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The potential of soil survey as a tool for surface geological mapping: a case study in a hydrological experimental catchment (Huewelerbach, Grand-Duchy of Luxembourg)

Jérôme JUILLERET, Jean François IFFLY, Lucien HOFFMANN & Christophe HISSLER

Centre de Recherche Public - Gabriel Lippmann - Département Environnement et Agrobiotechnologies (EVA), 41 rue du Brill, L-4422 Belvaux, Luxembourg.

ABSTRACT. The geological map is the basic and necessary information to perform a soil survey. Nevertheless, the scale of the geological map does not always correspond to the requirements of some hydropedological studies, especially when they are performed at the headwater catchment scale. Furthermore, in temperate climate regions, where the outcrops are not always available, the soil survey can contribute to give relevant information on the surface geology. In this paper, we show the importance of the soil C-horizon's description regarding the identification of the underlying bedrock. Performed in a hydrological experimental catchment in the Grand Duchy of Luxembourg, this approach allows to better determine the limits of the geological strata at a larger scale and delivers more relevant information to the hydrologists. We highlight the presence of the "Formation de Mortinsart" (ko) from Rhetian age, which was not mapped at the geological scale and which plays a key role in the water pathway and residence time in this little catchment.

KEYWORDS : C-horizon, Soil Typological Units, runoff processes, Argiles de Levallois.

1. Introduction

The development of agriculture during the nineteenth century enabled geologists to initiate the mapping of the soil cover in many European countries. This task was entrusted to them because of their expertise in observing relationships that may exist between the soil characteristics and the underlying geological formations. Hence, under the instigation of the Russian school of Dokoutchaiev, agricultural geology, and finally pedology was born (Tandarich, 1998; Legros, 1996). This historical summary shows how the modern pedology anchors its roots in the geological sciences. During the 19th-century, authorities asked for geological surveys to respond to the need of mining and oil exploitation, and for pedological surveys to respond to the necessity of a better arable land management. Both sciences developed their own concept on the soil-substratum system, especially in their mapping approach, but without real exchange. Nowadays, under the impulse of the sustainable development, environmental agencies frequently ask either for geological surveys or agricultural services to respond to questions concerning water and contaminant transfer by providing more precise and/or thematic maps. A pure geological or pedological approach to answer such questions is not sufficient, because water flows at the connection between soil and geology, in an intermediate system called regolith. The regolith is on the one hand the product of the rock weathering and on the other hand the host on which the soil has developed. Due to the traditional splitting, geological and pedological surveys tend to look outside their respective field of investigation by studying the regolith in a parallel way, i.e the "Regolite" programme of the French geological survey (BRGM) and the "Whole regolith pedology" symposium of The Soil Sciences Society of America in 1992. Nevertheless, at the present time, there is no evident general relationship between these two scientific communities and no real study, which has involved both competences to go forward in the understanding of the ecosystem. To answer environmental questions on water pathways and pollution transfer within the soils, it is necessary to consider the soil-saprolite in a global approach and it should be avoided to place artificial and mental barriers in a natural and continuous paradigm. Both soil scientists and geologists should follow such an approach towards a common classification scheme as claimed by Tandarich (1994) in his pedoweathering concept.

Within a soil profile, soil scientists designated the sequence of observed diagnostic soil horizons by a capital letter (A, E, B, C). A soil horizon is a layer, approximately parallel to the surface of the soil, distinguishable from adjacent layers by a distinctive set of properties produced by soil-forming processes. The traditional school of soil scientists used the *solum* concept, which refers to the upper and most weathered part of the soil profile represented by the A, E, and B-horizons above the C-horizon (Schaetzl & Anderson, 2005). However, a second school, much less widespread includes the C-horizon (A, E, B, C) in the *solum* concept (Whiteside, 1959; Baize, 1993; Tandarich et al., 1994). The C-horizon is the link between pure pedological and geological environments. Nevertheless, detailed studies of the C-horizon functioning and evolution are suffering of a lack of interest by many soil scientists (Tandarich et al., 1994). Indeed, the C-horizon is described as a horizon, which is less affected by pedological processes (FAO, 2006). This concept allows to better consider the functioning and the evolution of the entire system, because it relies more on the continuous system, which is considered by the hydrologists. The substrate is either the saprolite of the underlying bedrock, referred as C-horizon for the soil scientist (Velde & Meunier, 2008), or the fresh cohesive bedrock named R-horizon. The C-horizon contains useful lithogenic features such as the rock structure, the texture, which constitute potential information on its genetic geological formation Furthermore, mineralogical and chemical properties of the bedrock predetermine the soil that can potentially develop on its top, like a genetic code predetermining the characteristics of an organism (Wysocki et al., 2005).

Geological maps are the basic documents for any soil scientist. However, their scales are often unsuitable for soil surveys and do not sufficiently inform about the distinctive parent materials and soil substrates, from which and on which the soil grows, respectively. Conversely, information given by a basic pedological description, including some characteristics of the C-horizon, can easily provide information about the nature of parent materials that generated soils and therefore constitutes a window into the geology of the area (Wysocki et al., 2005). This concept is illustrated in this article, from a case study of mismatch between conclusions on the parent material obtained from a soil survey and the lithologies presented on the geological map 1:25000 (Colbach & Maquil, 2003). Like the precursors Thorp (1935, 1949), Millot (1980) and recently Lindholm (1993), who mapped the geology of the Culpeper Basin in northern Virginia (USA) using soil survey techniques, we wish to show the input of the soil science knowledge on surface geology mapping, in order to bring together the two scientific communities.

2. Study site and geological setting

The study area covers the hydrological experimental catchment of the Huewelerbach (2.7 km^2), which is monitored and studied since 1995 by the hydrologists of the Centre de Recherche Public – Gabriel Lippmann. This anaclinal creek, located in the western part of Luxembourg, cuts the Luxembourg sandstone cuesta (Désiré-Marchand, 1985) to reach the Attert River (Fig. 1A). The elevation ranges from 280 to 400 meters. The main valley is oriented South-North to the confluence with a tributary creek side, and continues with a South West – North East strike. Three dry valleys with no surface runoff are located in the west of the basin. The landuse is mainly forest on the plateau and on the slopes, whereas grasslands are found in the riparian zone and the footslopes.

According to the geological map (1/25000) (Colbach & Maquil, 2003), four geological formations constitue the catchment (Fig. 1B): The lower Sinemurian "Formation de Strassen" (li3) consists of alternating dark blue marls and calcareous sandstone. It is located in the upper basin and covers only 3.5% of the total area. The upper Hettangian formation of the "Grès de Luxembourg" (li2), which

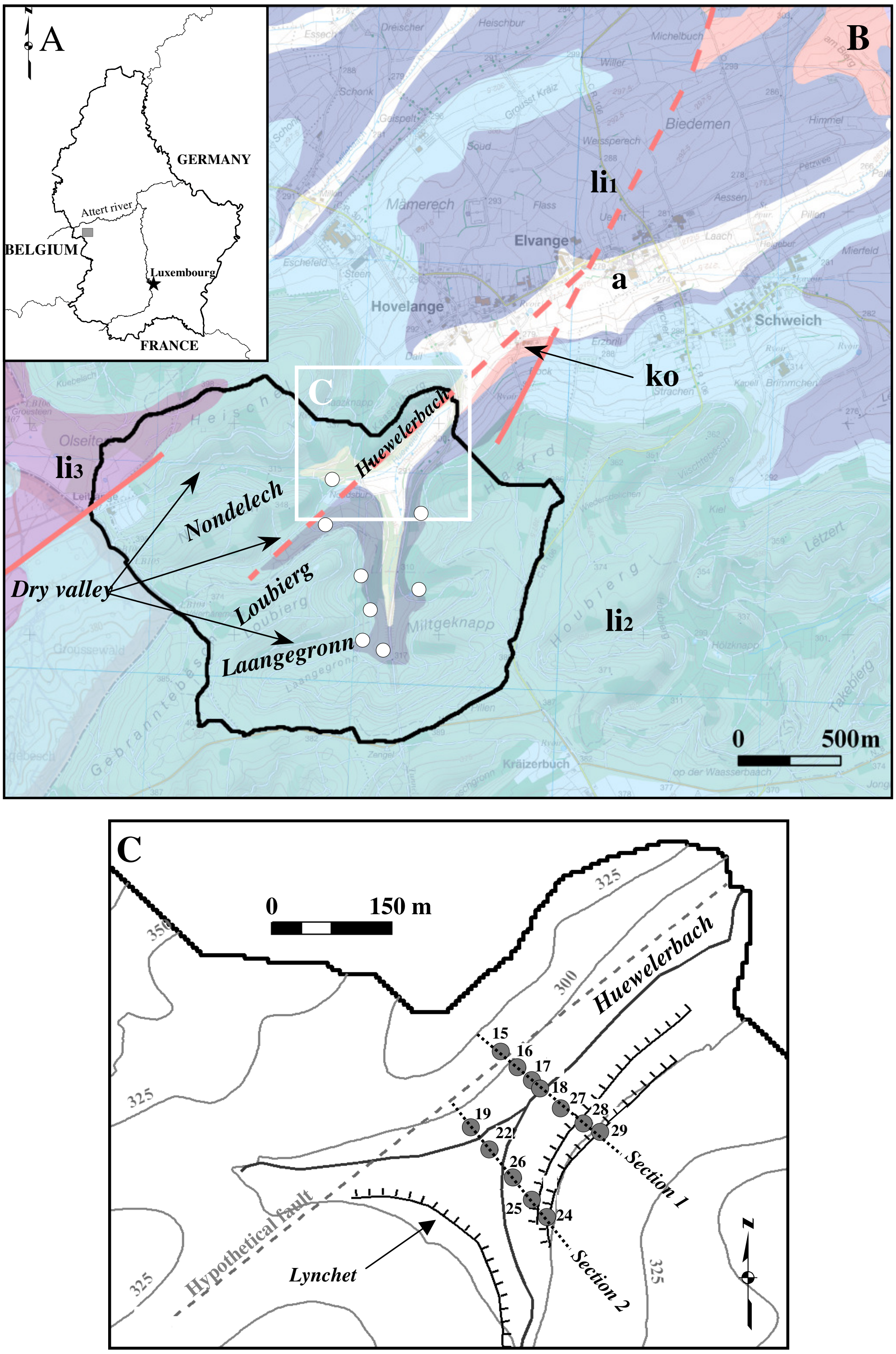

Figure 1. Location (A) and geology (B - from Colbach & Maquil, 2003) of the Huewelerbach experimental catchment. The white dots correspond to the captured springs, the red lines and dashed lines corresponds to fault and hypotheticals faults. li3: “Formation de Strassen” (dark blue marls and calcareous sandstone). li2: “Grès de Luxembourg” (calcareous sandstone). li1 : “Formation d’Elvange” (light gray marl and limestone layers). ko: “Formation de Mortinsart” (red clays, sandstone and black claystone). a: alluvium. C: location of the 12 mechanical drillings made during this study.

consists of calcareous sandstone, covers 81% of the total area. The lower Hettangian “Formation d’Elvange” (li1) covers 9% of the surface and consists of alternating light gray marl and limestone layers. Located below the li2 aquifer, the “Formation d’Elvange” (li1) acts as a hydrogeological barrier and allows the creek to maintain a very stable baseflow regime. The remaining 6.5% of the basin area is composed of a colluvial - alluvial complex.

3. Material and methods

Field investigations were conducted in two phases. We started the investigation by a standard pedological survey, following the litho-morphological approach of the “free survey” method (Legros, 1996). The hand auger allows reaching a maximum depth of 110 cm from the soil surface, which is generally sufficient to cover a soil profile down to the upper part of the C-horizon in temperate climate. A total of 70 drillings have been described throughout the basin using conventional parameters of the soil description such as texture, thickness and hydromorphy degree. In order to respect the prerogatives of the International Union of Soil Sciences, which recommends a classification according to a local or national system for large scale mapping, soil typological units (STU) were named according to the “Référentiel Pédologique” (Baize & Girard, 2008). However, a correspondence with the global repository (IUSS Working Group WRB, 2006) is given in Table 1.

In a second step, we used a mechanized coring machine, which can reach a maximum depth of 400 cm, i.e. either the lower part of the saprolite (C-horizon), or the bedrock (R-horizon). This complementary technique, generally not used in standard pedology, allows to better recognize the geological formation, which has been transformed through the weathering and pedogenetic processes. We carried out 12 drillings located for most of them along two parallel sections, perpendicularly to the riparian zone and the footslopes (Fig. 1C). The different layers, including the soil horizons, were differentiated using

Référentiel Pédologique	World Reference Base
CALCISOLS	Haplic Cambisol (Hypereutric)
PODZOSOLS OCRIQUES	Entic Podzol (Lamellic)
PODZOSOLS meubles	Albic Podzol
COLLUVIOSOLS sableux	Colluvic Regosol (Arenic)
COLLUVIOSOLS sableux rédoxiques	Colluvic Regosol (Arenic, Bathystagnic)
PELOSOLS TYPIQUES sédimorphes	Epistagnic Cambisol (Ruptic, clayic) Haplic Planosol (Ruptic, clayic)
BRUNISOLS sableux rédoxiques	Stagnic Cambisol (Ruptic, Arenic) Haplic Planosol (Ruptic, Arenic)
CALCISOLS bathycarbonatés	Haplic Cambisol (Hypereutric, Bathycalcaric)
CALCISOLS colluvionnés en surface	Haplic Cambisol (Hypereutric, Colluvic)
REDUCTISOLS	Haplic Gleysol
FLUVIOSOLS	Gleyic Fluvisol

Table 1. Correspondence between the French "Référentiel Pédologique" (Baize & Girard, 2008) and the World Reference Base (IUSS Working Group WRB, 2006) for the soil units identified in the Huewelerbach experimental catchment.

the texture, the Munsell chart color, the degree of hydromorphy, the abundance of coarse elements and the effervescence to hydrochloric acid (10%).

4. Results and discussion

4.1. Information revealed by the standard pedological mapping

The soil "free survey" mapping identified six Soil Map Units (SMU). We present them from the highest to the lower elevations of the catchment (Fig. 2).

The soils developed on the "Formation de Strassen" (li3), are moderately deep (40-60 cm). They present a clayey to silty-clayey texture and are characterized by a calcareous clayey C-horizon. They are related to "CALCISOLS bathycarbonatés". These soils present generally a low permeability and are characterized by imperfect drainage in winter. The dominant runoff process of these SMU is subsurface flow.

The soils developped on the "Grès de Luxembourg" (li2) cover the plateau and the slopes. They are characterized by an ocher color and a loose Bs-horizon, showing pedogenetic accumulation of iron sesquioxydes. Often, occurrences of clayey bands permit to also diagnose a Bt-horizon characterized by pedogenetic clay accumulations. The A-horizon is slightly elluviated and tends to be an Ae-horizon, but a clear albic E-horizon has still not been observed. These soils relate to the "PODZOSOLS OCRIQUES". Nevertheless, a clear albic E-horizon can be locally observed on the footslopes oriented to Northwest where sand colluvium is accumulated. In these cases, the soils are classified as "PODZOSOLS MEUBLES". From a hydropedological point of view, these soils are excessively drained and the deep percolation in the aquifer is the dominant runoff process.

In the dry valleys, the depth of the sandy colluvial deposits varies from several decimeters to several meters. The marly "Formation d'Elvange" (li1) located beneath the colluvium contributes to the development of localized perched and superficial aquifers. In this valley, according to the intensity of the hydromorphy, soils are either "COLLUVIOSOLS sableux", or "COLLUVIOSOLS sableux rédoxiques", characterized by a gleyic color pattern linked with the seasonal fluctuation of the water table.

Soils developed from the marl and limestone alternations of the "Formation d'Elvange" (li1) are decarbonated in their upper part, while the C-horizon has many limestone fragments and reacts strongly to the hydrochloric acid test. The occurrence of carbonate in the lower part of the soil allows classifying this SMU as "CALCISOLS bathycarbonatés". In this unit, the A-horizon has a silty clayey texture, while the structural B-horizon is slightly more clayey. From the mid-slope to the footslope positions, the sandy colluvium gradually covers the "CALCISOLS" on the "Formation d'Elvange" (li1). Hence, a transition zone between the "CALCISOLS colluvionnés" and the "COLLUVIOSOLS sableux" is related to the depth of the sand cover. According to the absence of hydromorphy, these soils present an efficient internal drainage, which may correspond to a subsurface flow dominant runoff process.

The area, which links the sandstone hills to the valley, presents a more complex distribution of the soils. The C-horizon, and sometimes the Bw structural horizon, described in this zone show high textural and color variations. For instance, color and textural variations can be observed laterally and vertically at very short distance scale (meter), from olive-brown sand (Munsell Color 2.5Y5/3) to heavy red clay (Munsell Color 5YR5/4). The sharp increase in clay content within a limited range of depths cannot be interpreted as the appearance of a

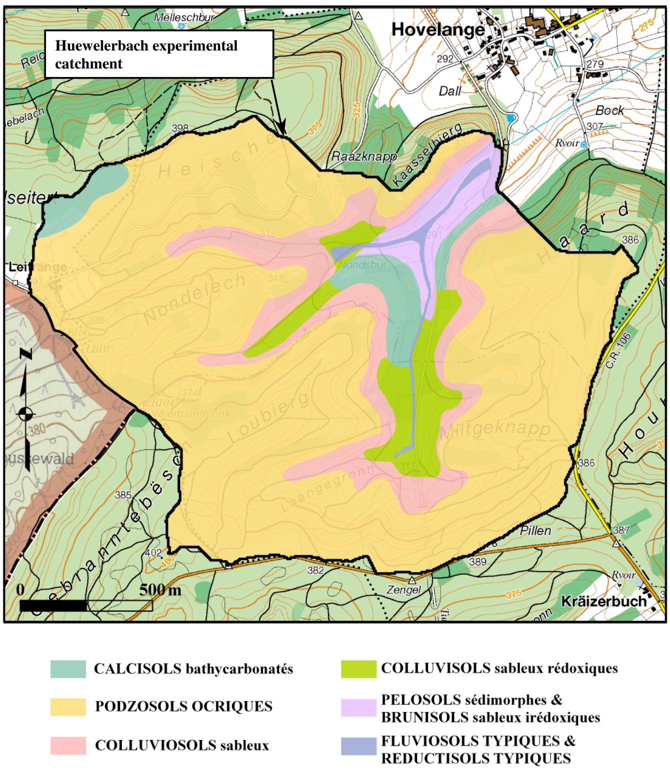

Figure 2. Pedological map of the Huewelerbach experimental catchment. Soil classification is in accordance to the "Référentiel Pédologique" (Baize & Girard, 2008). Correspondence with the World Reference Base (IUSS Working Group WRB, 2006) can be found in Table 1.

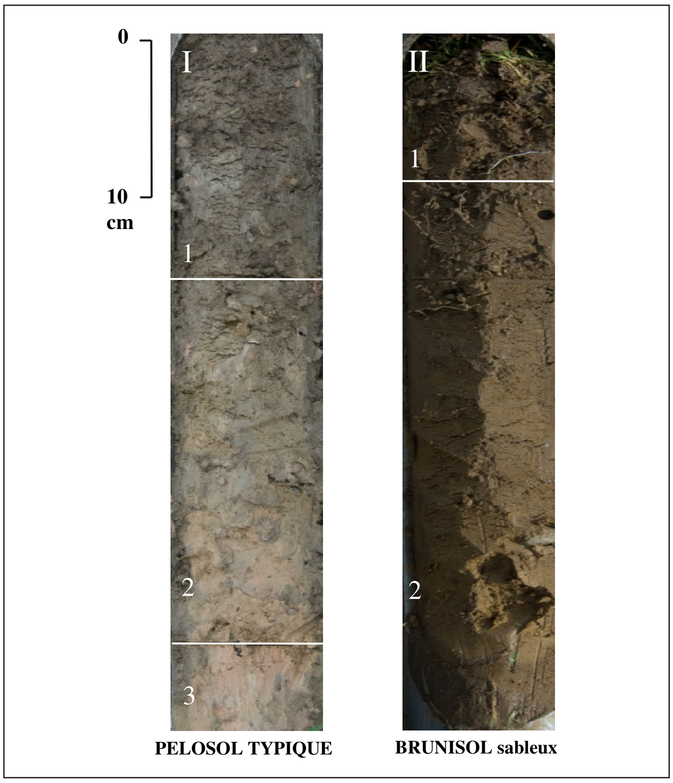

Figure 3. The two typological soil units (STU) identified in the grass-land area. I1 : A clayey organo-mineral horizon, I2 : Bw clayey cambic horizon; I3 : C clayey mineral horizon (saprolite of the "Argiles de Levallois" (ko2)); II1 : A sandy organo-mineral horizon; II2 : B sandy cambic horizon (presence of the weathered "Unterer Rhät" (ko1)).

Bt-horizon resulting from pedological processes, but as a lithological discontinuity of the parent material itself. According to the geological map, the soil may have developed from recent alluvial deposits. However, the geomorphology of the area, the related pedogenetic processes and the strong color and textural variations do not allow retaining the alluvial deposits as parent material of these SMU. From a pedological point of view, two Soil Typological Units (STU) were distinguished (Fig. 3). The "PELOSOLS TYPIQUES sédimorphes" present a A, Bw and C sequence of horizons with a heavy clay texture. A redoxic sandy horizon 2Cg is observed at varying depths directly below this sequence. For the "BRUNISOLS sableux", the A, Bw and C sequence is sandy with a clayey 2C-horizon. Despite these differences, these two STU are closely linked and were grouped into one SMU to satisfy the needs of the mapping. Hydromorphic features associated with water saturation conditions in the sandy horizon, above or below the impermeable clayey horizon, indicate the occurrence of perched water tables. During favorable hydro-climatic conditions, the drainage goes laterally by subsurface flow before reaching the groundwater.

The alluvial deposits have only a restricted extension along the stream and support "FLUVIOSOLS TYPIQUES", which are characterized by a variable texture. They show an increasing gleyic color pattern with depth. Close to the basin outlet, the soils present a higher level of hydromorphy with a reductimorphic color pattern close to the surface. They were classified as "REDUCTISOLS TYPIQUES". At these locations, the presence of a persistent water level at the surface of the soil can be related to a damming effect caused by the embankment of the old railway, which cuts the floodplain.

This preliminary soil survey highlighted the complex spatial variability of the soils in the grassland area, which links the sandstone hills to the valley. The two identified STU ("PELOSOLS TYPIQUES sédimorphes" and "BRUNISOLS sableux") revealed a mismatch between information provided by the geological map and those obtained through observation of Bw- and/or C-horizon characteristics. The remarkable difference between a red/clayey horizon and a grey/sandy horizon, allows differentiating between two easily distinguishable STU in the field. These two soil units could be explained by differences in the parent materials from different geological formations but could also be attributed to facies variations within the same geological formation. Such variations can be frequently identified in alluvial deposits, and this is precisely the information revealed by the geological map. However, based on the geological cross section (Fig.4), we also should test the hypothesis of the presence of the "Formation de Mortinsart" (ko), which underlies the alluvial deposits and which presents facies that could correspond to the pedological observations.

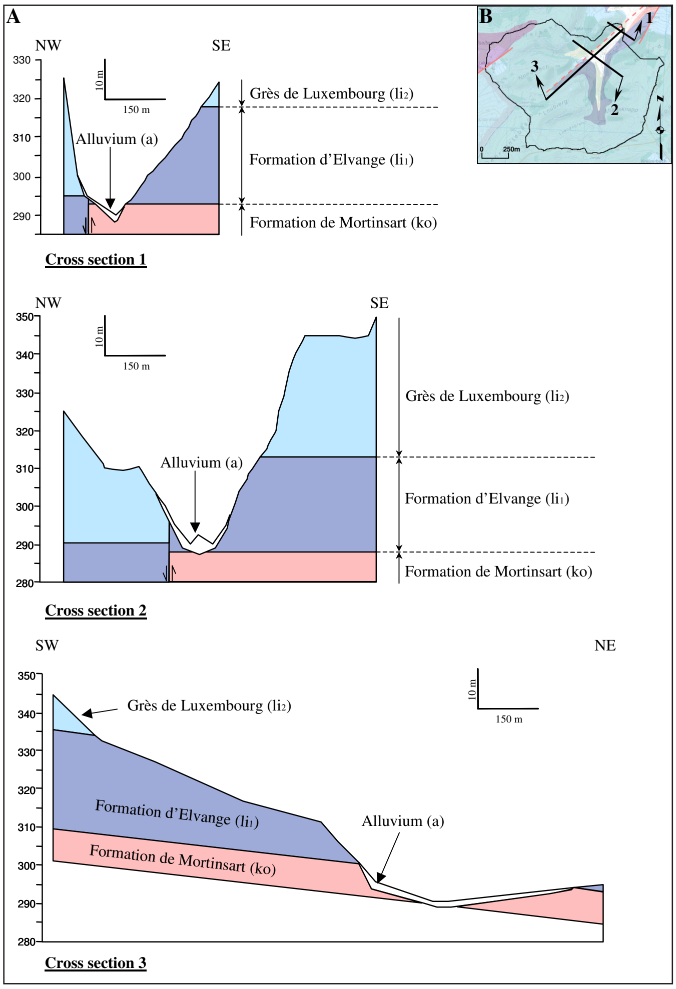

Figure 4. Geological cross sections made from the geological map of Rédange (Colbach & Maquil, 2003) by the Eurasol Company, Luxembourg.

4.2. Contribution of the deeper core drillings

In order to clearly identify the saprolite of the geological substratum to which belongs the red clay/grey sand alternation layers, we investigated the deep layers of the soil-saprolite system. The core drillings, which reach a maximum depth of 400 cm, were made along two sections crossing the valley (Figs 1 and 5).

The first section is made of 7 core drillings, in which two groups are distinguished according to their position to the stream. The core 15 is significantly different because its texture is always sandy, under the A-horizon, an E-horizon is observed. The latter cover a brown yellowish (Munsell color 10YR5 / 8) horizon showing slight clay enrichment with sesquioxydes accumulation interpreted as a Bts. The saprolitic C-horizon is made of sandy colluviums; the occurrence of blocks of calcareous sandstone attests to the presence of "fresh" Luxembourg sandstone residues. The cores 16, 17 and 18 located in the right bank present a similar sandy silty A-horizon. The following Bw-horizon is sandy for cores 17 and 18 while core 16 is characterized by a reddish clayey Bw-horizon. These cores differ from the succession of different C-horizons, which can be either a hydromorphic sandy horizon (cores 16 and 17), or the typical reddish clayey horizon (core 18) (Munsell color 5YR5 / 4) already observed in the paragraph 4.1. At the bottom of the drilling, these three cores are characterized by the occurrence of a typical 2C-horizon made of black micaceous sandy clay (Munsell color GLEY 2.5/5PB 2). The cores 27, 28 and 29 are located on the right side of the valley and present similar clayey A- and Bw- horizons. The latter is made of an olive brown clay color (2.5Y4 / 4), which tends to become more reddish with increasing depth. We interpret the Bw brownish horizon as a colour change of the red clay under the "brunification" pedogenetic processes. The C-horizons are similar for the cores 27 and 28 showing a more sandy texture before reaching a 2C-horizon made of the typical reddish clayey horizon (Munsell color 5YR5 / 4). C-horizon of the core 29 is characterized by an abrupt change of lithology: we interpret the calcareous limestone layer, observed at the bottom of the drilling, as the saprolite of the "Formation d'Elvange" (li1).

The second section is located one hundred meters upstream and consists of 5 core drillings. As already observed in section1 (cores 16, 17 and 18), the cores 19 and 25 characterize the high vertical variability for a similar parent material. The C-horizons correspond to the typical reddish clay described in the first section. Indeed, whereas the core 19 presents 3 levels of red clays in alternation with sandy material, the core 25 presents a unique and deep C-horizon made of the same red clays. In the deeper part of the core 19, we identified black micaceous sandy clay (Munsell color GLEY 2.5/5PB 2). The cores 22 and 26 were performed in the alluvial deposits. Both present loamy sandy alluvial soil characterized by a slight development of the Bw-horizon, the main pedological characteristic is the occurrence of gleyic properties attesting of a seasonal water level fluctuation. Typical gleyic Cr-horizon is reached in the core 26 at 160 cm depth. The core 24 crosses the same lithological unit than already described for the core 29 of the section 1 ("Formation d'Elvange" (li1)).

4.3. Identification of the "Argiles de Levallois" and the hydrological impact on the surface runoff processes

The historical bibliography related to the geology of Luxembourg (Lucius, 1948 ; Bintz et al., 1973 ; Dittrich, 1989 ; Colbach & Maquil, 2003) separates the Rhetian (ko), known as "Formation de Mortinsart" (Boulvain et al., 2001) in two stratigraphic units. The first unit, called "Oberer Rhät" (ko2) or "Argiles de Levallois" (Bintz et al., 1973; Mégnien, 1980), is made of red clays of the upper Rhetian. The second unit, named "Unterer Rhät" (ko1) is made of an alternation of sandstones and a black micaceous claystone.

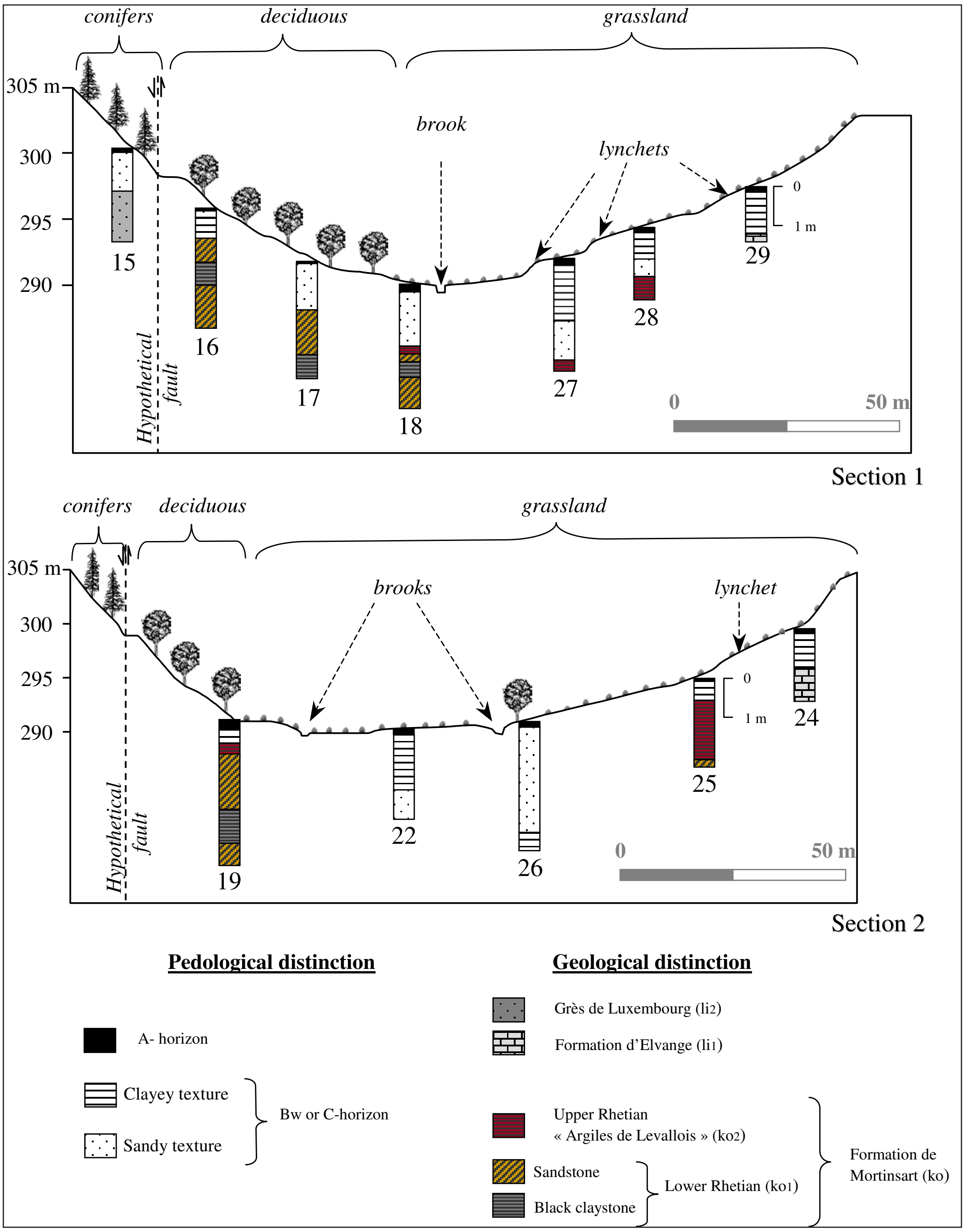

Figure 5. Location and description of the mechanized core drillings. The layers are distinguished both by pedological processes and by the underlying geological substrate. The location of the two sections is presented in Fig. 1.

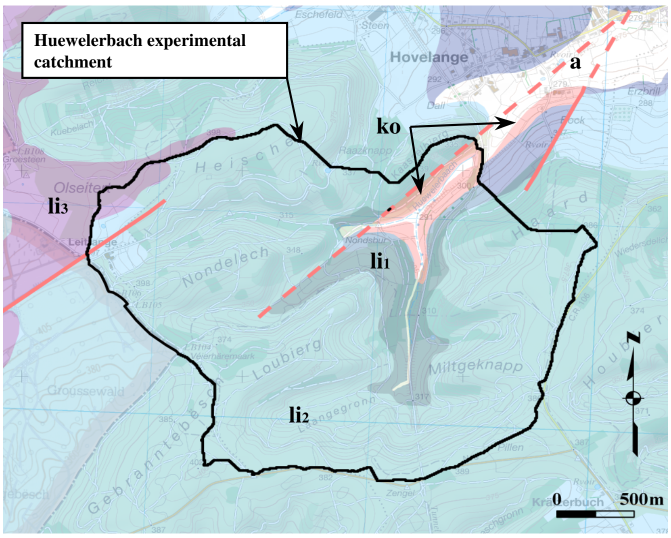

Figure 6. Proposal for a geological map of the Huewelerbach experimental catchment (adapted from Colbach & Maquil, 2003).

The occurrence in most cores of reddish clayey layers, and/or alternations of sandstone and the black micaceous claystone layer, serves to recognize the parent material of the Bw- and/or the C-horizon described during the pedological survey. These layers characterize the “Argiles de Levallois” (ko2) and not alluvial deposits. This assertion is strengthened by the geological map 1/25000 of Luxembourg (Colbach & Maquil, 2003) and by the geological cross sections (Fig. 4). Indeed, the figure 1B shows the “Formation de Mortinsart” (ko) on the right bank downstream from the basin outlet. We therefore conclude that the alluvial deposits are not so widespread as indicated by the geological survey, and that they have a limited lateral extension on both sides of the riparian zone (Fig. 6).

The soil texture observed in the cores performed in the right bank shows that the soil developped from the “Formation de Mortinsart” (ko) is principally clayey. This is due to the predominance of the “Argiles de Levallois” (ko2) in the first meter of the soil (Fig. 6). This is furthermore consistent with the grassland landuse of this area. The left bank presents more sandy topsoil under a forested area related to either sandstone layers (ko1) of the “Formation de Mortinsart” or to colluvial deposits generated by the erosion of the “Grès de Luxembourg” (li2). Consequently, the runoff processes that control the water fate on the two riversides are significantly different. On the right side, Bw and/or C-horizons made of heavy clay act as an impermeable floor, where dominant runoff processes are saturated overland flow and/or subsurface overland flow depending on the previous water saturation states in the soil. On the left side, the deeper sandy to sandy-silty topsoil increases the soil infiltration capacity and the main runoff process associates the lateral subsurface flow and the deep percolation. Moreover, the contact of these clay/sand alternation layers ("Formation de Mortinsart" (ko)) with the alluvial water table does not exclude exchanges in the opposite direction, from the groundwater to the slopes, and particularly when a sandy horizon is present beneath two clayey horizons.

5. Conclusion

The soil mapping survey of the Huewelerbach experimental catchment, located in Luxembourg, allowed linking the pedological observations made on the Bw and C-horizons to the "Formation de Mortinsart" (ko). This survey particularly confirms the lithologic origin of the red clays, which are identified as the "Argiles de Levallois" (ko2) of the Rhetian age. The link between the characteristics of the parent material and the observations of the Bw and/or C-horizon, allowed us to propose a useful complement to the geological map 1/25000 adapted to the scale of the hydrological studies. This technique is useful to map surface geology at larger scales in temperate regions where the relief is smooth and the outcrops are rare and covered by vegetation.

This study shows that soil surveys can be a useful approach for the surface geological mapping. The use of soil surveys in this context is essentially based on the recognition of the parental lithology using the C-horizon. It acts as a "keyhole" through which we can look on the "geology room".

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