Citation: Poch, R.M.,Rodríguez-Ochoa, R., Artieda, O., Balasch, J.C., Boixadera, J., 2021. Silt-sized sediments and gypsum on surface formations in the Ebro Basin: a disambiguation of the term "gypsiferous silts". Geologica Acta, 19.8, 1-21.
DOI: 10.1344/GeologicaActa2021.19.8

geologica acta

Silt-sized sediments and gypsum on surface formations in the Ebro Basin: a disambiguation of the term "gypsiferous silts"

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ABSTRACT

The term "gypsiferous silts" has been used since the 1960s by many authors, but it has relied on unclear, ambiguous criteria that attributed aeolian, colluvial or alluvial origins to these materials. The aim of this paper is to clarify the use of the term "gypsiferous silts" applied to silt-sized, gypsum-bearing sediments on surface formations in the Ebro Basin, using published and unpublished information.

We distinguished three types of materials with very different characteristics that had all been attributed to the general term "gypsiferous silts" in previously published work: i) gypsiferous silts *sensu stricto*, ii) loess and iii) flour-like gypsum. The recommendations of our study are that the first two terms should be applied to gypsum-containing sediments located in varied topographic positions with calcium carbonate contents up to 40-50% and coarse silty to fine sandy textures. Loess normally appears as thick outcrops (up to 12m) on slopes leeward from the main wind direction, with a limited pedogenesis consisting of a partial carbonate mobilisation and gypsum contents between 0 and 30%. Loess is the only category with an aeolian origin. The materials in the category "gypsiferous silts" *sensu stricto* are mainly colluvial-alluvial. The third term (flour-like gypsum) should be used to refer to materials on surface formations consisting of almost 100% silt- to fine sand size lenticular gypsum. These materials derive from on-site weathering of gyprock or by precipitation from calcium- and sulphate-saturated groundwater and surficial waters and show a variable spatial distribution: along footslopes, outcropping as metric surface formations, interstratified between limestone layers or as generalized karstified subsurface accumulations.

The proposed classification, based on morphological and physico-chemical characteristics, establishes a necessary distinction among the three types of materials, since they differ in their properties and geotechnical behaviour relevant for soil management and land use. Using the proposed classification will allow their distinct characteristics can be taken into account when performing geological or soil surveys in this and similar arid regions.

KEYWORDS **weathering; micromorphology; pedogenesis; gypsiferous soils; loess**

INTRODUCTION AND OBJECTIVES

"Gypsiferous silts" ("limos yesíferos" in Spanish) is a term that began to be used last century to name silt-sized, gypsum-bearing sediments on surface formations in the Ebro Basin, north-east Spain. However, the term has never been clearly defined, to the point that authors reporting these sediments have attributed different aeolian, colluvial or alluvial origins to these materials. The aim of this paper is to review and clarify the use of the term "gypsiferous silts" and to provide a framework for the classification of these materials.

The Ebro Basin is a large depression in the Northeastern part of the Iberian Peninsula, filled by sedimentary rocks during the Cenozoic (Paleocene to Miocene). Marine and continental sedimentation occurred until the Eocene. From the late Eocene, the basin became fully continental, without connection with the ocean (Costa *et al.*, 2010; Muñoz *et al.*, 2002; Riba *et al.*, 1983), with extended evaporitic depocenters progressively migrating to the west under a rather dry and hot climate (Calvo *et al.*, 1993); therefore, the bedrock geology consists of conglomerates, sandstones and mudstones at the basin boundaries, grading to marls, limestones, gypsum ($CaSO_4 \cdot 2H_2O$) and halite at the basin centre (Figure 1; Pardo *et al.*, 2004; Riba *et al.*, 1971; Valero *et al.*, 2014).

The Móra Basin is a complex graben located SW of the Catalan Coastal Range separated from the Ebro Basin by the Pàndols-Cavalls Range thrust sheets, which remained active as a Neogene depression (Teixell, 1988).

After the opening of the basin to the Mediterranean Sea during the Late Miocene-Pliocene (Arche *et al.*, 2010; Babault *et al.*, 2006; García-Castellanos *et al.*, 2003; Riba *et al.*, 1983), incision of the drainage network took place. From then on, different terrestrial processes (weathering, pedogenesis, erosion-sedimentation) produced an intense physical and chemical alteration of the bedrock that gave rise to diverse types of non-consolidated surface formations in the inner part of the depression, characterized by a silty texture, a high calcium carbonate content and different amounts of gypsum.

These materials, often referred to as "gypsiferous silts", have been identified and studied since 1960

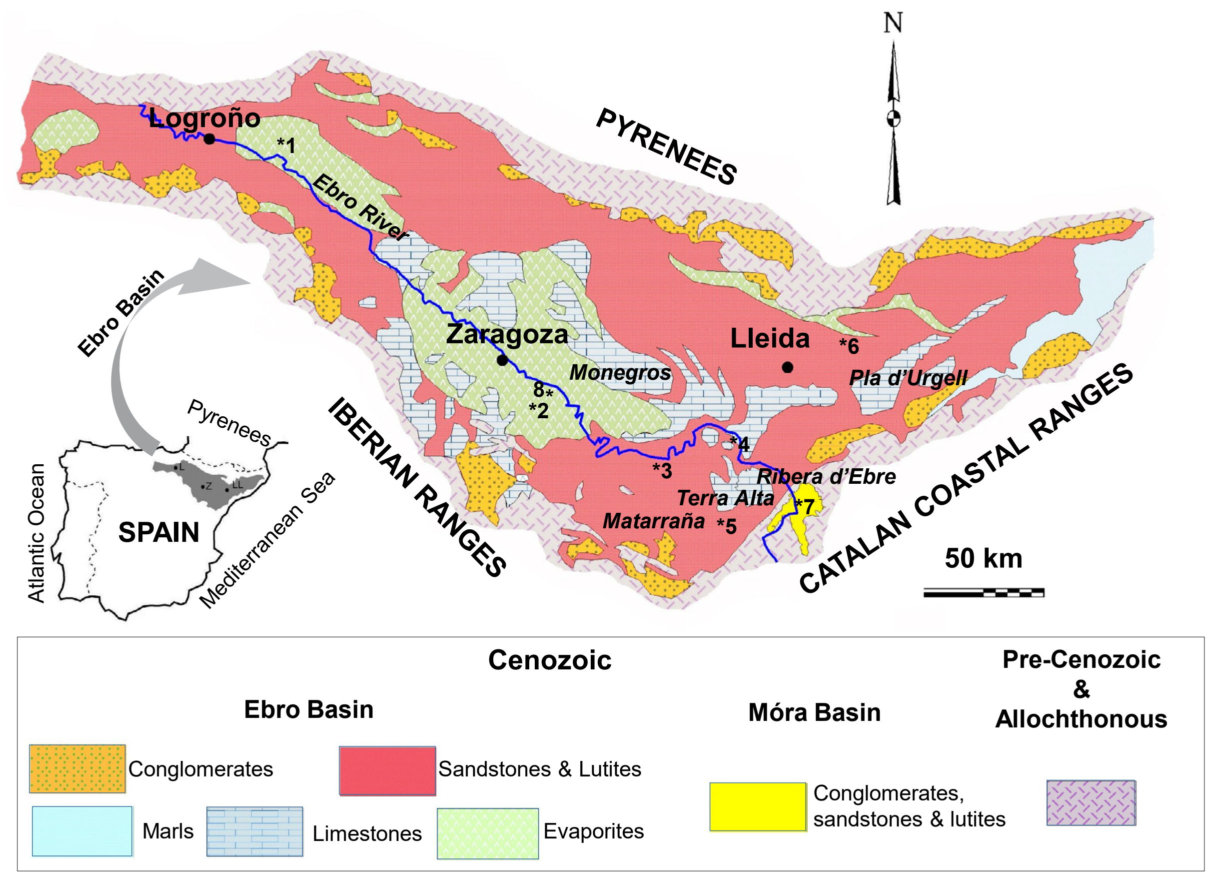

FIGURE 1. Lithological map of the Ebro Basin (based on Pardo *et al.*, 2004) and the Móra Basin (based on Orche *et al.*, 1981) with the location of the main sites cited in this paper. 1: Lerín. 2: Location of Figure 8; 3: Caspe. 4: Mequinenza. 5: Batea. 6: Bellcaire d'Urgell; 7: Móra de Ebro; 8: Quinto.

(Llamas, 1962; Torras and Riba, 1967/1968; Torras, 1974; Quirantes, 1978; Van Zuidam, 1976), although there are more recent references, *e.g.* Oteo (2011) and Desir *et al.* (2011) and they are reported in the Geological Map of Catalonia, *e.g.* Bellcaire d'Urgell sheet (Saula *et al.*, 2014). Some of the main references to "gypsiferous silts" deal with geotechnical problems mainly in hydraulic infrastructures, as subsidence, concrete corrosion and volume changes (Faraco, 1975; Hué and Llamas, 1961; Llamas, 1962; Pérez del Campo and Lanzarote, 1988; Riba and Llamas, 1962; Valdés, 1958). In particular, the engineering limitations of gypsiferous soils are well known, for example iron corrosion, sinkholes and subsidence by karstification (Benito *et al.*, 1995; Herrero and Boixadera, 2002), as well as the reaction of sulphates derived from gypsum with concrete and other building materials (Charola *et al.*, 2007; Crammond, 2002; Shanahan and Zayed, 2007).

A particular type of these materials, present in several soils developed on gypsum-rich parent materials was identified in the Ebro Basin, often with silty (flour-like feel, not cemented but hard when dry) gypsum (in Spanish, *yeso farinoso,* Herrero, 1987), and classified as a particular type of a gypsic horizon (Soil Survey Staff, 2014), namely the hypergypsic horizon (Eswaran and Zi-Tong, 1991) in Navarra (Arricibita *et al.,* 1988), La Rioja and Aragón (Artieda 2004; Herrero, 1987), Catalonia (Boixadera *et al.,* 1989; Herrero *et al.*, 1992; Herrero *et al.*, 1993, 1996; Poch, 1992), and in the soil map of Catalonia 1:250.000 (ICGC/DARP, 2019)

Riba *et al.* (1971, 1986) mentioned the presence of aeolian silts in glacis (alluvial polygenic pediments) and coarse-detrital sediment terraces in the lower Ebro Basin and noted their siliceous nature. The Móra Basin map, on the eastern side of the Ebro Basin (Figure 1) (Orche *et al.*, 1981), reports deposits thicker than 2-3 meters consisting of salmon-coloured silts on top of terraces and glacis but did not provide with any information about their characteristics or origin. These highly sorted silty deposits have been mapped and studied in the lower Ebro Basin (Terra Alta, Ribera d'Ebro counties) (Balasch *et al.*, 2011; DARP, 1987; DAR, 2010; Margarit and Monner, 1996). These authors noted them as having an aeolian origin. They are formed by coarse-silty to fine-sandy loess, in deposits with thicknesses reaching more than 10m in some zones, some of them with minor amounts of gypsum (Boixadera *et al.*, 2015). Its presence has been later extended to the West in several areas in Southeastern Aragón (Lower Aragón and Matarraña) (Rodríguez-Ochoa *et al.*, 2017).

Regardless of the denomination used, there is no common agreement among authors on the macromorphologies, analytical information (mainly gypsum contents) or the genesis of "gypsiferous silts" (aeolian, colluvial, alluvial, or weathering product). The references often combine and mix information on their position in the landscape as well as on morphological and analytical characteristics. For instance, terms such as "gypsiferous loess" have been applied to pure gypsum near gyprock outcrops with silty texture that do not have an aeolian origin (Riba *et al.*, 1986).

Given the large confusion among earth scientists when dealing with these silt-sized, gypsum-bearing Quaternary materials, the objective of this paper is to discern the different types of these materials in the Ebro Basin, their origin and characteristics (location, composition) in order to differentiate them, using published and unpublished information. Our hypothesis is that it is possible to distinguish three types of gypsum-bearing silty materials: gypsiferous silts *sensu stricto*, loess and flour-like gypsum, which can be defined and classified. This research contributes to improve the soil and geological mapping in the region, and to assess geomorphological and geotechnical risks in this and other regions with gypsum-rich substrates under dry climates.

REVIEW OF THE TERM "GYPSIFEROUS SILTS"

Llamas (1962) defined "gypsiferous silts" as "Quaternary sediments originating from the accumulation in the talweg and, especially in alluvial cones from ravines, produced by the weathering products of surrounding gypsiferous rocks". Regarding specific genesis, this author did not provide with any additional data, but pointed out that "Possibly the microscopic study, according to the technique of Kubiena (1938), of undisturbed samples of these gypsum silts would effectively contribute to clarify the problem."

In particular, Hué and Llamas (1961) and Llamas (1962) described the engineering problems related to gypsiferous materials encountered during the construction of irrigation canals on the right side of the Ebro Basin. They divided them into the geological gypsum (Triassic and Eocene to Miocene), mostly related to dissolution of the rock and to the chemical agressivity of sulphates on concrete, and the colluvia (*derrubios*) derived from them, locally named "white earths" which hardly reach 10% of gypsum (sic). The latter are mainly composed of silt, and their geotechnical behaviour (shrinking by hydroconsolidation) was related by these authors to that of typical loess. They stated that raw gypsum rock causes fewer geotechnical problems than the gypsiferous silts. Sometimes the skeleton materials are sandier, derived from the Cenozoic quartzitic sandstones, graywackes and subarkoses and they are cemented by gypsum (with contents 20 to 60%).

Torras and Riba (1967/1968) and Torras (1974) made the first sedimentological characterisation of gypsiferous silts as a weathering product of Cenozoic gypsum in the Ebro Basin. They recognized different types, among them those filling dry valley bottoms in the Ebro Basin (*vales*), mainly composed of very fine sand formed of lenticular gypsum, according to microscopical observations. According to Torras and Riba (1967/1968), they are predominantly composed of gypsum with variable amounts of calcium carbonate. They claimed these silts as being originated by both gyprock weathering and pedogenesis. From a petrographic point of view, they distinguished between pure gypsum silts and impure alluvial, or fluvio-aeolian silts. Pure gypsum silts would be composed by almost exclusively well sorted gypsum grains with no hydric transport, and eventually considered them as gypsiferous loess, *i.e.* with an aeolian origin. Torras (1974) considered that many of the gypsiferous silts that she identified were already studied by Kubiena (1953), who described the soils of "gypsum crust yerma" in the vicinity of Zaragoza, which are poorly developed soils on gypsum rock with similar macromorphological features as those later described by Artieda (2004). Torras (1974) indicated gypsum percentages from 2 to 70%, with an average of 15%. Again, these values do not agree with those of Llamas (1962), who reported gypsum contents less than 8%[1]. According to Riba *et al.*, (1986) the gypsum sands and silts studied by Torras and Riba (1967/68) originated from an intense wind action such as the one currently taking place in the North African "chotts", salt lakes or playa lakes. These sands and silts were later redistributed by water and wind and generated fluvial and aeolian deposits with varying gypsum contents. Based on crystal sizes of the pure gypsum silts measured by microscopy, they concluded that their origin is aeolian (gypsiferous loess). However, they did not take into account that these crystals may not be detrital but instead could have originated from post-sedimentary dissolution-precipitation processes from gypsum clasts from the sediment, or by precipitation from surface or subsurface waters with sulphate and calcium in solution, with modal sizes between 30-1000µm (Poch *et al.*, 2018).

Faraco (1975) studied "gypsiferous silts" from a geotechnical point of view and attributed their high gypsum contents to the colluvial or aeolian origin from gypsum sources. He reported a high susceptibility to collapse by hydrocompaction, similarly as in classical loess (Pye, 1995). Van Zuidam (1976) reported gypsum-containing materials (without indicating their specific content) both in infilled valleys (*vales*) and in alluvial fans. In the first case, the filling materials come from weathered gypsum, marl and limestone by transversal and longitudinal wash (mainly colluvio-alluvial processes), while he attributed the silty material with no macroscopic stratification to aeolian origin to some extent.

Riba *et al.* (1971, 1986) observed that terraces and pediments are discontinuously covered by aeolian silts, often gypsiferous, as shown in the Zaragoza and Lleida Geological Sheets 1: 200,000, especially in the central area of the Monegros (Riba *et al.,* 1986). They explained them as a product of current and ancient deflation of salty dust that formed in the most arid areas, where gypsum-bearing rocks of the Zaragoza Formation (Quirantes, 1978) often outcrop.

Another author claiming for an aeolian origin of gypsum silts is Quirantes (1978), who reported on the grain size of pure gypsum silts, similar to loess, and on their location on top of platforms South of Zaragoza and covering infilled valleys and leeward slopes in the area of Mequinenza. Indeed, Mandado *et al.* (1984) indicated that gypsiferous silts were the residue of the weathering of gyprocks. They also pointed out that this term is confusing and conducive to errors, since it frequently refers to "gypsum silts interbedded in alternating gypsum deposits with alabaster gypsum nodules", which are actually nothing other than the products of the dissolution and alteration of the most porous and exposed gyprock facies. In less weathered areas, as in quarry fronts and other recent cuts they completely disappear. Other authors, such as Soriano and Calvo (1987), pointed out that most of the filling materials of the infilled valleys of the Zaragoza area have their origin in the sedimentation of materials transported by ephemeral streams and also from contributions from the slopes. Similarly, Arauzo and Gutiérrez (1994, 1995) described different facies of "gypsiferous silts" in valley infillings, and they attributed their formation to hydric processes with different regimes, quoting Llamas (1962), Van Zuidam (1976) and Artieda (1993) to explain their origin from gyprock alteration.

"Gypsiferous silts" are also reported by Gutiérrez-Elorza *et al.* (2002) in special locations, such as yardangs developed in Miocene gypsum beds of the central sector of the Ebro Basin. They described dissolution features (karren) on the nodules of alabastrine gypsum, as well as streamlined deposits made of gypsum clasts with a matrix of "gypsiferous silts" as a result of the erosion of the detrital material. These "gypsiferous silts" on slopes locally show aeolian pits and flutes, which indicate that these areas can be the source of aeolian gypsum. The relation of gypsum silts and aeolian formations as dunes is pointed out by Desir *et al.* (2011), who reported accumulations of gypsum silts

[1] Gypsum contents referred in the literature must be taken with caution, since its determination is conflicting. On one side, it often appears as coarse, fragile crystals, which easily break down upon sampling and produces non-representative samples; and on the other side there is a lack of a reference, standardized analytical method (Porta, 1998).

derived from gyprock in the central area of the Ebro Basin, which are especially frequent in the infilled valleys, alluvial fans and thicker on leeward slopes due to the the "Cierzo" (dominant NW wind), but they did not refer to the gypsum content of the materials.

As a summary, the term "gypsiferous silts" refers to non-consolidated surface materials having in common only their predominant silt grain size and varying gypsum contents (from very little to almost pure gypsum) and located in a wide range of landscape/geomorphic positions. Different authors attributed to them very diverse origins (aeolian, weathering in situ, alluvial, fluvial, colluvial), sometimes by risky extrapolations from other environments and not providing enough information to make clear interpretations.

In the following sections the characteristics of flour-like gypsum and loess are reviewed as a way to reach a more precise definition of these gypsiferous non-consolidated materials, since their properties and genesis in the Ebro Basin are better understood.

THE FLOUR-LIKE GYPSUM MATERIALS

Identification and geomorphological context

The term flour-like gypsum was initially used by Herrero and Porta (1987) with an extensive definition from a micromorphological point of view (Herrero *et al.,* 1992). Macromorphologically (Artieda, 2004; Herrero, 1991) it is a powdery material, with a floury touch and whitish colour. It is generally structureless, massif or slightly laminated, with a content of 60% gypsum or more and carbonate contents less than 10%. The silt-size of the gypsum crystals is what gives the floury touch (Arricibita *et al.*,1988; Artieda, 1996, 2004; Herrero *et al.*, 1992; Poch, 1992; Poch *et al.,* 1998; Porta and Herrero 1988). A similar material was recognized by Van Zuidam (1976) as being ubiquitous in areas with Cenozoic gyprock formations, reaching thicknesses in the order of several metres and frequently presenting vertical cracks. It also appears on soils derived from lutites, limestones and fluvial deposits where gypsum predominates (Artieda, 1993, 1996, 2004).

Arricibita *et al.* (1988) described flour-like gypsum in Gypsiorthids of Navarra with higher gypsum contents (80%) than those reported by Herrero and Porta (1987), but micromorphological features are consistent in both studies. Poch (1992) also recognized flour-like gypsum in gypsic horizons (Soil Survey Staff, 2014; WRB-FAO, 2015) in the Catalan part of the Ebro Basin, formed from gypsum precipitated at distal parts of alluvial fans, and consolidates its micromorphological description with several physical characteristics relevant to root growth.

Field characteristics

Flour-like gypsum is found in soil horizons with silty to fine-sand field textures, always carbonatic, and are located as subhorizontal layers parallel to the surface, generally with thicknesses between decimeters and 1 meter. Data of Artieda (2004) on 20 horizons reported thicknesses always less than 65cm. In general, they do not have pedogenic structure and appear as massive. They can present vertical fissures and prismatic disjunctions and are compact or very compact. Among the samples studied by Artieda (2004), 18% of them do not present coarse fragments or lithorelicts. Coarse polygenic fragments appear in 50% of the horizons, consisting of lutite fragments (23%), limestone lithorelicts (5%) and gyprock lithorelicts (4%). The moist colours of 20 horizons reported by Artieda (2004) to have mainly 10YR hues (73% of the samples) and the rest 7.5YR with 2.5 and 5YR in minor amounts**.** Values of 83% of the samples are ≥ 7 and their chromas ≤3. These colours are very pale brown to pinkish grey and white.

The values of 26 horizons having more than 60% of gypsum reported by Poch (1992), Herrero (1991) and Artieda (1993) appearto be related to the gypsum content (Figure 2), in such a way that one value unit corresponds approximately to a 15% increase of gypsum. This relation cannot be set for samples with lower gypsum contents or highly organic materials, since their values are masked by those of predominant non-gypsum components.

Analytical and micromorphological characteristics

Flour-like gypsum horizons contain high amounts of gypsum, higher than 60%; with a modal content of about 80%. They have carbonate contents around 5%, normally lower than 10%. The pHs are neutral to slightly basic, between 7.3 and 8.1. The normal trend is that higher gypsum contents correspond to more neutral pH values.

The most frequent field textures for these materials are silt loam and silt (65%). Gypsum contents higher than 85% tend to have silt, very fine and fine sandy loam textures (Figure 3). Some of the particle size analyses that have been done of these materials are displayed in Table 1. It shows predominance of fine sand to fine silt.

Micromorphologically, the groundmass of these horizons is composed almost exclusively by (very) fine sand-sized lenticular gypsum crystals; and by a crystallitic b-fabric micromass, which grades from purely microgypsic to purely micritic when gypsum is only present in the coarse elements. In the latter case a grading to fine-sandier field textures is observed, to the point that it is possible

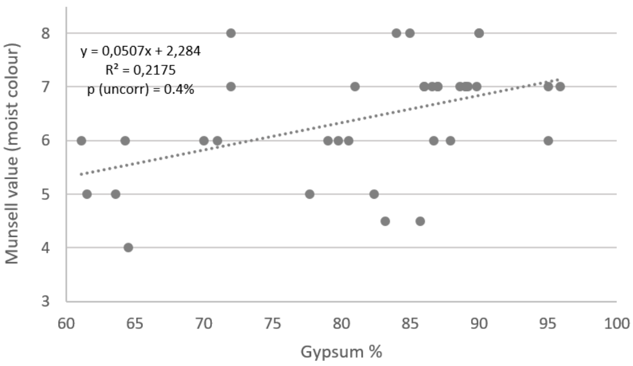

FIGURE 2. Relationship between Munsell value (moist colour) and gypsum content of 26 samples of horizons with more than 60% of gypsum in the Ebro Basin (Herrero, 1991; Poch, 1992a; Artieda, 1993).

to distinguish flour-like (siltier) from powdery (sandier) gypsum (Poch *et al.,* 2018), although they are grouped here for the sake of simplicity. The most frequent pedofeatures are gypsum infillings and coatings, gypsum nodules and intergrowths (Poch *et al.*, 2018).

Genesis of flour-like gypsum

The weathering and pedogenetic processes on pure gyprock involve repeated dissolution and reprecipitation of gypsum in situ, giving rise to a mass of silt-sized (microcrystalline) and fine-sand gypsum that have a flour-like appearance in the field in the contact area with the gyprock outcropping surface (Artieda, 1996; Herrero, 1991; Herrero *et al.,* 1992, Mandado *et al.,* 1984). A gypsification process, involving a gypsum enrichment has been proposed (Herrero *et al.,* 1992; Poch *et al.*, 2018; Stoops and Ilaiwi, 1981). They can also form by replacement of coarse-grained gypsum by fine-grained gypsum, proceeding from grain boundaries, similar to micritisation in calcrete development (Aref, 2003). Other authors agree on an in-situ formation of the flour-like gypsum from other gypsum-rich sedimentary materials, by the same process (Poch *et al.,* 2018). These soil horizons have variable thickness; and when located on slopes are subjected to slope processes including mud-flows, since they have high saturation water content and are quite permeable (Herrero *et al.*, 1992). As a result, the soils in the infilled valleys are formed by materials derived from them, together with those due to runoff.

Artieda (1993, 1996, 2004) reports on flour-like gypsum formed on different gypsum formations of the Ebro Basin appearing as continuous centimetre-thick layers interspersed with lutite layers at metric thickness levels, containing diagenetic dispersed gypsum nodules or fibrous gypsum. He describes various combinations of parent materials / landforms where flour-like gypsum is produced within the Ebro Depression, including flour-like gypsum intruding between the limestone strata, with varying content of rock fragments (Figures 4; 5), deforming the upper calcareous layers and even forming domes (Artieda, 1996, 2004).

i) Surface and/or intercalated in alluvial and colluvial detrital sediments. They are <1m thick; with gypsum and coarse elements commonly fragmented due to haloclasty. They are formed by vadose waters that are enriched in SO_4^{2-} and Ca^{2+} as they run on gyprock substrates (Artieda, 1996; type 1 of Figure 6).

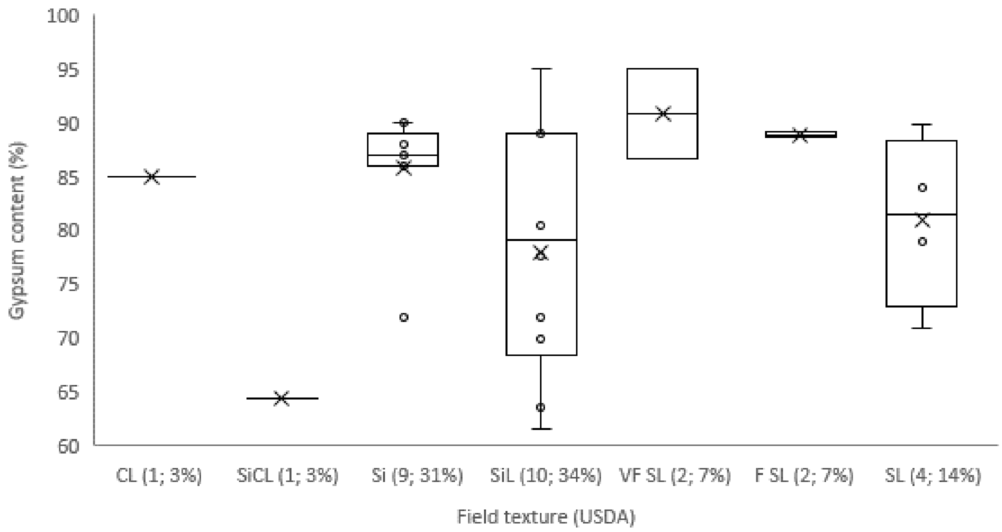

FIGURE 3. Box plot of field texture (USDA) frequency in relation to gypsum content of 29 horizons with more than 60% gypsum in the Ebro Basin (Herrero, 1991; Poch, 1992a; Artieda, 1993). Number and proportion of samples within each textural class between brackets. Crosses are the averages, boxes show the 50, 25, 75% frequency values, and the whiskers 1.5 the IQR (interquartile range). Atypical values are also shown as circles. CL: clay loam; SiCL: silty clay loam; Si: silt; SiL: silty loam; VF SL: very fine sandy loam; F SL: fine sandy loam; SL: sandy loam.

TABLE 1. Particle size distribution (USDA classification, method: Vieillefon, 1979) of some soils of the Pla d'Urgell County (East Ebro Basin), developed on distal parts of alluvial fans (Poch, 1992a)

Location and horizon	Coarse Sand (%)	Fine Sand (%)	Coarse Silt (%)	Fine Silt (%)	Clay (%)	$CaSO_4{\cdot}2H_2O$ %
Profile 1, By1		42.4		29.9	27.7	64.5
Profile 1, By2		54.1		17.7	28.2	77.7
Profile 1, Y		62.7		22.2	15.1	87.9
Profile 2, Apy		34.4		36.3	29.3	61.5
Profile 2, By		28.1		42.7	29.2	63.6
Profile 2, Y		31.5		53.5	15.0	86.6
Profile 5, Y1	1.4	38.0	23.9	32.6	4.1	80.5
Profile 5, Y2	1.6	44.2	22.0	22.0	3.7	88.6
Profile 5, Y3	6.4	41.5	22.8	23.7	4.5	89.2
Profile 5, Y4	9.5	41.9	30.3	11.4	6.1	89.8
Profile 8, Y1	3.1	36.3	27.4	27.0	6.2	86.7

ii) On the surface of limestones, sand and/or lutitic rocks, at water divides and summits. They are stony, shallow (<0.5m) and frequently have a dome morphology (Figure 4), with lateral extensions from metres to decametres at most. They occur intercalated in limestones, sandstones and lutites, on summits and / or slopes. These flour-like gypsum generate deformations such as folds, joint fillings and fractures in consolidated rocks. Wedge-shaped antiforms called *ensaimadas* by Artieda (1993, 1996) frequently appear at the edges of scarps of structural platforms and mesas (Figure 4; Type 2 of Figure 6).

iii) On the surface of gyprock at water divides, summits and / or gentle slopes. They are shallow

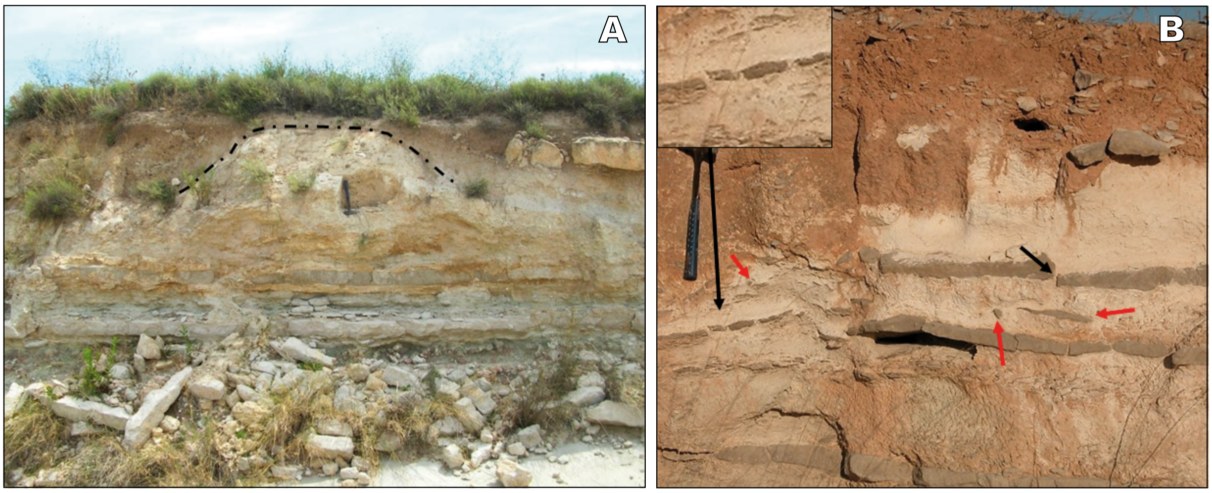

FIGURE 4. A) Gypsum dome formed between limestone strata. Note the deformation of the latter due to changes in volume caused by repeated cycles of dissolution-precipitation of gypsum. Sierra de Mequinenza, between Mequinenza and Caspe (Author: R. Rodríguez-Ochoa). B) Flour-like gypsum intercalated in continental (lake) limestone, located in the Quinto. The red arrows point to limestone fragments within the flour-like gypsum; the black arrows point to flour-like gypsum filled joints (upper square shows detail) (Author: O. Artieda).

FIGURE 5. Flour-like gypsum (salmon colour [F]) intercalated in continental (lake) limestone [L] and lutites, located in the Sierra de Mequinenza, between Mequinenza and Caspe (Authors: R. Rodríguez-Ochoa).

(<50cm) and quite continuous in the landscape. The slope aspect of flour-like gypsum outcrops does not relate neither to any preferential wind direction (Types 3, 4 and 5; Figure 6).

iv) On slopes on limestones, sandstones, gypsum, lutites and/or colluvia. Flour-like gypsum appears discontinuously on various combinations of continental tertiary rocks, extending horizontally from metres to decametres, and with thicknesses <1m. They appear on slopes often steeper than 20-30% and may be covered by colluvia or mud flows. The steepness of the slopes prevents the presence of stable wind deposits (Types 6 and 7; Figure 6).

v) On different types of sediments: in valley bottoms (infilled valleys, alluvial fans). They have either alluvial and colluvial origins (Artieda, 2004); or in the case of Quaternary gypsum-rich sediments such as those precipitating at the shore of sabkhas or distal parts of alluvial fans, gypsum-saturated waters can also be the starting point for the formation of these horizons (Herrero *et al.*, 1996; Poch, 1992). In some cases, the original layering of detrital material/ precipitating gypsum can still be seen (Poch, 1992; Figure 7; Type 8; Figure 6)

LOESSIC SILTS AND SANDS WITH GYPSUM IN THE EBRO BASIN

According to Pye (1995) loess is "a terrestrial clastic sediment, predominantly composed of silt-size particles and formed essentially by the accumulation of dust supplied by the wind". Pécsi (1990) defined "typical" loess as a loose, non-stratified, porous and permeable deposit, predominantly formed by coarse silt that is stable on vertical walls and is easily erodible by water.

In the Ebro Basin, loess is a silty material with a predominance of siliciclastic-carbonatic components, with or without gypsum, always as a very minor component and reported sometimes as gypsiferous loess (Iriondo and Kröhling, 2004, 2007; Luzón *et al.*, 2012).

The first comprehensive study on loess sequences in the lower Ebro Basin (Boixadera *et al.*, 2015) indicated that they consist of highly sorted fine sands and silts, 1 to 12m thick (though most typically 3-4m thick), and coarser than typical loess. They are highly uniform, lack any sedimentary structures and are pale ochre in colour. The deposits are calcareous (30-45% $CaCO_3$) and contain gypsum in minor amounts, normally less than 5% and in a few cases reaching 30%. Their composition is coherent with windward source areas close to the studied loess deposits, some of them containing gypsum in varying proportions (average around

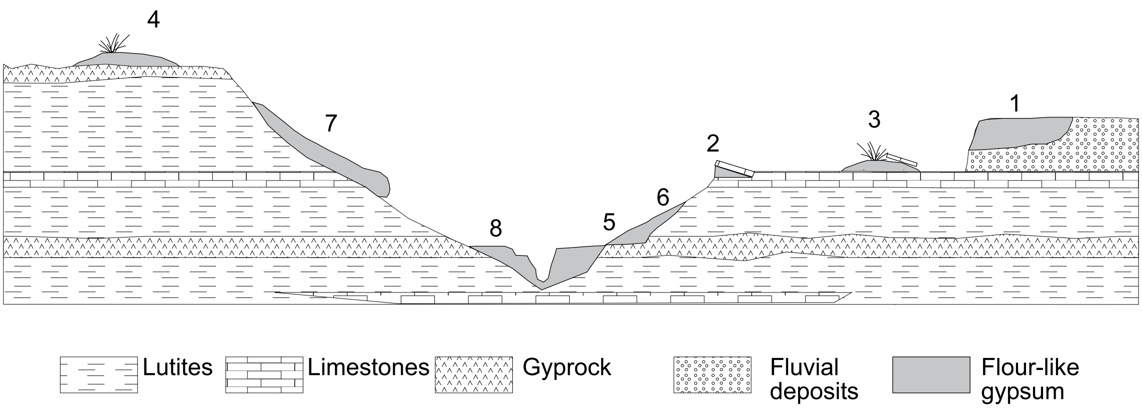

FIGURE 6. Occurrence of flour-like gypsum after Artieda (1996): 1) Intercalated or overlying primary or reworked fluvial gravels; 2) Domes (ensaimadas) between limestone strata; 3, 4) On somital positions; 5) On gyprock; 6) Slope deposits; 7) Mudflows; 8) Valley infillings.

3%, maximum up to 30%, Boixadera *et al.,* 2015). Due to their proximal origin, they are noticeably coarser than others described in the Western Mediterranean (Schaetzl *et al.*, 2018).

Subsequent surveys suggest that the loess covers are much more extensive than previously though (Plata *et al.,* 2019; Rodríguez-Ochoa *et al.*, 2017). At the westernmost part of the Ebro Basin, loessic materials have also been identified in the Ribera Navarra and the Lower Rioja (unpublished data). They are deposits with thicknesses from 2 to 8m, discontinuously covering the uplands near the Ebro River, in the Ribera Navarra and the Rioja Baja. They are frequent in Lodosa and Cárcar (Navarra) and Pradejón (La Rioja), on terraces of the Ebro river (T3 and T2), of the Cidacos river (T2), of the Ega river (T2), as well as on colluvial glacis and slope deposits. They overlie Cenozoic gypsiferous formations on smooth water divides at Lerín. They are very pale brown (7.5YR 7/4), massive deposits, mainly composed of coarse silt and very fine sand, with frequent vertical prismatic disjunction and without sedimentary structures. In some cases, $CaCO_3$ nodules appear and gypsum accumulations are frequent, although in most observations on the right bank there are no gypsum accumulations.

The area with loess outcrops of Lower Aragón-Caspe, Matarraña and some spots in Terra Alta (Catalonia) covers about 1900km^2 and is discontinuously covered by fine sandy loess on leeward positions. Some of their characteristics are shown in Table 2. The modal thickness of the deposits is between 3 and 4m, but some outcrops reach 10m (Rodríguez-Ochoa *et al.*, 2017). They are loose deposits, 10YR 5/6 in colour, but also 10YR 4/6 and 7.5YR 4/6. Almost all the studied outcrops present gypsum accumulations as vermiform gypsum and hard gypsum rhizocretions. The most common particle sizes are very fine sand (50 to 100µm; 32±11%), coarse silt (20-50µm, 20±8 %), fine silt (2-20µm; 17±7%) and clay (<2µm; 18±4%); which allow them to be classified as sandy loess (Coudé-Gaussen, 1990), similar to the loess appearing in the Tajo area (García Giménez *et al.*, 2012). The average gypsum content (61 samples) is 3.1% (0 to 19.2%) (Rodríguez-Ochoa *et al.,* 2017).

Other areas where they appear in very small outcrops (or spots) are the Lower Cinca area, Middle Ebro, Ebro high terraces (Luzón *et al.,* 2012) and Segre Valley (Boixadera *et al.*, 2015).

FIXING THE DEFINITION OF "GYPSIFEROUS SILTS"

Given the scarcity of detailed macromorphological and analytical data of these materials, as well as the confusion on their origin, we selected 81 samples of gypsum-containing non-consolidated materials from the Ebro Basin, from clearly non-aeolian, non-in situ weathered from Llamas (1962) and Artieda (2004). Eight samples out of the eleven reported by Llamas (1962) are considered. They have an average of 40.4% sand (2.0-0.6mm), predominance of silt over the clays (most likely it is a medium loam texture) and gypsum contents in the fraction <0.2mm between 8.3 and 3.3%, with an average value of 5.5%. Calcium carbonate was not measured but all the samples had abundant and persistent bubbling to the acid, which indicates contents close to or higher than 15-20% (Llamas, 1962). Artieda (2004) reported on the characteristics of the soils of the infilled valleys with a colluvial-alluvial dynamics. He classified them according to the rock formations where they are developed. A summary of their characteristics is presented in Table 3.

FIGURE 7. Flour-like gypsum formed by progressive precipitation of gypsum (gypsification) in the alluvial fan of the Ondara river (East of Lleida). Note the process of karstification due to its high solubility of gypsum. Length of the rule: 2m (Author: R.M. Poch).

These materials have very variable field textures, with a tendency to be sandier in areas with gyprock geological formations, and finer in lutite and limestone areas. It is possible that the reported earlier literature on "gypsiferous silts" are naming clay, sandy loam and loam textures as "silt" texture, *sensu lato*. Their colours are variable and cannot be set as a characteristic of these materials, since they are conditioned by the corresponding local geological materials. Indeed, changes in the chromatism of sedimentary fills (Figure 8) are frequently observed when passing from one lithological formation to another (Artieda, 2004). The proportions of gypsum show a high variability both within each type of sediment of the infilled valleys and also between their parent materials, which results in a lack of significant differences between types. The average gypsum content of these materials is 18.4%.

DISCUSSION

Exclusion of the aeolian origin for most of the reported "gypsiferous silts"

The genesis of "gypsiferous silts" according to Torras and Riba (1967/1968) and Torras (1974) was based on the water and wind transport of weathered materials from gyprock. They indicated the existence of gypsum silts in the infillings of flat valleys, but they are often filled with sedimentary materials lacking the characteristics of gypsum silts (Artieda, 2004). In turn, Van Zuidam (1976) considered water erosion of gypsiferous materials as the main source for these sediments, without excluding an aeolian origin in a few cases. Again, we must indicate that the aeolian genesis of silt and gypsum was based on sedimentological analyses based on grain size data; but it is conditioned by the sizes of the gypsum crystals, *i.e.* their crystallization sizes and not those of the original sediment and by the difficulties to determine their content. (Herrero, 1991; Artieda, 1993, 1996).

With some exceptions, such as certain loess in the Rhine Valley (Bronger and Hädrich, 1969), in the Czech Republic (Cilek, 2001), Ukraine (Veklitch, 1969), Russia (Khokhlova *et al.*, 2001), and other loess areas in Iberia (Boixadera *et al.*, 2015; García-Giménez *et al.,* 2012), gypsum is a rare component in typical loessic materials (Mestdagh *et al.*, 1999). In the case of the Ebro Basin it is present near the areas of exposed gypsum outcrops but absent in more external areas such as the Móra Basin. It may reach to 28% gypsum in some areas but is mainly absent in others. It is very noticeable that it appears as large crystals and gypsum roses; it is never similar to flour-like gypsum. In any case, absence or presence of gypsum in loess may be an important indicator of specific sources.

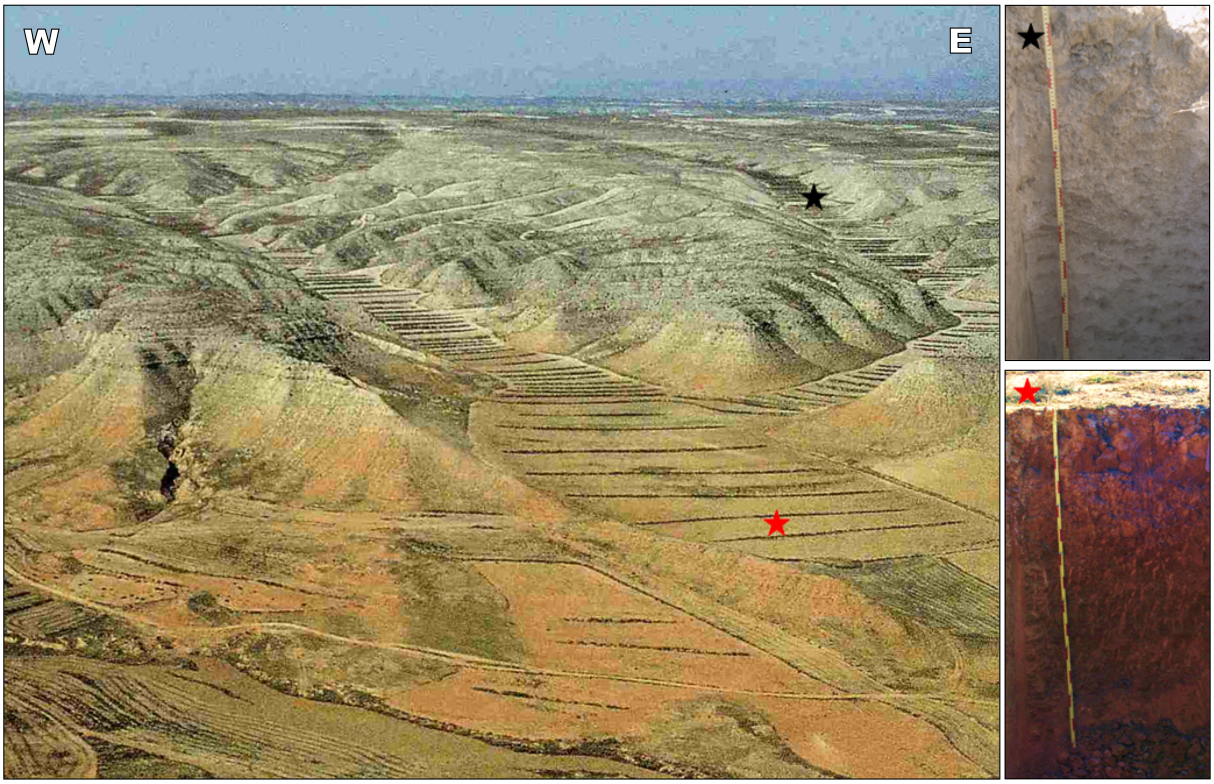

FIGURE 8. Aerial view of the SE side of La Lomaza de Belchite (Figure 1). Different colours of the valley infillings when they cross different lithologies, from whitish (hue 10 YR, values 5 and 6, chroma 3) to reddish (hue 7.5 YR and 5 YR hues, values 4 and 5, chromas 4, 6 and 8) when they cross gyprock and red lutites respectively (moist colours in the first meter). Length of the rules: 2m upper profile, 2.5m lower profile (Author: O. Artieda).

TABLE 2. Particle size distribution (USDA classification, method: Vieillefon, 1979) of some soils of the Pla d'Urgell County (East Ebro Basin), developed on distal parts of alluvial fans (Poch, 1992a)

Reference	Location	Very coarse sand % 1-2mm	Coarse Sand % 0.5-1mm	Medium Sand % 0.25-0.5mm	Fine Sand % 100-250µm	Very Fine Sand % 50-100µm	Coarse Silt % 20-50µm	Fine Silt % 2-20µm	Clay % <2µm	$CaCO_3$%	$CaSO_4 \cdot 2H_2O$ %	Munsell colour (moist)	Organic Matter (%)
Hué and Llamas 1961, canal*	Km 50			26.9			73.1		0	-	4.6	-	-
Boixadera *et al*., 2015	Almenara, Bwy3	0.1	0.2	0.6	4.6	34.0	28.7	16.9	14.9	35	2.9	10 YR 6.5/6	0.07
Rodríguez-Ochoa *et al*., 2017	Lower Aragon, av 61 samples	0.4	0.6	2.1	9.7	32	20	17.5	17.7	40.5	3.1	10YR 5/6	0.36
Own data	Navarra-La Rioja	0.1	0.4	1.7	5.4	39.7	19.9	12.4	20.4	28.1	6.4	7.5YR 5/6	0.1

*gypsum originally reported as $CaSO_4$-sulphates, limit between sand and silt at 60µm

Exclusion of the aeolian origin for the flour-like gypsum

Assuming that the silty gypsum materials derived from gyprock weathering were the origin of gypsiferous aeolian silts, they would contain high amounts of gypsum, their colours would be conditioned by this composition with very high values (7 to 9), and low chromas (less than 4). Moreover, an aeolian genesis would imply very variable thicknesses –an inherent characteristic of loess- but frequently thicker than 2m, and they would be absent or very scarce in many areas, such as on high or windward slopes, similar to the identified true loess. Their location would not be restricted to rock gypsum outcrops but would be more or less continuously extended over the other nearby gypsum-free geological formations located leeward of the former. All these characteristics are not fulfilled by flour-like gypsum.

Mandado *et al.* (1984), Herrero (1991) and Artieda (2004) indicated that the formation of flour-like gypsum is associated with subaerial exposure of gyprock and subsequent weathering. These accumulations are also produced by processes of water capillary rise and evapoconcentration (Artieda, 1996; Poch *et al.*, 1998), a common process for the formation of hypergypsic horizons *e.g.* in Syria (Ilaiwi, 1983); or in Russia and Central Asia (Yamnova and Pankova, 2013). When the characteristics of the soils in relation to the geological materials and relief units are combined on a detailed scale, these hypotheses are consistent with the observations and, as a consequence, their aeolian origin is excluded.

Primary loess deposits are normally located on hilltops or leeward from the direction of the wind (usually NW in the Ebro Basin). Flour-like horizons derived from weathering of gyprock are normally continuous in gyprock landscapes, following the relief. The latter have associated surface features as mud flows or domes, and some of them are found between limestone strata (Figures 4; 5). These characteristics completely exclude an aeolian origin.

Artieda (1993, 1996) outlined the possible formation processes indicated above and also exclude a wind explanation except when they appear in summit positions on any geological material. In particular, he noted that it is unlikely to consider flour-like gypsum as aeolian when

TABLE 3. Properties of gypsiferous silts reported by Llamas (1962) and soil materials with varying gypsum contents in infilled valley bottoms by Artieda (2004)

Samples n=84	Colour (moist) (Munsell)	Texture	Coarse fragments	Gypsum % interval (modal range)	$CaCO_3$ % interval (modal range)
Llamas (1962); n=8		Medium		5,5±2,0	≥15-20
Infilled valleys on limestone formations (Artieda, 2004) ; n=17	5YR 4-6/3-8	moderately fine and fine*	angular limestone and gypsum clasts	0-77 (17.8 ± 20.2)	15.1 - 46.3 (36.0 ± 14.1)
Infilled valleys on gypsum formations (Artieda, 2004); n=22	7.5-10YR 5-7/3-6	moderately coarse, medium, and coarse*	frequent gravels, gypsum and lutites	15 - > 80 (19.3 ± 20.7)	17 - 45
Infilled valleys on lutite formations (Artieda, 2004); n=22	5YR 4-6/3-8	moderately fine and fine*	angular limestone and gypsum clasts	0 - >58 (14.8 ± 21.8)	16.4 - >45 (32.3 ± 6.2)
Inifilled valleys on river terraces (Artieda, 2004); n=15	5-7.5YR 4-5/6-8	medium and fine*	few clasts	0 - >90 (22.1 ± 19.5)	10 – 47 (30.7 ± 21.2)

* Field texture

it appears as shallow, continuous deposits (to hectometric extensions), with common lithorelicts and coarse elements, and with higher gypsum and less carbonate contents than the supposed aeolian "gypsiferous silts".

Torras and Riba (1967/1968) proposed an aeolian source for gypsum silts (flour-like gypsum) using sedimentological techniques for their study; but they did not take into account the repeated processes of dissolution and recrystallization of gypsum observed later by soil micromorphologists. Indeed, the lenticular gypsum crystals are commonly found in soils and in subaqueous conditions by recrystallization from a gypsum-saturated soil solution or groundwater (Mees *et al.,* 2012) and do not result from wind sedimentation. True aeolian gypsum particles, as they are found in gypsum dunes (as the White Sands in New Mexico) behave as clasts and become more equant and rounded (Poch *et al.*, 2018).

Distinction between reported "gypsiferous silts" and flour-like gypsum

"Flour-like gypsum" differs from the "gypsiferous silts" *sensu stricto* regarding gypsum content (predominant in the former), origin (in situ in the former, detrital in the latter) and degree of sorting (lower in the latter). The predominant position of "gypsiferous silts" is infilled, flat valleys formed on materials of different nature, in contrast with the more continuous distribution of the flour-like gypsum on gypsum rock or gypsum-rich materials and which indicates different formation processes. Regarding flour-like gypsum, Artieda (2004) proposed the following processes, or a combination thereof: gyprock disgregation, subsequent transport of detritus (hydric, aeolian or gravitational), followed by in situ dissolution-precipitation processes and/or gyprock dissolution and subsequent gypsum precipitation, either in situ, in detrital materials or between strata.

On the presence of gypsum in some aeolian materials in the Ebro Basin

Although it is evident that material blown by winds (mainly "Cierzo") in the Ebro basin carries gypsum particles -some of them coming from weathered gyprocks or gypsum-rich materials- they are never found as original (primary) coarse fragments in the loess. Due to the high solubility of gypsum, it starts to undergo dissolution-reprecipitation processes and is mobilized through the loess profiles shortly after it is deposited, where it appears as pedofeatures (Boixadera *et al.,* 2015). A different case would be the formation of gypsum dunes in more arid –desert- environments, where a continuous dry climate prevents gypsum to dissolve, and thus gypsum particles behave as coarse fragments; which is not the case in the Ebro Basin.

Old aeolian deposits (Pleistocene) alternating with fluvial deposits formations have been recognized and preserved as a consequence of collapse due to karstification of the evaporite substrate in the Ebro Basin (Gil *et al.*, 2013; Luzón *et al.*, 2012). Other more recent (estimated Holocene) landforms related to wind activity have been recognized (Cuchí *et al.*, 2012; Desir *et al.*, 2011; Gutiérrez *et al.*, 2002; Sancho and Belmonte, 2000) and its present-day functionality has been proposed by Artieda and Herrero (1997) after observing the formation of nebkhas in Zaragoza region after a period of very strong winds. The micromorphology of these deposits showed a single-grain microstructure, made of lenticular (100-1000µm) and microcrystalline (<50µm) gypsum (gypsum lenses are oriented parallel to the surface), together with calcareous and siliciclastic silts.

PROPOSAL OF DIAGNOSTIC CRITERIA FOR GYPSUM-CONTAINING SILT-SIZED DEPOSITS IN THE EBRO BASIN

Gypsum content and field characteristics

The most important common characteristic shared by these materials is indeed their texture. Figure 9 shows the accumulative particle size distribution of typical surface materials in the Ebro Basin as described by Van Zuidam (1976) together with some loess and flour-like gypsum data from this work. Figure 9 shows the similarities of loess, materials formed by weathering of gyprock (flour-like gypsum) and "gypsiferous silts", and the low clay content of all materials (less than 12%) is noticeable. Apart of this, the amount of gypsum is perhaps the most important characteristic to distinguish these materials: in the case of loess the reported gypsum contents are seldom above 10%; flour-like gypsum have more than 60% (hypergypsic horizons (Soil Survey Staff, 2014)); and "gypsiferous silts" *sensu stricto* have intermediate gypsum contents, around 20%.

Micromorphology

Figure 10 shows the main differences of the fabric of these materials. Gypsum in loess appears as crystalline pedofeatures in a groundmass with a calcitic-crystallitic b-fabric (Stoops, 2003). It occurs more often as loose continuous and discontinuous gypsum infillings in pores (vermiform gypsum) and less commonly as gypsum crystals and gypsum intergrowths (gypsum roses) up to centimetric sizes. The internal fabric may be idiotopic (loose lenticular grains) but also hypidiotopic or xenotopic, as the result of the growth of gypsum from a gypsum-saturated solution in a confined pore space (Boixadera *et al.,* 2015). More seldom, gypsum rhizoliths have been observed (Poch *et al.*, 2018).

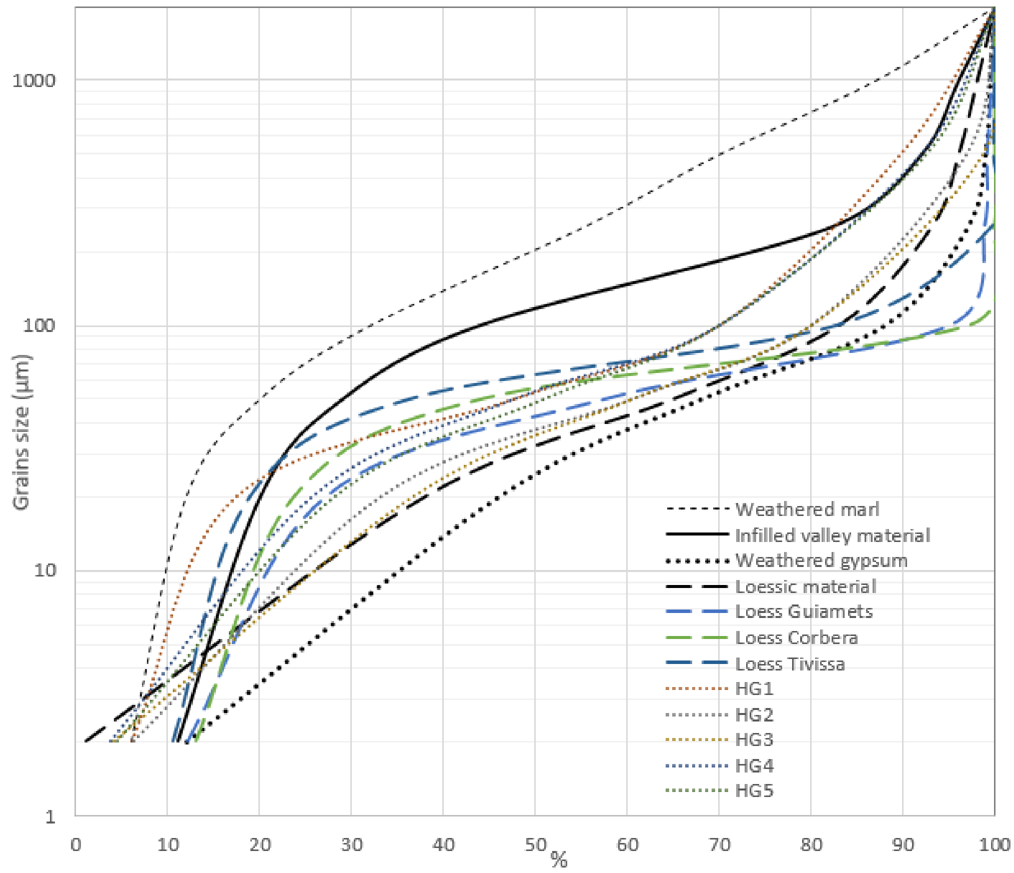

FIGURE 9. Grain size analyses of representative samples of weathered marl, weathered gypsum, infilled valley material in a gypsiferous marly area, and loessic material (redrawn from Van Zuidam, 1976, black lines); and from loess and hypergypsic (HG) horizons taken from this word.

On the contrary, flour-like or powdery gypsum from weathering of gypsum-rich materials or by direct precipitation from groundwater saturated with calcium and sulphates consists of a groundmass made of lenticular gypsum, of fine sand to coarse silt size, with little micromass made of a mixture of micrite and microcrystalline gypsum. Gypsum pedofeatures such as nodules or infillings are also commonly seen (Herrero *et al.,* 1992, 1996).

Geotechnical characteristics

Faraco (1975) distinguished weathering materials derived from gyprock (white powdery gypsum) from the "gypsiferous silts" (sic), as colluvium or loess, with different geotechnical problems as hydroconsolidation, piping and slope instability when moist.

Numerous references report on the structural collapse leading to hydroconsolidation and subsidence occurring in loess around the world, under the combined effects of loading and wetting (Assallay *et al.*, 1997). Wind deposition originates a loose, porous and metastable honeycomb structure, composed of quartz particles together with clay aggregates and carbonate grains. While this structure is rather strong when dry, it collapses upon saturation (hydrocollapse) bringing about a particle rearrangement into a denser structure and therefore a reduction of volume. This resulting material is still considered to be unstable because of the potential for differential settlements, which can damage structures built on loess (Miller *et al.*, 1998). Laboratory geotechnical tests show that, upon moistening, the effective apparent cohesion gradually increases and the effective internal friction angle decreases, until a moisture threshold is reached, beyond which the effective cohesion decreases rapidly and the effective internal friction angle stabilises at a residual value (Dijkstra *et al.*, 1994). These resulting materials have low plasticity indices and maintain a high porosity. Additional components, such as the presence of clay in the intergrain spaces, increases the volume change upon drying; while the effect of carbonate particles depend on whether they act as individual particles –as those of quartz- or as cement between the quartz grains (Delage *et al.,* 2008).

Silty materials with high gypsum contents (without indicating the origin) are reported to have very low densities

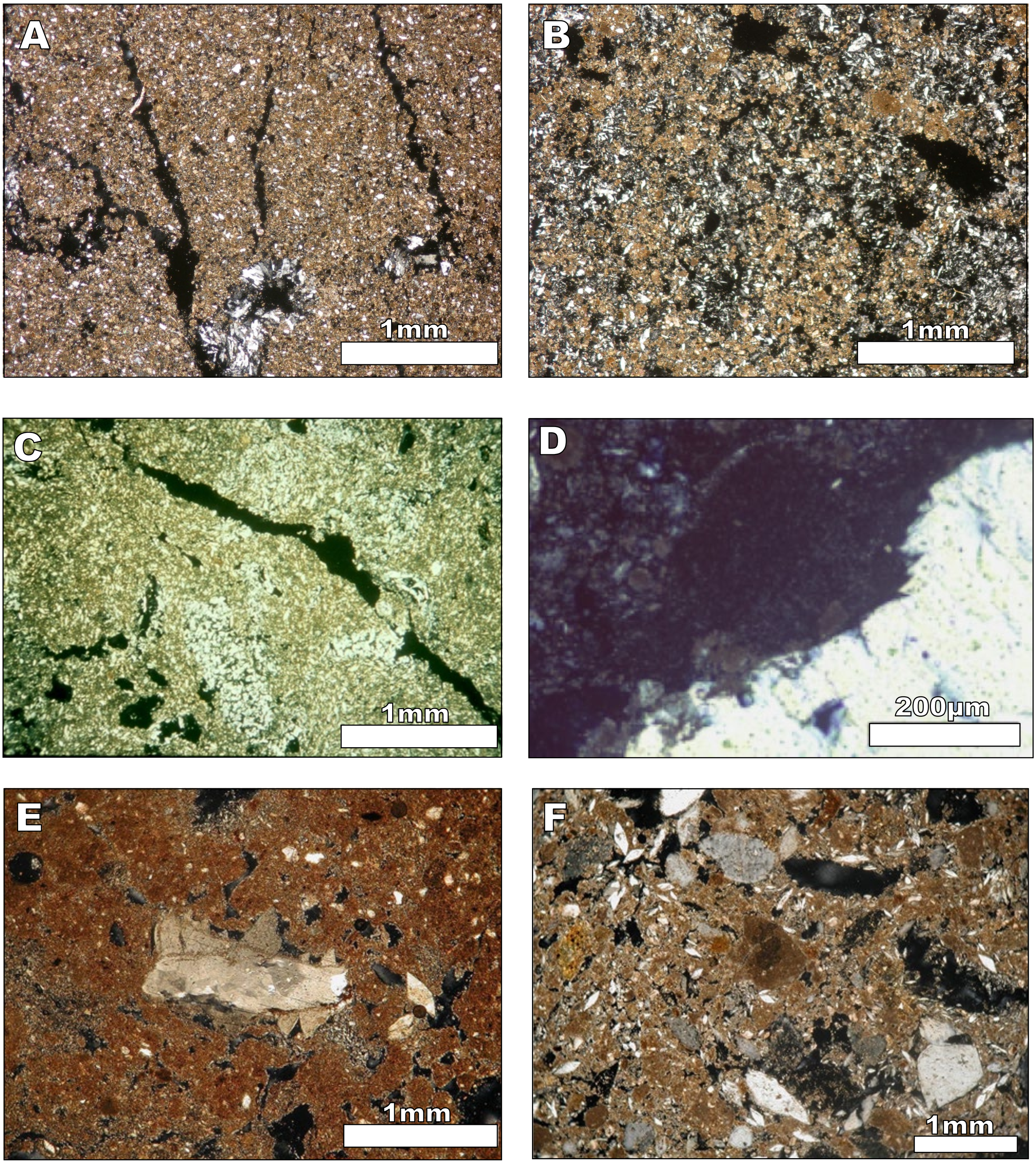

FIGURE 10. Fabric of the end-components of silt-sized, gypsum-containing materials in the Ebro Basin. A, B) Loess with secondary gypsum accumulations Batea profile, Bwy horizon (Boixadera *et al.*, 2015). C) Hypergypsic lenticular horizon formed on gypsum precipitated at distal parts of alluvial fans (Pla d'Urgell). D) Hypergypsic microcrystalline horizon formed on gyprock. The image displays the contact between microcrystalline gypsum (microgypsic microcrystalline b-fabric) and gyprock (Artieda, 2004). E) Silicatic groundmass with gypsum intergrowths corresponding to the silt loam field texture (upper meter) of a valley infilling developed on gyprock. F) Silicatic groundmass with abundant gypsum intergrowths corresponding to the sandy loam field texture located underneath (130cm deep) of the material described by Artieda (2004). All pictures correspond to Cross Polarized Light (XPL).

(1200-1300Mg/m^3) with high susceptibility to collapse when flooded (up to 30% in volume), which is attributed to the dissolution of sulphates (Oteo, 2011). Al-Dabbas *et al.* (2012) reported higher collapse potential, porosity, cohesion and grain sorting on soil samples from Iraq when they contain more than 25% gypsum, among other geotechnical properties. Regarding cohesion, hardening of hypergypsic horizons when drying has been explained by Poch and Verplancke (1997) as due to increase of effective stress caused only by water loss, without any intervention of any additional process as cementation.

The main engineering limitations of highly gypsiferous soils are iron corrosion, sinkholes and subsidence by karstification (Gutiérrez *et al.*, 1985; Gutiérrez, 1996; Herrero and Boixadera, 2002), subsurface mechanical erosion (piping) with subsequent collapse (Benito *et al.*, 1995), as well as the reaction of sulphate derived from gypsum and other building materials (Charola *et al.*, 2007). Gypsum in concrete forms ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}·26H_2O$)] (Shanahan and Zayed, 2007), but if the carbonate ion is present, thaumasite [$Ca_3Si(CO_3)(SO_4)(OH)_6·12(H_2O)$] will form (Crammond, 2002). The crystallization pressure of gypsum is of the order of 300atm (Winkler and Singer, 1972). All these mineral phases produce a strong expansion, which result in concrete decay and causes the collapse of the structures.

Land use constraints

Soils with gypsum present several constraints for agricultural use when gypsum content exceeds some threshold values. In general, when gypsum is less than 10-15% its main effect in soils is the saturation of the exchange complex with Ca^{2+} and the electrical conductivity of the soil solution (at any soil:water ratio) around 2.3dS/m at 25ºC. These characteristics are beneficial for agronomic purposes because the presence of gypsum in soil will buffer any process of sodification and of clay dispersion due to the constant supply of Ca^{2+} into the soil solution. This effect is used when applying gypsum as liming amendment to avoid acidification; or as amendment in sodic soils to improve their physical characteristics (clay flocculation).

When soils contain more than 30% gypsum, it has stronger implications for physical and chemical properties relevant for agronomic purposes (Casby-Horton *et al.*, 2015). A positive relationship between gypsum content and penetration resistance was demonstrated by Poch and Verplancke (1997), due to progressive clogging of pores by gypsum crystals, although they do not substantially affect soil hydraulic conductivity, also stated by Greyling and Van Rooy (2019). Roots have difficulties penetrating these highly irregular pores due to the lack of continuous and regular pore diameters (Poch *et al.*, 1998). Due to the soluble nature of gypsum, karstification is a common phenomenon: surface collapses and dissolution features along cracks are very frequent, which makes the irrigation of these soils very difficult because it obliges repeated levelling works. The low internal cohesion of the gypsum sands and silts make these materials very prone to water erosion and mass movements when they are on slopes (Food and Agriculture Organization, 1990). Water holding capacity is also determined by the texture resulting from the size distribution of the gypsum crystals: when they are coarser (sandier) the available water capacity is low, whereas it is higher in microcrystalline gypsum horizons (silt size).

Regarding chemical properties, the higher the gypsum content, the lower the silicate mineral content and therefore the material contains fewer clays and exchange complexes. Hypergypsic materials have a very low cation exchange capacity, and therefore no possibility to store nutrients as adsorbed cations. Moreover, the overwhelming proportions of calcium and sulphates in the soil solution interact with some micronutrients, hindering their absorption by plants, as molibdenum (as MoO_4^{2-}) or boron (B^{2+}).

Likewise, phosphorous is immobilized in these soils as hydroxyapatite (calcium phosphate) (FAO, 1990).

In relation to the agronomic properties of soils on loess, they are believed to be the parent materials of many of the mollisol / chernozem belts in Russia, US, China, or Argentinian Pampa, with favourable agronomic qualities as lack of stones, considerable rooting depth, high water holding capacity, good drainage and high nutrient content (eutrophic) when they are calcareous. When devoid of vegetation they are prone to sealing and crusting due to the high silt content; as well as to water and wind erosion (IUSS Working Group WRB, 2015).

Summary of characteristics

A summary of the proposed diagnostic characteristics of the materials is presented in Table 4. Intermediate cases could also exist: soils on valley bottoms may have materials with different origins: colluvial (mass movements), alluvial or even aeolian; and either primary or secondary, for example reworked aeolian materials from upslope. In these cases, the parent material is a mixture of pedosediments from gyprock and loess itself. Regardless of the formation processes, it is possible to make a first approximation of the type of materials taking only into account the degree of sorting and the gypsum content, according to Figure 11.

CONCLUSIONS

The original term “gypsiferous silts”, initially used to identify materials in the Ebro Basin in older references,

TABLE 4. Criteria to differentiate surface silt-sized materials containing gypsum in the Ebro Basin

	Loess	Hypergypsic Flour-like gypsum	Gypsiferous silts
Field occurrence	Mostly on leeward areas and hilltops, structural platforms, glacis or terraces. No relation with the underlying material (geological unconformity).	Parallel to the surface (as they are soil horizons), on gyprock or precipitated from gypsum-saturated watertables; on any slope aspect. Special microreliefs due to changes in volume caused by haloturbation and repeated cycles of gypsum precipitation.	Parallel or subparallel to the surface, on gypsum-rich materials; On any slope aspect. Location on slopes, flat infilled bottom valleys, alluvial fans.
Thickness of the deposit	2 - 8m, Maximum 12m	<1m	Very variable, from less than 1m to more than 5m.
Structure	Massive, not stratified nor cemented.	Massive, no sedimentary structures	With sedimentary structures (bedding)
Vertical fissures	Frequent	Occasional, mostly when intercalated between limestone strata or in fluvial deposits.	Frequent
Coarse elements and lithorelicts	Primary loess: neither clasts nor lithorelicts.	Frequent clasts or lithorelicts.	Very variable: none to 40% clasts and lithorelicts
Colour moist	10YR 5/4 most typical Hues: 10YR and 7.5YR Values: 5 to 6 Chromas: 4 to 6	10YR 7/3 most typical Hues: 10YR and 7.5YR Values: 7 to 9 Chromas: 2 to 3	Very variable, depending on the host materials Hues: 10YR, 7.5YR and 5YR Values: 4 to 6 Chromas: 3 to 8
Gypsum content	Normally less than 5%, few cases reaching 30%.	≥60%. Most typical, 70-90%	Very variable: none to 90%, most typical, 5-35%
$CaCO_3$ content	Known range: 18-54% Most frequent: 30-40%	Known range: <10%. Most frequent: 5-7%	Known range: 15 a 56% Most frequent: 23-40%
Sorting	High	High	Medium-low
Micromorphology	Calcareous groundmass, crystallitic-micritic b-fabric; gypsum absent or appears as crystallitic pedofeatures.	Lenticular gypsum crystals as main coarse fraction; crystallitic-micritic or crystallitic microgypsic b-fabric.	Very variable, gypsum pedofeatures (infillings, nodules, coatings) and gypsum lithorelicts.
Geotechnical behaviour	Hydroconsolidation, collapse when saturated and subsidence.	Karstification, piping, corrosion of concrete and steel. Mud flows on slopes.	Karstification, piping, corrosion of concrete and steel.
Land use conditions	Deep soils with moderately good agronomic qualities (high AWC, lack of stoniness, well drained); prone to erosion when bare.	Hard when dry, low chemical fertility.	Variable depending on gypsum content.

has proved completely insufficient for geomorphological and pedological interpretations, as well as for soil and geological mapping.

These three types of materials (loess, flour-like gypsum and "gypsiferous silts" *sensu stricto)* have their silty texture and varying amounts of gypsum in common. Nevertheless, they may be clearly differentiated by their origin (aeolian/ in situ by gyprock weathering or precipitation from waters saturated with calcium and sulphates/ mainly colluvial), by their gypsum content (low/ very high/ medium to variable), by their particle sorting (high/high – low/medium) as well as by their position in the landscape and by their geotechnical and agronomic characteristics.

The proposed criteria easily distinguishes between the silty deposits with an aeolian origin (loess) and those derived from an in-situ weathering of gyprock or direct precipitation from waters saturated with calcium and sulphates (flour-like). With this distinction we propose to narrow the application of the term "gypsiferous silts" to silty deposits that do not fulfill the conditions of "loess" or "flour-like", and which are mainly more heterogeneous alluvial or colluvial deposits with varying contents of gypsum. This distinction will help to understand the gypsum-bearing non-consolidated surface formations in the Ebro Basin and other similar materials in dry regions, and therefore improve their geological, geomorphological and soil mapping, as well as their interpretation for land use planning.

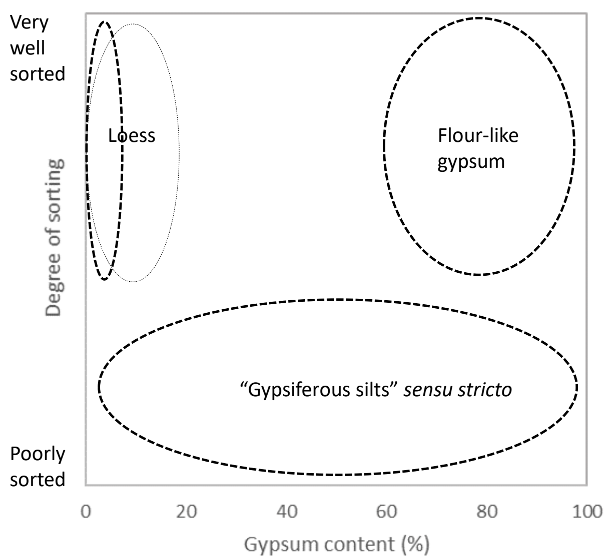

FIGURE 11. Distinction between the three gypsum-containing materials with silty-fine sandy textures in the Ebro Basin based on gypsum content and degree of particle sorting. Gypsum contents in loess do not normally exceed 6% (narrower ellipse), but some exceptions with higher amounts can be found (wider ellipse).

ACKNOWLEDGMENTS

This work has been done in the frame of the Project LOESSIBERUS, RTI2018-094927-B-I00, Ministerio de Ciencia, Innovación y Universidades, Spain. We thank Dr. G. Benito, C. Arenas and an anonymous referee for their constructive comments when revising the manuscript, and Dr. Michele Francis (U. Stellenbosch) for her careful language revision.

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Manuscript received December 2020;
revision accepted May 2021;
published Online June 2021.