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Historical rammed earth process description thanks to micromorphological analysis

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Abstract

Rammed earth was traditionally used in western European countries before industrial building materials replace it during 20th Century. Construction strategies developed by former builders were dictated by locally available construction materials and engendered local constructive cultures. Unfortunately, this knowledge was orally transmitted and is lost today. The rediscovery of these cultures can provide answers to modern rammed earth construction processes. Micromorphological analysis of earth walls provides information to rediscover traditional rammed earth process. This methodology is applied for the first time, on a rammed earth wall of a farm located in Bresse (France). Thanks to this methodology, pedological horizon, extraction depth and location of the material source are identified. The surface area excavated for the construction of the building is estimated. Micromorphological study gives information on mixing degree and water content at implementation time. Strain features associated with ramming effect and rammed earth boundary layer are also highlighted.

Running Head: Rammed earth micromorphological analysis

Key words: rammed earth; micromorphology; architectural heritage; pedology; earth construction process

1 Introduction

The need to save resources and energies consumed for housing has led to a renewed interest for construction using locally sourced and low embodied energy materials. Raw (unfired and unstabilised) earth is part of those materials (Floissac et al. 2009; Habert, Castillo, and Morel 2010; Habert et al. 2012; Morel et al. 2001). The construction strategies developed by former builders were dictated by the quality and the amount of locally available construction materials. These resource constraints, combined with neighbouring inhabitant needs, engender local constructive cultures, changing over time. The late 19th and early 20th century examples of earth constructions, in the western European countries, are the outcome of this evolution.

In this paper *soil* names the material in its natural context and *earth* names the material extracted for construction purpose. Traditional rammed earth is described as the manufacturing of locally available earth, slightly wet, tamped in a formwork using a wood rammer (Cointeraux 1791; Doat et al. 1979; Hall and Djerbib 2004; Jaquin, Augarde, and Gerrard 2007; Maniatidis and Walker 2003). Steps of this traditional process are extraction, preparation and ramming. Since topsoil is unsuitable, for convenient reasons (Cointeraux 1791; Doat et al. 1979; Maniatidis and Walker 2003; Hall and Djerbib 2004), earth is extracted in the layer just below the topsoil (Beckett 2011). Material supply is made as and when required by the needs of the site work (Cointeraux 1791). During material preparation, clods of earth are broken. Earth is gathered in a pile to let coarse elements roll down the pile and to be removed (Cointeraux 1791). The obtained bulk earth is placed by layers of 10 to 15 cm inside the shuttering. Each layer is spread by foot, and then tamped thanks to a rammer, with a more or less pointed edge. After compaction, rammed earth layers are 6 to 10 cm thick (Doat et al. 1979). Once all layers inside a shuttering are compacted, the formwork is moved horizontally to go on with the realization of the wall (Doat et al. 1979; Jaquin, Augarde, and Gerrard 2007). After completion of a level, called a “lift”, the shuttering is moved vertically to realize a new lift. The ramming effect is more important in the top of a rammed earth layer than in its bottom. Consequently, earth density is higher in the top of the rammed earth layer than in its bottom (Q-B Bui et al. 2009).

The information that survived until nowadays derived from precious testimonies of former builders who have made traditional rammed earth. The rammed earth process in Bresse region (France) is described in Perraud et al. (2015). Nevertheless, those testimonies are a narrow sample of the entire traditional rammed earth knowledge. A large part of the diversity of the know-how, transmitted orally for centuries in the western European countries, is lost as earth construction fell into disuse during the 20th century. The absences of written documents make it necessary to use an archaeological approach. In particular, the traditional rammed earth process should be described by rational means to discuss the sources of materials, the methods of extraction, the way of preparation and the implementation of earth.

From an architectural and a historical point of view, this knowledge would enable us to follow the evolution and the spread of earth construction processes. From a technical point of view, it would allow us to rediscover the solutions employed by former builders to overcome obstacles that are still relevant today: influence of soil, geography, geology and climate on construction process choices. Given the absence of suitable methodologies, the goal of this paper is to explore a rational methodology, based on micromorphology analysis of samples collected in heritage rammed earth buildings, aiming to describe the traditional earth construction processes.

Micromorphology derives from pedology science (Fedoroff 1979). It has been first employed in geoarcheology to study sedimentary sequences exposed by archaeological excavations, before to be used for archaeological architectural remains investigation (Cammas and Wattez 2009; Courty, Goldberg, and Macphail 1989). For archaeological building materials, micromorphology studies give access to features resulting of mechanisms that can reveal the elementary steps of the construction process (Wattez 2003; Gé et al. 1993; Cammas 2003). These studies help identifying building techniques for constructions ranging from Neolithic (Wattez 2003) to roman or even 17th Cad buildings (Cammas 2003).

To our knowledge, micromorphology was rarely used to characterize building materials, outside the archaeological context. Ajakane et al. (2007) used this method to describe the petrography of an earth material, but they do not describe nor study samples pedofeatures. The use of micromorphological investigation methods, for a 19th century rammed earth building is an original approach. It should be pointed out that, although the methodology proposed in this manuscript is illustrated with a particular case, it can be extended to any type of rammed earth buildings.

2 Materials and methods

2.1 Studied area

Renovation works performed in a residential building of a rammed earth farm, located in *Bresse* region, in *Cras-sur-Reyssouze* municipality (north of Lyon, France, see Figure 1), gave us the opportunity to collect rammed earth specimens of a well preserved inside wall. Specimens were sampled during the demolition of the wall. This wall was 5 m long, 4.7 m high and 0.5 m wide. As reported by a local source, the building dates back to 1860.

Topographical, geological and pedological contexts provide information about the soils surrounding the farm (Figure 2 and Figure 3). The farm is located on an alluvial terrace which is, topographically, above the Reyssouze valley, to the west, and below the Balvay plateau, to the east (Figure 2). According to the geological map (Bergerat and Fleury 1985), the farm is located on sprayings of siliceous broken stones, remains of a Riss fluvioglacial deposit, overlying a Plio-Quaternary geologic formation, called "*Marnes de Bresse"* (Figure 2). Arnal et al. (1981) and Vinatier (1987) proposed a description of common soils of Bresse region, called toposequence, based on pedological surveys preformed on 4 municipalities (Figure 3). Since the farm is located on a plateau, the local soil should correspond to a soil located on high topography of the toposequence, i.e. clayey sandy-silt soil with iron and manganese spots (1-2,Figure 3) or silty clay to clayey silt soils lying on marls (3, Figure 3). In order to precise the pedological environment of the farm, a field survey was carried out.

2.2 Pedological surveys

The variability of "*Marnes de Bresse*" geological formation (Bergerat and Fleury 1985) combined with their large cartographic scale made it necessary to carry a field study. In order to recognize the soils developed on the different geological formations and on the different topographical positions surrounding the rammed earth farm, and therefore to identify potential material sources, five hand auger surveys have been realized along an east-west transect, between the farm and the Balvay village. Those surveys are named *a* to *e* and presented in Figure 2. Their description is provided in Figure 4.

2.3 Wall specimens sampling and thin sections realization

It was not possible to distinguish to the naked eye neither layers nor lifts of the rammed earth wall in which the samples were collected. Therefore, the sampling location was randomly selected. For this first study it was decided to do a limited horizontal section (CRA1 and CRA2, Figure 5) and a limited vertical section of the wall (CRA3 and CRA4, Figure 5). Since glass slides used for thin sections are 6.5 cm wide, 13.5 cm long and the thickness of the sample must be large enough to perform several cuttings, in case of failure, the collected samples dimensions are 5×12×10 cm. Samples were carved by a craftsmen thanks to an angle grinder (Figure 5). Samples are wrapped in towel paper and firmly maintained with tape to strengthen them. Then, position and orientation with respect to the face of the wall are labelled on samples.

Samples are air dried and then oven dried at 45°C. Afterwards, according to Guilloré (1985), samples are soaked with synthetic resin. After one or two months polymerization, a slab of sample is cut. This slab is temporarily glued to a glass slide. The unattached face of the slab is levelled, grinded and glued definitively on a glass slide. The second face is grinded up to 25 µm, reference thickness for micromorphological analysis and for which the transparent observation of the thin section is possible, under plane polarized light (PPL) or crossed polarized light (XPL) (Stoops 2003). Finally, a thin glass slide is glued on the second face to protect the thin section.

Samples collected in the wall were prepared in order to realize 2 cross sections, the first one with samples CRA 1 and CRA 2 and the second one with samples CRA 3t, CRA 3d, CRA 4t, CRA 4d (Figure 5). A total of 6 thin sections are studied.

Thin sections descriptions are performed according to Bullock et al. (1985) and Stoops (2003) with the help of Mackenzie and Guilford (1980) and Delvigne (1998). The abundance of components is evaluated with an abundance charts (Bullock et al. 1985; Stoops, Marcelino, and Mees 2010). These references provide a system of analysis and description of soil thin sections. The term **groundmass** refers to the nature, the shape and the distribution of components; **microstructure** refers to the spatial arrangement of mineral particles and of voids; **fabric** refers to preferential orientations of particles; **inclusions** refers to sporadic elements; and **limits** refers to soil discontinuities.

3 Results of thin sections description

3.1 Groundmass

The material of the groundmass consists of an iron oxides rich silty-clayey fine fraction (Figure 6b) and a sub-millimetre sand fraction (40%) (Figure 6a). Sand particles are evenly distributed inside the micromass. Sand is almost exclusively composed of subangular to subrounded quartz, with regular surfaces. Finely fragmented vegetal remains, mostly roots, are also observed (Figure 6c). However, we note the presence of rare micas. The fine fraction is slightly birefringent.

3.2 Microstructure

At thin section scale, the material is constituted of subhorizontal units. The microstructure is quite dense with voids preferentially distributed inside horizontal units, creating an alternation of layers with greater and smaller porosity. Voids are unconnected and their faces are unaccommodated. They are distributed in the groundmass or linked to inclusions (clayey aggregates, ferromanganic nodules, biologic remains). The maximal observed diameter of voids is of the order of a millimetre.

A portion of the porosity (porosity of type 1) is constituted of channel voids. Some of these voids contain irregular aggregates, vegetal remains and/or Enchytraeids excrements (Figure 6d). Another portion of the porosity (porosity of type 2) has slightly rough walls of polyconcave, elongated or irregular shape. It does not contain aggregates or vegetal debris (Figure 6e). In the microstructure, cavities are frequently aligned and/or flattened along horizontal, tilted or vertical axes (Figure 6f and 6g).

3.3 Fabric

From thin section analysis, two main fabrics can be distinguished: Fabric 1, the most represented fabric, on which the sand fraction is randomly distributed inside the clayey-silty fine micromass (Figure 6a); and Fabric 2: locally, sand particles are organised along horizontal, tilted or vertical discontinuous lines (Figure 6h and 6i) and often associated with cavities alignments.

3.4 Inclusions

From thin section observation, the following inclusions, sorted by decreasing order, can be inventoried: (1) Ferruginous nodules, generally with sharp shape (size ranging from 0.3 to 10 mm) (Figure 6j and 6k); (2) multi-millimetric silty-clayey aggregates (2-5% sand) with texture finer than the one of the groundmass, often associated with cracks on their edge (Figure 6l); (3) some multi-millimetric charcoals (Figure 6m); (4) rare multi-millimetric siliceous elements; (5) rare millimetric calcareous elements; and (6) rare millimetric fired earth pieces. These inclusions are randomly distributed inside the groundmass.

3.5 Limits

In the material, two types of limits can be distinguished. The first type is characterized by obvious limits and materialized by the conjunction of three characters (Figure 6n): (1) abrupt change, from bottom to top, between a low porosity layer to a high porosity layer; (2) subhorizontal sand alignments along the limit; and (3) horizontally flattened voids along the limit.

The second limit type is a gradual transition, from bottom to top, between a more porous zone to a less porous zone (Figure 7). The analysis of a 24 cm vertical section, combining CRA3t, CRA3d, CRA4t and CRA4d thin sections, reveals 4 subhorizontal sharp limits that separate 5 layers. Within each of these layers, a transition between a lower zone, more porous, and an upper zone, less porous is evidenced (Figure 7).

4 Discussion

4.1 Representativeness

Samplings concern a portion of 24 cm vertically and 20 cm horizontally in a 4.7 m high, 5 m long and 0.5 m thick wall. The representativeness of this sampling has to be discussed. At the time of the construction the extraction of the earth is realized as and when required. Therefore, the rammed earth layers and lifts record the variations of the earth employed, more or less mitigated by the extraction, transportation and preparation stages. The contrast in earth composition is greater vertically, between the different rammed earth layers, than horizontally, along a single layer. Consequently, in a rammed earth wall, observations made on a vertical section could be considered as representative of all the entire layers intersected by this section. Contrariwise, these observations cannot be considered representative of layers located above and below this section.

4.2 Nature and source of the earth

Pedofeatures visible inside the wall are inherited from the history of the original soil in the ground and from modifications during construction stages. Once the earth compacted and dry, mechanisms driving soil particles transfer are off and the pedogenic dynamic is stopped. The aim is to distinguish the features inherited from the original soil to that inherited from the modifications engendered by men during construction process. This section focuses on features inherited from the original soil.

The presence of root debris (Figure 6c) or voids created after root decomposition (Figure 6d) evidenced a soil extraction in a horizon relatively close to the surface, but the absence of leaf or branch debris reveals that the extraction does not concern the litter. The presence of ferruginous oxides (Figure 6j and 6k) denotes a pedogenesis in a waterlogged environment. Another feature helping to identify the original soil is the decarbonation of the micromass. Among the soil type of Bresse (Arnal, Vier, and Bouteyre 1981; Vinatier 1987), the unique horizon that match this description is the Eg horizon of the type 1 (Figure 3). It is described as a “30-60 cm deep horizon, beige light with dark spots and concretions, more or less friable. The structure is polyhedral, fragile and root and worm porosity is high. This horizon, periodically waterlogged, is subjected to reduction, migration and precipitation of metallic oxides” (Arnal, Vier, and Bouteyre 1981). The noticeable difference between the wall material and the Eg horizon material concerns the structural arrangement of particles. This difference is hardly surprising, given the modifications and the compaction undergone by the earth in the rammed earth wall.

The absence of pedological data concerning the construction site environment necessitated a soil recognition on field via auger surveys. The objective of this recognition was the identification of the Eg horizon of type 1 soil, closest to the construction. As this kind of soils is only encountered in high topographic positions, the surroundings of the site as well as the plateau of Balvay were explored (Figure 2 and Figure 3). Among the horizons identified (Figure 4), horizon 2 of the profile *e* is the only one that offer pedological characteristics compatible with the material used for the wall construction. In order to compare with the particle size distribution of the wall material, five samples were collected in a 60 cm vertical section of the profile *e*, at respective depths of 0/-12, -12/-24, -24/-

36, -36/-48 and -48/-60 cm, and their particle size distribution and clay content were determined according to French standards NF P 94-056 (1996) and NF P 94-057 (1992) (Figure 9).

In a first step, the average depth of extraction is determined thanks to the soil clay content. The clay content of the material of the wall is 11 %. On the profile *e* (FigureFigure 4), 11 % clay content corresponds to a -17 cm depth (Figure 8). The extraction of the material source should then concern a 0 to -34 cm layer of the soil of the Balvay plateau. In a second step, in order to confirm this assertion, the particle size distribution of the rammed earth wall material (CRA) and these of the material collected between 0 to -36 cm depth on the Balvay plateau (BAL 0-36), are compared (Figure 9). CRA material have a greater sand fraction (30% by mass) than BAL 0-36 material. However the points of inflection of the particle size distribution of the CRA material at 0.02, 0.05 and 0.07 mm are also observed on the particle size distribution of the BAL 0-36 material (Figure 9). The mass frequency representation confirms this observation (Figure 9). The difference can be attributed to the natural variability of the soil. The granulometric signatures of these two materials can be regarded as similar.

The material source of the rammed earth wall can be identified on the Balvay plateau, located 1 km east to the site (Figure 2). The construction is dated 1860. The network and mean of transportation of this time enable us to envisage the carriage of the earth over such a distance. The extracted horizon is just below the humiferous horizon and principally concerns the Eg horizon present between -5 to -35 cm depth. This is in line with what is commonly asserted in the literature on the origin of the materials for rammed earth construction, that refer to subsoil (Maniatidis and Walker 2003; Beckett 2011; Hall and Djerbib 2004). Considering a 30 cm thickness of soil extracted, the surface excavated to build the wall is estimated to 40 m^2. The same calculation performed for the entire building gives an excavated area of approximately 800 m^2. The selection of a particular horizon, located at least 1 km away, requiring excavation of soil on such a large surface area, tells us how carefully the choice and the extraction of the earth for construction was made by the 19th century craftsmen.

4.3 Material preparation

Pedofeatures resulting from the mixing and its intensity are described in the literature (Courty, Goldberg, and Macphail 1989; Gé et al. 1993; Cammas 2003). Mixing induce a homogeneous distribution of the coarse fraction in the micromass and the presence of rounded residual aggregates. Here, the material of the wall does not present any characteristic of a mixing action (Figure 6l). Thus, the material has undergone, at most, a coarse mixing related to the handling of the earth during extraction, transportation and preparation.

Type 1 porosities contain Enchytraeids excretions and vegetal debris indicating their root decomposition origin (Figure 6d). Irregular aggregates inside these voids evidence the mechanical alteration of void walls and therefore, their aging. The preservation of type 1 porosities, despite the significant compaction of adjacent earth, strongly suggests that the decomposition occurred after the implementation of the earth in the wall. Type 2 porosity is of physical origin (Figure 6e). Type 2 porosities are mainly generated during the modifications engendered by rammed earth processing. Shape and roughness of their walls depends on the water content of the material during their creation, i.e. during extraction and implementation of the earth (Stoops 2003). Micromorphological characteristics resulting from preparation and implementation of the earth material, relative to water content at the fabrication time, for plastic to liquid state, are described by Cammas (2003) and synthetized in Table 1. Type 2 porosities have rough and irregular walls (Figure 6e). This sort of porosity, combined with the absence of pedofeatures associated to plastic to liquid state, suggest an implementation at solid state. These pedofeatures, significant of an implementation of the material at a relatively dry state, have never been depicted in the context of construction materials. This observation is in accordance with the hydric state of the earth for rammed earth construction, typically under the plastic limit (T.-T. Bui et al. 2014; Ciancio and Jaquin 2011; Kouakou and Morel 2009; Silva et al. 2013).

4.4 Material implementation

The continuous sand particles alignments combined with horizontally elongated voids separate five horizontal layers (Figure 7). In each layer, porosity gradually evolves from a more porous region, at the base, to a less porous region, on the top (Figure 7). Layer edges are underlined by an abrupt change from a closed porosity below and a more open porosity above. Sharp limits are interpreted as limits of material brings, resulting on the addition of a new earth layer. Sand beds associated with horizontal voids located on layers' top are interpreted as the result of vertical tamping that reduces the volume of bulk earth, flatten voids and create horizontal alignments of sand particles. The inside layer porosity evolution is interpreted as the indicator of the degree of compaction. The upper portion of a layer is more compacted than the lower portion (Quoc-Bao Bui et al. 2014). The superimposition of layers is responsible for the porosity contrast between sharp limits. The estimated rammed earth layers thicknesses are comprised between 3 to 9 cm (Figure 7). Literature refers to thickness values ranging from 6 to 10 cm for traditional rammed earth (Doat et al. 1979; Quoc-Bao Bui et al. 2014). Even if some layers can be regarded as thin (L2 and L4, Figure 7), layer thicknesses are in agreement with the literature values. The fineness of the earth employed for the construction did not enable us to distinguish on site the different layers with unaided eye. Only the micromorphological study permits this distinction.

Inside the layers, discontinuous sand alignments and flattened voids are observed. They correspond to the fabric of type 2 (Figure 6f, 6g, 6h and 6i). Occasionally, subvertical particles and voids alignments change direction downwards and get connected to a subhorizontal alignment, forming a corner shape figure (Figure 6i). Some alignments are highly visible, others are more indistinct. The horizontal particles alignments and flattened voids are the result of a vertical shortening. The tilted and subvertical sand alignments are interpreted as shear lines, a phenomenon compatible with the vertical shortening. The overlap of most of these deformation figures demonstrates the repetition of stresses undergone by the material, which superimpose strains on each other. The repetition of these strains across all layers generates a significant shortening, which is possible only with earth at bulk state. These figures accommodate localised vertical strains, repeated throughout the rammed earth layers. These figures are interpreted as the result of the craftsman compaction of the earth inside the formwork by treading it with his clogs and tamping it thanks to a rammer. The discontinuous sand particles alignments and oriented voids are therefore characteristic of the mechanical tamp undergone by the material at bulk state and is associated to the rammed earth process.

5 Conclusion

By combining geotechnical approach, conventionally used in earth construction, with pedological field survey and micromorphological approach, it is possible, in the case studied here to (1) identify geographical and pedological material source, (2) precise the depth of soil extraction, (3) estimate the excavated surface necessary to extract the earth, (4) provide information on the mixing degree and (5) on water content at fabrication time, (6) describe the effect of the manual rammer during the tamping phase and (7) distinguish rammed earth layers that were not visible on site.

The methodology proposed in this article provide extensive information on the construction process (extraction method, transportation, mixing, water content, compaction effect) employed to build this rammed earth farm, and to make the connection between this process and the type of earth used. By applying this methodology to buildings of different ages and different geographical contexts (soil type, climate, seismicity …) it is possible to describe the evolution of the rammed earth processes and their adaptations in specific contexts. Finally, in case of a doubt about the nature of the construction process used for a construction, this paper provides clear micromorphological criteria for identification of rammed earth process, applicable to building heritage and archaeological material.

The methodology proposed in this article is promising. Future developments of this work could be (1) to provide quantitative information in order to support observations, (2) to investigate other rammed earth constructions, with different implementations, from various regions and/or of diverse ages with the aim to experience this methodology and (3) to study constructions using other traditional earth processes (cob and adobe for example) to possibly generalise it.

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Figure captions

Figure 1. Location map of the rammed earth farm (Cras-sur-Reyssouze, France).

Figure 2. Geological East-West cross section of the surroundings of the rammed earth farm realized according to the geological map (Bergerat and Fleury 1985). Positions of pedological surveys are indicated (a, b, c, d and e).

Figure 3. Synthetic cross section presenting common soils of the toposequence proposed by Arnal et al. (1981) and Vinatier (1987).

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Figure 5. 3 dimension drawing of the 4 specimens sampling realized in the rammed earth wall (on left) and picture of the wall after sampling (on right).

Figure 6. Details of thin sections. a: coarse texture (PPL, × 2) (CRA1); b: fine texture (XPL, × 20) (CRA1); c: vegetal debris (PPL, × 2) (CRA4t); d: porosity of type 1 containing Enchytraeids excretions (PPL, ×2) (CRA4t); e: porosity of type 2 (XPL, ×10) (CRA3t); f: horizontally elongated cavity (PPL, × 2) (CRA4t); g: flattened cavities alignment (PPL, ×4) (CRA2); h: tilted sand particles alignments (PPL, × 2) (CRA4t); i: subhorizontal associated to a subvertical sand particles alignment (PPL, × 2) (CRA3t); j: sharp shape ferruginous nodule (PPL, × 2) (CRA2); k: indistinct shape ferruginous nodule (XPL, × 20) (CRA3t); l: silty-clayey aggregate (PPL, × 2) (CRA3t); m: piece of charcoals (PPL, × 2) (CRA4t); n: detail of an obvious limit, between a low porosity layer below and a high porosity layer above. This limit is underscored by a subhorizontal sand particles and flattened voids alignment (PPL, × 2) (CRA3t).

Figure 7. Vertical cross section, reconstructed thanks to 4 thin sections (CRA3t, CRA3d, CRA4t and CRA4d). Obvious limits are pictured by dotted lines. Obvious limits separate 5 layers, named L1 to L5, wherein porosity transition is evidenced.

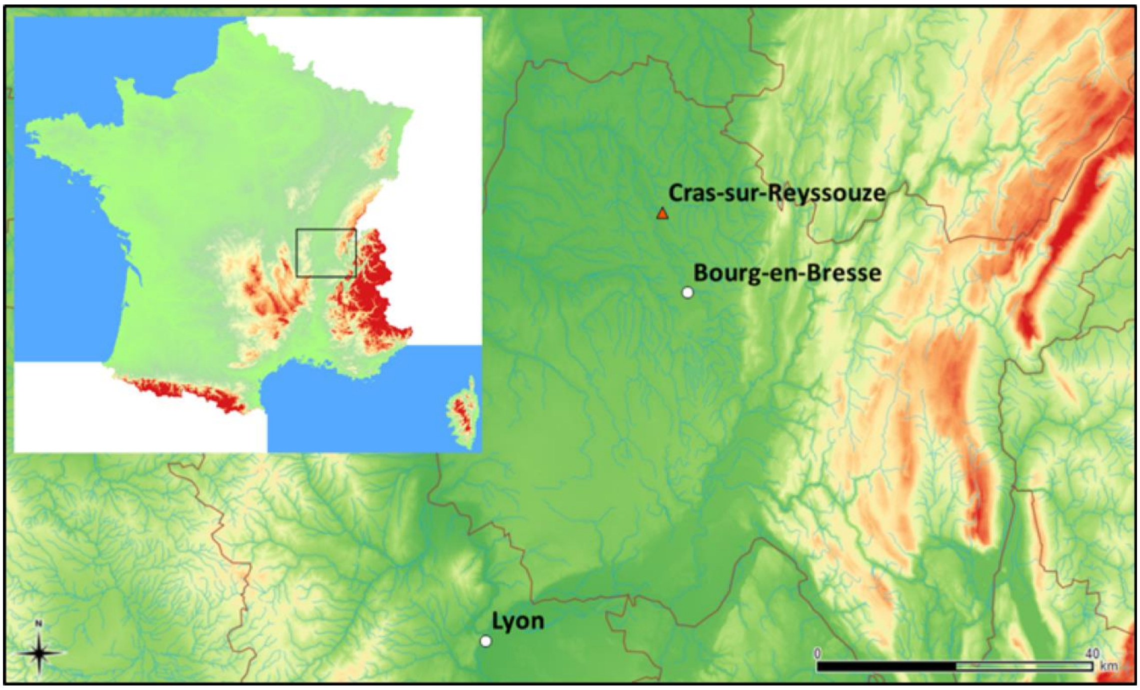
Figure 8. Clay content (2 µm passing) evolution with regard to depth of the *e* survey, located on the Balvay plateau

Figure 9. Comparison between particle size distributions and mass frequency of the rammed earth wall material (CRA) and material collected during the Balvay plateau survey, between 0 to 36 cm depth (BAL 0-36).

Table caption

Table 1 Micromorphological indicators of the manufacture water content, after Cammas (Cammas 2003)

Figures with titles



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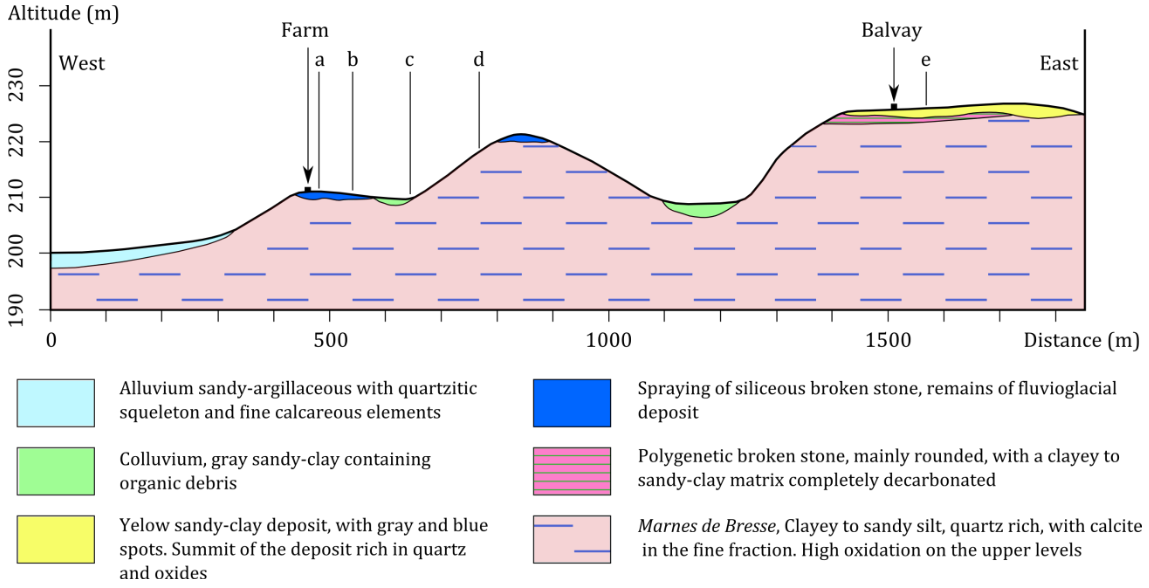

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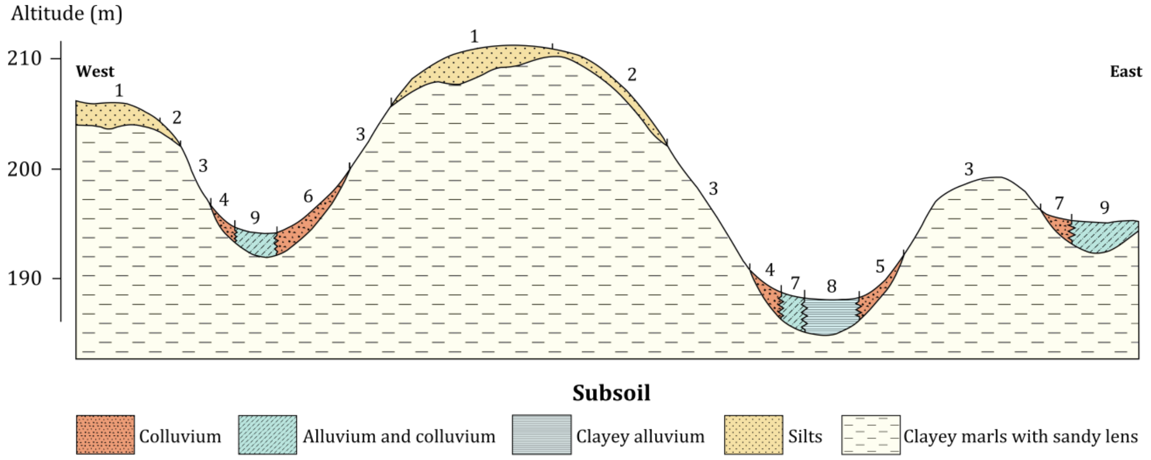
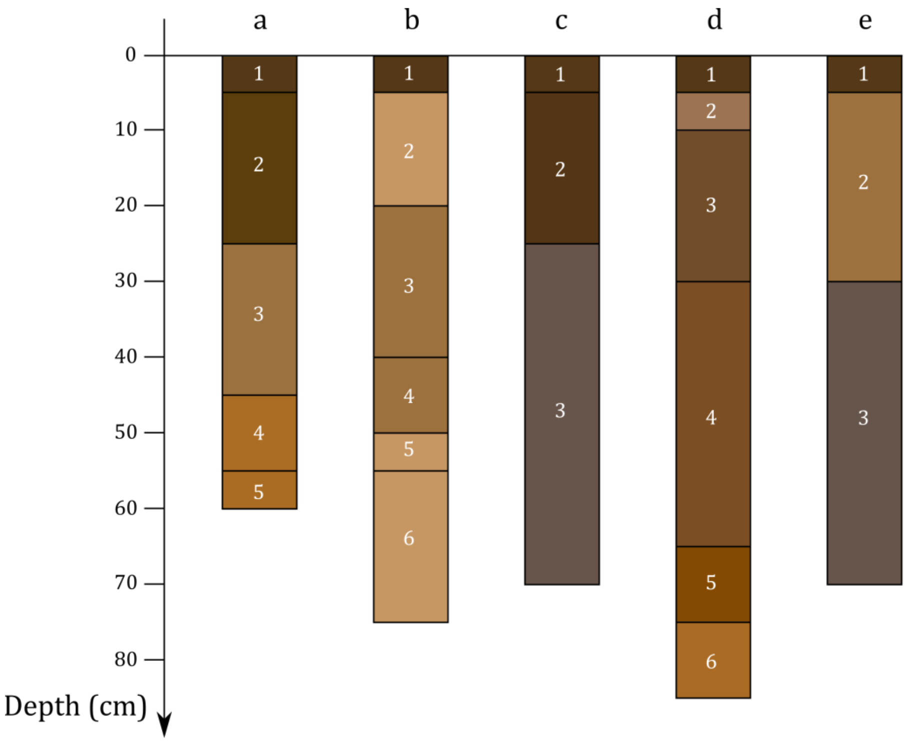


Main caracteristics of soils of Bresse region

1 : Clayey-sandy silt soil, with rust and dark spots under 20 cm, lying on a mottled horizon, most of the time composed of silty clay, appearing at 50-60 cm deep ; **2** : Clayey-sandy silt soil with rust spots, lying on a blue colored clay under 30-70 cm deep ; **3** : Silty clay to clayey silt soils lying on clayey marls, locally richer in silt or in sand, appearing at 30 cm deep ; **4** : Clayey silt to silty clay soils weakly mottled or spotted at around 50-70 cm deep, not calcareous ; **5** : Clayey silt to silty clay soils weakly mottled or spotted at around 50-70 cm deep, calcareous ; **6** : Clayey silt to silty clay soils mottled or spotted at around 30-40 cm deep ; **7** : Clayey silt to clay soils, mottled under 30-40 cm deep. Waterlogged under 30-40 cm deep ; **8** : Clayey soil with rust spots, mottled under the surface horizon. Completely waterlogged ; **9** : Clayey soil with sandy-clayey silt level, rust spots, mottled under the surface horizon. Completely waterlogged

Figure 3. Synthetic cross section presenting common soils of the toposequence proposed by Arnal et al. (1981) and Vinatier (1987).



a - 1: surface horizon, rich in roots, under a grassland ; 2 : sandy silt ; 3 : clayey-sandy silt, friable, with rust impregnations ; 4 : sandy-clayey silt, with bright aspect and red spots ; 5 : mottled sandy-clayey silt with spots and ferromanganese nodules.

b - 1 : surface horizon, rich in roots, under grassland ; 2 : alternations of gray and yellow to orange levels, similar to those of horizon 6 ; 3 : sandy silt with some impregnations and some ferromanganese nodules ; 4 : same as 3 but more clayey ; 5 : same as 4, more spotted and richer in nodules ; 6 : sandy-clayey silt with dark and red spots and white zones. Richer in clay than horizon 5.

c - 1 : surface horizon, rich in roots, under grassland ; 2 : silty clay with thin roots ; 3 : mottled silty clay with gray dominant color. Abundant ferromanganese impregnations and coals.

d - 1 : surface horizon, rich in roots, under grassland ; 2 : fine gray sand with roots ; 3 : sand more yellow and clearer than horizon 2 ; 4 : clayey sand more yellow than horizon 3 with ferromanganese impegnations ; 5 : clayey sand with coals ; 6 : mottled clayey-silty sand, clearer than horizon 5.

e - 1 : surface horizon, rich in roots, under grassland ; 2 : clayey-sandy silt (with fine sand), gradually richer in clay to the bottom, with some rounded pebbles, some ferromanganses impregnations and few millimetric coals ; 3 : gray mottled silty clay with centimetric ferromanganese impregnations.

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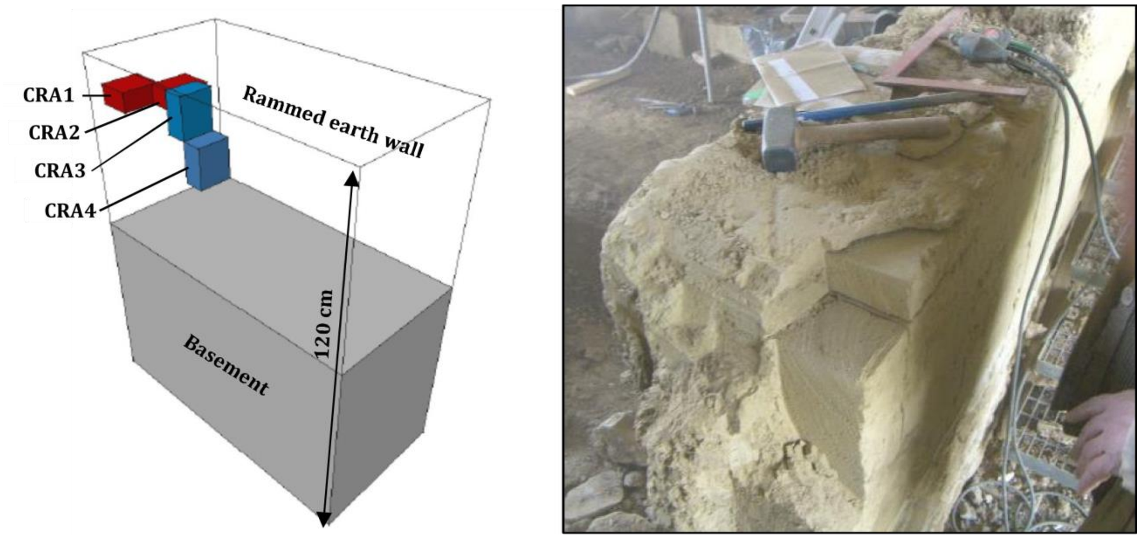

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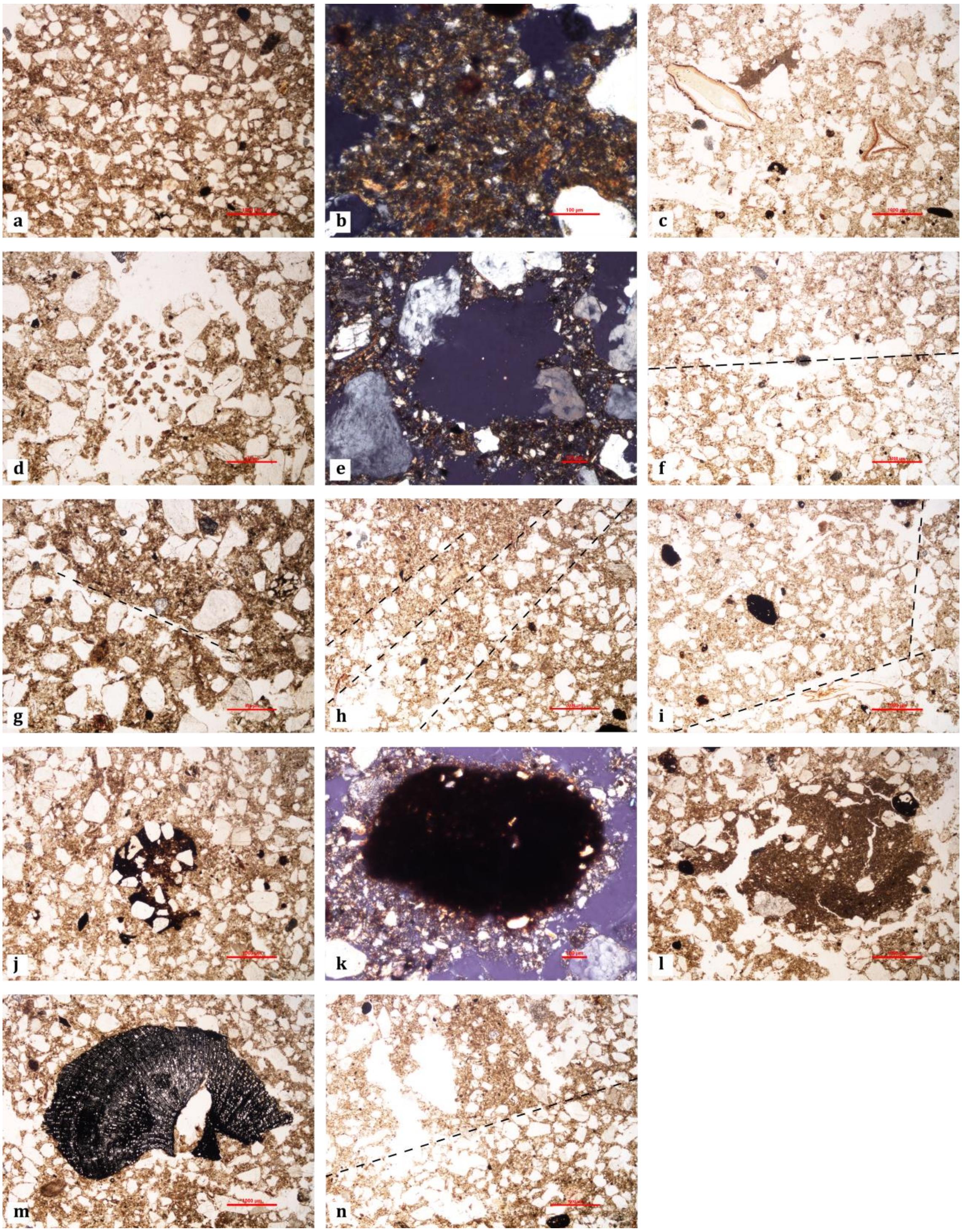

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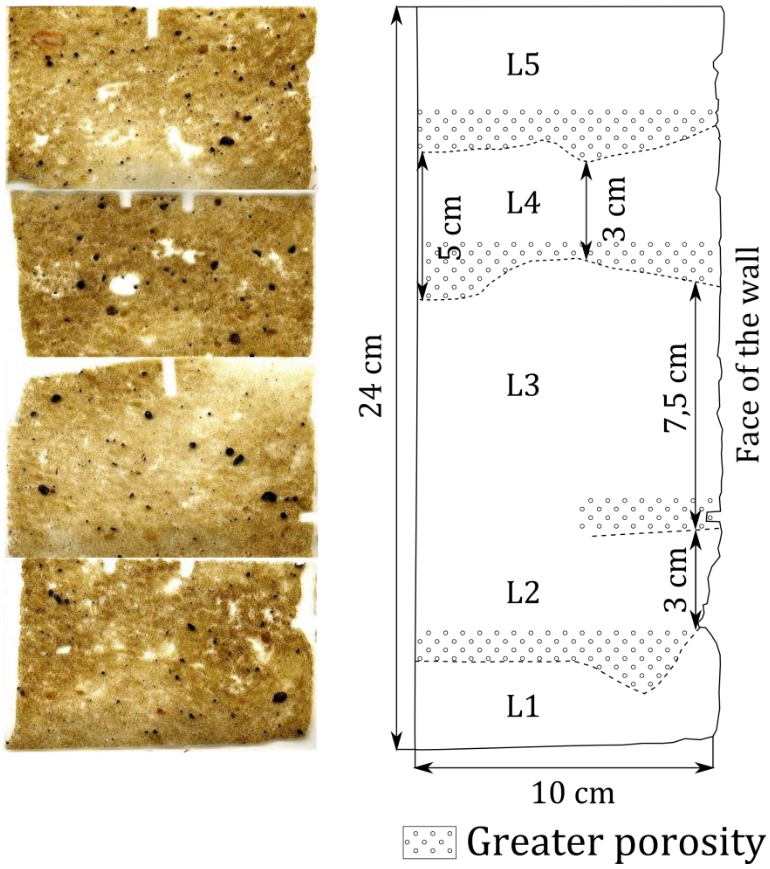

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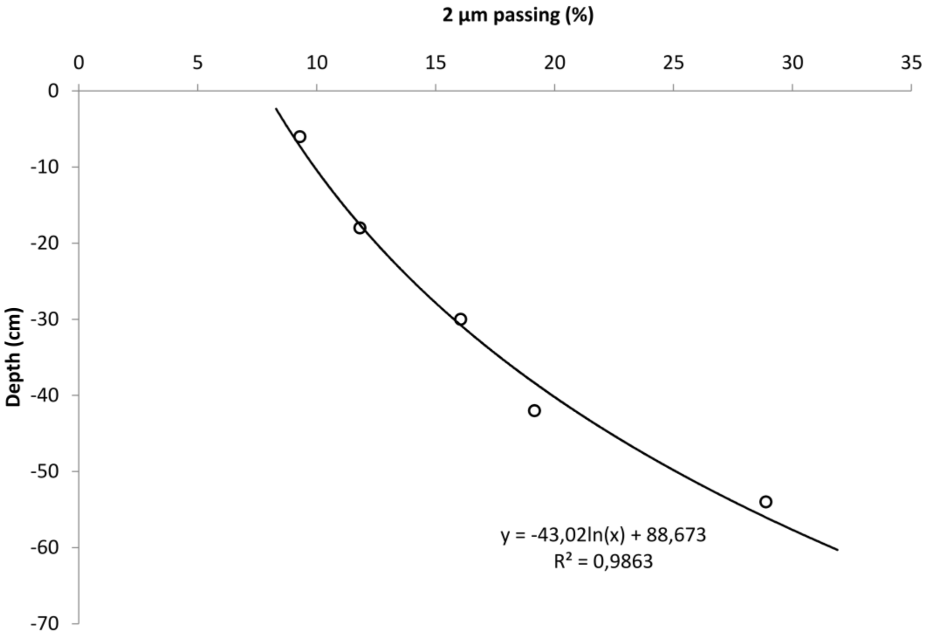

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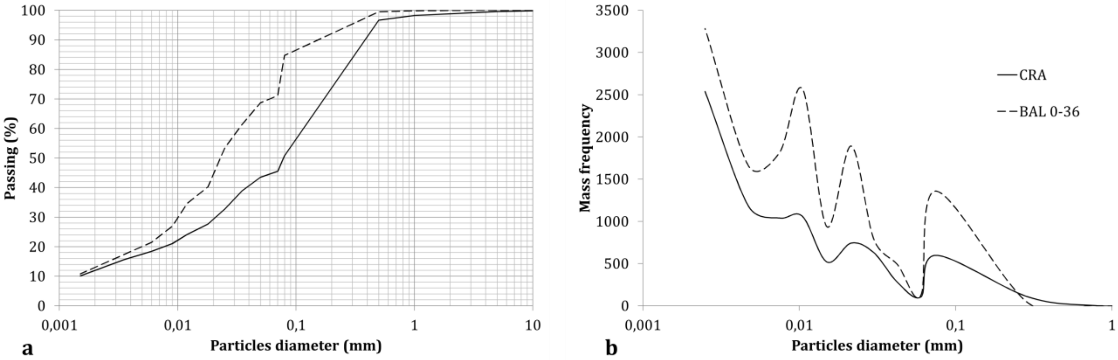

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Pedofeatures	**Water content**	
	Solid state	**Liquid state**
Mud intercalation frequency	-	+
Desilting area frequency	-	+
Vesicle frequency	-	+
Cavity roughness	+	-
Cavity sinuosity	+	-