil 37b strong cryoturbatic convolutions (amplitude of 20-30 cm), fossil segregation-ice structures and some incipient fossil ice-wedge casts (2-4 cm wide and 20-30 cm deep) occur, indicating that cold periods with permafrost proceeded and succeeded pedogenesis. In the accumulated silty sediments in between these two subsoils also cryoturbatic convolutions and small frost cracks are seen, showing that periods of valley floor aggradation interrupted the pedogenesis of unit 37. Upslope the two individual subsoils 37a and 37b converge into one palaeosol (unit 37; see Fig. 4). The cryoturbatic convolutions change upslope in subhorizontal tongues ('Hakenschlagen'). At steeper slopes even these tongues disappear.

The sediments and palaeosols of units 36 and 37 are lacking upslope and the hiatus (erosion discordance) is marked only by some sparse gravels or displaced human flint artefacts. On the sediments of unit 36 and 37 another series of LBS gelicolluvium is present, due to a climatic repercussion after unit 37, which again resulted in a more open vegetation cover, an advancement of permafrost and downslope washing and flowing of sediment (unit 38). Persevering cold and still more open environments accelerated this sedimentation of gelicolluvium. Brown clayey and humic mud lamina originate as a type of gelifluction tongues from the grey-brown tundrasol of unit 37 which outcrops upslope, whereas the pale yellow-white silt lamina were washed from the top of this palaeosol, sometimes leaving several centimetre-deep concave gullying patterns. In downslope position 1-2 metres of this gelicolluvium could be deposited in a rather short time. The whole sediment sequence contains many short vertical beetle channels (4-6 mm diameter, 5 cm deep) and some filled frost cracks (50-75 cm deep and 2 cm wide), indicating cold climatic conditions.

Units 39a-39c

Cambisol cycle (39a-39c) starts with a heavily truncated brown, strongly homogenised cambisol (unit 39a). The cambisol of unit 39a has a loose crumbly structure, with many iron coatings and some pale brown, weak clay coatings on the ped surfaces. From the surface of this palaeosol worm channels descending into the subsoil of unit 38 (diameter 6-8 mm). In the neighbourhood of the Veldwezelt quarry unit 39a of cambisol cycle 39a-39c is followed by erosion and the accumulation of white-greyish, slope-derived material with synchronous frost action, due to climatic deterioration and vegetation change (unit 39b; polygonal fossil ice-wedge network, diameter 75 cm, depth 100 cm and width 4-5 cm). Afterwards the accumulation of aeolian loess and minor synchronous humic pedogenesis caused the formation of a third humic marker loess (unit 39c). Many rodent digging channels start from this unit. At the Veldwezelt loess pit, however, the yellow brownish cambisol (unit 39a) is directly followed by a marker loess (unit 39c), with in between erosion and fossil ice wedge casts (unit 39b), without deposition of white-greyish slope derived material.

Units 39d-40c

The next Chernosem cycle (39d-40c) starts with humic Chernosem pedogenesis (unit 39d, former name N5) on top of the humic marker loess of unit 39c. From this humic Chernosem of unit 39d some worm channels penetrate into the subsoil (8 mm diameter). The upper 5 centimetres of this palaeosol are influenced by gley processes and contain some poorly preserved molluscan shells. The appearance of unit 39d strongly resembles that of unit 34. The presence of deer remains in the upper centimetres of unit 39d probably points to wooded biotopes in the neighbourhood (Cordy, 1998; De Warrimont, 2007). On top of unit 39d another marker loess was formed, devoid of any humus and sometimes presenting a faint lamination (unit 40a; fourth marker loess). It is slightly calcareous and probably represents the first allochthonous loess. Prevailing cold climatic conditions and the development of a more open vegetation led to the accumulation of another series of gelicolluvium with an LBS facies ('Lehmbrockelsande'), originating from upslope outcropping palaeosols (unit 40b). These phenomena indicate the presence of permafrost in the subsoil. The sequence is capped by the sedimentation of grey-yellow calcareous loess (unit 40c). Throughout the sediment, short vertical beetle channels are present (4 mm diameter).

Units 41-42

Above unit 40 all sediments are calcareous, originating from aeolian allochthonous loess, except for some erosion layers containing sediments from non-calcareous underlying outcrops and one decalcified cambisol of unit 50.

The period starts with tundrasol formation, represented by a grey, homogenised, partly decalcified, weak humic tundrasol (unit 41; see Fig. 4). The palaeosol contains some poorly preserved molluscan shells. It is followed by the most powerful linear erosion generated in the last glacial period (unit 42). In total the Hezerwater stream incised its bed 3-4 m deeper and created a steep 4-6 m high east-facing valley wall by lateral erosion, with slope percentages of 25-50%. In the valley wall, small and steep side-gullies were created. After this erosion renewed coldness generated gelicolluviation (with grit beds on the valley floor) and frost cracks and ice-wedges (1 m deep and 2-3 cm wide).

Next the Hezerwater stream raised its bed approximately two metres (see Fig. 3, between 10-30 m), with an alternation of sandy to gritty silt layers and gravel bodies. The bottom gravel bed exists of sorted river-washed gravel (approximately 4 cm diameter), with some large basal gravel and silt blocks (up to 30 cm diameter). The overlying gravel beds have a silty matrix, show moderate sorting with an average diameter of 4 cm (occasionally up to 10 cm diameter). These sediments were deposited under a braided drainage regime with 'cut and fill' structures. The individual gullies have an average width of 3-5 m and a depth of 50-75 cm and at times show cryoturbatic convolutions, with an amplitude of 20-30 cm.

The fluvial gravel beds pass upslope into washed calcareous silty slope sediments, descending from the steep east-facing valley wall of the Hezerwater valley. The fluvial silty beds pass upslope into geliflucted, slumped and flowed slope sediments, often containing lumps of humus and luvisol material. At times, micro- and macrobones are present within these deposits. Later on, when the Hezerwater stream moved in a more southeasterly direction, these fluvial deposits were partially eroded by a side gully (see Fig. 3, between 10-30 m). After a long time of erosion uphill and aggradation on the Hezerwater valley floor, drier climatic conditions caused predominant deposition of calcareous loess. Higher upslope sediments of unit 42 are lacking and the erosion discordance is only marked by some sparse gravels or displaced human flint artefacts.

Units 43-44

This period starts with climatic amelioration, generating syngenetic pedogenesis, resulting in the formation of a homogeneous slightly humic, calcareous brown-grey tundrasol, interlarded with rusty speckles (unit 43, former name TLB). Near the bed of the Hezerwater stream, this palaeosol may be subdivided into six individual syngenetic subsoils, with intercalating gritty, sandy, gravelly and silty layers. These intercalating layers are occasionally moulded into cryoturbatic convolutions (diameter 20-30 cm), indicating that periods of principal valley floor aggradation interrupted the pedogenesis of unit 43. More upslope, these individual subsoils pass into a single palaeosol (unit 43).

The tundrasol of unit 43 has a grey to brown-grey colour, but especially below steep cliff-like spots in the palaeolandscape, it may have a more brownish cambisol appearance. In this palaeosol many molluscan shells and micro- and macrofaunal remains have been found. In the complete sequence short vertical beetle channels are present. Especially in the lower portions of the valley wall, worm channels penetrate from this palaeosol into the subsoil (4-6 mm thick). Also filled digging channels (krotowina) occur (diameter 4-10 cm). They are preferably situated on the steeper parts of the palaeolandscape, in particular along the steep banks of the Hezerwater stream and its side gullies. Sometimes a larger hole was found.

This first tundrasol cycle continues with a climate repercussion, resulting in a more open vegetation, deep winter frost, the supply of allochthonous calcareous loess and the washing down of silty gelicolluvial sediments (unit 44, former name ML). Especially in drainage lines, the underlying palaeosol of unit 43 was completely eroded. The larger gullies contain at their bottom some gravel, coarse sand and displaced human flint artefacts. The supply of aeolian calcareous loess, however, resulted in the continuing accumulation of stratified silty sediments. Within a short timespan, all depressions in the palaeolandscape became filled with calcareous, strongly laminated gelicolluvial loess, with an alternation of grey-yellow, washed silt lamina and grey-brown, more clayey silt lamina. Along the slope it is obvious that grey-brown tongue-like laminae originate from the outcropping palaeosol of unit 43, whereas the grey-yellow lamina cut and undermine this palaeosol in the shape of shallow concave scorings.

Throughout this unit rodent digging channels (diameter 4-10 cm) and some scattered, small frost cracks are present (25 cm deep, 1 cm wide). Beetle burrows are lacking from here on. Probably, beetle activity stopped due to the massive accumulation of calcareous loess. The presence of moles in units 43 and 44 testifies to the absence of permafrost (Cordy, 1998; De Warrimont, 2007).

Unit 45

This period starts with climatic amelioration, resulting in the formation of a homogeneous slightly humic, calcareous brown-grey tundrasol (unit 45, former name WFL). The palaeosol developed on top of the laminated sediments of unit 44 and shows a grey to grey-brown colour. Especially below steep cliff-like spots in the palaeolandscape nearby the valley floor of the Hezerwater stream it may have a more brownish cambisol appearance. In these environments, the complete sequence is cut with innumerable 6-8 mm thick worm channels, sometimes filled with worm excrements. It shows an abundant occurrence especially of macrofauna, but also human flint artefacts (Bringmans et al., 2006). The human flint artefacts were particularly found in spots where the palaeosol of unit 45 forms the upper part of an old cliff in the palaeolandscape, near the Hezerwater stream. Downslope this palaeosol can be 80 cm thick (see Fig. 5). Upslope its thickness diminishes to 10 cm and still higher up it is often totally eroded or incorporated by later pedogeneses. Recovered mole remains from unit 45 rule out permafrost conditions during this period (Cordy, 2002).

Units 46-49

A long period of alternating loess accumulation and tundrasol pedogenesis followed, ending with the formation of ice-wedges and an ice-segregation zone. The intercalating stratified silt layers frequently become thicker slope upwards and sometimes even pass into homogeneous light grey-yellowish loess. During the different pedological periods the landscape was not entirely stable. Some washing of sediment continued; however, this was homogenised by syngenetic soil formation processes and incorporated into the tundrasol palaeosols.

Two brief periods of loess accumulation, pedological activity and minor erosion followed, leading to the formation of greyish calcareous tundrasols, with intervening periods of predominant calcareous loess accumulation. At their base, these tundrasols show an orange-like iron enrichment zone of 10 cm thick. From the top of the upper tundrasol a broad hole was dug, approximately 150 cm deep and 20 cm wide. Above the accumulation of stratified silt loam, with some yellow layers of homogeneous powdery calcareous loess continued. After a weak erosive period, leading to the deposition of a sparse gravel line, a long phase of pedogenesis followed. In the beginning, this soil formation had a syngenetic character. It resulted in a thick complex brown-grey to grey-brown tundrasol (unit 48a, former name MLB). Frequently this palaeosol has slightly decalcified and occasionally it shows a greyish colour in the lower part and a more brownish hue in the upper.

Especially near the valley floor of the Hezerwater stream a new 30-40 cm thick syngenetic brown-grey to grey-brown

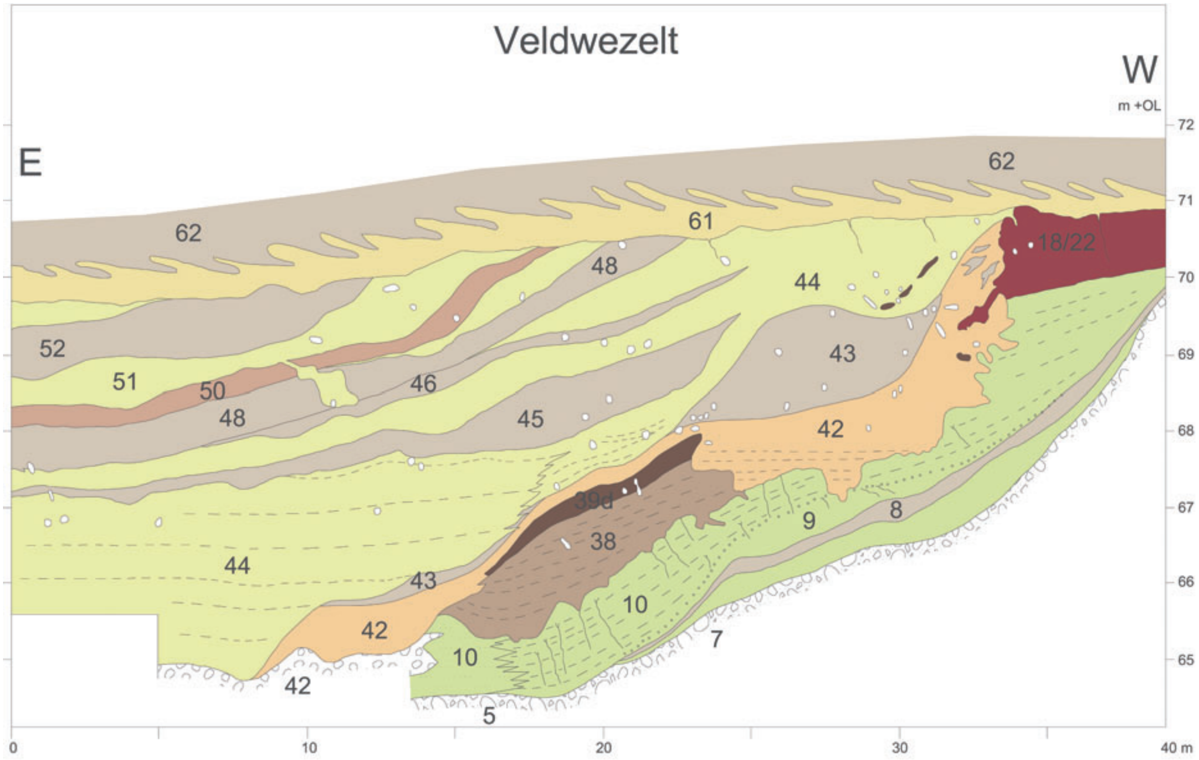


Fig. 5. *Veldwezelt west-east loess section 3; for location see Fig. 2.*

calcareous tundrasol may be present above this palaeosol (unit 48b), in which sometimes a vague lamination is recognised. Sometimes a filled ice-wedge cast penetrates downwards into this palaeosol of unit 48b (60 cm deep and 6 cm wide). The shoulders of the filled ice-wedge cast clearly show convex bulges and the ice-wedge cast is filled with grey-brown gelifluction material, originating from the upper part of the palaeosol. Above stratified silt follows, with an alternation of blank-grey (washed), grey-brown (gelifluctED) and homogeneous yellow (aeolian) silt lamina. In favourable horizontal and wet palaeoterrain conditions, the lower part of this laminated sediment (and the upper part of unit 48b) is deformed by cryoturbation processes.

Above follows again strongly laminated silt sediment with, in the centre, a network of deep fossil ice-wedge casts (200 cm deep and 15 cm wide), indicating former permafrost conditions (unit 49).

The whole sequence, both beneath and above the fossil ice-wedges of unit 49, contains many filled rodent digging channels (diameter 4-10 cm, occasionally 20 cm). From the fossil ice-wedge network of unit 49, but also from the networks present above, permafrost penetrated into the subsoil. As a result segregation-ice could easily develop in the more clayey and moist tundrasols of unit 48a and 48b. Afterwards melting of this segregation-ice led to the deposition of iron coatings on the subhorizontal, platy ped surfaces.

From the presence of micro- and macrofaunal remains, molluscan shells and filled digging channels in units 43-48, it can be concluded that climatic circumstances and vegetation were extremely attractive for land snails like hair snail, moss barrel snail, elongated amber snail, nude snail, high basket snail (Kuijper, 1996); for small (digging) animals like water vole, vole, mice, marmot, ground squirrel, hare; larger herd animals such as horse, ass, reindeer, woolly rhinoceros, bison, mammoth and carnivores such as hyena, cave lion, pole fox and badger (Cordy, 1998, 2002; De Warrimont, 2007). The predominance of horse in the macrofauna, water vole in the micro-assemblages and the hair and moss barrel snail in the molluscan fauna is apparent.

Units 50-51

In this cycle the sediment gradually becomes more and more homogenised and ultimately gets a brownish colour. It often forms a heavily truncated homogeneous, decalcified, 30-80 cm thick, brown cambisol (unit 50). The cambisol is clayey and has many (root) pores, but no clay coatings could be found on the ped surfaces. In one spot, a 75 cm deep hole was dug from the surface into this palaeosol, with upside a narrow entrance of 20 cm wide and downside a broad room of approximately 80 cm wide (see Fig. 5). From the lower part of this palaeosol worm channels penetrate into the subsoil (diameter 6-8 mm).

Especially downslope, near the valley floor of the ancient Hezerwater stream, the underlying sediment is enriched with lime to a depth of approximately 20-30 cm. This may be in the form of pseudomycelium or small calcareous concentrations ('loess dolls', diameter 2-4 mm). The decalcified character of this palaeosol is unique, while under- and overlying sediments are calcareous. After this cambisol pedogenesis, climatic deterioration triggered vigorous erosion, in which the underlying units 48-50 were cleared by a gully of 30 m wide and 3 m deep, discharging into the Hezerwater stream. In a very short time, however, this side gully became half filled with thick chaotic mud flows, incorporating large frozen lumps of eroded underlying palaeosols and sediments of units 48, 49 and 50 (up to 75 cm diameter). Next, the gully was further filled with aeolian and weakly laminated calcareous loess and occasionally some isolated ice wedges were formed. Later on not only this gully, but the whole landscape became covered by a metre of grey-yellow, frequently homogeneous and sometimes weakly stratified, calcareous loess.

Units 52-56

This period starts with another complex tundrasol cycle, showing an alternation of pedogenesis, loess accumulation, gelicolluviation and frost action. The accumulation of aeolian and laminated loess alternated with the formation of three syngenetic grey, calcareous tundrasols (units 52, 54 and 56). Some convolutions, frost cracks and ice-wedge casts are present within these deposits (to a depth of 40-80 cm), indicating overall cold climatic conditions. In the tundrasols many vertical root pores are present. Some digging channels were dug out from the surface of unit 52. The activity of worms and digging animals stopped, because in tundrasol of unit 52 the last filled fossil worm channels and digging channels were observed (diameter 2-3 mm and 4-10 cm, respectively). The tundrasol of unit 56 is the last unit with some dispersed molluscan shells, above it, no molluscs were encountered. This period is closed by the development of a deep permafrost.

Units 57-60

This period starts with continuing development of a deep permafrost. The vigorous permafrost conditions invoked strong gelifluction and overland flow, leading to the accumulation of heavily stratified silty deposits, with mm- to cm-thick greyish, yellowish and (red)brownish colours (unit 57, former name ZL). These accumulations resemble the LBS sediments or pellet sands of units 36-40 ('Lehmbrockelsande'), but here the palaeosol aggregates and lumps of denudated luvisols and Chernosems are lacking because they did not outcrop in the neighbourhood. In the westernmost corner of the Veldwezelt pit, however, the LBS deposits of unit 57 did contain remnants of stripped underlying luvisols and Chernosems.

Large convolutions, frost cracks and ice-wedge casts (up to 120 cm in depth) are common and testify to the harsh climatic conditions. These extensive and deep permafrost environments are characteristic of this period, but steadily became drier and drier. The first tundrasol cycle of unit 58 starts with sudden thawing of the frozen permafrost subsurface, causing the formation of steep undercutting erosion gullies (U-like) with a basal 5-10 cm thick grit bed filling (thermokarst: unit 58; see Figs 3 and 6). This erosion was probably invoked by ameliorated climatic conditions, but no accompanying palaeosol was found. In the upper filling of these thermokarst gullies a weak syngenetic tundrasol is present (unit 59). Above unit 59 some very deep frost cracks were observed (to a depth of 140 cm), indicating renewed cold climatic conditions.

The next tundrasol cycle of unit 60 starts with erosion of the subhorizontal sediments of units 58 and 59, leaving behind some steep incisions with grit beds on the gully floors and a small gravel line upslope (unit 60). The accumulation of stratified yellowish and light greyish silt loam followed, with the intercalated blackish Eltville tephra. Both below and above this tephra some mm to cm-thick sandy layers are present, with dispersed small gravels. No accompanying tundrasol could be found here either.

Units 61-65

The overall cold climate became extremely dry, resulting in the development of a polar desert. Extreme wind action during these vigorous and dry polar conditions formed a desert pavement with dispersed wind-varnished gravels (and human flint artefacts). This gravel line represents a major and extensive subhorizontal wind erosion unconformity (unit 61, former name PL 'Patina Layer'). From this erosion line some large frost cracks and filled fossil ice-wedge casts descend into the subsoil (to depths of 200 cm), indicating the presence of a deep permafrost.

In unit 61 strongly stratified dehydrated orange-yellowish to red brownish coloured sandy silt loam accumulated. During this time some isolated drainage gullies activated, showing undercutting features and occasionally grit bed fillings (see Fig. 6). Upwards the infilling sediment passes into more grey-yellowish weakly stratified loess.

In this sediment the humic darkbrown greyish tundrasol developed (unit 62, former name THB, known as the 'Tongued Horizon of Nagelbeek'; see Figs 4 and 6). Only one isolated rodent digging channel (krotowina) and some microfaunal remains in an owl pellet were observed. In this hummocky palaeosol a fossil polygonal ice-wedge network was deformed

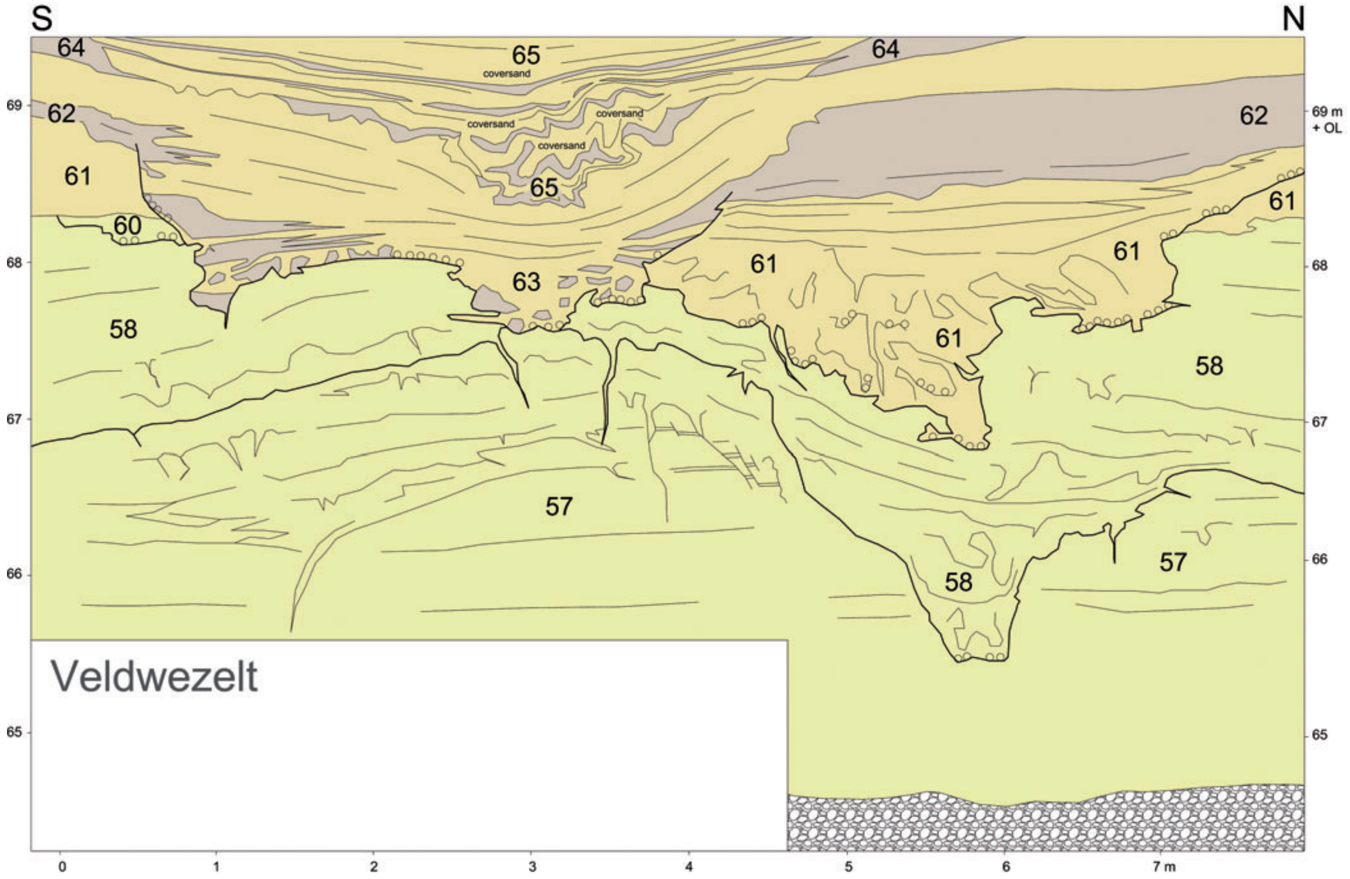


Fig. 6. *Veldwezelt north-south loess section 4; for location see Fig. 2.*

by cryoturbation due to the humid active layer (diameter 40-50 cm; depth 40-75 cm). As a result, the greyish humic soil material of unit 62 became intermingled with the underlying yellowish sediment of unit 61. In slope position soil creep caused tongue-like down bending, while on steep slopes the strong downward movement even straightened out these tongues.

Permafrost decay was responsible for the filling of existing ice-wedges with greyish soil material of unit 62 (diameter tens of metres, depth 3-4 metres). Some isolated erosion gullies activated and undercut the adjoining sediments. In the beginning these gullies were filled with grit bed material and the influx of geliflucted active layer material of units 61 an 62. On the valley floor near the Hezerwater stream fine yellow sand lenses (aeolian coversand) were blown in contemporaneously with the influx of gelifluted material from uphill areas, leading to a heavily stratified sediment sequence (unit 63; see Figs 4 and 6).

Ameliorating climatic conditions invoked the formation of a tundrasol (unit 64). Unlike the humic tundrasol of unit 62 this tundrasol has only a grey brownish humic appearance in valley floor position; upslope it developed as a faint light greyish thin tundrasol. The pedogenesis of unit 64 was accompanied by thawing conditions, causing ice-wedge decay. Later on these deep ice-wedge casts were filled with the faint grey-yellowish loess of units 63, 64 and the lower part of unit 65 (diameter tens of metres, depth 3-4 metres). More humid conditions were responsible for the activation of some isolated and shallow gullies (see Fig. 6). In valley floor position near the Hezerwater stream fine yellow sand lenses (aeolian coversand) were blown in contemporaneously with the influx of gelifluted material from higher terrain, leading to a heavily stratified sediment sequence (unit 65; see Figs 4, 6).

Afterwards the climate became again very rigorous and dry, building up a deep permafrost in the subsoil, with only a very thin active layer present in summer. Upland powdery homogeneous, calcareous, yellowish loess was deposited, with some dispersed mm-thick intercalating coversand lamina. Near the valley floor of the Hezerwater stream yellow aeolian sand lenses were blown in simultaneously with the influx of gelifluted material from uphill areas. Loess accumulation continued, but differed according to its topographical position in the palaeolandscape. Upslope loess has a powdery homogeneous appearance, while going downslope it steadily becomes more and more laminated. In valley floor position it eventually is heavily stratified, showing greyish silt loams intercalated with yellowish aeolian coversand lamina (strongly resembling unit 10).

Units 66-69

In this period accumulation of powdery homogeneous, calcareous, yellowish loess in the uplands and strongly stratified loess-coversand sediments on the valley floor continued during cold and very dry climatic circumstances. Above unit 65 another two (weak) tundrasols (units 66 and 68) are intercalated in homogeneous powdery yellowish loess sediment (upland) or stratified loess-coversand sediments (valley floor). In the whole sediment sequence some dispersed minor frost cracks are present (20 cm deep); above tundrasol 66 a frost crack is present with a depth of one metre. In fact the sediment of this cycle covers the whole palaeolandscape with a 4-5 m thick loess blanket, following the relief of the aeolian erosion layer of unit 61 (desert pavement). Also the isolated gullies of units 60, 61 and 63 were wholly filled during this cycle.

The presence of remains of collared lemming (*Dicrostonyx*) and the absence of water vole (*Arvicola terrestris*) in these sediments indicates the climate was significantly drier than previously (Cordy, 1998; De Warrimont, 2007).

Units 70-72

This period starts with an interglacial luvisol cycle. A sudden and dramatic climatic amelioration, caused decalcification of the subsurface and the formation of a red brown luvisol (unit 70; see Fig. 4). Occasionally some filled rodent digging channels (krotowina) are present. In the upper 10 cm of this luvisol a low concentration of volcanic heavy minerals of the Laacher See tephra could be traced in the grain size fraction 63-150 µm (4 green clinopyroxene and 3 brown amphibole minerals on a total amount of 800 heavy minerals; determination: E.P.M. Meijs).

Without any sign of in-between erosion a dark brown humic-like horizon follows direct on top of luvisol unit 70 (unit 71). It has the same massive soil structure as the underlying luvisol and in the lower part on the transition to unit 70 one volcanic heavy mineral of the Laacher See tephra could be found (1 brown amphibole mineral on a total amount of 1000 heavy minerals; determination: E.P.M. Meijs). Occasionally, some filled rodent digging channels (krotowina) are present.

Climatic deterioration invoked erosion of the underlying palaeosol of units 70 and 71. White-greyish slope derived material was deposited on top of this erosion line (unit 72). Prevailing cold conditions resulted at last in the formation of a polygonal ice-wedge network, with a diameter of 40 cm and a depth of 75 cm. In thawing condition the adjoining material became reduced by gley processes, due to the moist circumstances in these wedges (pseudogley). Volcanic heavy minerals of the Laacher See tephra could not be found in this sediment.

Units 73-74

After the short cold spell of unit 72, the warm Holocene period started, leading to the development of a luvisol (unit 74; see Fig. 4). Human agricultural activity and deforestation caused severe erosion of the landscape (from 6000 BP onwards). On the valley floor of the Hezerwater stream two colluvium sequences were accumulated (unit 73). The first colluvium has a rather homogeneous grey brown sticky appearance and is about 1 m thick. In this material displaced flint artefacts of the agricultural LBK culture were found. Above a colluvium of 2 m thick, grey brownish sediment follows, with three intercalating yellow-greyish gritty sand layers at an in between distance of 70 cm. In the upper gritty sand layer charcoal and mediaeval pottery was recovered from a subgully system.

Weathering processes during the Holocene were responsible for a deep luvisol-type pedogenesis. Upslope this luvisol overprints earlier palaeosols like the luvisols of units 70 and 71. On the valley floor a syngenetic luvisol formed during the accumulation of colluvium in the past 6000 years. In most palaeolandscape conditions, however, no accumulation of colluvium occurred between units 70 and 74, leading to a complex polygenetic luvisol 70-74.

Interpretation

The Veldwezelt sequence

In the Veldwezelt sequence two glacials and two interglacials can be detected. The oldest glacial starts with unit 4, representing gritbed infillings of an intense erosion period, in which ancient palaeosols were truncated uphill (see Fig. 3). After a cold and humid period with gravelly sediment flowing into the Hezerwater stream (units 6-7), the following extremely cold and dry stage was closed by the formation of an extensive ice-wedge network (units 8-10). At this stage aeolian loess was deposited before and after the development of a pronounced tundra gley. Near the Hezerwater stream fine yellow aeolian sand lenses were blown in from the wasted braided drainage beds, contemporaneously with the influx of geliflucted material from uphill areas, leading to a heavily stratified sediment sequence of unit 10 (the so-called 'sands and silts'). From unit 11 upwards, the still cold climate became more humid, leading to several gravelly unconformities, intervening stratified loess sediments and tundra gley palaeosols.

The oldest interglacial period starts with the luvisol pedogenesis of unit 18 and ends with the formation of a deep ice-wedge network of unit 28. In between another three interglacial luvisol pedogeneses took place (units 22, 24 and 27; see Fig. 3). In most parts of the palaeolandscape no accumulation of gelicolluvium sediments occurred between units 18 and 27, leading to a complex interglacial polygenetic luvisol 18-22, 18-24 or even 18-27.

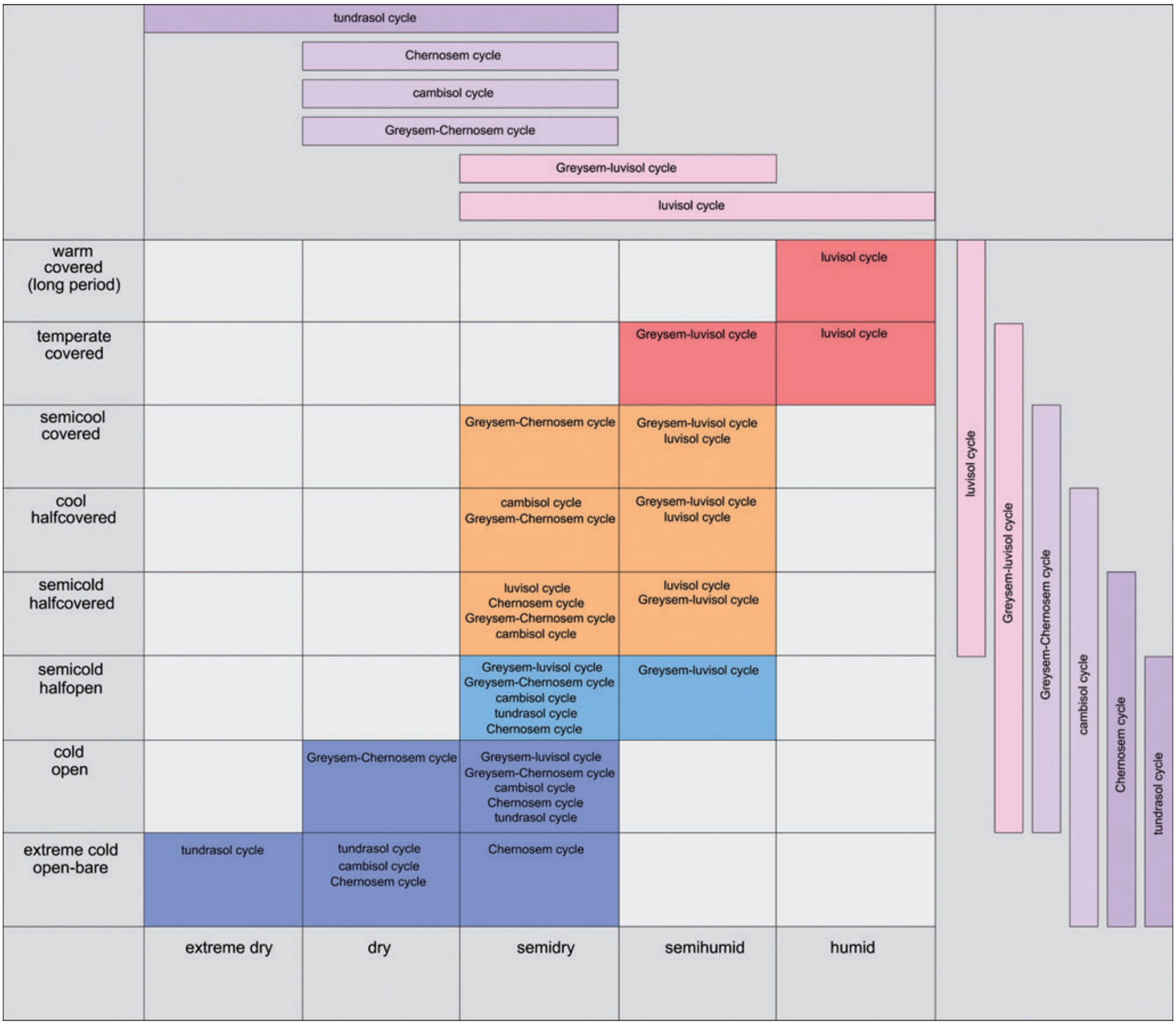
On top of these interglacial (complex) pedogeneses an extended and extremely deep polygonal ice-wedge network of unit 28 developed (sometimes up to 200 cm deep), with overlying marker loesses and more Chernosem-like palaeosols, indicating overall colder and drier climatic circumstances than before. The border between the last interglacial and the last glacial is assumed to be near the top of unit 27. Two warmer oscillations with Chernosem-like and cambisol palaeosols intervened (units 30 and 39a).

From unit 36 onwards, palaeoclimatic conditions were so rigorous that they caused permafrost formation, leading to heavy surface denudation because of a humid active layer (SL-discordance; see Fig. 8). Only in downslope environments was accumulation of slope-derived LBS sediment possible, while uphill severe surface denudation occurred. Unit 42 terminates this period with the most rigorous linear erosion of the last glacial, leading to the lowering of the Hezerwater stream and its discharging drainage lines by 3-4 m. By lateral erosion it created a steep, 4-6 m high valley wall, facing east, with slope percentages of 25-50% (TL discordance; see Fig. 8). Striking is the relative temperate climate between units 42 and 46 with moles present in the faunal assemblage and only minor allochthonous calcareous loess accumulation in the cold spell of unit 44. In this period signs of human activity were noted on two occasions (Bringmans et al., 2006). After this, the climate again became colder culminating in the formation of an extensive ice-wedge network of unit 49.

Very important is the cambisol pedogenesis of unit 50, which led to decarbonisation of overall calcareous loess sediments and an enrichment of calcium carbonate at its base (pseudomycelium or small loess dolls). Afterwards climatic deterioration eventually caused the formation of extensive and deep permafrost, leading to surface denudation because of a humid active layer (unit 57). However, the overall climate became harsher and drier, reflected by the absence of worms, rodents and molluscs. Due to permafrost decay during some climatic ameliorations, U-like depressions were formed in drainage lines by thermokarst, with undercutting features and basal gritbed layers (units 58, 60, 61 and 63).

The very dry and rigorous climatic conditions can also be deduced from the presence of collared lemming (*Dicrostonyx*), the absence of water vole (*Arvicola terrestris*), the blowing in of aeolian sands in drainage lines and the accumulation of homogeneous powdery loess uphill, despite prevailing permafrost conditions. In these times, the active layer must have been rather dry because of the action of katabathic and sublimating winds. It culminated in the formation of a real desert pavement (unit 61, patina discordance; see Fig. 8). In periods with less loess accumulation, just before and after the pedogeneses of units 62 and 64, extensive and very deep ice-wedge networks formed (until 400 cm deep). The last glacial period ends with an abrupt climatic amelioration, causing decalcification of the subsurface and the formation of a red brown luvisol (units 70 and 71; see Fig. 8).

After the short cold spell of unit 72, the warm interglacial climate continued, leading to the development of a luvisol (unit 74; see Fig. 8). However, in most parts of the palaeolandscape no accumulation of colluvium occurred between units 70 and 74, leading to a complex interglacial polygenetical luvisol 70-74.



	extreme dry	dry	semidry	semihumid	humid
warm covered (long period)					luvisol cycle
temperate covered				Greysem-luvisol cycle	luvisol cycle
semicool covered			Greysem-Chernosem cycle	Greysem-luvisol cycle luvisol cycle	
cool halfcovered			cambisol cycle Greysem-Chernosem cycle	Greysem-luvisol cycle luvisol cycle	
semicold halfcovered			luvisol cycle Chernosem cycle Greysem-Chernosem cycle cambisol cycle	luvisol cycle Greysem-luvisol cycle	
semicold halfopen			Greysem-luvisol cycle Greysem-Chernosem cycle cambisol cycle tundrasol cycle Chernosem cycle	Greysem-luvisol cycle	
cold open		Greysem-Chernosem cycle	Greysem-luvisol cycle Greysem-Chernosem cycle cambisol cycle Chernosem cycle tundrasol cycle		
extreme cold open-bare	tundrasol cycle	tundrasol cycle cambisol cycle Chernosem cycle	Chernosem cycle		

Fig. 7. Schematic representation of the interpreted pedo-sediment cycles in the Veldwezelt loess quarry.

Pedological interpretation

The loess sections in the Veldwezelt pit are composed of different individual cycles of pedogenesis, erosion, sediment accumulation and cryogenic processes, all needing specific climatic and vegetation changes in time (warm vs extreme cold, humid vs extremely dry and densely vegetated vs nearly bare; see Fig. 7).

Luvisol cycles 18-21 and 22-23 start with warm pedogenesis, followed by colder erosion, minor deposition of slope derived material with synchronous frost action, humic pedogenesis and close with gelicolluviation. Greysem-luvisol cycles 24-26 and 27-29 start with temperate pedogenesis, followed by colder erosion, minor deposition of slope derived material with synchronous frost action, humic pedogenesis and close with gelicolluviation. Greysem-Chernosem cycle 30-33 begins with semi-cool humic pedogenesis, followed by colder erosion, minor deposition of slope-derived material with synchronous frost action, humic pedogenesis and ends with deposition of aeolian loess and synchronous humic pedogenesis.

Cambisol cycles 39a-39c and 50-51 begin with cool pedogenesis, followed by colder erosion, minor deposition of slope-derived material with synchronous frost action and end with deposition of aeolian loess and synchronous humic pedogenesis. Chernosem cycles 34-36 and 39d-40c start with semi-cold humic pedogenesis, followed by deposition of aeolian loess and close with erosion, gelicolluviation and synchronous frost action. Tundrasol cycles begin with semi-cold pedogenesis and end with deposition of aeolian loess, erosion, gelicolluviation and synchronous frost action.

In general it seems that luvisol-like cycles start with a warm to temperate, dense woodland (or steppe forest) vegetation, changing into cold and more open environments at the end, while Chernosem-like and cambisol cycles evolve from intermediate to semi-cold (mixed) wooded grassland conditions into cold,

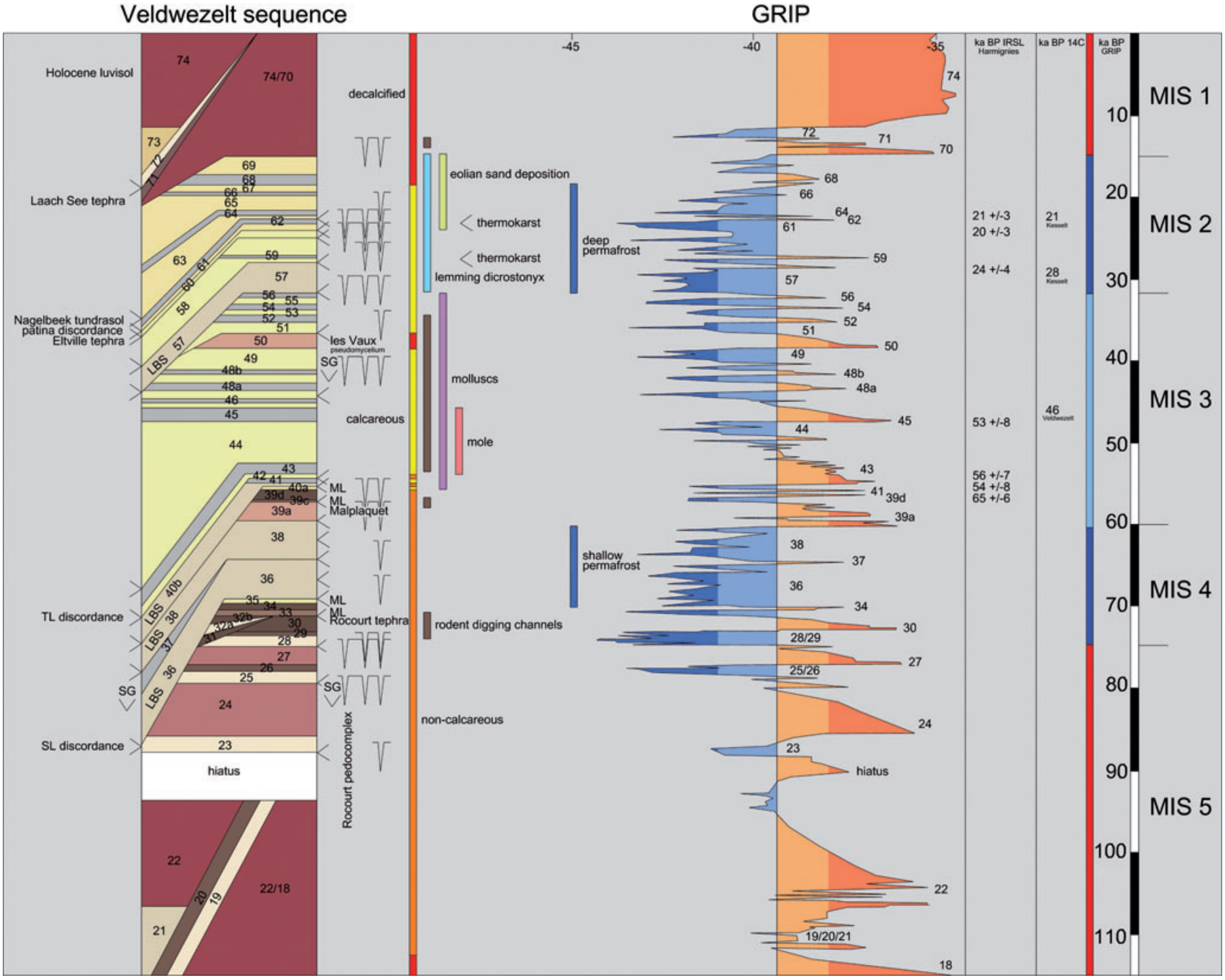


Fig. 8. Standard Veldwezelt sequence; its pedological, sedimentological, tephrochronological, faunal and cryogenic characteristics and (chrono)comparison with the Harmignies loess section and the Greenland GRIP ice curve. Abbreviations: ML = marker loess; SG = segregation-ice features; LBS = Lehmbrockelsande or pellet sands. GRIP curve according to Johnsen et al. 2001 (50ss09cl; chrono 2001).

semi-arid grassy steppes and close with cold, semi-arid and open tundras. Tundrasol cycles start with semi-cold tundra-steppe vegetation, moving into cold, arid and open tundras or tundra deserts.

Luvisol-like, Chernosem-like and cambisol cycles preferentially occur in the beginning and middle part of the last glacial, showing the activity of beetles (units 29-43), rodents (units 20, 29-33, 39c, 42-52), worms (units 18-52), water vole (units 39c-57), molluscs (units 40a-56) and marker loess accumulation (marker loess of units 33, 35, 39c and 40a). Tundrasol cycles are mostly present in the middle and late part of the last glacial and clearly represent colder, more open and drier environments, with massive (homogeneous) loess accumulation, dry permafrost, sand deflation (units 61-69), the presence of collared lemming (*Dicrostonyx*; units 57-69) and the absence of water vole (*Arvicola terrestris*) in units 57-69.

Worm and rodent activity especially started from palaeosol surfaces. Most molluscs and micro- and macrofauna were recovered from the upper part of the palaeosols. In units 53-69 climatic conditions were so harsh and dry that no worm or rodent activity was possible anymore. Even no molluscs were encountered in sequences above unit 56. Downslope palaeosols often show syngenetic pedogenesis, due to the greater influx of gelicolluviated sediment. Syngenetic pedogenesis that could not keep pace with sedimentation rate, sometimes resulted in multiple palaeosols near drainage lines (units 37 and 43).

Sedimentological interpretation

Except for the grey-yellowish powdery homogeneous loess, nearly all loesses are composed of more or less stratified silts. The most extreme lamination is present in the heavily stratified gelicolluvium of the so-called 'Lehmbrockelsande' or pellet sands (LBS). These stratified sequences consist of individual geliflucted and washed sediment layers. The washed lamina show yellow, grey and white colours and normally have a siltish sediment matrix, devoid of any clay and originating from overland flow processes (sheet wash). They often create gullying phenomena in underlying sediment strata. The geliflucted clayey lamina show grey, red and brown colours and have a larger, often sandier sediment matrix, originating from mud flows and other gelifluction processes. Both consist of slope-derived sediments accumulated under cold climatic circumstances with only sparse vegetation.

Probably these alternating processes have a seasonal origin, with flow processes over a still frozen subsoil in spring/early summer and more washing action in late summer/early autumn on an already thawed and dried subsurface. Obviously, these gelicolluvium beds are generated in environments with an open and sparse vegetation cover.

Heavily stratified gelicolluvium consists entirely of slope-derived sediments, indicating cold, open and humid conditions. Weakly stratified gelicolluvium often shows a component of non-reworked aeolian loess, also indicating cold and open vegetation environments, but rather dry climatic conditions.

Downslope near small drainage lines gelicolluvium deposits pass into grit beds and eventually into larger fluvial sediment sequences. Here the washed lamina change into fluvial sandy and gravelly series, while the geliflucted lamina turn into fluvial silty layers. Upslope humid conditions in the active layer, due to permafrost, invoked heavy denudation of the palaeolandscape. Part of this denudation material was deposited downslope (gelicolluvium beds), while most drainage lines were intermittently accumulated and eroded by grit beds. Only in extreme cold and dry climatic conditions, with katabathic and sublimating winds, did permafrost not cause oversaturation of the active layer, so also upslope accumulation was possible. In the melting season runoff processes were not possible anymore because of water shortage, so only minor gelifluction was active. Near the Hezerwater stream fine yellow aeolian sand lenses were blown in from the wasted braided drainage beds contemporaneously with the influx of geliflucted material from uphill areas, leading to a heavily stratified sediment sequence (the so-called 'sands and silts'). Upslope these laminated sands and silts gradually pass into powdery homogeneous loess sequences.

In the last glacial period one important subhorizontal deflation hiatus (unit 61) and eight major linear erosion discordances are present (units 36, 42, 51, 57, 58, 60, 61 and 63). The widespread subhorizontal deflation discordance 61 is related to the presence of a polar desert in these regions around the Last Glacial Maximum (LGM). The linear erosion discordances 36 and 57 are related to the presence of active permafrost, while the U-like linear erosion unconformities of units 58, 60, 61 and 63 (with basal grit beds and undercutting features), were in first instance invoked by permafrost decay.

In periods with permafrost the Hezerwater stream did not lower its bed because of the massive influx of gelicolluvial sediment (humid permafrost) or loess (dry permafrost). Especially in the deep permafrost cycle 57-67 a lot of (ground)water was fixed. During permafrost decay a lot of this ice fixed water was released, invoking incision of the Hezerwater stream. Climatic circumstances without permafrost could also cause vigorous linear erosion (units 42 and 52). Here linear erosion was probably caused by colder, but still humid, climatic conditions in environments with a rather intact vegetation cover (just after pedogenesis).

Cryogenic interpretation

In the cold interglacial spells and the transition to the last glacial period only incidentally could shallow permafrost form due to the overall thick snow cover. In these relatively stable landscapes with slow accumulation rates, pronounced polygonal ice-wedge networks could develop (units 23, 25 and 28). However, in glacial times high sedimentation existed over long periods (gelicolluviation, loess deposition), in which only isolated frost cracks or ice-wedges could form. The formation of polygonal ice-wedge networks needs landscape stability and semi-humid cold environments, which especially existed just prior to and just after pedogenesis (see also Antoine et al., 2009). Formation of cryoturbation phenomena with amplitudes of up to 0.5 m requires at least more or less flat and moist terrain, in combination with deep seasonal frost. Upslope these convolutions migrate into tongues by creep and when slope angles increase even these tongues are straightened out by flow processes. For greater amplitudes permafrost is needed.

In the last glacial deposits of the Veldwezelt section two major periods with continuous permafrost could be demonstrated by the presence of segregation-ice and large cryoturbation structures, pellet sands (LBS sediment) and ice-wedge networks (units 36-38: shallow permafrost and units 57-67: deep permafrost). In the cold spells between units 46 and 57 probably discontinuous permafrost was present. Especially for the formation of the extensive ice-wedge network of unit 49 permafrost was necessary. The beginning of stage 57-67 was less humid, but also generated LBS strata. Soon, however, this cycle became extremely dry (from unit 61 onwards), preferentially invoking gelifluction, sand blowing from drainage lines and the formation of a deep permafrost with extensive and deep polygonal ice-wedge networks. In these conditions the subsoil was too dry to create segregation-ice lenses.

Stratigraphy

Introduction

The Veldwezelt series provides an excellent high-resolution terrestrial archive of climate forcing for the Late Saalian, Eemian and Weichselian periods, showing cycles of landscape stabilisation and soil formation, erosion, cryogenic activity and deposition of loess and slope-derived sediments. It is composed of strata present only in the loess quarry of Veldwezelt itself.

In this respect the correlation with other areas should be more reliable.

The Veldwezelt section most closely resembles the extensive Harmignies sequence near Mons (Mons Basin, southern Belgium), which is also constructed from sediment series of the Harmignies quarry itself (Haesaerts & van Vliet-Lanoë, 1973, 1974, 1981). The near-lack of hiatuses, the presence of three tephra layers, the intact connection between downslope and uphill series and the extensive faunal, pedological, cryogenic and sedimentological data range from the Veldwezelt quarry is striking and without imitation.

Regional stratigraphy

Along the widened Albert Canal, in neighbouring loess quarries, but also at the Veldwezelt pit itself, samples have been taken for heavy mineral analysis, on the basis of which a chronostratigraphical model was developed for this region (Meijs, 2002, 2006; see also Pirson, 2007). On the basis of mineralogical research at the Veldwezelt section, it is concluded that the pronounced tundra gley of unit 8 belongs to the so-called 'Bruchköbeler Nassböden' of Saalian MIS-6 age and that the sediments above unit 27 are of Weichselian date (Meijs, 2002; for sample locations see Fig. 3).

The Eemian and Weichselian part of the Veldwezelt section roughly equals the loess frameworks of northern France (Antoine, 2002; Antoine et al., 1998, 2003), central and southern Belgium (Haesaerts et al., 1999, Haesaerts & Mestdagh, 2000) and western Germany (Schirmer, 2000, 2002). However, the actual Veldwezelt transects mostly resemble the numerous Harmignies sections near Mons and are therefore extensively compared.

The Veldwezelt section is chronostratigraphically correlated with the Weichselian tephra range (Pouclet et al., 2008) and the Harmignies loess sequence (Haeaserts & van Vliet-Lanoë, 1973, 1974, 1981; see Fig. 8 here). For the Harmignies section only dates from non-reworked loess are taken into account (Frechen et al., 2001), while at Veldwezelt just one date of unit 45 is available (uncalibrated C14 date of 45.4 ka BP; Bringmans, 2006; see Fig. 8). Units 57 and 62 of the Veldwezelt sequence are chronologically matched with the available absolute dates from the nearby Nelissen loess quarry at Kesselt (Gullentops, 2006; see Fig. 8).

On the basis of its pedostratigraphical position and preliminary thermoluminescence dates, it is suggested that luvisol cycles 18-21 would represent a Late Saalian 'Bølling-Allerød-type' climatic oscillation (Zeifen interstadial), just prior to the MIS 6-5e transition (Bringmans, 2007). The main loess stratigraphical frameworks of northern France, central and southern Belgium and western Germany, however, attest that the first luvisol developed in Saalian sediments should be of Eemian MIS 5e age (Haesaerts et al., 1999; Haesaerts & Mestdagh, 2000; Schirmer, 2000, 2002; Antoine, 2002; Antoine et al., 1998, 2003). Correlation between the Veldwezelt sequence and these west European frameworks suggests the luvisol of unit 18 should be the equivalent of MIS 5e.

Besides the Bølling-Allerød pollen record reaches high Holocene levels, making a luvisol-type palaeosol development possible, in contrast to the much lower pollen curves of the Zeifen oscillation (Woillard, 1978; Woillard & Mook, 1982).

At last the preliminary Veldwezelt thermoluminescence results (Bringmans, 2007) are similar to the those of unit EA2 at Harmignies (Frechen et al., 2001), indicating a chronostratigraphical position of units 19, 20 and 21 around MIS 5d. So the hypothesis that luvisol cycles 18-21 would represent a Late Saalian 'Bølling-Allerød-type' climatic oscillation is considered as most unlikely. Units 19 and 20 which yielded important human activity data from several excavation campaigns at the Veldwezelt quarry, are best dated assigned to MIS 5d.

In summary, it can be concluded that humans were active in the area of the Veldwezelt quarry at around 140 ka (Late Saalian; unit 15), around 115 ka (units 19-20), around 85 ka (unit 27), around 55 ka (unit 43) and around 46 ka (unit 45; see also Bringmans et al., 2006).

Normally the luvisol of unit 22 overprints the earlier developed luvisol of unit 18, leading to a complex polygenetic palaeosol 18-22. At the Veldwezelt pit, however, as well as at Harmignies, locally these two luvisols are superposed with a small erosion gully in between. Only in these cases can pedostratigraphical conclusions be drawn without the help of micromorphological research. Thus, Veldwezelt units 18 and 22 are pedostratigraphically correlated with units DA1 and EA3 at Harmignies. According to its pedological characteristics and stratigraphical position, the humic palaeosol FA at Harmignies is correlated with the Chernosem of unit 39d at Veldwezelt.

This correlation is corroborated by the fact that at both localities the first calcareous loess appears just on top of units FA and 39d, respectively. Also the segregation-ice formation stages at Harmignies (units EB1, GA-HB2, HC1-HC6) correspond to the segregation-ice periods at Veldwezelt (units 36-38, 41-49, 51-57).

Palaeosol 'les Vaux' is present in both sequences (units HB4 and 50), but also in northern France (Haesaerts & Van Vliet-Lanoë, 1973, 1974, 1981; Antoine, 2002). At Veldwezelt, in central-southern Belgium and northern France, this is characterised by decalcification and calcium-carbonate enrichment at its base (pseudomycelium: Haesaerts et al., 1999; Antoine, 2002). This palaeosol with decalcification and accompanying calcium-carbonate enrichment present in overall calcareous loess sediments forms an important pedostratigraphical marker. However, erosion processes often totally eradicated this 'les Vaux' marker. In those cases, the filled ice-wedge casts and accompanying segregation-ice features in the over- and underlying units HC6 and GA-HB2 at Harmignies and units 57 and 41-49 at Veldwezelt, can be a further clue for correlation. In this respect, it is important that units 41-49 may show filled rodent digging channels (krotowina), while these are definitely absent in unit 57.

In a regional context also the so-called 'patina' discordance of unit 61 is an important lithostratigraphical marker. It represents a deflation horizon with a polar desert pavement and is seen as the equivalence of the last glacial maximum (LGM).

Global stratigraphy

The Veldwezelt sequence is also chronostratigraphically correlated with the GRIP ice core of Greenland (Johnsen et al., 2001; see Fig. 8). Astonishing is the extremely cold environment existing at the beginning of the Weichselian MIS 4 period, around 75 ka BP. In addition to the Greenland GRIP curve, the Th230-dated oxygen isotope records of stalagmites (CaCO3) in central China also show an extremely cold period around 72 ka BP (Cheng et al., 2009). According to the O18 percentages in both curves this is by far the coldest period of the last Weichselian glacial.

In the Veldwezelt section, this 2 kyr period is most probably represented by the deep polygonal ice-wedge network of unit 28 (see Fig. 8). The semi-humid climate will have been rigorous, with thick snow and vegetation covering the palaeolandscape, preventing permafrost formation and the generation of LBS gelicolluvium series.

The 10 kyr period between 60-70 ka BP with severe semi-humid conditions and more open palaeolandscapes with sparse vegetation, is correlated with the accumulation period of units 35-38 in downslope environments at the Veldwezelt pit (see Fig. 8).

On the basis of its pedostratigraphical position and available preliminary thermoluminescence dates, it is suggested that the Veldwezelt luvisol cycles 18-21 would represent a Late Saalian 'Bølling-Allerød-type' climatic oscillation (Zeifen interstadial), just prior to the MIS 6-5e transition (Bringmans, 2007). The Zeifen oscillation is correlated to the 135 ka curve peaks in the Greenland Summit ice core of Dansgaard 1993 (Bringmans, 2006). However, it is most likely that these peaks in the deeper parts of the Greenland Summit ice core record were induced by ice tectonics (Boulton, 1993; Grootes et al., 1993; Taylor et al., 1993). In addition, at several locations in Europe and North America the palynological succession in the Saalian-Eemian transition period indicates a gradual evolution from open plant communities to closed forests (Reille et al., 1998; Binka & Nitychoruk, 2001; Jiménez-Moreno et al., 2007). Together with the regional stratigraphical arguments, also global stratigraphical interpretations indicate that the hypothesis luvisol cycles 18-21 would represent a Late Saalian 'Bølling-Allerød-type' climatic oscillation has to be considered as most unlikely. Units 19 and 20 which yielded important human activity data from several excavation campaigns in the Veldwezelt quarry, are best placed in MIS 5d.

Conclusions

From research at the Veldwezelt quarry it has become clear that the loess transects are comprised of different individual periods of pedogenesis, erosion, sediment accumulation and cryogenic processes.

It has yielded important pedological, sedimentological, faunal, tephrochronological and cryogenic data, on the basis of which palaeoenvironmental conclusions could be drawn and six types of pedosedimentological cycles distinguished: luvisol, Greysem-luvisol, Greysem-Chernosem, cambisol, Chernosem and tundrasol cycles, all needing specific climatic and vegetation changes in time (see Fig. 7).

Uphill and drainage-line environments reveal many hiatuses or discordances, because of truncation by erosion. Downslope accumulation often prevailed outside the drainage lines and prevented erosion, even during unstable periods. Consequently, downslope sections yield the most detailed environmental data, but often lack contact with uphill series. However, for stratigraphical correlation the contact between downslope and uphill sections is essential. In the Veldwezelt sequence this connection is intact, which, in addition, provides extra data on transitory processes.

Because of these special palaeoenvironmental conditions, which encompass the transition between downslope and uphill areas and a south-east trending Hezerwater stream, an extraordinarily detailed Late Saalian, Eemian and Weichselian loess sequence could be reconstructed at the Veldwezelt loess pit.

Along the widened Albert Canal, at nearby loess quarries, but also at the Veldwezelt pit itself, samples were taken for heavy mineral analysis, on the basis of which a chronostratigraphical model was developed for this region (Meijs, 2002, 2006; see also Pirson, 2007). On mineralogical evidence for the Veldwezelt section it is concluded that the pronounced tundra gley of unit 8 belongs to the so-called 'Bruchköbeler Nassböden' of Saalian MIS-6 age and that the sediments above unit 27 are of Weichselian date (Meijs, 2002; for sample locations see Fig. 3).

Additional stratigraphical conclusions could be drawn by correlating the Veldwezelt section with western European loess frameworks and tephra sequences, the sediment series at Harmignies and with the Greenland GRIP ice core (see Fig. 8). The hypothesis that luvisol cycles 18-21 would represent a Late Saalian 'Bølling-Allerød-type' climatic oscillation is considered most unlikely. Units 19 and 20, which yielded important data on human activity during several excavation campaigns at the Veldwezelt quarry, are best situated in MIS 5d.

In summary, it may be concluded that humans were active in the area of the Veldwezelt pit at around 140 ka (Late Saalian; unit 15), around 115 ka (unit 19-20), around 85 ka (unit 27), around 55 ka (unit 43) and around 46 ka (unit 45).

The Veldwezelt sequence convincingly documents two important Weichselian permafrost periods in MIS-4 and MIS-2 (see Fig. 8). Astonishing is the extremely cold setting at the start of the Weichselian MIS 4 period, around 75 ka BP. Based on O^{18} values this is by far the coldest interval of the Weichselian glacial. This 2 kyr period is assumed to be represented by the deep polygonal ice-wedge network in unit 28, which developed in whitish, slope-derived material. During this time, the semi-humid climate must have been harsh, with thick layers of snow and vegetation covering the palaeolandscape, preventing permafrost formation and the generation of LBS gelicolluvium series.

The 10 kyr period between 60-70 ka BP, with severe semi-humid conditions and more open palaeolandscapes with sparse vegetation, is correlated with the accumulation period of units 35-38 in downslope environments at the Veldwezelt quarry. Because of the overall thick snow cover permafrost could not develop easily; instead, there was shallow permafrost with accompanying segregation-ice structures. Each melting season gelifluction and sheet wash could strip the outcropping Chernosems and luvisols uphill. As a result of this widespread denudation extensive LBS series occur, equivalents of which are seen in all western European loess sequences. The first calcareous loess appears around 60 ka BP, just on top of the FA and the 39d palaeosol at Harmignies as well as at Veldwezelt.

In addition to the important Rocourt tephra layer (on top of unit 30) and the characteristic 'patina' deflation horizon of unit 61, the decalcified palaeosol of unit 50 ('les Vaux palaeosol') with accompanying calcium-carbonate enrichment at its base in between calcareous loess sediments, forms an important pedostratigraphical marker. In cases where this important palaeosol of unit 50/HB4 is missing due to erosion, the characteristic filled ice-wedge casts with accompanying segregation-ice features from the over- and underlying units 57/HC6 and 41-49/GA-HB2 can be helpful in correlation (Veldwezelt/Harmignies). In this respect, it is important that units 41-49 may show filled rodent digging channels (krotowina), while in unit 57 these are definitely absent. Only the widespread subhorizontal erosion unconformity of unit 61 is related to deflation, with an estimated age of around 20 ka BP (last glacial maximum; LGM). In these times, metres of outcropping sediment were deflated by strong winds, leaving a flat polar desert pavement. The other Weichselian erosion discordances have a non-deflational origin.

Erosion in units 36 and 57 is related to the presence of permafrost, while in units 58, 60, 61 and 63 gully erosion with basal grit beds and undercutting features, was probably primarily triggered by permafrost decay. Also in times without permafrost, linear erosion could have been vigorous (units 42 and 51). Here erosion was probably caused by rapidly deteriorating cold and humid conditions in environments with a rather intact vegetation cover (often directly following pedogenesis). With the exception of the grey-yellowish homogeneous powdery loess, which was deposited in particular during the last extremely dry part of the Weichselian, nearly all loesses show some stratification. The most extreme lamination is present in the heavily stratified gelicolluvium of the so-called 'Lehmbrockelsande' (LBS sediment or pellet sands). These stratified sequences consist of individual geliflucted and washed sediment layers, accumulated under cold climatic circumstances with only sparse vegetation. Probably, these alternating processes have a seasonal origin, with flow processes over a still frozen subsoil in spring/early summer and more washing action in late summer/early autumn on an already thawed and dried subsurface. Upslope humid conditions in the active layer, due to permafrost, led to heavy denudation of the palaeolandscape. Part of this denudation material was deposited downslope (gelicolluvium beds), while most small drainage lines accumulated intermittently and were eroded by grit beds. In drainage lines these grit beds pass into larger fluvial sedimentary sequences. The washed lamina change into fluvial sandy and gravelly series, while the geliflucted lamina turn into fluvial silty layers.

Only under extremely cold and dry climatic conditions, with katabathic and sublimating winds, did permafrost not cause oversaturation of the active layer during the melting season, meaning that also upslope accumulation was possible. In such times, powdery homogeneous loess was deposited uphill, while heavily stratified sands and silts were formed near drainage lines, due to the blowing in of aeolian sands from the nearby wasted braided drainage beds.

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