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Natural versus anthropogenic genesis of mardels (closed depressions) on the Gutland plateau (Luxembourg); archaeometrical and palynological evidence of Roman clay excavation from mardels

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Abstract

Mardels, small closed depressions, are distinctive landforms on the Luxembourger Gutland plateau. In the present landscape most mardels are shallow fens, filled with colluvial sediments. The genesis of mardels has been studied intensively, inside and outside Luxembourg. Some researchers suggested a natural development and consider mardels as subsidence basins due to subsurface solution of gypsum veins, other researchers suggested cultural causes and consider mardels as prehistorical quarries.

In the Gutland, mardels occur on various substrates. Mardels on the Strassen marls (li^3) are abandoned quarries, related to clay excavation in Roman Time. Mardels on the Luxembourger sandstone (li^2) are sinkholes, related to joint patterns in the sandstone formation. Mardels on the Keuper marls ($km^{1,3}$) are originally subsidence basins, related to subsurface dissolutions of gypsum lenses and veins, filled with colluvial clay. The results of pollen analysis and archaeometrical tests demonstrate Roman extraction of clay for the production of ancient ceramics. So, the natural depressions have been enlarged to the present mardels. After excavation, the sedimentation of colluvium restarted in the abandoned quarries.

1 Introduction

The geological structure (Fig. 1) of the Luxembourger Gutland is inherited from Tertiary and Quaternary landscape evolution, which was initiated by the Pliocene tectonic uplift of the entire region Luxembourg (Lucius, 1948). The present Gutland is a cuesta landscape, underlain by alternating tilted sedimentary rock formations with different resistance to weathering and erosion.

During the Pleistocene the landscape has been subjected to several cycles of weathering and erosion by the alternation of glacial and interglacial periods (Lucius, 1948; Verhoef, 1966). During glacial periods landscape development was dominated by ero-

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sion and denudation under periglacial conditions. During interglacial periods, the landscape became vegetated, denudation was reduced and soil profiles could develop.

The Holocene landscape evolution started in a landscape with thin regolithic slope covers and Pre-Holocene gravelly deposits on the valley floors (Heuertz and Heyart, 1964; Verhoef, 1966). Plant growth, rock weathering and soil formation were the dominant processes in the Early Holocene (Slotboom and van Mourik, 2016).

Typically for the geomorphology of the Gutland plateau is the occurrence of mardels, small closed depressions. Mardels occur on various substrates, in particular on Lias and Keuper marls and may have different genesis (Fig. 2). In these mardels, fens and wetlands developed which potentially contribute to the geodiversity and biodiversity of the present landscape. Peat and clayey mardels deposits are important soil archives for the paleoecological reconstruction of the Late Holocene landscape evolution (Slotboom and van Mourik, 2015).

The oldest descriptions of the mardels on the Luxembourger Gutland plateau were done by Lucius (1941, 1948). He ascribed mardels, occurring on the Steinmergelkeuper (km^3) and the Pseudomorphosekeuper (km^1) to subsurface solution of calcareous or gypsum inclusions, followed by collapse and subsidence of the overlying beds. He postulated that mardels can also form by subsidence as a reaction on tectonic stress, causing joints in the Luxembourger sandstone formation.

Slotboom (1963) investigated 108 mardels on Gutland plateau on the Keuper marls. Based on his detailed field observations he confirmed the genetic conclusions of Lucius and considered mardels as natural phenomena.

Braque (1966) suggested that the mardels, observed on the plateau of Nivernais (France) are also geological phenomena that developed under periglacial conditions during the Late-Glacial and by karst processes during the Holocene.

Barth (1996) investigated mardels in Lorraine (France). Based on soil descriptions she confirmed the geological evolution of mardels in “Lorraine Gypsiferous Keuper” and rejected anthropogenic geneses. Also she postulated that the formation of mardels is still ongoing in the present landscape.

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Thoen and Hérault (2006) investigated the development of CD's in forests in Lorraine. They suggested Holocene subsurface solution of evaporitic lenses of halite, gypsum and carbonate as the major process to explain the development of the CD's. They observed a range of depressions from mature to juvenile and concluded that the development of mardels is still going on.

The above cited researchers interpreted the mardels as the result of geological processes. Pollen diagrams of mardel fillings are produced of a selection of the Gutland mardels; the palynological age of the fillings is Post Roman, never older (Slotboom, 1963; Poeteray et al., 1984).

Schmalen (2002) made an actualized inventory of mardels on the Gutland plateau and also found mardels on the Lias formations (li^3 and li^2). In these formations soluble inclusions are absent. For that reason she suggested an anthropogenic genesis of these mardels. However, her study focused on water quality and wetland species in these unique biotopes and without additional observations it is impossible to qualify these mardels as natural or anthropogenic.

Etienne et al. (2011) considered anthropogenic factors as principal explanation for CD's in the Lorraine landscape. The sediments in the majority of these CD's could palynological be dated as Post Roman and consequently the majority of the depressions raised as Roman excavations with a Post Roman colluvial filling. They reported also the occurrence of some older and younger natural mardels, indicating that also in this region mardels could develop by subsurface dissolution of evaporitic lenses and soil subsidence. They postulate that in the present geomorphological context, genetically different CD's as periglacial pingos, sinkholes, subsidence basins and human excavations can have similar shapes. Therefore it is complicated to identify the correct genesis of such depressions.

Most of the mardels on the Gutland plateau occur in forests. It is assumed that outside the forest most mardels may have been masked out by agricultural levelling (Poeteray et al., 1984). Most mardels occur in clusters. On the li^3 (Strassen Marls) examples of mardel clusters are found in the Scheiwelterboesch (eastern of Beaufort),

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the Laangebusch (soutwest of Berdorf) and in Oustert/Kalefeld, (east of Medernach). In the previous study by Poeteray at al. (1984) a pollen diagram of mardel Kalefeld was published (reproduced in Slotboom and van Mourik (2015), Fig. 10) and suggested a post Roman age of the filling, based on palynological time markers (e.g. *Fagus* and *Fagopyrum*) and radiocarbon ages. The ^{14}C dates of Soil Organic Carbon (SOC), extracted from colluvium were not reliable due to the reservoir effect and overestimated the real age. The authors did not provide information about the genesis of the mardel, natural or anthropogenic. Therefore, Slotboom and Van Mourik (2015, Figs. 6 and 8) investigated the colluvial profiles of two mardels on the li^3 near Berdorf and Beaufort. Based on the pollen curves (e.g. *Fagus* and *Fagopyrum* and aquatics) and reliable radiocarbon dates of a thin basic layer, deposited on the bottom of the quarry (≈ AD 260) the mardel filling could be interpreted as post Roman. The CD's came into being after the excavation of clay and deeply weathered Strassen marls. It is a probability that Romans used local dug clay to produce their ceramics, which is supported by the finds of Roman pottery close to Kalefeld (Schmidt, 1995). After clay excavation, clayey colluvium has been deposited during the Subatlantic on completely truncated palaeosols (Slotboom and van Mourik, 2015).

On the li^2 (Luxembourger Sandstone) elongated mardels in sink holes occur in linear clusters, related to faults and joints in the sandstone formation (Slotboom and van Mourik, 2015). Good examples are found in the Esselbur (western of Beaufort). Slotboom and van Mourik (2015, Fig. 4) investigated the filling of mardel Eltesmuer. At first, this mardel was filled with sandy colluvium and after that, due to water stagnation, peat could accumulate. The palynological and radiocarbon age of the basic layer of the peat deposit is Subboreal (≈ 2500 BC), that means pre Roman.

On the km^3 (Steinmergelkeuper) examples of mardel clusters are found in the Gebrannte Boesch and Brasert (western of Stegen) and the Bois Biischtert (eastern of Michelbrough). In the studies of Lucius (1948) and Slotboom (1963) they were interpreted as natural depressions, developed by soil subsidence after subsurface solution of gypsum veins. Gypsum veins and lenses are included in de Keuper marls, but these

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researchers do not present geological data to confirm the natural genesis and to exclude anthropogenic processes. Poeteray et al. (1984) published a pollen diagram of mardel Brasert (reproduced in Slotboom and van Mourik (2015), Fig. 12) and suggested, just as in mardel Kalefeld, a post Roman age of the filling, based on palynological time markers (e.g. *Fagus* and *Fagopyrum*) and radiocarbon ages.

The first aim of this study was to determine the natural versus anthropogenic genesis of the mardels on the Steinmergelkeuper. For this purpose we sampled the sediment of the mardels Medernach, Brasert2 (close the previously investigated Brasert mardel) and Michelbouch.

The second aim of this study was to answer the question if Romans extracted mardel for the production of ceramics. For this purpose we applied archaeometrical tests to match clay samples from mardels and soils with fragments of Roman pottery, found in the Bois Biischtert, close to the mardel Michelbouch (Jacobi, 2011).

2 Materials and methods

2.1 Profile and sample selection

The palynological references of the vegetation development will be based on the pollen diagram of the deposits in mardel Dauwelsmuer, a fen in a closed depression in the debris deposits of a landslide. Previously, Schwenninger (1989) published a rough pollen diagram (vertical resolution 15 cm). We resampled the profile with a vertical resolution of 2.5 cm. Also we sampled the fillings of the mardels Medernach, Brasert2 and Michelbouch on the Steinmergelkeuper, (vertical resolution 2.5 cm) for pollen analysis. Additionally, we took samples from the mardel deposits and the soil beside the mardel for the grain size analysis and for the archaeometrical tests. Sample depth was 50–60 cm.

Samples from soft sediments (peat and mardel clay) were taken with a peat sampler; samples from more resistant sediments (soil clay and weathered marls) were taken

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with an “Edelman” soil auger. The soil determination was based on the World Soil Resources Report 103 (Isric/Fao, 2006).

2.2 Pollen extraction and pollen zonation

Pollen extractions of the samples were carried out using the tufa extraction method (Moore et al., 1991). The exotic marker grain method was applied on the preparations for estimation of the pollen densities. For the identification of pollen grains the pollen key of Moore et al. (1991) was applied. The pollen extractions were performed in the Laboratory for Palynology of IBED, University of Amsterdam.

The pollen scores were calculated as percentages of the total pollen sum ($200 < \sum < 400$) of arboreal and herbal plant species. Curves of species with incidental scores were excluded from the pollen diagrams, the incidental scores of profile Dauwelsmuer are presented in Appendix A. A pollen density curve is added to the diagrams to show the discontinuity between deposits and the (truncated) palaeosols.

The geochronology of the diagrams presented in this paper is based on the palynological markers as recorded and on reliable radiocarbon dates in the profile of Dauwelsmuer. Some well dated palynological reflections of the vegetation and agricultural history can be observed, such as the transition of the *Quercetum mixtum* into the *Fageto-Quercetum*, the Subatlantic peaks of *Fagus*, the appearance of *Fagopyrum and the appearance of Picea* (Persch, 1950; Slotboom, 1963). The mardel sediments could only palynologically be dated, not absolute because of the unreliability of radiocarbon dates. Organic matter, extracted from mardel deposits has been affected by reservoir effects (Mook and Streurman, 1983; Slotboom and van Mourik, 2015) and due to the input of inorganic carbon, supplied by the groundwater flow and of soil organic carbon, supplied by soil erosion the radiocarbon dates overestimate the real ages of the clayey sediments.

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2.3 Analysis of macro remains

From the Dauwelsmuer core the section has completely been analyzed for macro remains. The height of the examined samples was 2.5 cm, a total of 93 samples between 0 and 232.5 cm below surface have been analyzed. Since the core was intended for palynological research, a corer was used with a diameter of 2.5 cm. As a consequence the samples for macro analysis remains were small and only a limited picture of local conditions regarding the vegetation (and fauna) was obtained. After cleaning and taking the pollen samples an average of 4 cm^3 ($\pm$1 cm^3) of material remained for the research of macro remains. After carefully sieving with tap water on a sieve with meshes of 0.4 mm the residue was inspected with the help of a microscope (Wild, M7a). All seeds were identified, wood was identified in some occasions, the buds were not identified. The animal remains were assigned to a "group".

2.4 Archaeometry

Provenance analysis of ancient ceramic materials has been the scope of extensive research over the past decennia. Many studies employ geochemical techniques in order to discriminate sources of ceramic production. It is generally accepted that clay raw materials utilized in the production of ceramic materials have a uniform chemical composition in which differences in ceramic chemistry reflect differences of the clay sources, and thus potential provenances (Hein et al., 2004; Braekmans et al., 2011; Degryse and Braekmans, 2014).

As an analytical technique, X-ray fluorescence analysis (XRF) has played a major role in sourcing ancient ceramics and determining the original clay resource. XRF utilizes the emission of characteristic "secondary" (or fluorescent) X-rays from a material that has been excited by bombarding with high-energy X-rays. The emitted radiation has energy characteristic of the atoms present. The phenomenon is frequently applied for elemental analysis of solids, powders or liquids.

In this study fourteen samples have been analyzed for their chemical composition: five soil samples, five mardel samples and four pieces of ceramics. All analyzed samples were powdered and oven dried at low temperature (70 °C) for at least 24 h.

For XRF analysis the measurements were performed at the X-ray facilities of the Materials Science and Engineering department, Delft University of Technology. The instrumentation used was a Panalytical Axios Max sequential wavelength dispersive x-ray fluorescence spectrometer (WD-XRF) and data evaluation was done with SuperQ5.0i/Omnian software. The system is equipped with an Rh anode featuring 4.0 kW operating power, 160 mA tube current and 60 kV excitation. Powder was pressed into tablet with binder (H_3BO_3) and measured in vacuum. Data was collected for the following major elements: SiO_2, Al_2O_3, Fe_2O_3, MgO, K_2O, TiO_2, CaO, P_2O_5, Na_2O, MnO (expressed as wt %); and minor elements Ba, Zn, Zr, S, Cl, Cr, Rb, Ni, Pb, Sr, Nb, Ce, Y and Cu (expressed as parts per million – ppm). Statistical procedures and analyses were conducted in a Statistica software package (version 8.0).

3 Results

3.1 The reference diagram Dauwelsmuer

Mardel Dauwelsmuer (Fig. 3a) is a fen in the debris of a landslide on a sand stone escarpment, developed on the right slope of the river Ernz Noire southwest of Berdorf (49°48′28′′ N/6°19′25′′ E; altitude 244 m). Such landslides took place in the Late-glacial and Preboreal after the disappearance of the permafrost (Lucius, 1948). During the late summer this fen is dry, the rest of the year it is filled with 10–50 cm water. The soil is a histic Stagnosol (clayic), overlying a sapric Histosol. Geologically, the profile is a sequence of four formations. The pollen diagram is presented in Fig. 4, the radiocarbon dates are specified in Table 2, the incidental pollen scores in Fig. 5, the macro remains in Fig. 6.

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The oldest formation (4Ah-4C) consists of gravelly sand, deposited after the landslide on the sand stone debris of the land slide. The 4C horizon is palynologically sterile. The 4Ah horizon developed in sandy parent material (4C) under deciduous forest. Bioturbation caused pollen infiltration, the pollen densities are low. The infiltrated pollen content of the 4Ah is younger (Atlantic) than the sandy sediment (Late-glacial/Preboreal). The pollen spectra reflect the presence of the *Quercetum mixtum*, a palynological expression for the sum of the pollen species *Quercus, Tilia, Ulmus, Fraxinus* and *Acer* (Faegri and Iversen, 1989). *Alnus* and *Corylus* are present as well. Macro remains are very scares in this horizon.

The second formation (3H) consists of sapric peat accumulated from ≈ 6000 until ≈ 550 BP during the Atlantic, Subboreal and a part of the Subatlantic. The prefix sapric indicates a high degree of decomposition of organic tissues, indicative for a regime of variable water tables during the seasons. The peat accumulation started in the Atlantic around 5400 BC and stopped around AD 1360 in the Subatlantic. During the Atlantic the pollen spectra are dominated by the *Quercetum mixtum*; the percentages of herbal species are very low. During the Subboreal *Alnus* expanded. In the beginning of the Subatlantic, *Tilia* and Ulmus decreased, *Fagus* and *Carpinus* appeared. The forest transformed from a *Quercetum mixtum* into a *Fageto-Quercetum*. The *Fagus* curve shows the characteristic regional Subatlantic peaks (Slotboom, 1963), F1 (100 BC–AD 200), F2 (AD 700–800), F3 (AD 1200–1300) and F4 (AD 1700–1900). Besides, is the Subatlantic characterized by deforestation (decrease of arboreal pollen, increase of herbal pollen) and extension of agriculture (appearance of culture indicators Cerealia, *Secale* and *Fagopyrum*). The macro remains of the 3H indicate an accumulation of peat in a forested area during this period. Over a distance of about one meter, seeds are regularly present. In the lower 30 cm of the 3H horizon we see the combination of wood, bud (-scale) and leaf fragments. The peat above contains wood and bud (scales), the amount declines higher in the 3H (50–90 cm). By wood and seeds the presence of some species growing in de tree and shrub layer is demonstrated: *Quercus* sp., *Fraxinus excelsior*, *Tilia* sp., *Betula* sp., *Corylus avellana*, *Sambucus nigra* and *Rubus*

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fruticosus. These species indicate that the peat was formed in a forest. There was no closed canopy since enough light was available for the growth of various swamp plants like *Alisma* sp. and *Carex pseudocyperus*. The terrain was wet, but not wet enough for the presence of water plants. Only *Callitriche* sp. and a *Lemna*-species could grow in the shallow water puddles, where *Cladocera* (water flees) and *Copepoda (crustaceans) lived as well*. All other species found are terrestrial plants which grew in very wet (swamp, shore) to damp habitats. Probably, the groundwater level fluctuated around the ground surface. Such hydrological conditions stimulate the decomposition of folic tissues to sapric peat. The species point to rather nutrient-rich conditions; *Urtica dioica* is a good example of this.

The third formation (4C) consists of silty clay and was deposited between ≈ 550 until ≈ 200 BP. The increase of herbal pollen (Poacae, Asteraceae, and cultural indicators) points to proceeding deforestation and extension of agriculture. Slotboom and van Mourik (2016) suggested an increase of soil erosion for this period, with maximal values during the Little Ice Age. The Strassen marls on the plateau of Berdorf were the source of the clay, transported by soil erosion to mardel Dauwelsmuer. *Fagopyrum* is found in the spectra of the clay deposit. The concentration of macro remains in the 2C horizon is very low.

After the Little Ice Age the accumulation of peat (H) restarted. *Picea* appeared and *Pinus* expanded in the pollen records after AD 1800 due to forest plantations, started by the Regional government (Riezebos and Slotboom, 1974, 1978). The macro remains of the upper peat layer (H) contain wood, buds and tree leafs. The tree *Fraxinus excelsior* is present. *Callitriche* sp. and water flees (*Cladocera*) point to a water rich environment. The peat is formed in a swamp forest with shallow puddles and humid land situations.

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3.2 The pollen diagrams of the mardels on the Steinmergelkeuper

3.2.1 Mardel Medernach

Mardel Medernach (Fig. 3b, pollen diagram Fig. 7) is situated in the Seitert forest, western of Medernach (49°49′06″ N/6°11′75″ E; altitude 324 m). The soil in the mardel filling is a Stagnosol (clayic, colluvic), the soil around the mardel is a stagnic Alisol (clayic), developed in a regolithic cover of 130 cm weathered Keuper marls. The current dominating soil process is lateral leaching of clay by overland flow and piping, triggered by the dispersion of clayey earth worm droppings (Cammeraat, 2006; Cammeraat and Kooijman, 2009).

The oldest zone (2C/2Cca) is the lower part of the truncated (palaeo)sol, developed in the regolithic cover of the Steinmergelkeuper. The pollen densities in this part the profile are low and show a sharp decrease downwards, characteristic for pollen infiltration (van Mourik, 2001, 2003). The 2C consist of light gray clay with pinkish grey mottles, the 2Cca consist of gritty weathered Steinmergelkeuper. The infiltrated pollen grains are not or slightly corroded, very well preserved under the colluvial layers. The pollen spectra reflect the *Fageto-Quercetum*. The relatively high percentages of herbal pollen, indicate an open place in the forest. Remarkable is the presence of pollen of the (semi)aquatic species *Callitriche* and *Sagina*), These plants do not occur on the drained forest soils in the surroundings and indicate moist to wet conditions at the time of infiltration.

The C2 horizon, light gray clay, is the basic layer of the colluvial filling. A part of the pollen grains is hardly corroded (sin-sedimentary pollen), a part is severely corroded (pollen, originating from the eroded topsoil in the surroundings). Pollen of *Callitriche* is still present, pointing to wet conditions at the time of deposition. The herbal pollen species decrease, the arboreal species increase, indicating recovering of the forest. *Fagus* peaks F2 and F3 are recognizable, pointing to a palynological age between ≈ 500 and ≈ AD 1500.

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The C1 horizon, grey clay, is a colluvial layer, deposited since ≈ AD 1500. The appearance of *Fagopyrum* and the extension reflect the Little Ice Age. In the AC horizon (dark grey clay) the appearance of *Picea* reflects the forest plantations after AD 1800.

3.2.2 Brasert2

The Brasert2 mardel (Fig. 3c, pollen diagram Fig. 8) is situated in the Brasert forest (49°49′ 42″ N/6°08′48″ E; altitude 356 m) on the Steinmergelkeuper (km^3) under *Fageto-Quercetum.* Similar to mardel Medernach, the soil in the mardel filling is a Stagnosol (clayic, colluvic), the soil around the mardel is a stagnic Alisol (clayic), developed in a the regolithic cover of weathered Keuper marls.

In previous studies of the mardels in the Brasert forest (Poeteray et al., 1984; Slotboom and van Mourik, 2015) a difference of 150–250 cm between the level of the weathering front in the calcareous Keuper in the mardels and outside the mardels was established. This difference is explained by subsidence of the surface after de dissolution of gypsum lenses. The thickness of the majority of gypsum lenses and veins, occurring in the Steinmergelkeuper ranges from 0.5 to 3 m (Lucius, 1948).

The zoning of the pollen diagram (Fig. 8) is similar to diagram Medernach. A truncated palaeosol (2C, 2Cca) had developed in the weathered Keuper marls in which pollen had infiltrated. Relatively high percentages of herbal pollen and aquatics can be observed (in this diagram *Myriophyllum* and *Typha*). A colluvial basic layer (C2, gray clay) was deposited between AD 500 and 1000 (before the F2), with pollen spectra reflecting recovering of the forest. A colluvial layer top layer (C1) was deposited since AD 1000 with the palynologically reflection of the Little Ice Age and the *Picea* plantations.

3.2.3 Michelbouch

Mardel Michelbouch (Fig. 3d, polen diagram Fig. 9) is located in the “Biischtert” forest, east of Michelbouch (49°48′58″ N/6°01′55″ E; altitude 357 m). In the mardel filling a

Stagnosol (clayic, colluvic) was discovered and in the forested surroundings a stagnic Alisol (clayic) was present.

The zonation of the diagram (Fig. 9) is rather similar to the diagrams Medernach and Brasert2. Two differences can be noticed: the distinction of three instead of two colluvial layers and the presence of a well-developed F horizon. The basic layer (2C, light grey silty clay with grey pinkish mottles) is part of the truncated palaeosol, with infiltrated pollen, reflecting a moist to wet open environment. It was not possible to reach the 2Cca horizon with the auger on this site . The oldest colluvial layer (C3, light grey clay) is deposited after the Roman Time but before the F3. All the spectra show high percentages of herbal pollen. The C2 (grey clay) layers was deposited between ≈ AD 100 and ≈ 1500. The pollen spectra reflect the forest recovery. The pollen densities in this humic colluvial layer show high values. The colluvial top layer (C1, light grey clay) was deposited since AD 1500 and reflects the appearance of *Fagopyrum* and *Picea* like in the diagrams of Medernach and Brasert2.

3.2.4 Archaeometrical results

Table 2 presents the results of the grain size analyses of samples from mardel colluvium and the surrounding soils. The pH values ranges from weak acid to neutral, the percentages organic carbon from 1.9 to 10.9. The texture of the mardel samples is clay, of the soils samples clay or clay loam. This reflects the results of soils erosion and clay dispersion of the earth worm droppings (Cammeraat and Kooijman, 2009).

Table 3 presents the chemical results of the WD-XRF analyses of fourteen samples. Soils (S samples) and mardels (M samples) are derived from the sites under study: Beaufort (BEAU), Medernach (MED), Michelbouch (MICH), Brasert (BRAS) and Berdorf (BER).

A multivariate statistical analysis was conducted to determine group attribution and variability of the soils, mardels and archaeological ceramic samples. The PCA scores were calculated on $\log_{10}$ transformed concentration values (in ppm). Elements SiO_2,

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CaO, TiO_2, K_2O, Fe_2O_3, MgO, Na_2O, Al_2O_3, Zr, Sr, Cr, Rb and Ba were retained for this analysis.

The abundances of major and trace elements are fairly consistent for most elements in the ceramic materials. All analyses from the same locale, i.e. soil and mardel show similar geochemical values. Nevertheless, significant variation is present between the uniform ceramic materials and some mardel and soil samples. The compositional analyses from the mardels at Michelbouch and Brasert are highly similar and consistent with chemical values the ceramics. Generally SiO_2 content is higher in both the mardel and soil samples opposite to the ceramic materials. Total Fe_2O_3 content is in general also slightly elevated. The alkalis show uniform concentrations for Na_2O (~ 0.3 wt %) but are quite variable in K_2O concentrations (from ~ 2 to 3.5 wt %).

A SiO_2/Al_2O_3 plot (Fig. 10) is often used as a grain size indicator in geological studies (Dypvik, 1979). A higher proportion of quartz/coarse fractions cause higher SiO_2 values. Clay-based material suitable for ceramic production, with good grain size distribution should have a higher content in aluminum. This is clearly the case for all ceramic samples as well as the mardels from Michelbouch and Brasert. All soil samples have generally higher SiO_2 values and are therefore richer in a sand fraction.

A bivariate plot of K_2O versus MgO (Fig. 11) clearly separate both soil and mardel samples from Beaufort and Berdorf, excluding them as potential sources for the production of the local ceramics form the Biischtert near Michelbouch.

A cluster analysis through PCA analysis was carried out incorporating the multivariate aspect of the compositional data. The first two PCs account for nearly 71 % of the variance in the data. Eigenvalues are reported in Table 4.

All samples show low levels of P_2O_5 which signifies restricted post depositional alterations of the ceramic materials, but was excluded from the statistical analysis.

A graphical output of the principal component analysis defines the presence of at least two distinct groups (Figs. 12 and 13). Group 1 is composed of all ceramic samples, as well as both soils and mardels from Michelbouch and Brasert. A clear separation can be observed with the soil and mardel samples from Berdorf and Beaufort.

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While less distinct than the previous two sites, the mardel and soil composition from Medernach differentiates from the ceramics mainly in terms of a lower Fe_2O_3 ($\sim$5 wt % vs. $\sim$9 wt %) and higher MgO content ($\sim$7 wt % vs. 4.5 wt %).

Based on these observations it can be concluded that the composition of the mardels from Michelbouch and Brasert are consistent with the ceramic compositions. Moreover the mardels of Berdorf and Beaufort are significantly different from the other mardel and soil samples. These mardels are especially depleted in MgO content and have significantly lower total Fe values.

4 Discussion

4.1 Palynological dating of the mardel deposits

The first aim of this study was to determine the natural versus anthropogenic genesis of the mardels on the Steimergelkeuper. We acquired relevant paleoecological information by comparing the zoning of three pollen diagrams of mardel fillings with the zoning of a radiocarbon dated reference diagram.

The pollen content of peaty deposits as in profile Dauwelsmuer is sin-sedimentary and the palynochronology is sustained by reliable ^{14}C dates. The pollen content of mardel deposits is partly sin-sedimentary, partly post sedimentary, with consequences for the interpretation of the pollen spectra (van Mourik, 2001, 2003). Dating of such diagrams cannot be based on absolute dates but only on palynochronological markers.

- The transfer of the *Quercetum mixtum* into *Fageto Quercetum* (reflected by deciduous tree species) and the start of the anthropogenic deforestation and extension of agriculture (reflected by herbal species and cultural indicators) at the end of the Subboreal (Slotboom and van Mourik, 2016).

- The four peaks of Fagus; F1 (100 BC–AD 200), F2 (AD 700–800), F3 (AD 1200–1300), F4 (AD 1700–1900) (Persch, 1950; Slotboom, 1963; Daniels, 1964). The

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Fagus minima and maxima correlate with the Subatlantic climatic oscillations (Loehle, 2007).

- The appearance of *Secale* (or the extension of Cerealia) in the Celtic/Roman time (Slotboom and van Mourik, 2016).
- The appearance of *Fagopyrum* after AD 1450 (Leenders, 1987).
- The expansion of *Picea* and *Pinus* after AD 1800 (Slotboom and van Mourik, 2016).

The pollen diagrams of the previous investigated mardel fillings on the Strassen marls (Slotboom and van Mourik, 2015) and the diagrams of the analyzed mardel fillings on the Steinmergelkeuper have some diagnostic palynological characteristics in common.

- The drastic decrease of the pollen densities from the colluvial basic layer into the weathered marls, pointing to truncation of the former soil in the Steinmergelkeuper by excavation of pre Roman colluvium.
- The mardel fillings are Subatlantic (post Roman), deposited after the transition of the *Quercetum mixtum* into the *Fageto Quercetum* and the F4.
- The pollen spectra of the basic layers of the colluvial deposits contain species from (semi)aquatic plants.
- Some pollen, including (semi)aquatics, infiltrated into the truncated marl soil (low pollen density).
- Cerealia are present in all the horizons of the deposits.
- (Some) peaks of Fagus are observable in the diagrams.
- The appearance of *Fagopyrum* is observable.
- The extension of *Pinus* and *Picea* is observable.

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The interpretation of the forest dynamics, reflected by the pollen records, e.g. the forest transition and the Subatlantic *Fagus* peaks, and the impact on soil erosion and colluviation needs some additional remarks.

a. The pollen content of the basic layers of mardel deposits (the truncated soil in weathered Steinmergelkeuper) is post sedimentary; consequently, the age of the parent material is older than the palynological age.

b. The pollen composition of the colluvial layers is a mix of aeolian pollen deposition and pollen present in eroded and redeposited slope material. Consequently, older and corroded pollen grains are mixed with sin-sedimentary fresh pollen. Beside, pollinating species occurring on the eroded slopes can be overrepresented in pollen extractions of colluvium.

c. Wind pollinated species are overrepresented in pollen spectra, insect pollinated species underrepresented. Besides, it is known that the pollen production and dispersion of wind pollinated species can vary significantly. This is an important topic for a correct interpretation of the *Fagus* peaks.

d. The pollen production of a monoculture of *Quercus* is around $35 \times 10^6\,\mathrm{ha}^{-1}$, of *Fagus* around $20 \times 10^6\,\mathrm{ha}^{-1}$ (Andersen, 1970). Consequently, a displacement of *Fagus* by *Quercus* inside a forest stand can result in an increase of the total scores of arboreal pollen that is not related to forest extension (Faegry and Iversen, 1989).

e. Optimal environmental conditions for the *Fageto-Quercetum* are base rich substrates, a mean annual temperature of 7–9 °C, annual precipitation of 600–800 mm and a topographical altitude of 200–550 m (Slotboom and van Mourik, 2015). Fluctuations in temperature and precipitation affected the ratio between *Quercus* and *Fagus* trees (Loehle, 2007). The colder and wetter climate during the Dark Ages and the Little Ice Age promoted the extension of *Quercus* trees at the expense of *Fagus*, warmer and moister conditions during the Roman Time and Middle Ages promoted the extension of the *Fagus* trees (Slotboom and van Mourik, 2015).

f. There is no consensus in the literature on the question whether the decline of *Tilia* in the *Quercetum mixtum* during the Subboreal is the consequence of human activities or of the 2–3 °C decline in summer temperatures. Firbas (1949) suggested a crucial role of the climate in the decline of *Tilia*. Fanta (1995) suggested that in the northwestern lowlands *Fagus* arrives in the Subboreal by natural migration; the decline of *Tilia* and the extension of *Fagus* during the Celtic/Roman Time (F1) was promoted by a moister soil regime and an increasing temperature, but also the Neolithic population contributed to the decline of *Tilia* by tree cutting and using the leafs, bark and wood.

g. Before the arrival of *Fagus* in the Gutland the deposition rate of alluvium on valley floors was low, indicating a low rate of soil erosion under the *Quercetum mixtum* (Slotboom and van Mourik, 2014). It is assumed that the *Fagus* trees in the *Fageto-Quercetum* promote soil acidification, clay dispersion and soil erosion (Cammeraat, 2006; Cammeraat and Kooijman, 2009).

h. Based on studies of valley floor deposits (Slotboom and van Mourik, 2016) it was suggested that the rate of soil erosion and accumulation of colluvium on valley floors and in mardels accelerated in the Subatlantic due to deforestation. During the Subatlantic climatic oscillations and land use controlled the rate of soil erosion, as demonstrated in the profile studies of the mardels Brasert and Kalefeld (Poeteray et al., 1984; Slotboom and van Mourik, 2015).

i. Palynologically, the extension of arable land at the expense of pasture in a deforested landscape was observed from AD 1500–1800 (the Little Ice Age) (Poeteray et al., 1984). Farmers continued with the development of the cultural landscape, but probably they switched to crops, resistant to colder and wetter climatic circumstances, like *Fagopyrum* (Slicher van Bath, 1960). The increase of soil erosion

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during the Little Ice Age is clearly recorded in the Dauwelsmuer diagram by the deposition of the clay layer (3).

j. The development of subsidence basins on the Steinmergelkeuper proceeded during the entire Holocene. Also soil erosion is a process that proceeded during the entire Holocene. However, soil erosion accelerated in the Subatlantic and during the entire Holocene mardels functioned as sediment trap and were filled with colluvium, before and after Roman Time.

4.2 Archaeometrical matching of mardel clay and Roman ceramics

The second aim of this study was to answer the question if Romans extracted clay from mardels for the production of ceramics. This was investigated by archaeometrical comparison of the properties of various potential source materials for the production of ceramics to clay samples from mardel deposits and surrounding soils.

The results show a reliable matching of the properties of the Roman potsherds of the Biischtert excavation site with clay samples from the mardels and surrounding soils on the Steinmergelkeuper (firstly Michelbouch, but also Brasert2 and Medernach).

The properties of the clay samples of the Strassen marls are different. The textural properties of the clay samples from the mardels and surrounding soil indicate suitable material for the production of ceramics. To confirm the match of this source material with ceramics, a comparison with findings from an excavation site on the Strassen marls is required. However, currently no such findings were present at our disposal.

4.3 Natural and anthropogenic genesis of mardels

It is assumed that the Romans preferred the mardels as preferred sites for the extraction of clay to produce ceramics. They could excavate clay in mardels on the Gutland plateau, close to the settlements, for the production of ceramics. Other sources, such as clayey fluvial alluvium, where at that time not available in the vicinity at that time (Slotboom and van Mourik, 2016).

The mardels in the Gutland, developed on the Strassen marls (li^3) are the result of historical clay excavation (Slotboom and van Mourik, 2015); the published pollen diagrams (Berdorf and Beaufort) demonstrate a post Roman age for the colluvial fillings of these mardels on a truncated soil in weathered marls. Most probably, the excavation started in shallow, moist depressions in the relief, related to the joint patterns in the underlying sandstone (li^2) formation.

The mardels on the Steinmergelkeuper (km^3) developed as subsidence basins, caused by the dissolution of subsurface gypsum lenses and veins. Such basins developed since the Early Holocene (Barth, 1996; Thoen and Hérault, 2006). These depressions functioned as sediment traps. The Romans excavated the pre Roman mardel fillings, at first in the bigger mardels, later on also in the smaller ones. Not only the colluvial filling was extracted but also the top of the underlying (soft) soil in the weathered marls. Afterwards, the deposition of clayey colluvium restarted in the abandoned quarries. The development of mardels on the Steinmergelkeuper is summarized in Fig. 14.

5 Conclusions

Palynological dating demonstrated a post Roman age of the mardel fillings on the Strassen marls and on the Steinmergelkeuper.

- these fillings were deposited on the floor of an excavation;
- Romans excavated pre Roman colluvium (including the soft topsoil), deposited in initial natural depressions for the production of ceramics;
- archaeometrical tests demonstrate the match between the properties of clay from mardels on the Steinmergelkeuper and fragments of ceramics, found on the Biischtert excavation site;

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– the combination of palynological and archaeometrical data show that the mardels on the Gutland plateau developed initially as natural depressions, afterwards they were transformed into the present shapes by excavation.

Acknowledgements. We honourable dedicate this article to the late dr. Ruud Slotboom. The first results of the research of the Gutland mardels have been published by him in his PhD thesis (Slotboom, 1963). 50 years later, triggered by the contrasting results of researchers as Etienne et al. (2011), we decided to return to the Gutland to find new data to contribute to the controversial issue natural/anthropogenic mardel genesis. Some preliminary results concerning the mardels on the Strassen marls have been published (Slotboom and van Mourik, 2015) short before Ruud passed away in February 2015. The authors of this paper decided to finish the Gutland mardel study with the diagrams of the mardels on the Keuper marls and the final archaeometrical tests to correlate mardel deposits and Roman pottery.

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Table 1. Radiocarbon dates of the peat deposits of the profile Dauwelsmuer.

GrA code	Sample depth (cm)	Material	^{14}C age (BP)	Calibrated age (1-σ,*)
63108	Dauwelsmuer 57.5	leaf particles	555 ± 30	AD 1325–1345, 1395–1420
33111	Dauwelsmuer 102.5	leaf particles	4265 ± 35	2910–2880 BC
63110	Dauwelsmuer 140	leaf particles	5035 ± 35	3940–3860, 3815–3775 BC
63109	Dauwelsmuer 195	leaf particles	6505 ± 40	5520–5385 BC

* Calibrated with OxCal version 4.2.4.

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Table 2. pH, LOI and texture of soil and mardel samples.

pH, LOI, texture	Beaufort		Berdorf		Medernach		Brasert		Michelbouch	
	Soil	Mardel	Soil	Mardel	Soil	Mardel	Soil	Mardel	Soil	Mardel
pH-H_2O	5.2	5.6	7.1	4.7	5.6	4.9	6.5	4.4	6.7	7.5
LOI 375 °C	2.1	4.9	2.4	4.6	1.9	9.6	2.0	10.9	1.9	3.8
Texture fraction	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
2000–63 µm	16.0	7.0	4.0	5.5	4.5	2.5	8.0	2.0	13.0	3.0
63–32 µm	8.5	10.0	5.5	4.5	6.5	1.5	3.5	1.5	4.5	3.0
32–16 µm	10.0	8.0	8.0	5.5	15.0	3.5	7.0	4.0	6.5	2.0
16–8 µm	9.5	8.5	8.0	6.0	11.5	3.0	9.0	4.5	7.0	6.5
8–4 µm	6.5	7.5	8.0	6.0	7.5	6.0	11.0	6.0	8.0	8.5

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Table 3. Geochemical composition of all samples (ceramics, mardels and soils) by WD-XRF. Major and minor elements are expressed as wt % of oxides, trace elements as ppm.

		Ceramics				Mardels					Soils				
Sample		CER-1	CER-2	CER-3	CER-4	BER-M	BRAS-M	BEAU-M	MED-M	MICH-M	BER-S	BRAS-S	BEAU-S	MED-S	MICH-S
SiO_2	wt %	57.29	58.92	60.18	58.72	68.59	60.39	71.15	63.11	61.34	71.74	62.49	71.52	64.81	65.39
Al_2O_3	wt %	22.05	21.98	20.16	21.12	20.70	19.81	19.65	19.82	21.43	17.01	21.16	19.22	18.09	19.85
Fe_2O_3	wt %	8.53	9.25	9.59	9.62	3.98	7.95	2.24	5.35	6.49	5.54	5.86	2.98	6.21	4.81
MgO	wt %	5.55	4.41	4.23	4.40	2.02	6.33	1.88	7.02	4.96	1.53	5.32	1.92	6.80	4.37
K_2O	wt %	3.64	3.25	3.51	3.50	2.30	3.12	2.14	2.86	3.58	2.05	3.06	2.48	2.53	3.44
TiO_2	wt %	1.16	1.10	1.02	1.05	1.01	1.04	0.91	0.89	1.02	1.05	0.99	0.88	0.78	1.02
CaO	wt %	0.33	0.30	0.34	0.25	0.79	0.49	1.31	0.24	0.45	0.56	0.44	0.42	0.14	0.39
P_2O_5	wt %	0.22	0.14	0.12	0.17	0.06	0.07	0.19	0.11	0.08	0.07	0.08	0.07	0.05	0.08
Na_2O	wt %	0.22	0.20	0.30	0.29	0.23	0.28	0.20	0.31	0.26	0.21	0.27	0.21	0.32	0.29
MnO	wt %	0.09	0.07	0.09	0.06	0.01	0.19	0.01	0.03	0.07	0.03	0.03	0.03	0.06	0.03
Ba	ppm	788	1065	985	1191	555	877	519	654	904	448	672	475	600	761
Zn	ppm	448	376	349	412	54	134	81	90	412	54	81	63	107	313
Zr	ppm	385	313	331	322	412	322	367	358	295	421	412	394	313	304
S	ppm	224	233	412	573	269	295	1083	403	295	233	466	251	206	304
Cl	ppm	206	412	1039	1665	161	161	242	179	197	143	233	161	188	161
Cr	ppm	197	197	179	215	152	134	179	179	170	170	161	125	170	215
Rb	ppm	197	152	179	179	125	197	98	125	161	107	161	107	116	143
Ni	ppm	152	107	98	81	63	170	63	63	107	n.d.	72	81	54	63
Pb	ppm	63	45	63	54	45	90	45	27	54	45	n.d.	63	54	54
Sr	ppm	63	63	81	81	90	116	81	72	81	98	90	81	63	63
Nb	ppm	36	27	27	36	27	18	18	18	36	90	18	18	18	27
Ce	ppm	n.d.	385	278	n.d.	287	340	n.d.	331	n.d.	n.d.	251	313	n.d.	439
Y	ppm	n.d.	45	45	45	45	45	36	27	36	45	36	36	27	36
Cu	ppm	n.d.	n.d.	n.d.	n.d.	501	72	n.d.	36	81	63	n.d.	439	n.d.	81

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Table 4. Eigenvalues of the matrix and related statistics.

	Eigenvalue	% Total variance	Cumulative eigenvalue	Cumulative %
1	6.869800	52.84462	6.86980	52.8446
2	2.320805	17.85235	9.19061	70.6970
3	1.438116	11.06243	10.62872	81.7594
4	0.769357	5.91813	11.39808	87.6775
5	0.746001	5.73847	12.14408	93.4160
6	0.428477	3.29597	12.57256	96.7120
7	0.157536	1.21182	12.73009	97.9238
8	0.151845	1.16804	12.88194	99.0918
9	0.054451	0.41885	12.93639	99.5107
10	0.040597	0.31229	12.97699	99.8230
11	0.016286	0.12527	12.99327	99.9482
12	0.005023	0.03864	12.99829	99.9869
13	0.001705	0.01312	13.00000	100.0000

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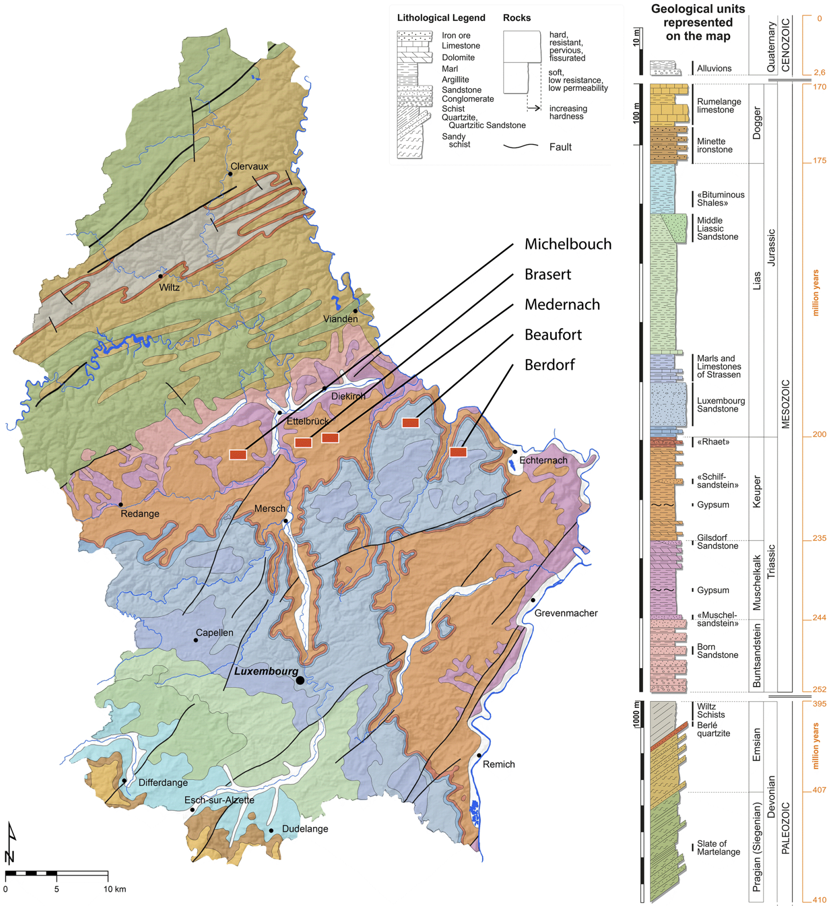

Figure 1. Geological map of Luxembourg with sample locations.

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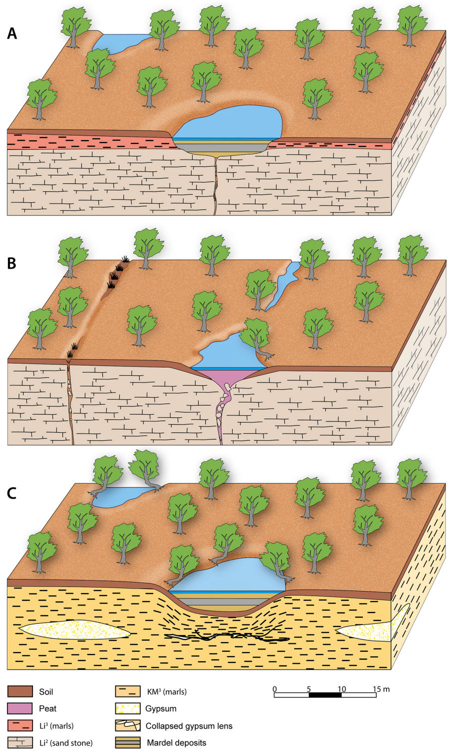

Figure 2. Typology of mardels on various substrates according to Slotboom and van Mourik (2015). **(a)** Mardels on the Strassen marls (li^3), historical quarries (clay excavations), filled with clayey colluvium. **(b)** Mardels on the Luxembourger sandstone (li^2), sink holes determined by faults or joints, filled with sandy colluvium and peat. **(c)** Mardels on the Steinmergelkeuper (km^3), subsidence basins caused by subsurface solution of gypsum lenses, filled with clayey colluvium.

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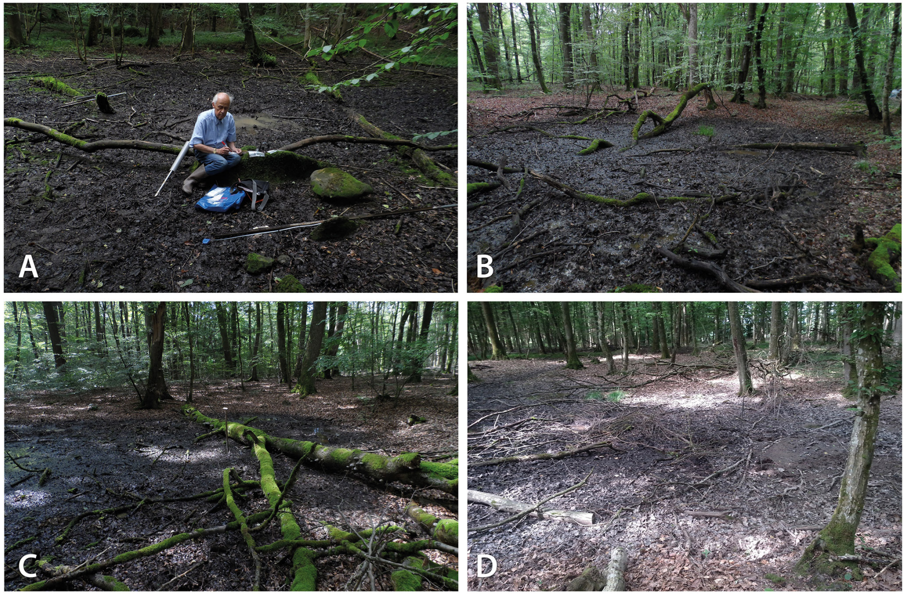

Figure 3. Pictures of the sampled mardels. **(a)** Dauwelsmuer July 2014 (with Ruud Slotboom), **(b)** Medernach July 2014, **(c)** Brasert2 July 20143, **(d)** Michelbouch May 2015. Locations of the sample sites indicated in Fig. 1.

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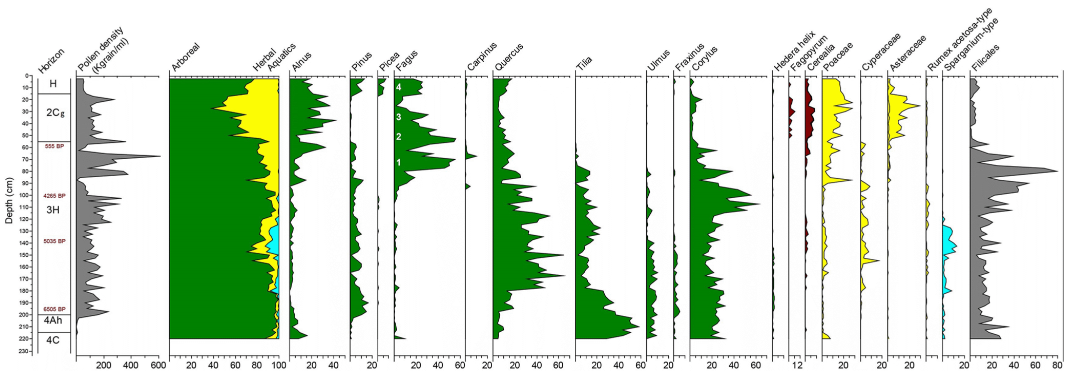

Figure 4. Pollen diagram Dauwelsmuer. Incidental pollen scores are presented in Fig. 5, macro remains in Fig. 6. Radiocarbon dates (BP) are indicated in the column "Horizon" and specified in Table 1.

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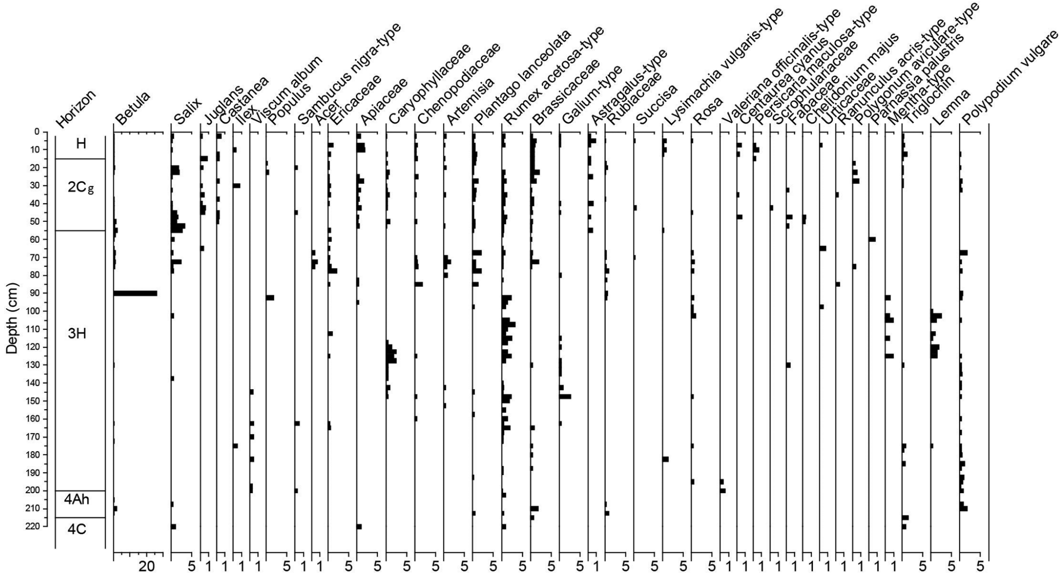

Figure 5. Incidental pollen scores of pollen diagram Dauwelsmuer.

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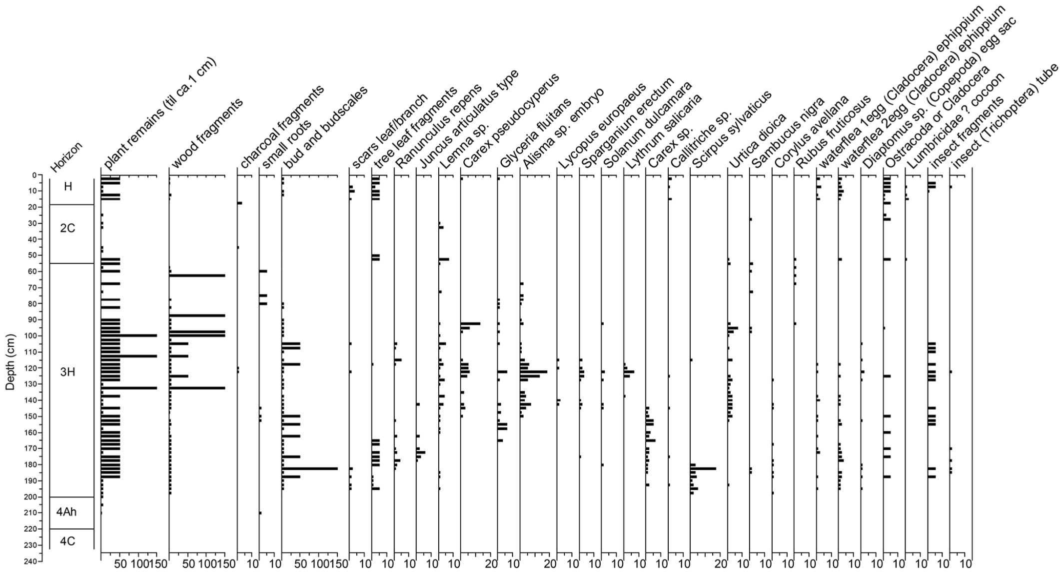

Figure 6. Macro remains of diagram Dauwelsmuer.

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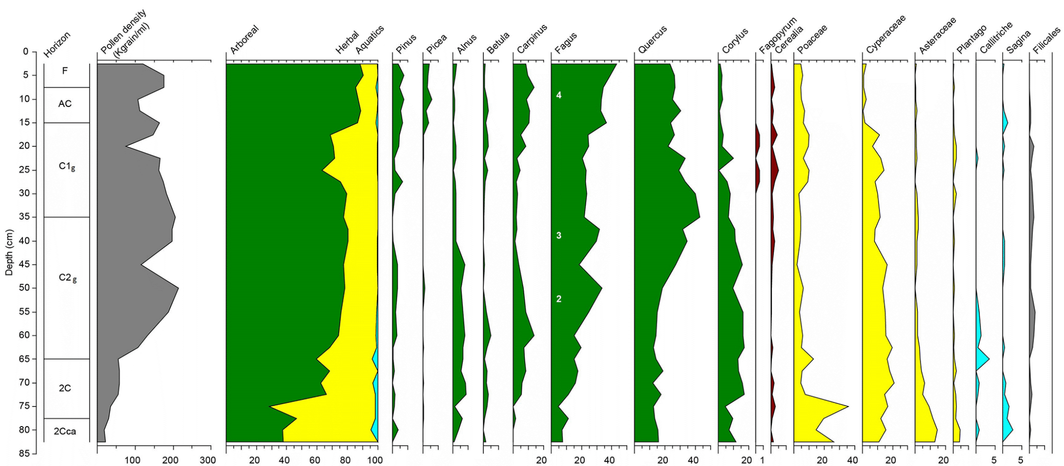

Figure 7. Pollen diagram Medernach.

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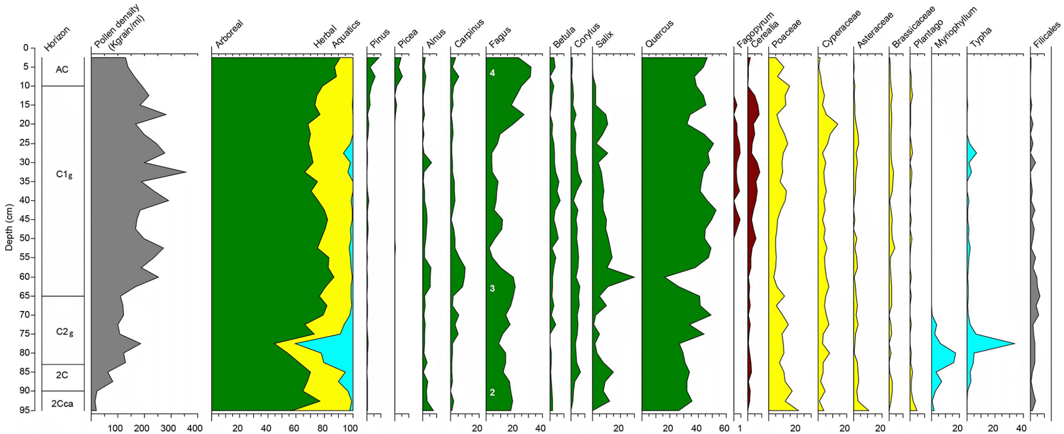

Figure 8. Pollen diagram Brasert2.

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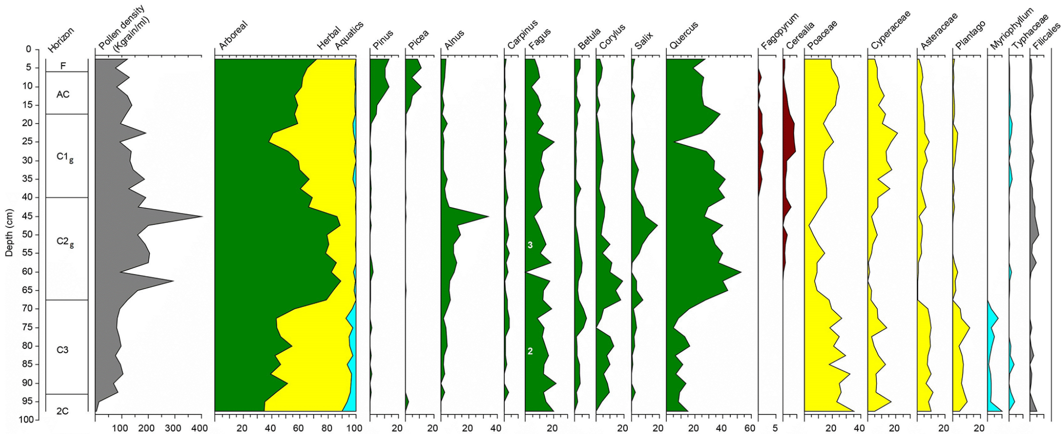

Figure 9. Pollen diagram Michelbouch.

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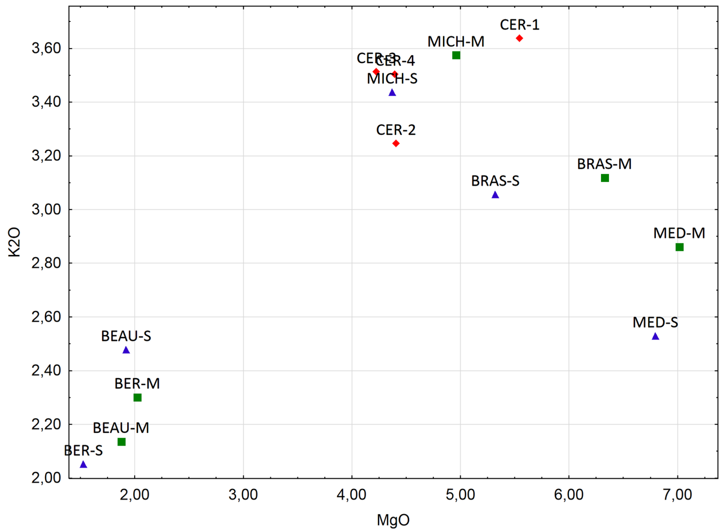

Figure 10. SiO_2/Al_2O_3 plot of the 14 samples.

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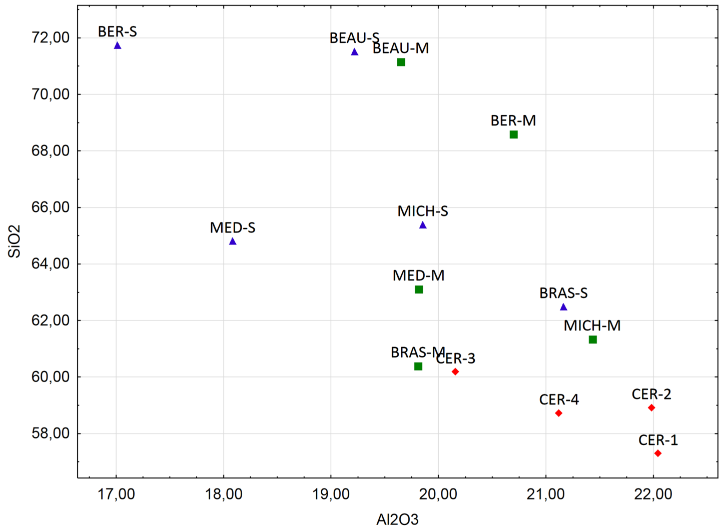

Figure 11. K_2O/MgO plot of the 14 samples.

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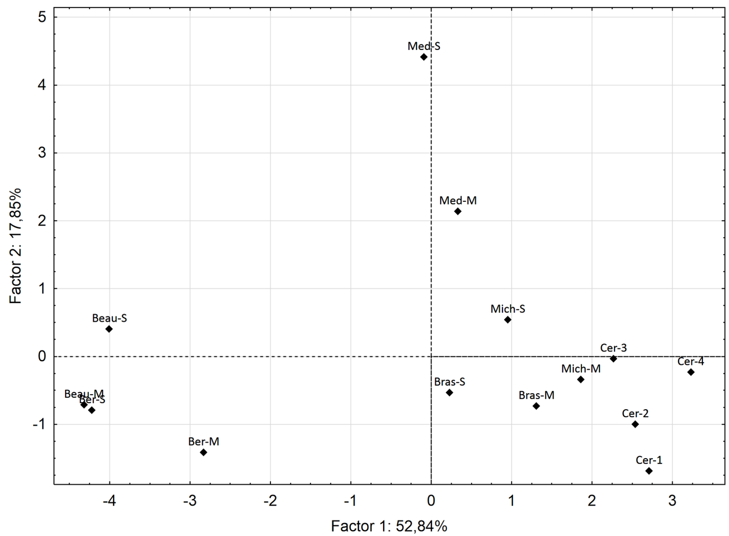

Figure 12. Score plot of principal components 1 and 2 (PC1 vs. PC2), representing 53 and 18 % of total variance.

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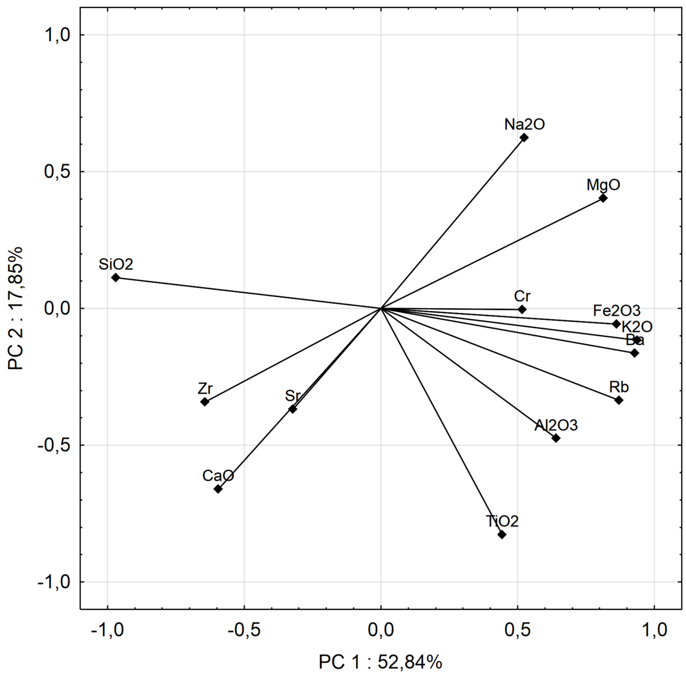

Figure 13. Loading plot of principal components 1 and 2 (PC1 vs. PC2), representing 53 and 18 % of total variance.

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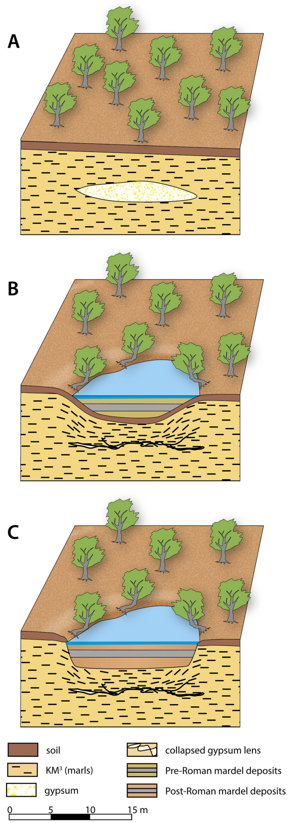

Figure 14. The development of mardels on the Steinmergelkeuper. **(a)** Initial landscape on the Steinmergelkeuper (km^3), with a subsurface gypsum lens, **(b)** the development of a subsidence basis, caused by dissolution of the gypsum lens, filled with pre-Roman clayey colluvium, burying the descended palaeosol, **(c)** mardel after Roam clay excavation, filled with post-Roman clayey colluvium, burying the quarry floor.

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