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Soil catena along gypseous woodland in the middle Ebro Basin: soil properties and micromorphology relationships

Propiedades del suelo y relaciones micromorfológicas de suelos yesosos forestales en el Valle medio del Ebro
Propriedades do solo e relações micromorfológicas dos solos florestais gessosos no Vale do Ebro

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ABSTRACT

Gypsisols, mainly distributed in arid lands, support a key economic activity and have attracted a lot of scientific interest due to their particular physical and chemical properties. For example, Gypsisols show a high erodibility, low fertility and a variable water holding capacity that can be attributed to different gypsum particle sizes. This study aims to describe some representative Gypsisols from the middle Ebro Basin. Five representative soil profiles (mainly Gypsisols by WRB) were selected and sampled at different positions along a hillside where soils where developed on gyprock. Furthemore, it links micromorphological properties with soil water retention. Soils have a dominant loamy texture, more rarely stoney. Gypsum is abundant in all soil profiles, ranging from 6 to 84% with minimum values in Ah horizons and maximum in By and Cy. The soils have a low level of salinity and a very low cation exchange capacity (CEC). The soil organic matter (SOM) is medium or abundant in the Ah horizons, otherwise it is low. Soil aggregate stability (SAS) is related significantly and positively with SOM and porosity, which is also positively related with moisture retention at field capacity and saturation humidity. However, there is no significant correlation between porosity and permanent wilting point (PWP). Soil water retention is dependant on the gypsum percentage and textural class. Low levels of gypsum have no influence on water retention, but high gypsum levels (> 60%) enhance the field capacity (FC) and decrease PWP, especially when the gypsum is microcrystalline. Gypsum levels between 40 and 60% also increase available water contents (AWC) due to a decrease in PWP. There is a positive and significant correlation between PWP and FC in Gypsisols, except for those which are loamy and have gypsum values over 40%. The higher available water capacity (AWC) than expected is related to microcrystalline gypsum, predominant in the studied soils. These high AWC values are counteracted by an increasingly irregular pore space not suitable for root growth. All these cited characteristics result in a low fertility, influenced by the weather and the human impact, which deforested the highest part of these mountains in the Middle Ages.

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RESUMEN

Los Gypsisoles son suelos localizados fundamentalmente en zonas áridas, de forma dispersa. No obstante, soportan una actividad económica fundamental y atesoran un elevado interés científico. Presentan una serie de peculiaridades relacionadas con su comportamiento físico y químico. Así, por ejemplo, se atribuye a los Gypsisoles una alta erosionabilidad, baja fertilidad y una variable retención de humedad que puede ser atribuida a los diferentes tamaños de las partículas de yeso. Este trabajo describe Gypsisoles de una misma catena, en la que los suelos se han desarrollado sobre yesos miocenos en el Valle medio del Ebro. Además, relaciona la capacidad de retención de agua del suelo con sus propiedades micromorfológicas. Los horizontes presentan mayoritariamente una textura franca. El yeso es abundante en los horizontes estudiados, encontrándose en un rango que varía entre el 6% y el 84%, con valores mínimos en los horizontes Ah y con máximos en los By y Cy. Se aprecia además un bajo nivel de salinidad, una muy baja capacidad de intercambio catiónico (CIC) y también escasa materia orgánica (MO), aunque este último parámetro asciende a "medio" o "abundante" en los horizontes más superficiales. La estabilidad estructural (EE) se relaciona significativa y positivamente con la MO y la porosidad, la cual también está significativa y positivamente relacionada con la retención de agua en capacidad de campo y en humedad de saturación. Sin embargo no se aprecia una relación significativa entre la porosidad y el punto de marchitez permanente (PMP). La retención de agua de un horizonte varía en función del porcentaje de yeso presente y de la clase textural. De esta forma, bajos niveles de yeso no tienen influencia en la retención de agua, pero elevados niveles de yeso (> 60%) incrementan la capacidad de campo (CC) y disminuyen el PMP, especialmente cuando el yeso se presenta en forma microcristalina. Porcentajes de yeso entre el 40% y el 60% tienden a disminuir el PMP. Se ha comprobado en estos Gypsisoles una relación directa y significativa entre el PMP y la CC, que se cumple con todos los horizontes excepto para los horizontes francos que tienen valores de yeso superiores al 40%. Los valores de agua útil (AU), superiores a los esperados, están relacionados con la presencia de yeso microcristalino, predominante en los suelos estudiados. Estos elevados valores de AU son contrarrestados por el crecimiento irregular del espacio poroso, que impide la profundización de las raíces por ellos. Todas estas características citadas producen una escasa fertilidad de los suelos, influenciada por el clima y el impacto humano que deforestó la parte más alta de estas montañas durante la Edad Media.

RESUMO

Os Gypsisols localizados principalmente em solos áridos constituem uma atividade chave sob o ponto de vista económico e apresentam grande importância científica devido às suas particulares propriedades físicas e químicas. Assim, por exemplo, atribui-se aos Gypsisols uma elevada erodibilidade, uma baixa fertilidade e uma capacidade de retenção de água variável, o que pode ser atribuído às diferentes dimensões das partículas de gesso. Este estudo tem como objetivo principal descrever alguns Gypsisols representativos, desenvolvidos sobre gessos miocénicos do Vale do rio Ebro. Para além disso, relaciona-se a capacidade de retenção de água destes solos com as suas propriedades micromorfológicas. Os seus horizontes apresentam maioritariamente uma textura franca. O gesso está sempre presente nos horizontes estudados, numa gama que varia entre 6% e 84%, com valores mínimos no horizonte Ah e máximos nos horizontes By e Cy. Estes solos apresentam igualmente um baixo nível de salinidade, uma muito baixa capacidade de troca catiónica (CTC) e um baixo teor de matéria orgânica (MO), embora este último parâmetro possa atingir valores "médios" ou "elevados" nos horizontes superficiais. A estabilidade estrutural (EE) está significativa e positivamente relacionada com a MO e porosidade, a qual também está significativa e positivamente relacionada com a capacidade de retenção da água em condições de capacidade de campo e humidade de saturação. Contudo, não se verifica qualquer relação significativa entre a porosidade e o coeficiente de emurchecimento (CE). A retenção de água de um horizonte varia de acordo com a percentagem de gesso presente e com a classe textural. Assim, baixos níveis de gesso não influenciam os níveis de retenção de água, mas níveis elevados de gesso (> 60%), aumentam a capacidade de campo (CC) e diminuem o CE, especialmente quando o gesso está presente sob a forma microcristalina. Percentagens de gesso entre 40% e 60%, tendem a diminuir também o CE. Verificou-se nestes Gypsisols para todos os horizontes uma relação direta e significativa entre o CE e a CC, exceto nos horizontes francos com níveis de gesso superiores a 40%. Os valores para a água útil (AU) mais elevados do que o esperado estão relacionados com a presença de gesso microcristalino, predominante nos solos estudados. Estes valores elevados de UA são compensados por um crescimento irregular do espaço entre os poros, o que impede a penetração profunda das raízes. Todas estas características citadas conduzem a uma baixa fertilidade dos solos, influenciada pelo clima e impacto humano, responsável pela desflorestação da parte mais elevada destas montanhas durante a Idade Média.

KEY WORDS
Microcrystalline gypsum, water tension, Gypsisol, available water content, forest soils

PALABRAS CLAVE
Yeso microcristalino, tensión del agua, Gypsisol, agua útil, suelos forestales

PALAVRAS-CHAVE
Gesso microcristalino, tensão da água, Gypsisol, água útil, solos florestais

1. Introduction

Gypsisols are extremely scarce in the world (IUSS 2007), making up less than 0.1% of European soils (EC 2005). Gypsisols are usually distributed in arid environments (IUSS 2007), and are especially represented in Spain and particularly in the Middle Ebro Valley. Despite occupying a small area, these soils have a high level of scientific and economic importance due to the presence of endemic plants and also because of their concentration in places where soil is needed for agriculture (Laya et al. 1993). In recent decades the level of interest in soils with gypsum ($CaSO_4 \cdot 2H_2O$) has increased, with studies focusing on agricultural land (Porta and Herrero 1990; Eswaran and Zi-Tong 1991; Poch 1992; Poch and Verplancke 1997; Poch et al. 1998; Porta 1998; Herrero 2004; Dultz and Kühn 2005; Poch et al. 2010). However forested land over gypseous soils has been scarcely studied, although some studies report a limited vegetation development (Olarieta et al. 2000; Olarieta et al. 2012).

Gypsisols have some peculiarities in relation to their physical and chemical behaviour, causing low fertility and lack of structure (Mashali 1996). From the viewpoint of soil moisture retention, some authors report very low values (Herrero 2005), while others report the opposite. This can be attributed to different gypsum particle size and to the degree of mixing of the gypsum infilling with the groundmass (Poch et al. 1998).

The objective of this study is to describe some representative Gypsisols (IUSS 2007) from this catena (Gypsic Haploxerept in the Soil Taxonomy System -SSS 2010) using a chemical and physical approach, and to examine the water retention capacity of the horizons using micromorphological analysis.

2. Study Area

The studied soils were located at different hillslope positions in the Castejón Mountains (NE-Spain). These mountains lie in a NE-SW direction, and divide the basins of the Gállego River in the East and the Arba River in the West. The study was carried out in Western part of Castejón Mountains, on the left side of Ebro River (**Figure 1**). The catena is located between 400 and 460 masl, close to Pola trig point (UTM 30T X658002, Y4639196).

The parent material is gypsum with marl intercalations from the Miocene (Arenas and Pardo 1999), late Ramblian to early-middle Aragonian. Gypsum rock has a high level of richness: 88.6% of gypsum and 3.0% of lime (Mandado 1987). Gypsum rock is located in the lowest part of the Castejón Mountains, under limestone and grey marl. According tothe palaeomagnetic analysis of Pérez-Rivarés et al. (2004) this deposit is between 16.14 Ma and 21.2 Ma old. These sediments are the result of a lacustrine system placed on the central part of the Ebro Basin during early and middle Miocene period. Sulphate deposition areas correspond with the shallow water of that old lake (Arenas and Pardo 1999).

The geomorphological context consists of ravines, which run from the top of the mountain to the flat areas where sediments are deposited. These ravines have been mainly eroded by water. Between the ravines, the geomorphology unit found is the slope, with similar characteristics to the one selected in this study.

The climate is characterized by two long dry periods in summer and winter. The average rainfall is 428 mm/year, the average annual temperature is 13.9 ºC and the evapotranspiration is 1244 mm according to DGA (2004). Wind events with gusts over 30 m s^{-1} are common in the area (Cuadrats Prats 2004). The soil temperature regime is mesic (Soil Survey Staff 2010) while the moisture regime is xeric in head-slope and aridic in the rest of the profiles (Jarauta and Porta 1990).

The vegetation is a scrub such as rosemary (*Rosmarinus officinalis* L.), thyme (*Thymus vulgaris* L.) and *Gypsophila struthium* L. subsp. *hispanica* (Wilk.). At the bottom of the slope, there is an Aleppo pine forest (*Pinus halepensis* L.) with an undergrowth of kermes evergreen oak (*Quercus coccifera* L.), *Ononis tridentatae* L. and Mediterranean false-brome (*Brachypodium retusum* (Pers.) Beauv.). There are some protection zones for birds close to this area (SPA, ES0000293) and the environment is protected (SCI, ES2430080) and included on “Natura 2000” network.

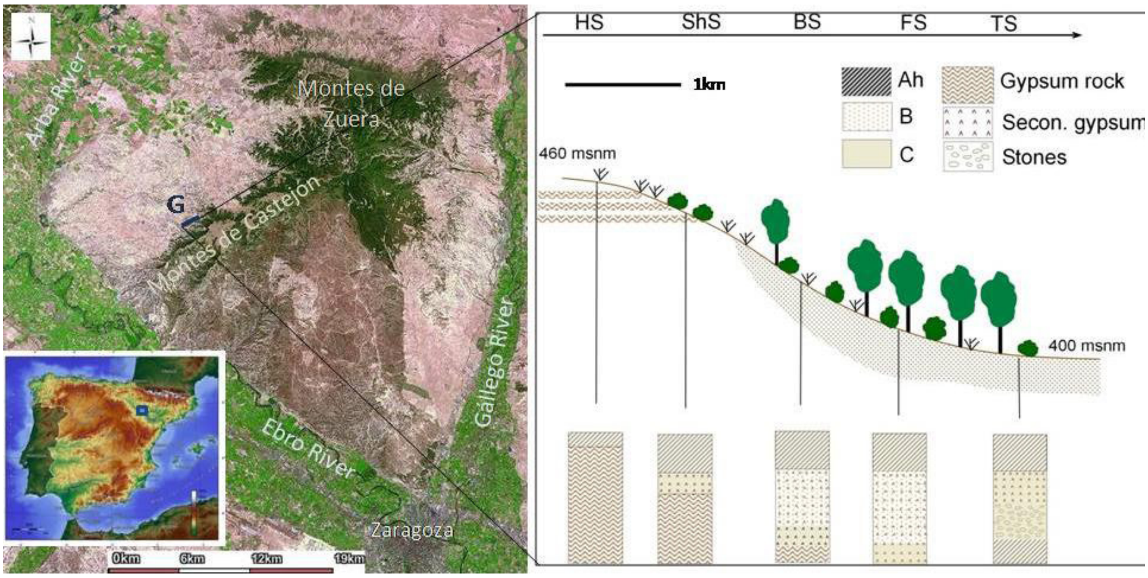

Figure 1. Location of the study area (NE-Spain) and catena of gypseous soils (G). HS) Head-slope. ShS) Shoulder-slope. BS) Back-slope. FS) Foot-slope. TS) Toe-slope.

3. Materials and Methods

Five profiles were sampled along a slope and labeled according to their position as: head-slope, shoulder-slope, back-slope, foot-slope and toe-slope profiles.

Soil samples were collected for physical and chemical analyses. The morphological properties of each horizon were described following FAO methodology (2006): color (dry and moist), consistence and accumulations. The laboratory analyses were carried out using the fine earth fraction (< 2 mm). Air-dried samples of the soils were gently sieved to separate 1-2 mm macroaggregates, which were used to measure Soil Aggregate Stability (SAS); it was assayed by wet-sieving with the single sieve method (Kemper and Koch 1966). Porosity was calculated by way of bulk density, obtained with the paraffin method (Blake and Hartge 1986). Water availability at a permanent wilting point (PWP) (-1500 kPa) and at field capacity (FC) (-33 kPa) were measured using a volumetric pressure plate extractor (Richards 1947). The water holding capacity (WHC, as mm/profile) was calculated as the difference in water retention between field capacity and permanent wilting point (USDA 2012).

Particle size determination in (hyper)gypseous soils cannot be performed accurately due to the lack of clay dispersion when gypsum is present in the soil (Vieillefon 1979). Laser diffraction provides at least some results that can be compared with field texture determinations and in our experience it has provided acceptable matches. Particle size distribution was therefore measured with a Malvern Mastersizer 2000, which uses laser method. This method underestimates clays in favor to fine silt, so the clay value was corrected according to the equation: $y = 3.089x – 2.899$ (Taubner et al. 2009), where "x" is the clay value obtained with laser method and "y" is the corrected value to standardize with pipette method. Textural class is shown in the USDA system.

The pH was determined in a 1:2.5 ratio in H_2O, total carbonate content by calcimetry, total soil organic C by wet oxidation (organic matter was estimated using the van Bemmelen factor, 1.724), Cation Exchange Capacity (CEC) by extraction with $AcONH_4$, soil salinity by checking Electrical Conductivity (ECe) of the extract at 25 ºC, and soluble ions were measured in the extract (Page et al. 1982). Total N was obtained for each horizon with Kjeldahl method. Gypsum content was measured by gravimetry according to Vieillefon (1979). The sodium adsorption ratio (SAR) was measured according to the US Salinity Laboratory Staff (1954).

Soil thin sections of selected horizons were prepared using standard techniques (Benyarku and Stoops 2005). Their micromorphological description was done according to Stoops (2003) using a polarizing microscope.

4. Results and Discussions

4.1. Morphological properties

The main field morphological characteristics of the profiles are summarized in **Table 1**. In general, top horizons show vermiform gypsum accumulations in a calcareous matrix, while subsurface horizons (By) are whitish, massive, with generalized flour-like gypsum accumulations. Dry consistency is classified as soft for all Ah horizons and all the horizons of toe-slope but it is getting harder in depth.

4.2. Chemical properties

Soil pH is basic for all the horizons due to the presence of $CaCO_3$, except the 2Az horizon in toe-slope, which is very basic because of sodium and magnesium carbonates (**Table 2**). These results are similar to others obtained in Gypsisols (Herrero 1991; Machín and Navas 1993; Artieda 1996; Florea and Al-Joumaa 1998; Cantón et al. 2003). Gypsum content ranges from 6 (Ah) to 84% (By). Carbonates increase significantly when gypsum decreases ($R=-0.86$; $n=15$; $p<0.001$). Both components are important because arid climate imposes many properties of the parent material to the soils, limiting chemical and physical reactions (Claridge and Campbell 1982). The gypsum content in the upper horizons is lower than in subsurface horizons, confirming some temporal stability of the slope (Badía et al. 2013). All the horizons show salinity levels (between 2 and 4 dS m^{-1}) expected for soils with gypsum and not more soluble salts (Gutiérrez et al. 1995; Florea and Al-Joumaa 1998; Cantón et al. 2003; Angulo-Martínez et al. 2012). The exception is, again, the buried horizon 2Az on toe-slope, which shows a very high salinity level.

The highest levels of soil organic matter (SOM) are located in the surface horizons of back-slope and foot-slope, decreasing a little bit on toe-slope because of the influence of a main slope. SOM on the head-slope and shoulder-slope is very low due to erosion, mainly because of water and also wind. However, interparticle cohesion enhanced by gypsum (Gomes et al. 2003) can decrease wind erosion. Water plays an important role in the erosion of the study area, especially because precipitation is scarce but intense. C/N ratio ranged from 6.0 to 12.3. Highest values are found in the A-horizons. These values are similar to studies in the Pyrenees with forests (Badía and Martí 1999). However, they show differences with forest soils in the Ebro Basin, where it was reported a C/N ratio of 17.1 (Badía 1989).

Table 1. Selected properties of field description. Abbreviations: Dry consistency: SO, soft, MO, moderate, HA, hard. Secondary gypsum type: V: vermiform gypsum; F, flour-like gypsum; secondary gypsum abundance: vf, very few; f, few; c, common. Structure grade: w, weak; m, medium; s, strong; vs, very strong; structure type: G, granular; Sbk, subangular blocky; ms, massive

Slope position -	Hor. -	Thickness (meters)	Colour, dry	Colour, Moist	Dry consistency	Secondary accumulation (gypsum)	Structure (grade, type)
Head-slope	Ah	0.15	2.5Y 8/2	2.5Y 7/3	SO		w, G
Shoulder-slope	Ah	0.25	10YR 7/2	10YR 5/3	SO	F, f	m, Sbk
	Cy	0.25	10YR 8/1	10YR 7/2	MO	F, c	ms
Back-slope	Ah1	0.25	10YR 6/2	10YR 5/3	SO	V, f	vs, G
	Ah2	0.25	10YR 6/2	10YR 5/3	SO	V, c; F, c	vs, G
	By	0.50	10YR 8/1	10YR 7/2	MO	F, c	ms
	Cy	0.30	10YR 8/2	10YR 6/3	MO	F, c	Apedal
Foot-slope	Ah	0.30	10YR 6/3	10YR 4/3	SO	V, vf	vs, G
	Bwy	0.25	10YR 7/3	10YR 5/3	MO	V, c	s, Sbk
	By	0.55	2.5Y 8/2	2.5Y 6/3	HA	F, c	ms
	Cy	0.40	2.5Y 7.5/3	2.5Y 6/4	HA	F, c	Apedal
Toe-slope	Ah	0.15	10YR 6/2	10YR 5/2	SO		s, G
	By	0.45	10YR 7/2	10YR 6/3	SO	V, f	ms
	Cy	0.40	10YR 7/2	10YR 6/3	SO	V, f	ms
	2Az	0.50	10YR 6/2	10YR 4/2	SO		m, G

There is a significant and positive correlation between organic matter content and available phosphorus ($R=0.94$; $n=15$; $p<0.001$) and potassium ($R=0.54$; $n=15$; $p<0.05$). Phosphorous and potassium contents are highest in topsoil horizons, proving that both nutrients are related to organic matter mineralization. Soluble calcium content is much higher than the magnesium, sodium and potassium contents. High levels of calcium are due to high levels of gypsum and calcium carbonate. Cation exchange capacity (CEC) is significantly related to the organic matter playing a secondary role other parameters (**Table 3**).

Ortiz et al. (2002) found a similar equation to the third one shown in **Table 2**, although they reported it from an oak forest with shrubs and herbaceous plants in SE-Spain. CEC decreases significantly with gypsum ($R=-0.83$; $n=15$; $p<0.001$). However, it may be that carbonates show this positive relation with CEC because gypsum has a negative relationship with it. The predominant clay in the soil is illite according to Badía (2009) who reported illite as the most abundant clay in soils from the studied area and is consistent with the measured $cmol_+$ kg^{-1} (around 11.8 $cmol_+$ clay kg^{-1}).

Table 2. Main properties of the profile. HS: Saturation Humidity. FC: Field Capacity. PWP: Permanent Wilting Point. AWC: Available Water Capacity. *SAR: Sodium Adsorption Ratio

Slope position	Hor.	Thick-ness	HS	FC	PWP	AWC	Poro-sity	SAS	Gra-vels	Soil Texture	pH (H_2O)	CO_3 Eq	Gyp.Eq	ECe	OM	CEC	SAR
-	-	M	%	%	%	%	%	%	%	Class	1:2.5	%	%	dSm^{-1}	%	$\text{cmol}_+\text{kg}^{-1}$	*
Head-slope	Ah	0.15	38.1	20.7	7.7	13.0	55.4	24.2	53.6	Sandy Loam	8.1	29.0	40.0	2.4	1.12	2.6	0.03
Shoul-der-slope	Ah	0.25	41.8	28.8	6.9	21.9	56.8	49.1	22.3	Loam	8.0	15.2	52.9	2.4	2.62	3.2	0.04
	Cy	0.25	50.9	35.2	5.6	29.6	59.8	43.2	16.5	Loam	8.1	7.5	79.2	2.4	1.41	1.6	0.04
Back-slope	Ah1	0.25	53.5	32.5	11.7	20.8	63.6	95.0	6.2	Loam	8.0	21.1	35.8	2.8	5.95	5.9	0.07
	Ah2	0.25	53.1	32.2	13.6	18.5	62.7	93.2	1.4	Loam	8.1	21.5	27.2	3.0	5.04	6.3	0.25
	By	0.50	42.5	36.6	4.7	31.9	61.9	22.1	0.4	Loam	8.1	6.5	84.2	2.5	1.28	1.2	0.01
	Cy	0.30	41.8	32.6	6.8	25.8	55.1	60.5	25.3	Loam	8.1	10.4	60.7	2.5	1.80	3.2	0.03
Foot-slope	Ah	0.30	66.0	32.2	18.8	13.4	61.4	95.3	2.9	Loam	8.0	35.2	5.6	1.6	5.67	20.2	1.28
	Bwy	0.25	47.7	29.2	12.0	17.2	54.2	81.2	3.2	Clay Loam	8.0	27.7	38.2	2.6	3.00	9.2	0.12
	By	0.55	37.6	23.6	6.5	17.1	53.4	23.1	2.7	Sandy Loam	8.0	23.5	55.9	2.6	0.82	3.5	0.10
	Cy	0.40	42.4	17.3	5.0	12.3	50.4	7.8	2.6	Sandy Loam	8.0	19.3	58.2	2.7	0.36	3.7	0.10
Toe-slope	Ah	0.15	48.2	30.2	12.7	17.5	60.6	69.4	39.1	Loam	7.9	46.8	10.8	3.1	3.49	11.8	0.15
	By	0.45	44.9	28.8	7.3	21.5	50.0	66.8	59.5	Loam	8.0	29.1	43.5	2.6	1.58	3.9	0.06
	Cy	0.40	40.3	29.1	10.9	18.2	57.8	22.0	56.8	Loam	8.1	30.0	27.1	3.5	0.93	5.8	0.45
	2Az	0.50	46.6	28.3	13.7	14.6	57.5	4.7	8.8	Silt loam	8.8	27.2	15.3	14.6	1.39	11.7	8.97

Table 3. Pedotransfer equations relating SOM, clay, gypsum and carbonates with CEC

CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 2.24 (OM%)	($n=15$; $P<0.0001$; $r^2=0.72$)
CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 2.31 (OM%) – 0.007 (gypsum%)	($n=15$; $P<0.0001$; $r^2=0.72$)
CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 1.17 (OM%) + 0.21 (clay%)	($n=15$; $P<0.0001$; $r^2=0.79$)
CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 0.93 (OM%) + 0.024 (clay%) + 0.17 (carbonates%)	($n=15$; $P<0.0001$; $r^2=0.84$)
CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 0.82 (OM%) + 0.44 (clay%)– 0.08 (gypsum%)	($n=15$; $P<0.0001$; $r^2=0.89$)
CEC ($\text{cmol}_+ \text{kg}^{-1}$) = 0.72 (OM%) + 0.29 (clay%) – 0.08 (gypsum%) + 0.11 (carbonates%)	($n=15$; $P<0.0001$; $r^2=0.91$)

4.3. Origin of the buried horizon

The values of SOM, salinity, SAR and pH in the horizon 2Az of the toe-slope are very different to those found in the other horizons. This is because the horizon 2Az was buried, unlike the rest of the horizons. The 2Az horizon was probably buried as a result of increased erosion between the XVI and XIX centuries. During this period, the Spanish landscape was particularly subject to erosion because of the increased demand from the new American markets for cereals and wood, among others factors (Puigdefábregas and Mendizábal 1998).

A document dated from 1270 reports that there was a forest in the plateau atthe top of these mountains (Giménez-Soler 1922). The document regulated the exploitation of the area, preserving trees. Today there is no forest on this plateau (including head-slope and shoulder-slope of this catena). In this area, Braun-Blanquet and De Bolos (1957) point out the dominance of *Artemisia herba-alba* Asso and *Salsola vermiculata* L., which show evidence of past cultivation. Evidently, deforestation of huge areas of the Ebro Basin played an important role in Ebro Delta formation, which was accelerated between the XV and XVII centuries (Fatoric and Chelleri 2012). Constante and Peña-Monné's (2009) study showed sediment accumulations in a closed area, even on the left margin of the Ebro River. They cite a sediment accumulation, which is similar to our toe-slope profile over the 2Az, because of the position, gravel percentage and depth. This sediment dates back between the XVII and XVIII centuries.

4.4. Physical properties

Loam textural classes predominate in these soils, but on the head-slope sand is of greater importance. Gravels are negligible on the back-slope and foot-slope; however they make up more than a half of the head-slope and the By and Cy horizons of toe-slope. The high concentration of gravels at the top of the slope is because the bedrock is very close to the surface; whereas their accumulation in the lower part is due to gravity. The toe-slope in the studied slope is also part of a main slope. This explains why there are no gravels in the soils of medium studied slope.

Horizons show mainly a 10YR hue (**Table 1**), with values ranging from 6 to 8 and chroma from 1 to 3 (light gray and light brownish gray). This is due to the high gypsum content and low SOM content for most of the horizons. The value shows a significant correlation with gypsum content (R=0.84; n=15; p<0.001) and with SOM (R=-0.74; n=15; p<0.002). This strong relationship between color, soil component and SOM was previously reported (Badía et al. 1998).

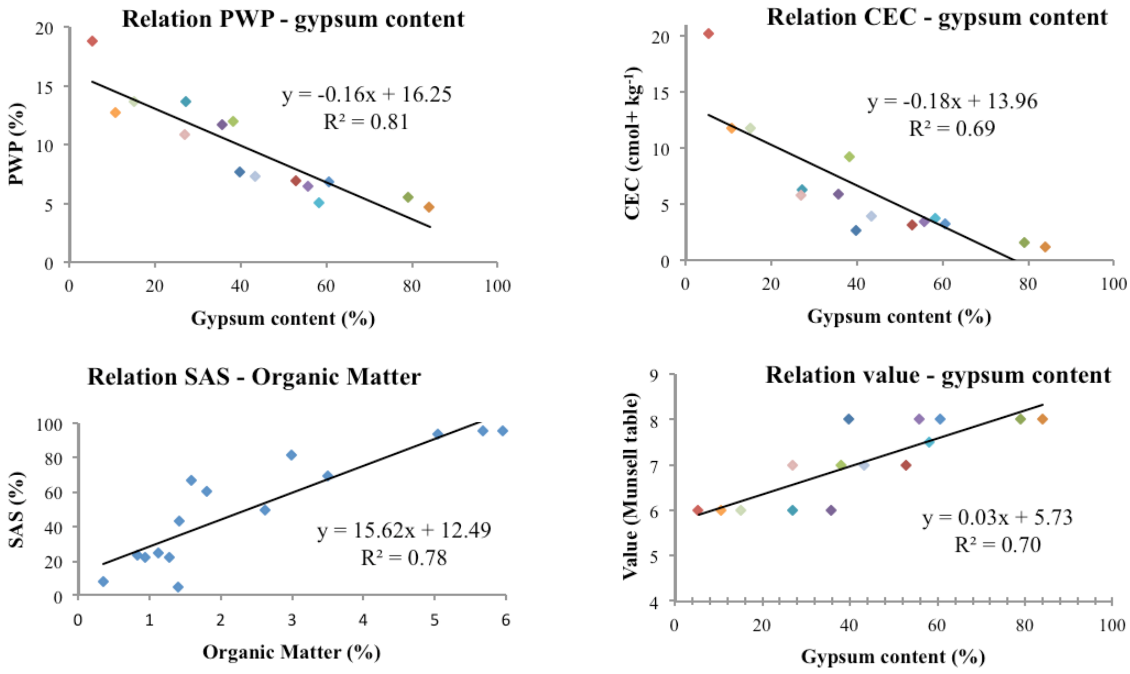

Figure 2. Relation between PWP, CEC and value color with gypsum content, and relation between organic matter and SAS. All show a p<0.001.

The highest level of soil aggregate stability (SAS) is found in surface horizons, where SOM content is highest. Similarly to previous results (Badía and Martí 1999; Martí et al. 2001; Otal et al. 2005; Badía et al. 2010), a logarithmic, significant and positive relationship between % SOM and SAS was found:

$$\text{SAS (\%)} = 29.73 + 36.45 * \ln(\%\text{SOM})$$
$$(R=0.89;\ n=15;\ p<0.001)$$

The high SAS ensures a high porosity as evidenced by the significant and positive correlation between both parameters ($R=0.88$; $n=15$; $p<0.001$) and this in turn ensures a high water retention. Thus, porosity shows a significant and positive correlation with moisture retention at field capacity, FC ($R=0.78$; $n=15$; $p<0.001$) and saturated water content ($R=0.62$; $n=15$; $p<0.02$) but not with PWP.

4.5. Water properties

Available water capacity (AWC) ranges from very low to very high (for the aridic/xeric regime), according to the USDA criteria (2012). The head-slope´s soil has a very low AWC per profile (13 mm) due to the shallowness (0.15 m). The soils in back-slope and foot-slope have a very high AWC per profile (359 mm and 314 mm, respectively), influenced by the absence of gravels (<5% in foot-slope) but mostly by their large thickness. Usually, the AWC increases while the slope decreases because the soil thickness increases. In this work, only the presence of gravel in the toe-slope profile produces slight changes in this trend.

Furthermore, AWC is considered as total water holding at 33 kPa (FC) besides as PWP subtracted from FC, because most of the species are xerophytes able to extract most of the PWP water (**Table 4**). Badía et al. (2010) showed that AWC expressed using only FC is double the AWC calculated as FC-PWP, however in the studied soils it is not so high. The main difference is the low PWP that is obtained in these soils, especially for horizons with high gypsum levels. Even these horizons show a high value for FC.

Table 4. Retention of available water in the profiles along the hillslope, as available water-holding capacity (WHC = FC-PWP), and as Field Capacity (FC), in mm 1.50 m^{-1} of profile or superficial lithic contact

Landform	Head-slope	Shoulder-slope	Back-slope	Foot-slope	Toe-slope
AWC as WHC (mm 1.5 m^{-1})	13	132	359	314	213
AWC as FC (mm 1.5 m^{-1})	21	164	471	502	367
AWC as WHC (USDA 2012 class)	Very low	Moderate	Very high	Very high	High
AWC as FC (USDA 2012 class)	Very low	Moderate	Very hight	Very high	Very High

Gypsum by itself does not have any special property for water holding; however there is a high influence due to size and distribution of gypsum crystals (Poch et al. 1998). Accordingly, we chose only loam horizons (n=10), with similar particle sizes to examine the water retention properties. The results of AWC (%) calculated as PWP subtracted from FC are in agreement with other studies focussed on horizons with high gypsum contents (Poch et al. 1998). The relations between gypsum content and water holding are shown (**Table 5**); where the regression coefficient does not improve if we add the variable sand percentage to the regression.

Table 5. Water retention at different tensions for loamy horizon and relation between water tension and gypsum content

AWC (%) = 0.209 (gypsum %) + 12.99	(n=10; $P<0.001$; r=0.98)
PWP (%) = -0.151 (gypsum %) + 16.34	(n=10; $P<0.001$; r=0.91)
FC (%) = 0.058 (gypsum %) + 29.33	(n=10; $P<0.100$; r=0.58)

As it is shown in **Figure 3**, low levels of gypsum have no influence on water retention because it depends on the other components (Poch et al. 1992). However, horizons with a high gypsum content (> 60%) show an increase in FC and a decrease in PWP (**Figure 4a**). These results agree with Heinze and Fiedler (1984) and Poch et al. (1998), who reported a relationship between gypsum and water retention when gypsum is microcrystalline.

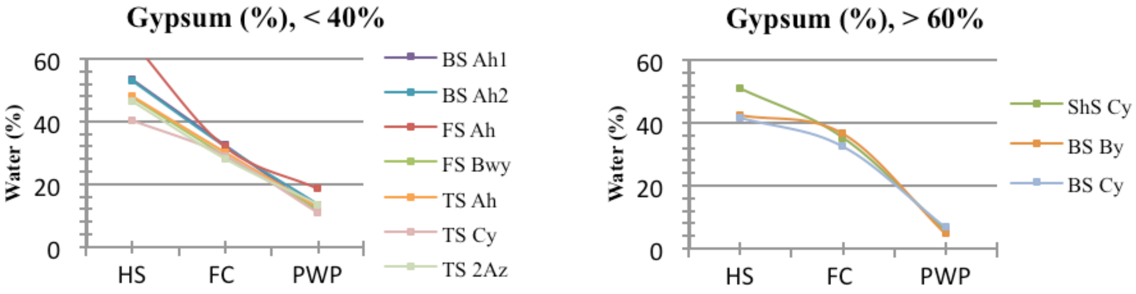

Figure 3. Soil gypsum content and water retention relationship at different tensions. HS: Saturation Humidity. FC: Field Capacity. PWP: Permanent Wilting Point. ShS: shoulder-slope. BS: back-slope. FS: foot-slope. TS: toe-slope.

Furthermore, analyzing some Gypsisols (those with texture, gypsum percentage, PWP and FC reported) that were described by other authors (Herrero 1991; Olarieta et al. 1991, Badía et al. 2006; Badía et al. 2008) and the horizons of this paper, a relationship is found between PWP and FC. For most of these horizons (blue circles in **Figure 4b**) the relationship can be described as PWP (%) = 0.470 (FC %) - 1.749 (r=0.84; n=44; $p<0.001$). However, some horizons (n=11, red triangles in Figure 4b) do not follow this regression. All of them are loamy horizons with a gypsum content higher than 40%, which shows that a gypsum percentage of more than 40% provokes a difference in water retention for loamy horizons. However, other loamy horizons with less gypsum (< 40%) show a similar behaviour to the rest of the Gypsisol horizons (n=44) defined by the previous equation.

In the studied horizons of this catena (n=15), where gypsum levels range from 40% to 60%, a decrease of PWP (and also FC in sandy-loam horizons) is observed. However, these horizons have more sand, which also influences AWC. The sand percentage affects AWC according to the following regressions:

AWC (%) = 0.18 (gypsum %) + 11.99
(r=0.71; n=15; $p<0.01$)

AWC (%) = 0.22 (gypsum %) – 0.26 (sand %) + 22.14
(r=0.83; n=15; p=0.001)

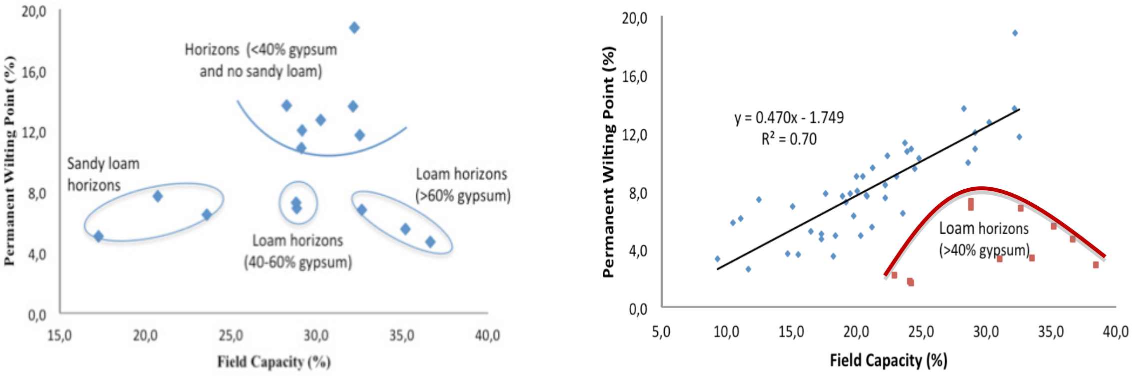

Figure 4. a) Relation between PWP and FC for all the horizons of the studied toposequence. Four groups have been established according to their position and features. **b)** Relation between PWP and FC for horizons of this work and also for other horizons described by other authors (see text) in Gypsisols of the Ebro Valley. Two groups were established, one which holds the loamy horizons with a gypsum content higher than 40%, and a second one including the rest of the horizons.

4.6. Micromorphological properties

The gypsum of these soils is mainly microcrystalline, silt-sized and with a flour-like consistency in the field. Powdery gypsum, made of sand-sized lenticular gypsum crystals (Poch et al. 2010), was not observed in the field. Flour-like gypsum predominates in all the horizons, which is in agreement with the micromorphological observations of the Ah2 and By horizons of the back-slope profile (**Figures 5-9**), where this gypsum size is found in the micromass and also as pedofeatures. Microcrystalline gypsum occupies almost all the horizon volume in By (**Figure 8**).

Table 6. Main nutrient content of the studied soil profiles

Slope position	Hor.	N-tot	C/N	P-ava	Ca	Mg	Na	K
-	-	%	Ratio	mg/kg	exchangeable (cmol$_+$/kg)			
Head-slope	Ah	0.08	7.8	2	199.4	0.3	1.02	0.31
Shoulder-slope	Ah	0.15	10.4	2	196.8	0.4	0.99	0.38
	Cy	0.08	10.0	1	197.2	0.4	0.94	0.12
Back-slope	Ah1	0.29	12.0	5	190.8	0.6	0.92	0.34
	Ah2	0.26	11.2	4	189.0	2.5	1.02	0.30
	By	0.07	10.6	2	189.1	0.1	0.88	0.05
	Cy	0.11	9.4	1	190.7	0.3	1.07	0.14
Foot-slope	Ah	0.27	12.3	6	20.7	4.2	0.56	1.21
	Bwy	0.17	10.0	3	192.3	1.2	1.01	0.44
	By	0.05	9.1	1	171.9	0.9	0.90	0.20
	Cy	0.03	6.0	1	182.0	0.9	1.13	0.20
Toe-slope	Ah	0.19	10.9	4	52.2	0.8	0.56	1.15
	By	0.09	9.8	2	189.7	0.6	1.11	0.54
	Cy	0.07	7.7	1	192.3	4.4	1.56	0.35
	2Az	0.08	10.5	1	8.2	21.5	3.32	0.30

Lenticular gypsum is found as nodules or coatings that are interpreted as recrystallizations of primary gypsum. Furthermore, we find some iron oxy-hydroxide nodules, which are considered relict from a past seasonal soil flooding because they are found inside soil aggregates (**Figures 5** and **7**). The By horizon also has lenticular gypsum crystals and isles fabric, but microcrystalline gypsum is more general (**Figures 8** and **9**). Microcrystalline gypsum found in the studied soils is due to gypsum rock weathering in the process explained by Herrero et al. (1992), while lenticular gypsum is either the result of precipitation from a gypsum-rich solution, or from the reprecipitation of microcrystalline gypsum. The main processes are dissolution and precipitation, together with biotic ones in microcrystalline gypsum (Herrero 1991).

Herrero (1991) reports high AWC values in microcrystalline gypsum horizons, which hold more water than lenticular ones due to the smaller porosity and the association between gypsum and some organic materials. However, roots have problems in using this water because the growth of gypsum crystals (as loose infillings) creates irregular, discontinuous packing pores where roots cannot penetrate (Poch and Verplancke 1997); see also **Figures 5** and **8**. This could explain, together with low rainfall and low nutrient level (**Table 6**), why the vegetation is so scarce in the area, in spite of having a high AWC.

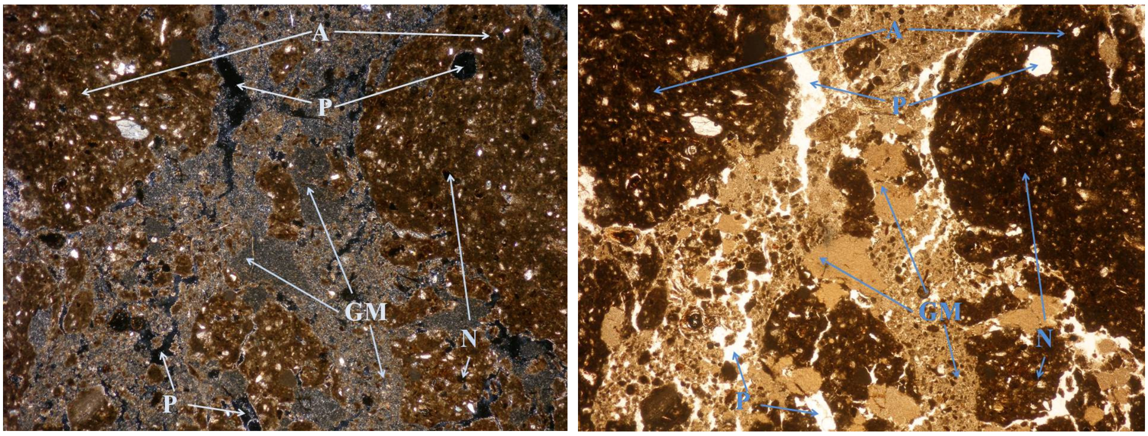

Figure 5. Micromorphology of Ah2 horizon (Back-slope), cross-polarized light (left) and in plane polarized light (right). GM) Infillings of microcrystalline gypsum. A) Aggregates of calcite, fine silt and clay. P) Pores. N) Iron oxy-hydroxide nodules. Frame length: 6 mm.

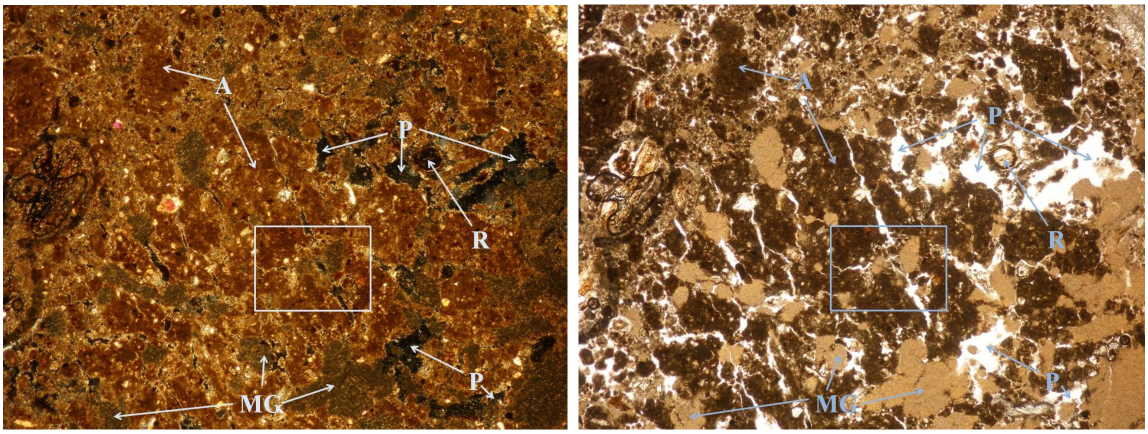

Figure 6. Micromorphology of Ah2 horizon (Back-slope), XPL (left) and PPL (right). MG) Nodules of microcrystalline gypsum. A) Aggregates of calcite, fine silt and clay. P) Pores. The rectangle refers to the area magnified in **Figure 7**. Frame length: 6 mm.

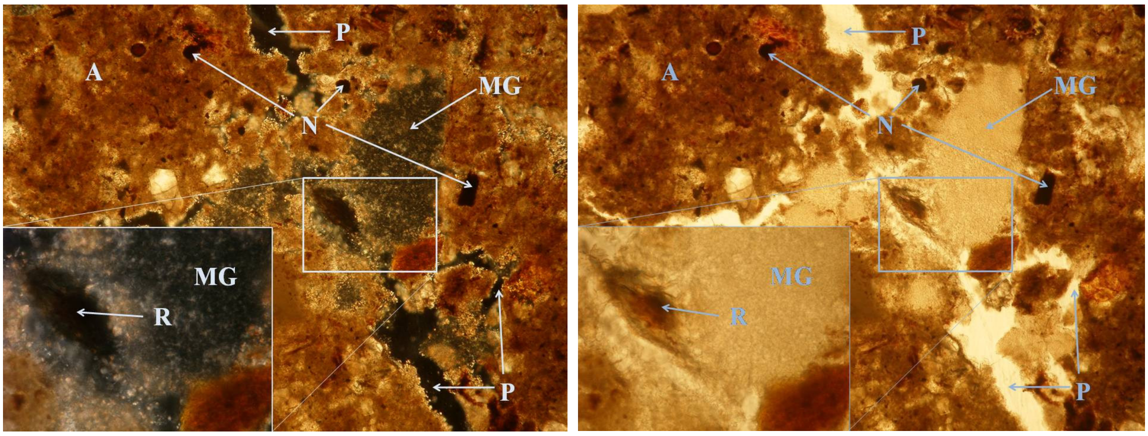

Figure 7. Micromorphology of Ah2 horizon (Back-slope) magnified from Figure 6, XPL (left) and PPL (right). MG) Nodule of microcrystalline gypsum. Note the almost isotropy of the nodule due to the random packing of silt-size gypsum crystals. A) Aggregates of calcite, fine silt and clay. P) Pores. N) Nodules of iron oxy-hydroxides. R) Root section. Frame length: 1.2 mm in the main picture and 0.3mm for the box placed down-left.

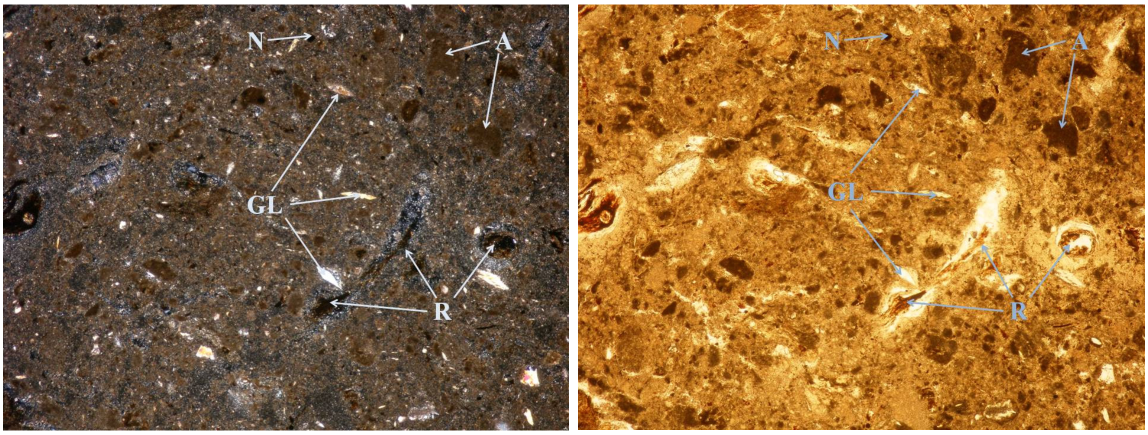

Figure 8. Micromorphology of By horizon (Back slope), in XPL (left) and in PPL (right). GL) Lenticular gypsum. N) Nodule of iron oxy-hydroxides. A) Fragment of original marl. R) Root sections. Almost all the volume is occupied by microcrystalline gypsum, which also appears filling the pores. Frame length: 6 mm.

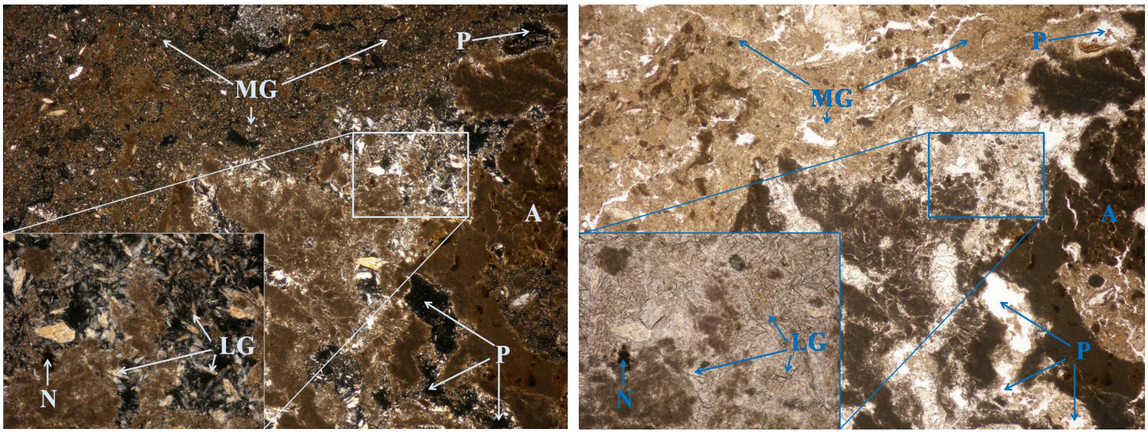

Figure 9. Microphotographs of By horizon (Back slope) developed on gypsum rock: sand-sized lenticular gypsum infilling pores and void spaces, surrounded by a mass of microcrystalline gypsum, in XPL (left) and in PPL (right). LG) Lenticular gypsum. MG) Microcrystalline gypsum. P) Pores. A) Fragment of original marl. N) Nodule of iron oxy-hydroxides. Frame length: 6 mm in the main picture and 1.2 mm in the smallest one.

4.7. Soil classification

Soils were classified using the Soil Taxonomy System (STS) and the World Reference Base (WRB), according to diagnostic horizons and their properties. The soil profile in the head-slope is classified as Haplic Gypsiric Leptosol while the others are classified as Gypsisols, belonging to various units depending on the gypsum content, stoniness, etc. (**Table 7**).

Table 7. Soil forming processes, horizons and diagnostic properties, and classification of the soils studied in accordance with the WRB (IUSS 2007) taxonomy system and Soil Taxonomy System (Soil Survey Staff 2010)

Geomorphic unit	Main soil forming processes	Horizons and diagnostic properties	Soil Taxonomy System (SSS 2010)	World Reference Base (IUSS 2007)
Head-slope	Erosion	Gypsiric material Lithic contact	Lihic Torriorthent	Haplic Gypsiric Leptosol
Shoulder-slope	Gypsification	Hypergypsic Lithic contact	Lithic Haploxerept	Hypergypsic Leptic Gypsisol
Back-slope	Gypsification	Hypergypsic	Gypsic Haploxerept	Hypergypsic Humic Gypsisol
Foot-slope	Gypsification	Gypsic	Gypsic Haploxerept	Haplic Humic Gypsisol
Toe-slope	Gypsification Salinization	Gypsic & Salic Fluvic properties	Gypsic Haploxerept	Endosalic Skeletic Gypsisol

5. Conclusions

The studied soils have a high gypsum content, together with low salinity and basic pH values due to the presence of carbonates. At the top of the slope, soils show the lowest levels of soil organic matter, soil aggregate stability, cation exchange capacity (CEC) and available water contents (AWC); these values increase for the rest of the slope. Soils have poor chemical fertility due to abundance of gypsum and lime, which form soils with low CEC because of the low clay content and low organic matter in this arid environment. Also, physical fertility is poor due to the pore characteristics features in gypsum-rich horizons, which are not suitable for root penetration.

In loam horizons, AWC increases when microcrystalline gypsum contents are high (> 40%). This increase is higher in horizons with gypsum content > 60% because an increase in field capacity (FC) occurs together with a decrease in permanent wilting point (PWP). However, in horizons with gypsum content between 40-60% also the increase in AWC is only due to a decrease in PWP. Field capacity is notably reduced by an increased sand percentage. Microcrystalline gypsum, mainly due to gyprock weathering, can form lenticular gypsum by dissolution and reprecipitation; both gypsum forms are secondary.

These high AWC values are counteracted by an increasingly irregular pore space not suitable for root growth, making it difficult for roots to develop in these horizons, as is shown in the field. This behaviour should be studied in future researches with Gypsisols with other textures than loam.

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