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# Soil – landscape relationships in the Empordà basin (Catalonia, NE Iberian Peninsula)

*Relaciones suelo-paisaje en la cuenca del Empordà (Cataluña, NE de la Península Ibérica)*
*Relação solo-paisagem na bacia Empordà (Catalunha, NE Península Ibérica)*

**AUTHORS**

**Boixadera J.**[1,2@]
jaume.boixadera@gencat.cat

**Antúnez M.**[2]

**Poch R.M.**[2]

[@] Corresponding Author

[1] Departament d'Agricultura, Ramaderia, Pesca i Alimentació, Generalitat de Catalunya. Av. Rovira Roure 191. 25198 Lleida, Catalonia, Spain.
[2] Departament de Medi Ambient i Ciències del Sòl, Universitat de Lleida. Av. Rovira Roure 191. 25198 Lleida, Catalonia, Spain.

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## ABSTRACT

Soils developed in representative landforms, which were previously mapped at a detailed scale in the Empordà Basin, were selected to characterize their main pedogenetic processes and to improve the soil maps through a better understanding of the soil – landscape relationships. This basin is a relatively large region (1,300 km$^2$) in Northeastern Catalonia, where Neogene and Quaternary sediments outcrop. They are alluvial and delta fan deposits that mainly reflect a continental environment. Besides varying degrees of soil rubefaction, we can identify calcium carbonate redistribution, clay illuviation and sodication as the main soil forming processes, together with abrupt textural changes, vertic and redoximorphic features. These processes and features are expressed under different morphologies in the area, depending not only on parent material, landform and age, but also on human action, which allows us to refine the conceptual soil-landscape model. Calcium carbonate redistribution is a key process reflecting both changing general environmental conditions and local chemical soil conditions. The actual soil characteristics and the soil forming processes allow us to propose that (i) aeolian dust inputs in these soils have been low to moderate throughout, and that (ii) the rainfall pattern in the last part of the Holocene was able to remove these dust inputs, but unable to leach carbonates from medium textured, moderately calcareous soils in the area when they are some kilometres from the sea and not directly affected by the dune system.

## RESUMEN

*Se han estudiado suelos de referencia en el Empordà, desarrollados en unidades del paisaje representativas de un área, previamente identificadas a escala detallada con el fin de caracterizar los principales procesos edafogenéticos y para mejorar la cartografía de suelos en la zona y en otras similares mediante una mejor comprensión de las relaciones suelos – paisaje. Se trata de una región relativamente extensa (1.300 km$^2$) en el noreste de Cataluña, donde afloran sedimentos Neógenos y Cuaternarios. Estos depósitos son de tipo continental, de abanicos aluviales y de delta. Los suelos estudiados muestran diversos grados de rubefacción y los principales procesos formadores de suelo identificados son la redistribución de carbonato de calcio, iluviación de arcilla y sodificación, además de cambios texturales abruptos y características vérticas, y rasgos redoximórficos. Estos procesos se expresan en la zona con diferentes morfologías, de acuerdo no sólo al material de origen, forma de relieve y de su edad, sinó también a la acción humana, de forma que nos permiten refinar el modelo conceptual de suelo-paisaje. La redistribución de carbonato de calcio es un proceso clave que refleja tanto las condiciones cambiantes ambientales generales como las*

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*condiciones químicas locales del suelo. Las actuales condiciones del suelo y los procesos de formación investigados en los suelos estudiados nos permiten proponer que las entradas eólicas de polvo en estos suelos han sido bajas a moderadas, que el régimen de lluvias en la última parte del Holoceno fue capaz de eliminar estas entradas de polvo, pero no ha podido lixiviar los carbonatos en los suelos moderadamente calcáreos de textura media, cuando se encuentran a algunos kilómetros del mar y no se ven afectados directamente por el sistema de dunas.*

## RESUMO

*Os solos desenvolvidos em acidentes geográficos representativos, e anteriormente mapeados numa escala detalhada na bacia Empordà, foram selecionados para caracterização dos seus principais processos pedogenéticos e para melhorar os mapas de solo através de uma melhor compreensão da relação solo-paisagem. Esta bacia é uma região relativamente grande (1.300 $km^2$) no nordeste da Catalunha, onde afloram sedimentos do Neogénico e quaternário. São depósitos aluviais e de deltas que refletem essencialmente um ambiente continental. Para além de vários graus de laterização do solo, podemos identificar uma redistribuição do carbonato de cálcio, iluviação de argila e sodização como os principais processos de formação do solo, juntamente com mudanças texturais abruptas, e características vérticas e redoximórficas. Esses processos e características são expressos sob diferentes morfologias na área, dependendo não só do material de origem, acidente geográfico e idade, mas também da ação humana, que nos permite afinar o modelo conceptual solo-paisagem. A redistribuição do carbonato de cálcio é um processo chave refletindo quer as alterações das condições ambientais gerais quer das condições químicas locais do solo. As reais características do solo e os processos de formação solo permitem propor que (i) entradas de poeira nestes solos foram baixas a moderadas (ii) o padrão de precipitação na última parte do Holocenico foi capaz de remover essas entradas de poeira, mas incapaz de lixiviar carbonatos de solos de textura média, moderadamente calcários na área quando estes se localizam a alguns quilômetros do mar e não são diretamente afetados pelo sistema dunar.*

**KEY WORDS**
**Mediterranean soils, genesis, mapping, clay illuviation, carbonate translocation, sodication, vertic features**

**PALABRAS CLAVE**
Suelos mediterráneos, génesis, cartografía, iluviación de arcilla, translocación de carbonatos, sodificación, rasgos vérticos

**PALAVRAS-CHAVE**
Solos mediterrânicos, génese, mapeamento, iluviação de argila, translocação de carbonato, sodização, características vérticas

# 1. Introduction

The nature and properties of the soil cover are the result of soil forming factors interacting on landforms modelled by geomorphological factors. The soil cover provides us with a lot of information about (palaeo) environmental features (climate and geomorphology among others). The soil map is the representation of the soil cover (Hole and Campbell 1985).

Soil mapping is based on the so-called soil-landscape paradigm (Hudson 1992) and was only defined after many uncertainties about the soil mapping exercise itself had been raised (Hudson 1990). The quality of a soil map is strongly dependent on the model the soil surveyor uses to map the area (Western 1979). This model, described in detail by Hudson (1992), is in most cases a conceptual one (Dijkerman 1974); it is mentally constructed by the surveyor during the time of the mapping and it is one of the most widely used in Pedology. The roots of this model are found in Marbut's idea that soils are landscapes, as well as profiles (SSS 1937). The surveyor, when starting the survey uses his/her own knowledge together with that acquired through own experience and from reports, maps, scientific and technical papers, which help to build up a preliminary soil-landscape model that is refined afterwards during the survey. It relies heavily on the soil landscape units, a concept similar to the landform, but more precisely defined by Hudson (1990).

The quality of the available soil-landscape model is of paramount importance to the quality of the mapping results, using conventional soil mapping techniques (Lagacherie et al. 1995; Legros 1996; De Bruin et al. 1999), digital soil mapping ones (McBratney et al. 2003; Lagacherie 2008) or even models of soil formation (Samouëlian and Cornu 2008) or of landscape evolution (Minasny et al. 2015).

Very often the knowledge of the soil forming processes is inadequate; therefore additional work about soil genesis needs to be done during the survey. This means that when a new area is mapped, there is a need to investigate the key soil forming processes because their expression through a set of soil properties can be used to identify the soil types in the field.

After detailed (1/25,000) mapping (Boixadera et al. 1990) of an area in the lower reaches of the Fluvià River (Empordà Basin), several questions arose about the morphology, soil formation and soil classification of several of the mapped soils. Therefore research was conducted with the aim of developing a better understanding of the soil-landscape model in the Empordà Basin, by studying the main pedogenetic processes in benchmark soils developed on representative landforms.

In the Empordà Basin there are geomorphic surfaces at least Pliocene in age, on which red (Mediterranean) soils have developed. These soils have merited a lot of attention in the literature and their geneses have been reviewed recently by Fedoroff and Courty (2013). A significant part of the research reported in this paper is devoted to these soil types.

## 2. Physical setting

The Empordà Basin is a relatively large area (1,300 km$^2$) in the northeast of the Iberian Peninsula, opening to the sea at its eastern part. The basin is a relatively flat, bounded to the north by the Pyrenees, the south by Les Gavarres (Hercinian massif), the west by the Transversal Mountain Range and the east by the Mediterranean Sea. The center of the basin is divided by the Montgrí and Valldevià Mountains into two parts: the southern one (*Baix Empordà*) – domains of the Ter and the Daró rivers - and the northern one (*Alt Empordà*) – domains of the Fluvià and the Muga rivers. The infilling of the Empordà Basin is composed by the sedimentation of several Neogene and Quaternary alluvial and delta fans, deposited in a mainly continental environment. Some of these fans have grown as far as the coastline; favoring their transit and/or progradation over the sediments of marine and/or continental/marine transition (Montaner and Solà 1998). The sub-recent alluvial plain is entrenched between the older high lying reliefs (Bach 1987).

The altitude ranges from sea level up to 200 m. The climate is typically Mediterranean with an annual rainfall about 500 mm and a mean annual temperature of 15 ºC (xeric moisture regime and thermic temperature regime; SSS 2014). Both dry land and irrigated agriculture are the main land uses, besides some areas occupied by natural vegetation.

From a morphological point of view, the Empordà Basin is formed by several glacis, mainly of detrital character, developed at the foot of the high-lying areas and later affected by the drainage system (Serra et al. 1994). Some volcanic materials appear, such as the Vilacolum outcrop, consisting of Miocene volcanic materials (trachyte) covered by Pliocene sediments (Martinell et al. 2000).

The studied profiles were selected in the low Fluvià (*Baix Fluvià*) reaches, in an area of about 7,000 ha, located east of the Ventalló mountains, north of Vilademat and south of the Muga River, with the Mediterranean sea as the eastern boundary, in the center of the Empordà basin (**Figure 1**).

In the study area there are lower Pliocene deposits (**Table 1**) of the Sant Climent delta fan outcrop (SGC-ICC 1996), made of Palaeozoic granites, metamorphic rocks and quartz from the Northern Rodes Mountains (Picart et al. 1996). These fan outcrops are located in the margins of the basin and their palaeochannels flow to the center of the basin. Other fans, such as the Vilademat delta fan (SGC-ICC 1995) as well as some deposits from the Sant Mori fan, made of metamorphic and quartzitic rocks (SGC-ICC 1996) outcrop in the area (**Table 1**).

The Pleistocene deposits in the study area are mainly represented by the terrace system of Vilademat-Ventalló (IGME 1983), but other authors identify, at a larger scale, a part with calcareous rocks covered by Upper Pleistocene and Holocene fans (SGC-ICC 1995).

The lower parts of the basin, to the East, are of Holocene age and are occupied by a recent

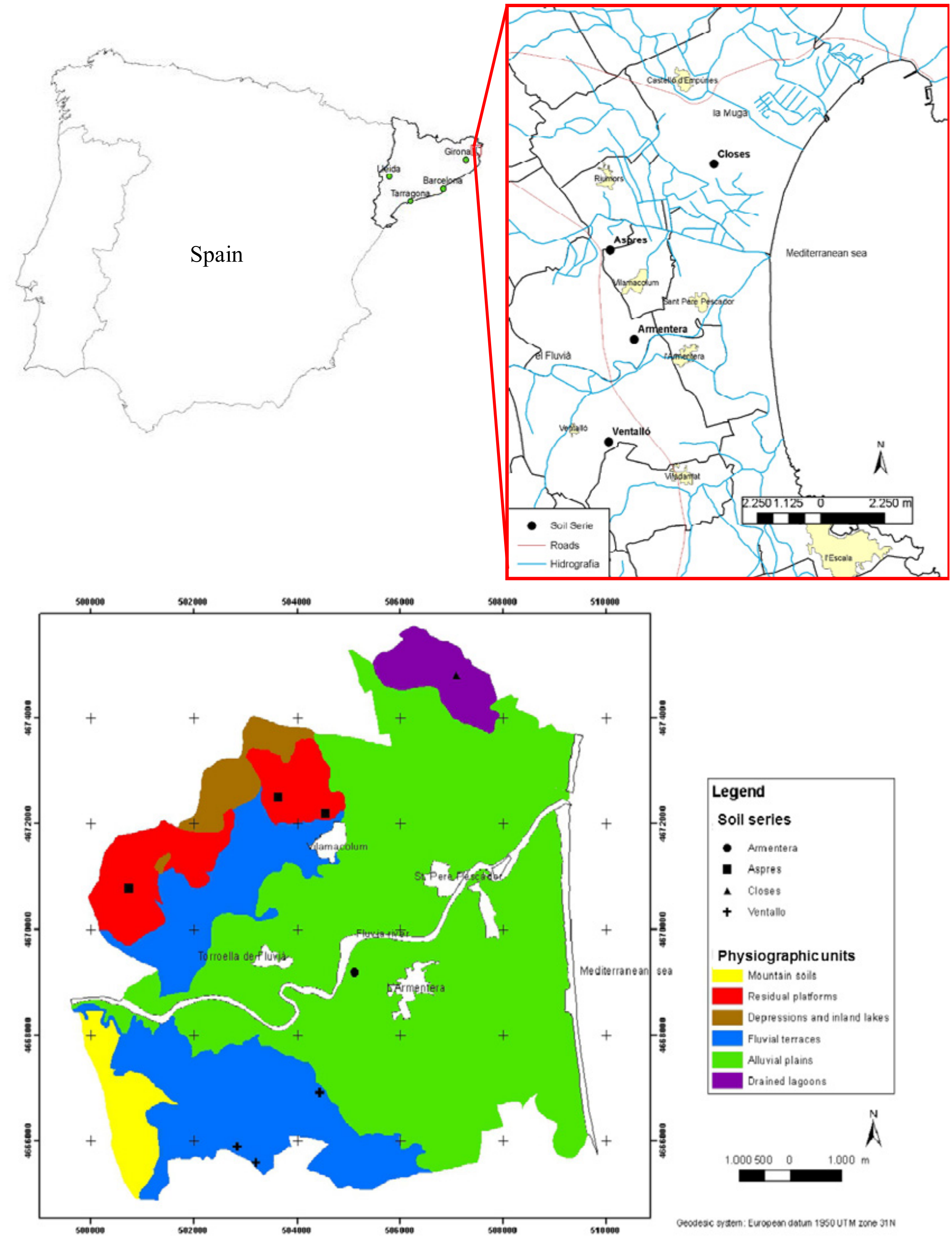

**Figure 1**. Physiographic units of the study area and position of the studied profiles.

**Table 1.** Location, landform, geological unit, parent material and age of the geomorphic surface of the studied profiles

| **Soils and profiles (SSS 2014)** | | **Coordinates of the profile UTM (ED-56)** | | **Altitude a.s.l. (m)** | **Landform** | **Geological unit and parent material** | **Age of the geomorphic surface** |
|---|---|---|---|---|---|---|---|
| | | X | Y | | | | |
| **Aspres soils** | E-43 Typic Palexeralf | 500750 | 4670780 | 45 | Residual platform | Sant Mori alluvial system. Very poorly sorted deposits with metamorphic and quartzite fragments | Pliocene (SGC-ICC 1996) |
| | E-22 Typic Palexeralf | 504550 | 4670780 | 12 | Residual platform | Sant Climent delta fan. Very poorly sorted quartzitic and schist deposits | Upper Pliocene > 2.5 My (SGC-ICC 1996) |
| | B8-9 Vertic Palexeralf | 503650 | 4672500 | 14 | Residual platform | Sant Climent delta fan. Very poorly sorted quartzitic and schist deposits | Upper Pliocene > 2.5 My (SGC-ICC 1996) |
| | E-30 Petrocalcic Palexeralf | 500780 | 4671300 | 35 | Residual platform | Fluvià alluvial fan. Lutites and poorly sorted deposits with limestone and granites | Pliocene (SGC-ICC 1995) |
| **Ventalló soils** | B8-8 Petrocalcic Palexeralf | 502850 | 4665900 | 33 | River terrace | Fluvià Quaternary alluvial fan. Alluvial and coluvial deposits; reddish-brown clays and silty sands with gravel lenses | Upper Pleistocene (30,000 Ky) (IGME 1983) Pleistocene (SGC-ICC 1995) |
| | E-135 Petrocalcic Palexeralf | 503220 | 4665600 | 35 | River terrace | Fluvià Quaternary alluvial fan. Alluvial and coluvial deposits; reddish-brown clays and silty sands with gravel lenses | Upper Pleistocene (30,000 Ky) (IGME 1983) Pleistocene (SGC-ICC 1995) |
| | E-112 Petrocalcic Palexeralf | 502780 | 4662800 | 18 | River terrace | Fluvià Quaternary alluvial fan. Alluvial and coluvial deposits; reddish-brown clays and silty sands with gravel lenses | Upper Pleistocene (30,000 Ky) (IGME 1983) Pleistocene (SGC and ICC 1995) |
| **Armentera soils** | B8-10 Typic Xerofluvent | 505120 | 4669200 | 6 | Alluvial plain/levee | Baix Fluvià alluvial fan. Silt with some sandy levels, light brown to grey | Holocene < 2Ky (Montaner et al. 2014) |
| **Closes soils** | 26CTP-80 Sodic Calcixerept | 507107 | 4674804 | -0.2 | Flood plain: drained lagoons | Baix Fluvià-La Muga flood plain inter flood plain lobes (Estany de Sant Pere). Grey-black clays and silty clays | Holocene (Montaner et al. 2014) |

alluvial flood plain, made of fine-textured deposits. They show different degrees of salinity and drainage conditions depending on local topography and sedimentary environments. They include paludal areas reclaimed in historical times, locally named closes. In some other cases these areas are related to the prograding coastal dune system. The lagoon system is located in the lobes of the rivers and although their reclamation (drainage) started in the XV century, it was accomplished in the XIX century in the case of the Estany (pond) de Sant Pere (Serra et al. 1994). The sediments are silts and clays with some organic matter and salts due to their former connection with the sea.

Around 5,000 years BP the sea level reached similar levels to the present (Riba 1981) and the growth of the present Mediterranean deltas started. We should mention the fact that according to Montaner et al. (2014) the dynamics of the sea has been transgressive for at least 4,000 years.

The deposits where Armentera soils have developed (Table 1) form the levee of the Fluvià river, with an age younger than 2,000 years BP according to the studies carried out by Montaner et al. (2014) in the Empordà floodplain. The progradation of the Fluvià river created lateral contact depressions where palustrine or flooding environments dominated (Montaner and Solà 1998). These lagoon deposits, according to Montaner et al. (2014) are younger, have a high organic matter content and salinity, and reflect the influence of aeolian and alluvial sedimentation.

Finally, well-developed dune systems exist. Two different ones, the continental and the coastal, may be identified (Marquès et al. 2011). The first one is furnished by the alluvial plain and the second by the sand coming from the sea coast (Sainz-Amor and Julià 1999). The area has very favourable conditions for the development of such systems: the abundant fluvial deposits and the strong NNE-N wind locally called *Tramontana*.

## 3. Materials

The investigated soils were selected by taking into account the main soil types existing in the area, the main landforms and the known soil-landscape relationships (Table 2). Some of them (the benchmark ones) were studied in more detail and the results are presented in the main body of this article. Information about other profiles is presented as supplementary material. These soils are developed on different geomorphic units with different parent materials (Table 1) and may be summarized as follows:

**Soils of the older surfaces (Pliocene) (Aspres soils)** (Table 1). The most extensive soils developed on the Pliocene terrestrial sediments belong to the Aspres series, a Typic Palexeralf. Other soils (Aspres variants) show either vertic features (Vertic Palexeralf), are acidic or, in some small depressions, have poor drainage. When developed on calcareous parent material they have a petrocalcic horizon (Petrocalcic Palexeralf).

**Soils of the Fluvià terraces and related surfaces (Pleistocene) (Ventalló soils)** (Table 1). The terraces of the Fluvià River and

**Table 2.** Soil types in the Baix Fluvià area, typical horizon sequence and main soil features

| Physiographic unit | Soils (SSS, 2014) (+ main; - minor) | Typical horizon sequence | Main soil features[1]: clay features (Cl), rubefaction (RB), calcareous/non-calcareous (C/NC), redoximorphic (RX) |
|---|---|---|---|
| Hills | Typic Calcixerept (+)<br>Calcic Palexeralf (-)<br>Calcic Haploxeralf (-)<br>Petrocalcic Calcixerept (-) | Ap-Bk<br>A-Bt-Btk<br>A-Bt-Btk<br>Ap-Bkm | RB,C<br>Cl, RB, NC (40)/C<br>Cl, RB, NC (65)/C<br>C |
| Pliocene surfaces | Typic Palexeralf (+)<br>Petrocalcic Palexeralf (+)<br>Mollic Palexeralf (-)<br>Vertic Palexeralf (-)<br>Calcic Palexeralf(-)<br>Petrocalcic Calcixerept (-)<br>Typic Calcixerept (-) | A-Bt<br>A-Bt-Bkm<br>A-Bt-Btg<br>A-Bt<br>A-Bt-Btkc<br>Ap-Bkm<br>Ap-C-Ckc | Cl, RB, NC<br>Cl, RB, NC (Bkm)/C<br>Cl,NC<br>Cl, NC, RX<br>Cl, RB, NC (95)/C<br>RB, C<br>C |
| Pleistocene terraces and related surfaces | Petrocalcic Palexeralf (+)<br>Petrocalcic Calcexerept (+)<br>Taphto-alfic Xerofluvent (-)<br>Petrocalcic Rhodoxeralf (-) | Ap-Bt-Bkm-Btkc<br>Ap-Bkm<br>Ap-Bw-2Bt<br>Ap-Bt-Bkm | Cl, RB, NC (Bkm)/C<br>RB, C<br>Cl, RB, C<br>Cl, RB, C |
| Former inland lakes and depressions | Gypsic Haploxerept (+)<br>Petrocalcic Calcixerept (-) | Ap-Bw-2Aby-2Bwy-2Bw<br>Ap-C-Bkm | C<br>C, RX |
| Holocene alluvial plain and delta | Typic Xerofluvent (+)<br>Oxiaquic Xerofluvent (+)<br>Aquic Xerofluvent (+)<br>Aquic Calcixerept (-)<br>Sodic Calcixerept (-) | Ap-Bw-C<br>Ap-Bw-C<br>Ap-Bw-Bwg-C<br>Ap-Bw-Bwkc-C<br>Ap-Btkcn-Btn-C | C<br>C, RX<br>C, RX<br>C, RX<br>Cl, C, RX |

[1] RB: 5YR or redder; NC (xx): non calcareous up to this depth (cm); NC (Bkm): non calcareous up to this horizon.

related surfaces are occupied by red soils that appear in some cases clearly buried by colluvial materials, close to the footslope of the Ventalló and Valldevià mountains. Most of this area has soils with a petrocalcic horizon (Boixadera et al. 1990). They are mostly loamy Petrocalcic Palexeralfs (Ventalló series) and Calcixerepts and a very few Rhodoxeralfs (Table 2). The Palexeralfs merge gradually into the recent flood plain, as it occurs near Viladamat but also in the northern part of the area.

**Soils of the (sub)recent (Holocene) alluvial plain (Armentera soils)**. The Armentera soils are very deep, calcareous, well drained soils, with an Ap-Bw-C horizon sequence, being classified as Typic Xerofluvents (Armentera series) (Table 1). They are developed on the Fluvià alluvial plain and are all irrigated.

**Soils of the inter floodplain (Holocene) lobes (Closes soils)**. These soils are developed on the paludal sediments of the drained lagoons. The Closes soils includes imperfectly drained soils with calcium carbonate accumulations as nodules and other hard concretions at about 50 cm depth (Closes variant). They are located in depressions that used to be pastures surrounded by trees, a land use type locally named closa (from where the series name), but nowadays they are also used for irrigated field crops. They are classified as Sodic Calcixerepts (Table 1).

This study uses information from Boixadera et al. (1990) and also from other surveys nearby (Carrillo et al. 1999; Margarit et al. 1993), all of them from the 1:25,000 Catalonia Soil Map, as well as from studies about soil-vegetation relationships (Porta et al. 1994). Soil series in the Catalonia Soils Map were defined following the concept of Boulaine (1980) and SSS (1993) and their classification and names are used throughout this paper. The criteria to define the soil series were parent material, drainage class, particle size distribution, genetic horizons, content of calcium carbonate and soil classification according to Soil Taxonomy (Boixadera et al. 1989 and DARP-ICC 1993). The concept of “variant” was used following Soil Survey Manual (SSS 1993).

# 4. Methods

The studied profiles (Table 1, Figure 1) were described following the guidelines of SINEDARES (CBDSA 1983). Genetic horizon nomenclature follows Soil Taxonomy (SSS 2014). Samples were taken for physicochemical and mineralogical analyses. Undisturbed samples were collected at selected profiles and horizons for micromorphological analyses. The physicochemical analyses of the profiles were done according to MAPA (1993): soil pH was measured in a suspension 1:2.5 (soil:deionized water); electrical conductivity was measured with a conductimeter in a suspension 1:5 (soil:deionized water) at 25 ºC, and calcium carbonate equivalent was determined with a Bernard calcimeter. Particle size distribution was determined by the pipette method, after organic matter removal with $H_2O_2$ and dispersion with Na-hexametaphosphate. Cation exchange capacity was determined by displacement with 1 M $NH_4OAc$ (pH 7), and the exchangeable cations were measured by atomic absorption. Organic carbon and total nitrogen were determined following Walkley-Black and Kjeldahl methods respectively. Salinity analyses of the saturated paste extract were performed in one of the profiles, according to Richards (1954). Soils were classified according to Soil Taxonomy (SSS 2014) and Soil Taxonomy diagnostic horizons, and their terminology is used throughout the paper. The classification according World Reference Base (IUSS Working Group WRB 2014) is given (Table 3) only for correlation.

Micromorphology was performed according to the procedures of Benyarku and Stoops (2005) for making vertical thin sections, 13 cm long and 5.5 cm wide, from air-dried undisturbed soil blocks. Stoops (2003) guidelines were followed for their description and study.

Total iron was determined after digestion by HCl and $HNO_3$ (Amacher 1996). Dithionite soluble Fe was determined in an extraction with sodium citrate 17% + sodium dithionite 1.7% buffered with sodium bicarbonate method according to Mehra and Jackson (1960). Oxalate extractable Fe and Al were determined by extraction with acid ammonium oxalate 0.2 M at pH 3 (Schwertmann

1964). In all extracts, Fe was determined by atomic absorption.

Reddening was assessed as a colour (moist) index the redness index by **equation 1**

| **Eq 1** | RI= [(25-nhue) * chroma]/value |
|---|---|

modified from Hurst (1977) with the constant increased from 10 to 25 following Martín-García et al. (1998) and nhue value being: 10YR = 10; 7.5YR = 7.5; 5YR = 5; 2.5YR = 2.5; 10R = 0.

We calculated Fe index (Wagner et al. 2014) defined as Fe index in **equation 2**

| **Eq 2** | Fe index = (%Fed - %Feox)/(%Fet/%Clay) |
|---|---|

being Fed: Fe extracted with citrate-dithionite; Feox: Fe extracted with ammonium oxalate; and Fet: total Fe.

Semi-quantitative clay mineralogy was carried out through X-ray diffraction, using a Siemens D-500 diffractometer. The clay samples were treated with acetic acid 0.5 N to remove the carbonates and prepared as powder, oriented air-dry samples, and heated at 500 ºC during 3 hours.

The mineralogy of fine and coarse sand was done by separation of heavy and light minerals after elimination of carbonates and iron oxides (Stoops 1987). Light minerals were stained using the method of Bailey and Stevens (1960), and minerals identified and counted under the petrographic microscope at 2x to 10x magnifications. Heavy and light minerals of the sand fractions were counted over 50 and 100 grains respectively.

# 5. Results

## 5.1. Soil properties

**Table 2** presents the soil types of the Baix Fluvià area, their horizons sequences and the identified soil features. The main soil forming processes are redistribution (leaching, accumulation and cementation) of calcium carbonate, clay illuviation, rubefaction and sodication.

In **Tables 3, 4, S1, S2** and **S3** the main morphological, physicochemical and mineralogical characteristics of the studied of soils are shown.

***Soils of the Pliocene surface. Aspres soils.*** Some of the most prominent features of these soils are the strong abrupt textural change from the coarser, whitish topsoil to the clayey subsoil. The typical horizon sequence is A-Bt with or without textural discontinuities visible in the field (**Table 3, Table S1**). All the profiles have a large content of coarse elements: the whitish topsoil (up to 40-60 cm in some cases) contains only quartzitic rocks and the Bt horizon contains, in addition to that, weathered granites and schists in a clayey matrix. The weathering of granites is especially noticeable, with even the larger blocks down being disaggregated to sand and gravel particles. Profile B8-9 (Aspres variant) has redoximorphic features from 80 cm down with chroma 1; it has also slickensides from 55 cm down (Btss).

When the soil is developed on calcareous parent materials a Bkm horizon appears. The Bt horizon qualifies for argillic horizon. The base saturation is high; therefore the soils never qualify for an Ultic subgroup.

***Soils of the Pleistocene surface. Ventalló soils.*** The profile B8-8 (Ventalló series) is developed on an old terrace (Pleistocene) of the Fluvià river (**Table 2**). The Ventalló series has a central position in the wide range of soils of the terraces. It is a complex profile, only slightly calcareous at the surface, and with a petrocalcic horizon at some depth (**Table 3**). It is classified as a Petrocalcic Palexeralf.

**Table 3.** Morphological characteristics of the studied benchmark profiles: Aspres and Ventalló

| Soil, profile number and classification (SSS 2014; IUSS WRB 2014) | Horizon | Depth (cm) | Sand | Silt | Clay | Texture$^1$ USDA | Colour (moist) | R.I.$^2$ | Coarse fragments Ø$^3$ > 2 mm (volume %) | Soil structure | Main features |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | (%) | | | | | | | |
| **Aspres variant, B8-9, Vertic Palexeralf**<br>**Vertic Abruptic Skeletic Luvisol (Clayic, Cutanic, Hypereutric)** | Ap | 0-22 | 43.7 | 36.9 | 16.4 | L | 10YR3/3 | 15 | 16-35 | Subangular blocky | Coarse fragments: unweathered quartzites |
| | A2 | 22-33 | 46.0 | 24.6 | 29.3 | SCL | 10YR5/3 | 9 | > 70 | Subangular blocky | Coarse fragments: unweathered quartzites |
| | 2Bt | 33-55 | 21.0 | 8.5 | 70.4 | C | 7.5YR5/8 | 28 | > 70 | Blocky to prismatic, fine | Frequent clay coatings, coarse fragments: unweathered quartzites |
| | 3Btss | 55-80 | 31.3 | 13.0 | 57.7 | C | 10YR6/8 | 20 | 16-35 | Blocky to prismatic, fine | Frequent clay coatings, some slickensides and pressure faces, unweathered quartzites |
| | 4Bt | 80-230 | 53.4 | 15.0 | 31.5 | SCL | 10YR6/8 | 20 | > 70 | | Frequent clay coatings, some slickensides and pressure faces; mottling (7.5 YR 7/1), frequent pisoliths (Fe and Mn); very many coarse fragments highly weathered granites and schists, unweathered quartzites. |
| **Ventalló series, B8-8, Petrocalcic Palexeralf**<br>**Chromic Luvisol (Loamic, Colluvic Regosol, Cutanic, Hypereutric, Petrocalcic)** | Ap | 0-23 | 64.8 | 17.9 | 17.3 | SL | 7.5YR4/6 | 26 | 5-15 | Strong, granular, medium | Coarse fragments; polygenic and petrocalcic fragments |
| | AB | 23-48 | 64.8 | 17.6 | 17.7 | SL | 5YR3/6 | 40 | 5-15 | Weak, subangular blocky, medium | Coarse fragments; unweathered polygenic |
| | 2Bt | 48-80/99 | 46.0 | 19.8 | 34.1 | SCL | 2.5YR4/6 | 34 | 5-15 | Strong, subangular blocky, medium | Frequent clay coatings and clay bridges between grains; coarse fragments: unweathered subrounded-spheroidal poligenic |
| | 2Bkcm | 80/99-103/107 | - | - | - | - | - | - | - | - | Moderately cemented by carbonate, banded hard and soft nodules; coarse fragments in the petrocalcic horizon |
| | 3Btkc$_1$ | 103/107-163 | 52.8 | 22.5 | 24.7 | SCL | 2.5YR5/8 | 36 | 1-5 | Moderate, subangular blocky | Few clay coatings, very abundant carbonate nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal polygenic |
| | 3Btkc$_2$ | 163-213 | 52.4 | 19.7 | 27.9 | SCL | 2.5YR5/6 | 27 | 1-5 | Weak, subangular blocky, medium | Frequent clay coatings, frequent carbonate nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal polygenic |
| | 4Btkc$_3$ | 213-269 | 54.2 | 22.8 | 23.0 | SCL | 5YR6/6 | 20 | 1-5 | Weak, subangular blocky, medium | Frequent clay coatings and abundant clay bridges, frequent CaCO$_3$ nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal polygenic |

[1] Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam; [2] R.I.: Redness Index; [3] Ø: diameter.

The horizon sequence in the Ventalló soil is A-2Bt-2Bkm-3Btkc, with other soils showing calcium carbonate accumulation above or below the Bkm horizon (**Tables S2 and S3**). The Bt horizon qualifies for an argillic horizon.

***Soils of the alluvial plain. Armentera soils.*** The profile B8-10 belongs to the Armentera series. It shows a clear fluventic character, and charcoal fragments are found at some depth. It is classified as Typic Xerofluvent. The horizon sequence is A-Bw-C. The Bw horizon does not qualify for a cambic horizon.

***Soils of the drained lagoons. Closes soils.*** Profile 26-CTP-80 belongs to a variant of the Closes series. It is the only salt-affected soil that has been studied (**Table 4**). Besides redoximorphic features starting at 32 cm depth, it also presents sodic conditions (**Table 9**). They are classified as Sodic Calcixerepts.

**Table 4.** Morphological characteristics of the studied benchmark profiles: Armentera and Closes

| Soil, profile number and classification (SSS 2014; IUSS WRB, 2014) | Horizon | Depth (cm) | Sand | Silt | Clay | Texture[1] USDA | Colour (moist) | R.I.[2] | Coarse fragments Ø[3] > 2 mm (volume %) | Soil structure | Main features |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (%) | | | | | | | | |
| **Armentera series B8-10 Typic Xerofluvent**<br>**Calcaric Orthofluvic Fluvisol (Siltic)** | Ap | 0-22 | 37.7 | 46.6 | 15.7 | L | 10YR4/6 | 23 | Absent | - | - |
| | $Bw_1$ | 22-33 | 32.6 | 51.4 | 16.0 | SiL | 10YR4/6 | 23 | Absent | Moderate, subangular blocky, medium | - |
| | $Bw_2$ | 33-55 | 28.8 | 54.7 | 16.5 | SiL | 10YR4/6 | 23 | Absent | Moderate, subangular blocky, medium | Very few carbonate pseudomycelia |
| | $Bw_3$ | 55-80 | 33.2 | 50.7 | 16.1 | SiL | 7.5YR4/4 | 18 | Absent | Moderate, subangular blocky, medium | Very few carbonate pseudomycelia |
| | $Bw_4$ | 80-230 | 27.5 | 52.5 | 20.0 | SiL | 10YR4/6 | 23 | Absent | - | |
| **Closes variant 26CTP-80 Sodic Calcixerept**<br>**Haplic Calcisol (Fluvic, Hypocalcic, Loamic, Epiprotosalic, Sodic, Alcalic)** | $Ap_1$ | 0-13 | 13.4 | 49.3 | 37.3 | SCL | 10YR4/3 | 11 | Absent | Very weak, subangular blocky, medium | Vertical cracks, 1 cm width |
| | $Ap_2$ | 13-32 | 15.9 | 45.0 | 39.1 | SCL | 10YR4/3 | 11 | Absent | Weak, subangular blocky, medium | - |
| | Btkcn | 32-82/96 | 24.0 | 42.4 | 33.6 | CL | 10YR5/4 | 12 | Absent | Strong, prismatic, medium | Frequent mottling, frequent soft and hard carbonate concretions, Fe and Mn concretions |
| | 2Btn | 82/96-96 | 50.8 | 28.3 | 20.9 | L | 10YR5/6 | 18 | Absent | Very weak, subangular blocky | Frequent coatings on ped faces, frequent mottling |
| | 3Btkcn | 96-130 | 79.3 | 9.6 | 11.1 | SL | 10YR5/6 | 18 | Absent | Moderate, prismatic, coarse | Frequent coatings on ped faces, frequent mottling, hard carbonate and Fe and Mn concretions |

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SiL: silty loam; SL: sandy Loam; [2]R.I.: Redness Index. [3]Ø: diameter.

**Table 5.** Chemical characteristics of the studied benchmark profiles

| Soil, profile number and classification (SSS 2014) | Horizons | pH $H_2O$ 1:2.5 | EC[1] 1:5 (dS/m, 25 ºC) | $CaCO_3$ eq. (%) | OC[2] (%) | CEC[3] (cmol$_{(+)}$/kg) | V[4] (%) | Exchangeable cations (cmol$_{(+)}$/kg) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ |
| **Aspres variant, B8-9**<br>**Vertic Palexeralf** | Ap | 6.1 | 0.19 | - | 2.3 | 12.3 | 100 | 9.7 | 1.2 | 0.2 | 1.2 |
| | A$_2$ | 6.3 | 0.11 | - | 0.6 | 13.6 | 88 | 9.6 | 1.5 | 0.2 | 0.7 |
| | 2Bt | 6.9 | 0.11 | - | - | 23.1 | 100 | 18.3 | 3.8 | 0.3 | 0.7 |
| | 3Btss | 7.5 | 0.14 | - | - | 21.2 | 100 | 17.0 | 3.5 | 0.3 | 0.4 |
| | 4Bt | 7.5 | 0.16 | - | - | 14.9 | 100 | 11.3 | 3.2 | 0.2 | 0.2 |
| **Ventalló series, B8-8**<br>**Petrocalcic Palexeralf** | Ap | 8.1 | 0.15 | 6.5 | 1.4 | 9.3 | 100 | 8.4 | 0.5 | 0.1 | 0.3 |
| | AB | 8.1 | 0.13 | 6.5 | 0.5 | 8.1 | 100 | 7.4 | 0.4 | 0.1 | 0.3 |
| | 2Bt | 8.0 | 0.12 | 1.5 | 0.3 | 13.6 | 100 | 12.5 | 0.8 | 0.1 | 0.3 |
| | 2Bkcm | - | - | 57.2 | - | - | - | - | - | - | - |
| | 3Btkc$_1$ | 8.5 | 0.11 | 23.6 | - | 10.8 | 100 | 9.5 | 0.7 | 0.4 | 0.2 |
| | 3Btkc$_2$ | 8.4 | 0.11 | 29.1 | - | 10.3 | 100 | 9.3 | 0.6 | 0.2 | 0.2 |
| | 4Btkc$_3$ | 8.4 | 0.12 | 6.2 | - | 10.9 | 100 | 9.8 | 0.6 | 0.2 | 0.2 |
| **Armentera series, B8-10**<br>**Typic Xerofluvent** | Ap | 8.1 | 0.16 | 30.8 | 1.2 | 8.5 | - | - | 0.9 | - | - |
| | Bw$_1$ | 8.3 | 0.13 | 21.6 | 0.3 | 6.1 | - | - | 0.9 | - | - |
| | Bw$_2$ | 8.3 | 0.13 | 31.3 | 0.2 | 6.0 | - | - | 1.1 | - | - |
| | Bw$_3$ | 8.2 | 0.26 | 27.2 | 0.2 | 6.1 | - | - | 2.1 | - | - |
| | Bw$_4$ | 8.2 | 0.27 | 27.1 | 0.3 | 6.2 | - | - | 2.7 | - | - |
| **Closes variant,**<br>**26CTP-80**<br>**Sodic Calcixerept** | Ap$_1$ | 8.9 | 0.89 | 21.0 | 2.1 | 14.2 | - | - | - | - | - |
| | Ap$_2$ | 9.4 | 1.20 | 19.9 | 1.7 | 14.1 | - | - | - | - | - |
| | Btkcn (32-64) | 9.6 | 0.77 | 19.1 | 0.3 | 9.3 | - | - | - | - | - |
| | Btkcn (64-96) | 9.6 | 0.74 | 19.2 | 0.2 | 9.1 | - | - | - | - | - |
| | 2Btn | 9.5 | 0.85 | 19.9 | 0.3 | 9.6 | - | - | - | - | - |
| | 3Btknc | 9.5 | 0.86 | 19.8 | 0.3 | 14.1 | - | - | - | - | - |

[1]EC: electrical conductivity; [2]OC: organic carbon; [3]CEC: cation exchange capacity; [4]V: base saturation.

The horizon sequence is A-Btkcn-2Btn-3Btkcn. The Btn horizons neither qualify for a natric nor argillic horizon. The Btkcn horizon has calcium carbonate nodules.

In all profiles, clay mineralogy (**Table 5**) is dominated in all cases by illite. There is a very significant amount of kaolinite in the *Aspres* soil. Smectite is present only in very low amounts in the same profile and is absent in the rest. Fleta and Escuer (1991) mentioned the presence of smectite in the Pliocene parent materials. Pardini and Gispert (2013) noted the presence of montmorillonite in a profile belonging to the Closes series, with similar parent material and geomorphological age to the Armentera soil.

The sand mineralogy of the Aspres and Ventalló soils (**Table 6**) shows a predominance of quartz in the light fraction. The distribution of heavy minerals with depth, mostly opaques and minerals typical for metamorphic rocks in profile B8-9 (Aspres variant) confirms the lithological discontinuities observed in the field in this

**Table 5.** Semi-quantitative clay mineralogy (X-ray diffracion) of selected horizons of the benchmark Baix Fluvià soils (relative %; tr: traces; nd: non detected)

| Soil, profile | Horizon | Depth (cm) | Minerals | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Quartz | Feldspar | Calcite | Goethite | Illite | Kaolinite | Smectite | Chlorite |
| **Aspres**<br>**B8-9** | Ap | 0-22 | 9 | 6 | nd | 2 | 70 | 13 | nd | nd |
| | 2Bt | 33-55 | tr | tr | nd | 3 | 72 | 25 | tr | nd |
| | 3Btss | 55-80 | tr | tr | nd | 3 | 73 | 23 | tr | nd |
| **Ventalló**<br>**B8-8** | Ap | 0-23 | 6 | 5 | tr | 4 | 72 | 5 | nd | 8 |
| | 2Bt | 48-80 | 6 | 4 | nd | 2 | 80 | 8 | nd | nd |
| **Armentera B8-10** | Ap | 0-27 | 4 | 3 | 18 | 2 | 66 | 7 | nd | tr |
| | Bw1 | 27-72 | 7 | 5 | 22 | 2 | 59 | 5 | nd | tr |

**Table 6.** Sand mineralogy: profiles B8-9 (Aspres variant) and B8-8 (Ventalló series)

| Heavy and light minerals | Profiles and horizons | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | B8-9 | | | B8-8 | | | | | |
| | Ap | 2Bt | 3Btss | Ap | AB | 2Bt | 3Btkc$_1$ | 3Btkc$_2$ | 4Btkc$_3$ |
| **Heavy minerals in fine sand** | | | | | | | | | |
| Opaques | 32 | 14 | 19 | 26 | 26 | 28 | 39 | ne[1] | ne |
| Zircon | | 1 | | | 4 | | 2 | ne | ne |
| Rutile | 2 | 1 | 1 | | | | | ne | ne |
| Kyanite | 2 | 3 | 1 | 4 | 2 | 2 | | ne | ne |
| Sillimanite | | 2 | 3 | 2 | 1 | | | ne | ne |
| Andalusite | 5 | 3 | 5 | 3 | 1 | 3 | | ne | ne |
| Staurolite | | 1 | 1 | | 1 | | 1 | ne | ne |
| Garnet | 2 | 3 | 4 | 1 | | 1 | 1 | ne | ne |
| Hornblende | | 11 | 3 | 1 | 2 | 2 | 1 | ne | ne |
| Augite | | 1 | 1 | | 1 | 1 | | ne | ne |
| Epidote | 2 | 2 | | 1 | 2 | 1 | | ne | ne |
| Diopside | | | | 2 | 5 | | | ne | ne |
| Hyperstene | 2 | | | | | 1 | | ne | ne |
| Chlorite | | 1 | 5 | | | | | ne | ne |
| Rock fragments | 1 | 4 | 4 | 4 | 1 | 1 | | ne | ne |
| Alterites | 2 | 3 | 3 | 6 | 4 | 10 | 6 | ne | ne |
| **Light minerals in fine sand** | | | | | | | | | |
| Quartz | 56 | 80 | 58 | 57 | 56 | 69 | 55 | 56 | 60 |
| K-feldspars | 17 | 12 | 6 | 11 | 13 | 14 | 12 | 9 | 16 |
| Ca-feldspars | 27 | 8 | 36 | 32 | 31 | 17 | 33 | 35 | 24 |
| **Light minerals in coarse sand** | | | | | | | | | |
| Quartz | 56 | 39 | 35 | 41 | 42 | 44 | 30 | 46 | 40 |
| K-feldspars | 10 | 8 | 9 | 5 | 13 | 8 | 6 | 2 | 8 |
| Ca-feldspars | 9 | 12 | 12 | 28 | 27 | 28 | 32 | 24 | 30 |
| Rock fragments (mainly quartzite) | 25 | 41 | 44 | 26 | 18 | 20 | 32 | 28 | 22 |

[1]ne: not enough grains for counting.

**Table 7.** Clay-free sand and silt particle size distribution of profiles B8-9 (Aspres variant) and B8-8 (Ventalló series)

| Soil, profile | Horizon | Sand (diameter, mm) | | | | | | Silt (diameter, mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2.00-1.00 | 1.00-0.50 | 0.50-0.25 | 0.25-0.10 | 0.10-0.05 | Total 2.00-0.05 | 0.05-0.02 | 0.020-0.002 | Total 0.050-0.002 |
| **Aspres variant, B8-9** | Ap | 4.5 | 9.2 | 11.0 | 12.4 | 17.1 | 54.2 | 22.7 | 23.1 | 45.8 |
| | A$_2$ | 18.6 | 13.6 | 10.2 | 13.2 | 13.2 | 65.2 | 15.0 | 19.8 | 34.8 |
| | 2Bt | 13.9 | 13.2 | 13.2 | 15.6 | 15.6 | 71.2 | 15.6 | 13.2 | 28.8 |
| | 3Btss | 12.4 | 15.1 | 15.6 | 12.2 | 12.2 | 70.7 | 14.4 | 14.9 | 29.3 |
| | 4Bt | 0.6 | 23.2 | 16.2 | 10.2 | 10.2 | 78.1 | 11.3 | 10.7 | 21.9 |
| **Ventalló series, B8-8** | Ap | 31.9 | | 48.3 | | | 80.1 | 10.9 | 9.0 | 19.9 |
| | AB | 31.5 | | 50.1 | | | 81.6 | 8.7 | 9.7 | 18.4 |
| | 2Bt | 25.5 | | 46.5 | | | 71.9 | 12.6 | 15.5 | 28.1 |
| | 2Bkcm | - | | - | | | - | - | - | |
| | 3Btkc$_1$ | 22.5 | | 44.4 | | | 67.0 | 14.0 | 19.0 | 33.0 |
| | 3Btkc$_2$ | 19.8 | | 44.5 | | | 64.2 | 14.9 | 20.9 | 35.8 |
| | 4Btkc$_3$ | 23.3 | | 42.6 | | | 65.9 | 14.5 | 19.6 | 34.1 |

profile. These discontinuities are supported by the particle size analyses of the clay-free fine earth of these profiles (**Table 7**) and of additional profiles of the Aspres and Ventalló soils (**Table S5**), where there is more than 5% difference at the discontinuities in most of the fractions.

**Table 8** displays the different content of iron oxides of the studied soils as well as their ratios. When interpreting these data we have to consider the different mineralogy of the parent materials: total iron and Fet/Clay is very variable in the studied soils. The Bt horizons have in general higher weathering indexes (Fedt/Fet) ratios, while the ratio of crystalline iron to total iron (Fedt-Feox)/Fet is higher in Bt than in Bw horizons. Also, crystalline iron is much higher in Bt than in other B horizons (Btkc, Btkcn, Btn, Bw). Poorly crystalline iron (Feox) is higher in topsoils, younger soils and poorly drained soils. According to Blume and Schwertmann (1969) the low crystallinity in the topsoils is due to organic matter. The free iron (Fedt) is higher in the Bt horizons of older soils (Aspres and Ventalló). Btkc horizons of old soils as well as the B horizons of recent soils have lower Fedt contents.

**Table 8.** Total iron and forms of iron of the studied soils

| Profile | Horizon | Depth (cm) | Soil colour (matrix, moist) | R.I.[1] | Clay[2] (%) | $Fe_t$[3] (%) | $Fe_{dt}$[4] (%) | $Fe_{ox}$[5] (%) | $Fe_{dt}/Fe_t$ | $Fe_{ox}/Fe_t$ | $Fe_{ox}/Fe_{dt}$ | $Fe_{dt}-Fe_{ox}$ | $Fe_t-Fe_{dt}$ | $(Fe_{dt}-Fe_{ox})/Fe_t$ | $Fe_{dt}/Clay$ | $Fe_t/Clay$ | Fe index[6] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aspres Variant B8-9** | Ap | 0-22 | 10YR3/3 | 15 | 16.4 | 1.77 | 1.01 | 0.13 | 0.57 | 0.07 | 0.13 | 0.88 | 0.76 | 0.50 | 0.06 | 0.11 | 8.0 |
| | $A_2$ | 22-33 | 10YR5/3 | 9 | 29.3 | 2.97 | 1.82 | 0.13 | 0.61 | 0.04 | 0.07 | 1.69 | 1.15 | 0.57 | 0.06 | 0.10 | 16.9 |
| | 2Bt | 33-55 | 7.5YR5/8 | 18 | 70.4 | 5.20 | 3.77 | 0.07 | 0.73 | 0.01 | 0.02 | 3.70 | 1.43 | 0.71 | 0.05 | 0.07 | 52.8 |
| | 3Btss | 55-80 | 10YR 6/8 | 15 | 57.7 | 4.66 | 2.99 | 0.07 | 0.64 | 0.02 | 0.02 | 2.92 | 1.67 | 0.63 | 0.05 | 0.08 | 36.5 |
| **Ventalló series B8-8** | Ap | 0-23 | 7.5YR4/6 | 26 | 14.0 | 2.05 | 0.98 | 0.03 | 0.48 | 0.01 | 0.03 | 0.95 | 1.07 | 0.46 | 0.07 | 0.15 | 6.3 |
| | AB | 23-52 | 5YR3/6 | 40 | 14.8 | 2.05 | 1.16 | 0.05 | 0.57 | 0.02 | 0.04 | 1.11 | 0.89 | 0.54 | 0.08 | 0.14 | 7.9 |
| | 2Bt | 52-80 | 2.5YR4/6 | 34 | 34.8 | 3.53 | 2.08 | 0.08 | 0.59 | 0.02 | 0.04 | 2.00 | 1.45 | 0.57 | 0.06 | 0.10 | 20.0 |
| | $3Btkc_1$ | 107-163 | 2.5YR5/8 | 36 | 35.2 | 2.50 | 1.51 | 0.02 | 0.60 | 0.01 | 0.01 | 1.49 | 0.99 | 0.60 | 0.04 | 0.07 | 21.2 |
| | $3Btkc_2$ | 163-213 | 2.5YR5/6 | 27 | 36.8 | 2.37 | 1.56 | 0.03 | 0.66 | 0.01 | 0.02 | 1.53 | 0.81 | 0.65 | 0.04 | 0.06 | 25.5 |
| | $4Btkc_3$ | 213->269 | 5YR6/6 | 20 | 29.1 | 2.70 | 1.83 | 0.05 | 0.68 | 0.02 | 0.03 | 1.78 | 0.87 | 0.66 | 0.05 | 0.09 | 19.7 |
| **Armentera series B8-10** | Ap | 0-27 | 10YR4/6 | 23 | 15.7 | 2.11 | 0.88 | 0.10 | 0.42 | 0.05 | 0.11 | 0.78 | 1.23 | 0.37 | 0.06 | 0.13 | 6.0 |
| | $Bw_1$ | 27-72 | 10YR4/6 | 23 | 16.0 | 2.53 | 1.33 | 0.10 | 0.53 | 0.04 | 0.08 | 1.23 | 1.20 | 0.49 | 0.08 | 0.16 | 7.6 |
| | $Bw_2$ | 72-123 | 10YR4/6 | 23 | 16.5 | 2.69 | 1.40 | 0.11 | 0.52 | 0.04 | 0.08 | 1.29 | 1.29 | 0.48 | 0.08 | 0.16 | 8.9 |
| | $Bw_3$ | 123-167 | 10YR4/4 | 15 | 16.1 | 2.18 | 0.85 | 0.11 | 0.39 | 0.05 | 0.13 | 0.74 | 1.23 | 0.34 | 0.05 | 0.14 | 5.2 |
| **Closes variant 26CTP-80-20** | $Ap_2$ | 13-32 | 10YR4/3 | 11 | 38.8 | 3.50 | 1.26 | 0.17 | 0.36 | 0.05 | 0.13 | 1.09 | 2.24 | 0.31 | 0.03 | 0.09 | 12.1 |
| | Btkcn | 32-82 | 10YR5/3 | 9 | 33.6 | 3.38 | 1.50 | 0.10 | 0.44 | 0.03 | 0.07 | 1.40 | 1.88 | 0.41 | 0.04 | 0.10 | 14.0 |
| | 2Btn | 82-96 | 10YR5/6 | 18 | 20.9 | 3.61 | 1.74 | 0.10 | 0.48 | 0.03 | 0.06 | 1.64 | 1.87 | 0.45 | 0.08 | 0.17 | 9.5 |
| | 3Btkcn | 96-130 | 10YR5/6 | 18 | 36.2 | 3.90 | 1.90 | 0.14 | 0.49 | 0.04 | 0.07 | 1.76 | 2.00 | 0.45 | 0.03 | 0.11 | 16.0 |

[1]R.I.: Redness Index; [2]Clay: clay %, in profiles B8-9 (Aspres) and B8-8 (Ventalló) on carbonate-free fine earth; [3]$Fe_t$: total; [4]$Fe_{dt}$: extraction with dithionite-citrate; [5]$Fe_{ox}$: extraction ammonium oxalate; [6]Fe index = $(\%Fe_{dt} - Fe_{ox})/(\%Fe_t/\%Clay)$.

## 5.2. Micromorphology

***Aspres soils.*** The B8-9 profile (Aspres variant) is non-calcareous, which is shown in thin section in specific b-fabrics: stipple–speckled at the surface to progressively mosaic- and striated fabrics as clay content increases, reaching cross-striated fabrics (expression of slickensides described in the field) in depth (**Figure 2a**). These features indicate a micromass made of clays with some shrink-swell properties. The lithologic discontinuities observed in the field are expressed as different c/f ratios (proportion coarse/fine material), from 4/1 to 1/2 depending on the horizon. Coarse mineral grains are highly weathered, mainly in the deepest horizons, as is shown in the plagioclase and schist fragments, which show a strong pedoplasmation (**Figure 2b**); in the surface horizon such coarse mineral grains are absent. The complete micromorphological descriptions of the horizons are found in **Table S7**.

Clay illuviation is very well expressed in the most gravelly/sandy horizons, as coatings of grains and infillings of packing pores. The coatings are made of microlaminated clay, but with a moderate to strong degree of deformation due to the nature of the clays and the age of the soil (**Figures 2a, 2b**).

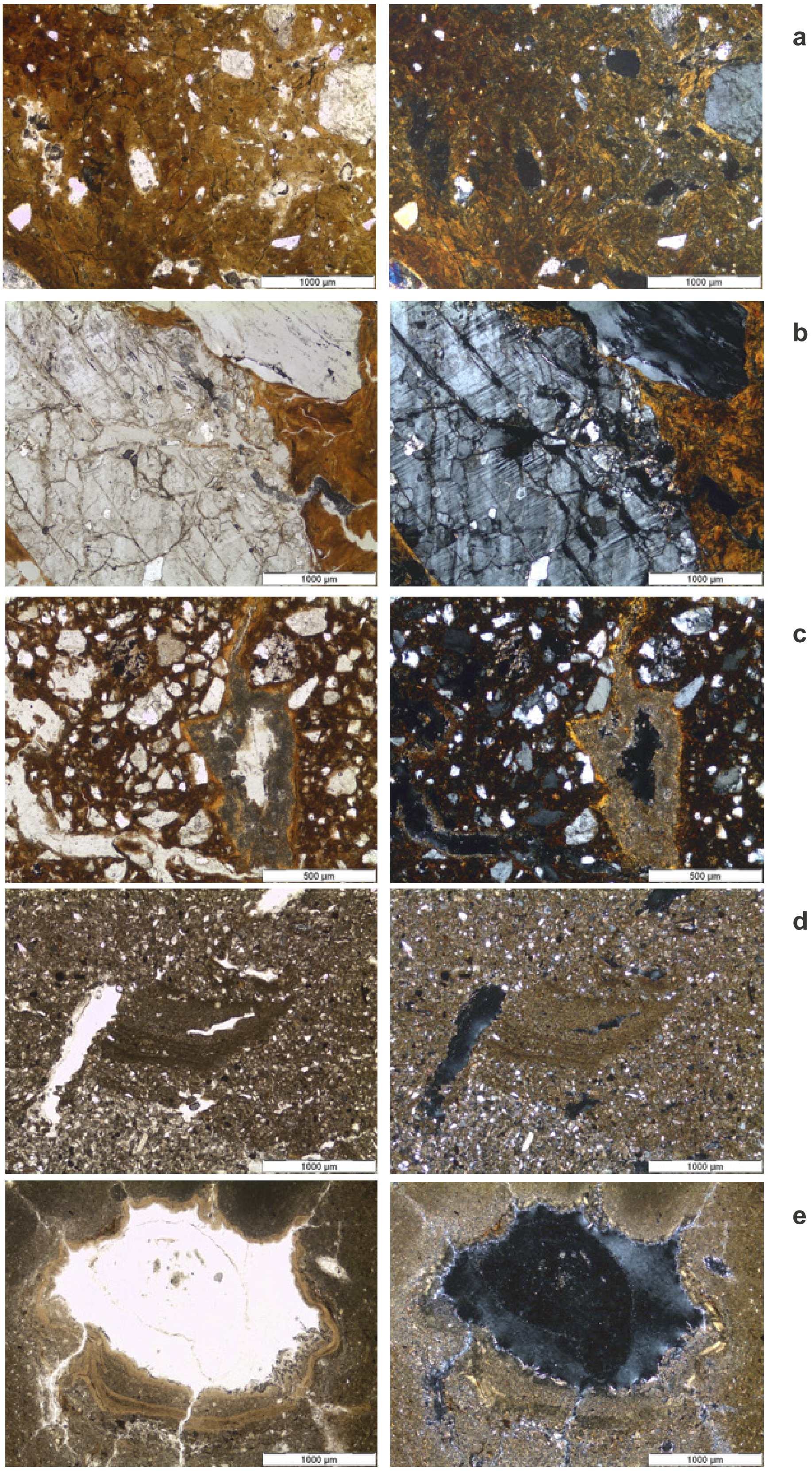

**Figure 2**. (a) Grano- and cross-striated b-fabric, 3Btss (60-80 cm), Aspres variant, profile B8-9; (b) Highly weathered plagioclases next to deformed clay coatings, 4Bt, Aspres variant, profile B8-9; (c) Coating of micrite on a previous clay coating, 3Btkc2, Ventalló series, profile B8-8; (d) Fragment of a crust-like layered material next to a channel, Bw3, Armentera series, profile B8-10; (e) Compound coatings of clay, silt and fine sand, 3Btkcn, 26CTP-80, Closes variant. Left: PPL; Right: XPL.

In-situ (orthic) nodules of Fe-oxihydroxides are found from 33 cm down, with no relation to the present-day pore system, which means this Fe mobilization is probably a palaeofeature formed during wetter periods, contemporary with the clay illuviation.

The Bt horizons of profile E-30 (Aspres variant, **Tables S1 and S3**) are made of quartzitic gravels and coarse sand, and a decarbonated micromass made of clay, fine silt and iron oxides. The c/f related distribution is mainly chitonic and close porphyric in some spots, with packing pores as main voids. In the latter, the b-fabric is mosaic-speckled and striated, which points to swelling clays as possible components of the micromass. Microlaminated clay coatings are ubiquitous around the coarse fragments. Some of them are deformed and mixed with the striated micromass. Another pedofeature is the presence of few typic nodules of Fe-oxihydroxides.

***Ventalló soils.*** The micromorphological descriptions of profile B8-8 (Ventalló series) are found in **Table S8**.

The upper horizons from profile B8-8, down to 49 cm, contain randomly oriented limestone and calcareous fragments of petrocalcic horizons, some of them with internal laminated clay coatings in a decarbonated micromass. These features are compatible with a pedosediment as the parent material of these layers. At 80 cm there is strong carbonation as a Bkcm with secondary carbonates formed by micrite and needle calcite as pseudomorphs of plant remains. Coarse fragments are quartz grains, limestone and petrocalcic fragments. There is some clay mobilization at the upper part of the 2Bkcm, probably due to a short-range illuviation just at its upper abrupt boundary coming from the upper, decarbonated horizon.

The groundmass of the underlying Bkcm horizons from profile B8-8 is partly decarbonated. They are argillic horizons, calcium carbonate free, but with calcitic coatings on clay illuviation features (**Figure 2c**), that are sometimes broken by the calcite growths. Nevertheless, some fine clay coatings are found covering secondary calcite, which indicates that both processes (carbonation and clay illuviation) took place almost simultaneously within this horizon, acting at different microsites, e.g. carbonation of root channels due to biological activity while clay becomes dispersed and illuviated in patches of the decarbonated groundmass. In the deepest horizons carbonation is shown as fan-like carbonate crystals.

Redoximorphic features only appear below 60 cm at profile B8-8, as orthic, weakly impregnated nodules of Fe-oxihydroxides, both above and below the carbonate-cemented horizon. As in the Aspres soils, their presence does not have any relation with the present porosity, therefore they should be considered as a palaeofeature.

Bt horizons of profile E-135 and the Bt horizon in profile E-112 (**Table S1 and S3**) show a completely decarbonated micromass with a stipple-speckled b-fabric, and few microlaminated clay coatings as pedofeatures around coarse fragments that are mainly quartz and quartzites. At that depth very few impregnative hypocoatings of micrite, probably due to decomposed roots, are observed.

***Armentera soils.*** Micromorphologically, the horizon differentiation in the B8-10 profile is almost absent (**Table 8**). Its microstructure is channel (apedal), due to faunal activity (pores as channels (**Figure 2d**) and chambers, star-like pores by coalescence of faunal excrements) and the only pedofeatures are some silt coatings. A remarkable feature is an incipient banded fabric formed by clay lamellae, probably inherited from the alluvial material. The soil is well drained and free from redoximorphic features throughout.

***Closes soils.*** Profile 26 CTP-80, belonging to this series, shows features typical for alluvial–palustrian materials, as mixtures of fine and coarse materials, crust fragments and sorted materials, in a clustered, heterogeneous distribution. The redoximorphic pattern is mainly stagnic: orthic Mn and Fe nodules, aggregate, moderately impregnated nodules of Fe- and Mn-oxides within the aggregates, while most pores show Fe-depleted hypocoatings (**Table S9**).

The upper part of the profile, with high exchangeable Na-saturation, shows features due to a low structural stability of the materials: vesicular porosity (due to air bubbles) and intercalations and compound coatings of clay, silt and even fine sand around pores (**Figure 2e**). The lowermost calcic horizon has typical impregnating nodules of calcite, and coatings of small prismatic sparite crystals around pores (**Table S9**).

# 6. Discussion

## 6.1. Soil forming processes

*Soil colour, iron oxides and rubefaction*

The Bt horizons of the Aspres and Ventalló soils have a reddish colour (2.5YR-5YR) even in the recarbonated horizons. However, the B8-9 profile, a somewhat poorly drained Aspres variant, has not such a red colour.

The red colours of these soils are attributed to the presence of hematite (Davey et al. 1975), which gives red hues to soils (7.5YR and redder). Torrent et al. (1983) stated that the colour, evaluated through a redness index (RI, **Table 8**) could be used to predict the hematite content of the soils. Martín-García et al. (1998) also consider that the alternating drying and moistening, typical of Mediterranean climates, favours reddening through crystallization of iron oxides. Hematite has a much stronger pigmenting effect than goethite, and even at low concentrations of hematite the colour becomes redder than 5YR (Schwertmann and Taylor 1982). We may assume that goethite is dominant in the less well drained soils on the Pliocene surfaces, which may be explained by their wetter conditions (Schwertmann and Taylor 1982). Crystalline iron (**Table 8**) tends to be higher in older soils than in younger ones, but the results are not very evident.

Díaz and Torrent (1989) stressed the sensitivity of goethite-hematite systems to pedoenvironmental factors and the limited value of iron oxide contents for the estimation of palaeoclimatic conditions. They rather related the differences of iron oxides to palaeoenvironmental factors as pH or to a moister pedoclimate.

The close agreement (**Table S6**) of the clay and free iron oxides Bt/A ratios points to a coilluviation process for the Aspres and Ventalló soils.

Neither the Armentera series nor the Closes variant show brunification. Instead, the latter presents mottling due to redox processes. The lack of brunification may be explained by their highly calcareous nature (Duchaufour 1982).

*Redoximorphic features*

The observed redoximorphic features are most probably very old, as the ones observed in the Aspres and Ventalló soils. Only in the Closes variant are they related to the present void system and should be considered functional: mottling is present below 30 cm, and Fe concentrations and depletions are present with chromas of 2 or less. The Armentera series has no redoximorphic features and in the Aspres and Ventalló series mottles are present (below the petrocalcic horizon in the latter).
Translocation of carbonates

In the Aspres series carbonate accumulation is absent in the upper 2 meters when the parent material is calcium carbonate free. However soils in the Pliocene surfaces with calcareous rocks in the parent material develop a petrocalcic horizon. These soils are polycyclic and have undergone several additions of calcareous and siliceous materials during its formation, together with carbonation / decarbonation processes and clay illuviation.

Notwithstanding a possible aeolian origin of the carbonates in the Ventalló series, the sole presence of limestone gravels as skeleton in the petrocalcic horizon and upper horizons could be the source for the calcium carbonate accumulations below. The petrocalcic horizon is moderately expressed. It shows a conglomeratic-like morphology under a laminated layer acting as contact with the overlying Bt horizon. The recarbonation of the underlying horizons is very strong. All the calcite in these horizons is present as pedofeatures and absent in the groundmass.

Calcite nodules and infillings of micrite and sparite break previous clay coatings and disturb the original fabric in a process similar to the one reported by Gile and Grossman (1968), as can be seen in the microphotographs of **Figure 2c**.

The origin of the calcitic concretions in the Closes variant is probably the water table, as has been explained for similar $CaCO_3$ accumulations in the area and in other places (Knuteson et al. 1989). However the depth of accumulation suggests a double flow, upwards and downwards (Boettinger 2002) for the calcification process. The fact that they are formed by micrite, and not by larger calcite crystals, suggests that they were recently formed, once the soil started to be drained (Durand et al. 2010). Also the sodic conditions of the profile may enhance $CaCO_3$ accumulation. It is interesting to note the patchy distribution of this soil variant (Carrillo et al. 1999), in complex association with soils without calcium carbonate concretions.

Only few pseudomycelia of calcite indicate very slight carbonate redistribution in the Armentera series (not identified in thin sections). We must point out that these soils are on young landforms (river levees) that have a very high available water holding capacity (> 200 mm), which slows down the leaching of carbonates.

*Vertic properties*

Besides the clay accumulation, the B8-9 profile (Aspres variant) shows the development of vertic features both in the field and in thin section, where slickensides and argilloturbation are very evident. These features make difficult the identification of clay coatings in the 3Btss horizon due to the high deformation by argilloturbation (**Figure 2a**). The clay mineralogy does not agree completely with these observations, since smectite is a minor component and illite the dominant 2:1 clay (**Table 5**). However, this may be explained by the large amount of clay, as has been observed in other places where illite is also dominant and where strong vertic features form (Isbell 1991; Imbellone and Mormeneo 2011). Not all Aspres soils present such features: they seem to be more abundant in the clayey and poorly drained soils, besides the fact that the large content of coarse elements prevents the development of true Vertisols. Nevertheless, slickensides have also been observed in the most clayey soils of the Pleistocene terraces as well in the soils of the inner depressions (**Table 2**).

*Clay and silt translocation*

Clay illuviation in the Aspres soils is strongly expressed, mostly in the most gravelly / sandy horizons, as microlaminated clay coatings (B8-9 and E-30). The frequent deformation of such microlaminations and the fragments of clay coatings in the groundmass can be attributed to an ageing of the coatings (not functional at present) and to the argilloturbation, evident in the whole profile.

Illuvial clay is present as oriented coatings from the 2Bt horizon down in Ventalló soil (B8-8) (**Table 3**). The presence of numerous fragments of clay coatings and oriented clay in the groundmass, not related to present pores, shows that illuviation also occurred in the past. Nonetheless, the clearest evidence supporting this old age is the relation between calcite and clay accumulation in the horizons under the petrocalcic horizon, where calcite coatings or infillings cover previous clay coatings, giving evidence of recarbonation (**Figure 2c**).

The few silt coatings observed in thin sections in the Armentera soil are probably inherited from sedimentary processes. Some of them are associated with the biopores. They are due to short-range silt dispersion and accumulation in pores probably due to turbulent flow through macropores, deposition in faunal cavities, reworked by animals and incorporated to the matrix.

The Closes variant has high sodicity (SAR: 21 to 76) and low salinity (ECe: 1.8 – 4.9 dS/m at 25 ºC) (**Table 9**) with very low concentration of both $Ca^{2+}$ and $Mg^{2+}$, (1.0 or less $cmol_{(+)}$/L in the Btn horizons and slightly higher in the top soil: 5.7 $cmol_{(+)}$/L). This sodicity produces a disruption of the soil structure. As a result, the micromorphological observations provide evidence of translocation of Na-dispersed fine material, as silt or even a few oriented clay coatings (**Figure 2e**). This, together with other features such as prismatic structures and clay- and Fe- depletion hypocoatings around pores, could indicate the natric character of the B horizons. Bulk density is also very high (data not presented).

*Salinization and sodication*

The Closes variant soil is located in a former large paludal area (Estany de Sant Pere) that was artificially drained. Probably the leaching of salts in the reclamation process led to their sodication and later alkalinisation ($HCO_3^-$, $CO_3^{2-}$, 6.8 to 15.2 $cmol_{(+)}/L$) (**Table 9**). Porta et al. (1994) found similar soils in other parts of the Empordà Basin, showing similar processes of sodication.

*Abrupt textural change*

The Aspres soils show a large increase of clay content between A and Bt horizons in almost all the studied profiles and this could qualify for and abrupt textural change (**Tables 3 and S1**). However in the profile B8-9 a lithological discontinuity between the topsoil (Ap, $A_2$) and deeper horizons was described in the field. Notwithstanding the fact that there has been a strong new clay formation from weatherable minerals and an intense clay illuviation, changing the sand mineralogy and size distribution, both sand mineralogy (% of opaque and light minerals in the coarse sand, **Table 6**) and the clay-free coarse sand size distribution provide evidence of strong discontinuities (**Tables 8 and S3**).

In the Ventalló soil (B8-8), the textural change between the top horizons (Ap, AB) and the underlying ones occurs together with a lithological discontinuity, evidenced by the particle size distribution of the clay-free fine earth (**Tables 8 and S3**). Besides, the sand mineralogy (**Table 6**) indicates additional discontinuities within the Bt horizons. In this case it is clear that the addition of new material from upslope soils has taken place, also evidenced by the fragments of carbonate crusts, and therefore the textural change again may not be attributed only to clay illuviation.

**Table 9.** Soil salinity, profile 26CTP-80 (Closes variant)

| Horizon | Depth (cm) | Saturation moisture (%) | pHs[1] | ECe[2] (dS/m, 25 ºC) | SAR[3] $(mmol/L)^{1/2}$ | ESP[4] (%) | Salinity (saturated paste extract)($cmol_{(+,-)}/L$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | $Cl^-$ | $SO_4^{2-}$ | $HCO_3^-$ | $CO_3^{2-}$ | $NO_3^-$ |
| **$Ap_1$** | 0-13 | 59.3 | 8.1 | 3.8 | 21.3 | 30 | 3.0 | 2.5 | 35.3 | 0.7 | 12.8 | 12.6 | 7.6 | 1.0 | 7.1 |
| **$Ap_2$** | 13-32 | 58.3 | 8.7 | 4.3 | 27.1 | 38 | 3.0 | 2.7 | 45.7 | 0.3 | 15.2 | 19.2 | 13.1 | 1.0 | 1.9 |
| **Btkcn** | 32-64 | 46.6 | 8.9 | 4.9 | 76.1 | - | 0.4 | 0.6 | 53.8 | 0.8 | 20.4 | 18.5 | 12.8 | 2.4 | 1.5 |
| **Btkcn** | 64-96 | 31.7 | 8.8 | 2.5 | 34.5 | 50 | 0.5 | 0.5 | 24.4 | 0.3 | 10.4 | 7.8 | 6.4 | 0.5 | 0.6 |
| **2Btn** | 82-96 | 28.9 | 8.9 | 1.8 | 27.4 | 40 | 0.4 | 0.5 | 18.4 | 0.2 | 7.3 | 5.5 | 6.3 | 0.5 | 0.5 |
| **3Btkcn** | 96-130 | 61.6 | 8.6 | 2.9 | 38.3 | 57 | 0.4 | 0.8 | 29.7 | 0.2 | 13.1 | 9.6 | 6.9 | 0.5 | 0.4 |

[1]pHs: pH in saturated paste extract; [2]ECe: electrical conductivity in saturated paste extract; [3]SAR: sodium adsorption ratio; [4]ESP: Exchangeable sodium percentage.

## 6.2. Soil horizons, soil forming processes and soil-landscape relationships

The clear relationships between the soil processes acting on the different landforms (soil-landscape units) and the resulting diagnostic features establish a firm soil-landscape model for the area. Calcium carbonate redistribution, clay illuviation and rubefaction are the main soil forming processes that have always been operating in the studied profiles and landforms. However, the imprint is more distinct in the older (Pliocene and Pleistocene ages) than in the youngest ones (Holocene ages). The very distinct morphology of the soils on the Pleistocene geomorphological units clearly shows different cycles of polygenesis, while the soils on the Pliocene surfaces do not show addition of materials e.g. from runoff or further pedogenesis. The lithological discontinuties in the profiles should be attributed to the nature of the parent material (alluvial fan deposits, **Table 1**). In any case aeolian inputs may not be discarded, and indeed they perhaps explain the high base saturation of the soils on the Pliocene surfaces, very different from the ones studied in Central Spain with a similar age but with a moister present climate than the Empordà (Gallardo et al. 1987; Espejo 1985; García-

Marcos and Santos-Francés 1997). The most significant diagnostic horizons in the area (i.e. calcic and argillic horizons) show very different morphologies, but the micromorphological and physicochemical studies confirm the field classifications. None of the studied profiles in the whole Baix Fluvià study area have epipedons other than ochric.

The soils developed on the Pliocene surfaces on detrital, non-calcareous parent materials (Table 1) are now the only ones that are non-calcareous throughout. The Aspres series and variants have an argillic horizon and an abrupt textural change, partly of pedogenic origin, but clay illuviation is not very well expressed in the field. In spite of that, the thin section study reveals the presence of fragments of clay coatings, deformed and fragmented, with the original microlamination disturbed by the argilloturbation, together with a grano-striated b-fabric, more clearly shown when the clay content is higher. The Aspres series encompasses a wide range of soil colours (2.5YR to 7.5 YR) and soil reaction (5.5-7.4, full data not shown) in the Bt horizons. Other soils developed on Pliocene calcareous parent materials (Aspres variant) have always some forms of carbonate accumulation in the profile, although some of them may have a non-calcareous Bt.

Rubefaction is well expressed in both, the Aspres and the Ventalló soils (2.5YR for the Bt horizons) although when recarbonation takes place (Ventalló soils; Tables 3 and S1) or when the drainage is worse (B8-9) it diminishes (5YR or less). Erosion-sedimentation processes were very active in the Quaternary and as a result, in many of the soils in the Pleistocene, recarbonated argillic horizons occur (Palexeralfs, when they have a petrocalcic horizon). In some cases the former clay-illuviated horizon is hardly identifiable due to the strong erosion and recarbonation (petrocalcic or calcic horizon) and thus a Calcixerept is mapped (Table 2). In other cases the former Alfisols are buried below 70 cm (Thapto-Alfic Xerofluvent, Grau series, Table 2; data not presented). Interestingly the described Soil Taxonomy Subgroups are similar to the ones on several terrace levels in Central Spain (Roquero et al. 1999). These soils are the ones which better fit into the concept of red Mediterranean soils, characterized by accretion and erosion of materials and latter pedogenesis (Fedoroff and Courty 2013) and are similar from the point of view of types of iron oxides to some of the ones reported by Bech et al. (1997) in others parts of Catalonia. It is interesting to note the lack of Rhodoxeralfs, only present in minor spots in the area (Table 2).

Pliocene surface soils show a progressive pedogenesis in all the cases according to the model proposed by Johnson and Watson-Stegner (1987). Pleistocene surface soils have had, according to the same model, stages of regressive and progressive pedogenesis.

Both, Aspres and Ventalló soils, present an abrupt textural change between the A and Bt horizons. In the Ventalló series such textural change may be explained, both, by a sedimentary as well as by a pedogenic one (clay illuviation). The presence of $CaCO_3$ in the soil matrix tells us that an addition of material has also taken place, from eroded upslope material. As a result of these processes the Ventalló series has an argillic, a petrocalcic and a nodular calcic horizon. Regarding the Aspres soils, the geomorphology and the widespread presence of the abrupt textural change do not suggest the idea of a major role of sedimentation. On the other hand the large amount of clay in these soils seems to be very difficult to explain only by translocation or in situ formation and therefore the idea of Phillips (2007) of a multiply causality (bioturbation, translocation, in situ clay formation) seems to be highly pertinent in our case. It is worth mentioning that the abrupt textural change is not giving rise to stagnic conditions, although some soils may show a somewhat poorer drainage.

The well-drained soils of the Holocene fluvial plain (Armentera series) do not present any diagnostic endopedon. In these medium textured, very calcareous soils the identification of a cambic horizon is hampered by the lack of any visible carbonate removal on the Bw horizons, in spite of a very well developed soil structure. Also the young age of the deposit, less than 2,000 years, plays a role.

The soils of the drained areas (Closes variant) have carbonate concretions (calcic horizons). These profiles show a clear sodication process (ESP 26 to 76%) and alkaline conditions (very high pH) that have led to the removal of divalent cations from the soil solution. These conditions, combined with the rather low salinity (ECe 1.8 dS/m in some horizons, **Table 9**), favour the collapse of the structure and the dispersion of the fine material (silt and clay) in this soil. The illuvial pedofeatures are in many cases related to the present pore system. All these processes have been driven or enhanced by the artificial drainage of the lagoon (as $CaCO_3$ accumulation). However these morphological and chemical characteristics do not suffice to identify a natric horizon because there is an insufficient clay increase with depth (SSS 2014). The age of these soils can hardly be established and their development started much earlier than when drainage works were completed.

We should point out the limited geographical expression of some soil types in the area (**Table 2**), among them the Haploxeralfs and the soils with a cambic horizon. This is likely to be is related to the poor extension of suitable landforms dating to the late Pleistocene or perhaps early Holocene. Younger landforms do not seem to be able to develop a cambic horizon as is demonstrated by the Armentera series.

### 6.3. Palaeoenvironmental implications of the present soils

The studied soils do not conform to a chronosequence in the most strict sense but may rather be regarded as a sequence where the time factor (from a few hundred years to more than 2.5 M years, **Table 1**) dominates the other pedogenetic factors (Huggett 1998), in spite of the different nature of the parent materials. They therefore provide us with a clear view of the expression of the soil forming processes acting on this landscape.

Calcium carbonate redistribution is a major process in the soils of the area. At this very moment the present soil water balance seems wet enough to prevent calcium carbonate accumulations in the non-calcareous soils (i.e. most of the Aspres series and variants) and can even give rise to acidic topsoils (profile E-43; **Table S3**) and in general to counterbalance general or local aeolian supply of this component in non-highly calcareous soils.

It has been suggested that the soils of southern Europe are affected, to one degree or another, by the dust transported from Africa (Muhs et al. 2010), following the ideas presented much earlier by Yaalon (1987). Àvila et al. (1996) have provided data about the dust in rains in the region, and Fiol et al. (2005) summarize the dust inputs in a much broader area in the West Mediterranean. In the study area Marquès et al. (2011) give a very detailed account of the existing sand dunes, and Sáinz-Amor and Julià (1999) describe their mineralogical composition. The lack of calcium carbonate accumulations in most of the Aspres soils seems to support the idea that dust inputs, either from long or short distances, fall well below the range suggested by Yaalon (1987) that is incorporated into the soil (50 g/m$^2$ per year), in agreement with the data reported by Àvila et al. (1996).

Reddening of the soils, as is generally accepted, takes place after a full removal of carbonates (Duchaufour 1982), and only afterwards rubefaction occurs. The soils on Pleistocene surfaces, but also the well-drained ones on Pliocene surfaces, show these phenomena to the highest degree, even in the soils that are fully recarbonated after this process. Some Aspres soils have been only partly reddened: this may be explained, to some extent, by poorer drainage conditions as is demonstrated by their redoximorphic features. Some authors (Vidal Bardán 1993) have been claiming, in the Ebro Valley, a transport of already reddened materials for soils in similar latitudes on different geomorphic positions, but this seems not to be the case in this area because they are in isolated Pleistocene platforms disconnected from any source of red materials.

In the old soils (Aspres and Ventalló) the ratio Fedt/Clay is between 0.04-0.08 in the Bt horizons, and the ratios %Clay Bt/%Clay Ap are quite similar to %Fedt Bt/%Fedt Ap as well (**Table S6**). This suggests a co-illuviation of clay and iron oxides, despite some small discrepancies due to the higher clay mobility as indicated by Bornand (1978).

Aspres soils are developed on Pliocene surfaces, in the absence of a more precise dating of these forms (**Table 1**). They have a strong abrupt textural change under a very coarse topsoil (sand and coarser quartzitic materials). We can accept that the high clay content of the B horizons comes partly from in situ neoformation in an already clay rich, gravelly parent material. Some micromorphological observations, such as bands of oriented clay within the schist fragments, following schistosity planes, suggest that at least part of the clay has been formed in situ, as observed also by Keller (1964) or Smeck et al. (1968) in other argillic horizons. In addition to that, clay illuviation has taken place, since the anisotropy and microlamination related to voids are very clear (**Figure 2b**) and in the deepest horizons most of the fine material is oriented as broken fragments in the groundmass, which indicates that the process has been acting for a long time. The abrupt textural changes, when no lithological discontinuities exist, are a proof of such illuviation as a long lasting process likely reinforced, as Phillips (2007) suggests, by biological activity. Also the higher amounts of kaolinite demonstrate the higher degree of weathering of the Aspres soils.

The Aspres soils developed in the best preserved Pliocene surfaces, high lying platforms isolated from the present drainage network and in a succession of terraces. **Table 2** shows other soils from Pliocene materials with different degrees of soil development, showing evidence of truncation and rejuvenation. However these Aspres soils should be interpreted mostly as soils that have been subjected only to minor erosion processes; discontinuities should be interpreted as differences in the parent material.

Soils with an abrupt textural change are scarce in Catalonia and have been described in a few places (Boixadera and Poch 2008; Poch et al. 2013) pointing out the exceptionality of this feature.

The soils of the Pliocene surfaces (Aspres soils and variants) do not show the extreme kaolinitzation and planosolic character development seen in the Pliocene soils in other Spanish areas (Espejo 1987; Gallardo et al. 1987; Pérez González 1987; García-Marcos and Santos-Francés 1997) although significant differences do exist between them (Mulders et al. 1988). This suggests that these surfaces were not that old or that their (palaeo)climate was different.

The Ventalló soil shows, at least, a full cycle of decarbonation-reddening/clay illuviation-recarbonation-decarbonation (partly)-clay illuviation (older than Holocene). This is the situation of most of the soils on Pleistocene surfaces, attesting the above-mentioned soil erosion-sedimentation processes. They are linked to the position of these landforms in relation to the higher reliefs of Ventalló and Valldevià calcareous mountains and to the climatic oscillations during the Quaternary. The presence of a 2Bt over the petrocalcic horizon shows that the soil has undergone several climate cycles and successive erosion/addition of materials. The anorthic carbonate nodules and fragments of calcareous crusts (petrocalcic), as coarse fragments on top of the petrocalcic horizon of the B8-8 profile could be considered to form a true stone line, and demonstrates the polycyclic nature of this soil. It indicates the existence of at least two cycles of illuviation separated by an erosional episode in this soil during the Pleistocene. Nevertheless, clay illuviation in this top 2Bt is by far not as well expressed as in deeper horizons. In the case of the B8-8 profile (Ventalló series), carbonation overprints illuviation and rubefaction features, although in a few spots, mainly at the boundaries between Bt and Bk horizons, fine clay coatings cover some carbonated features. The origin of the recarbonation is thus clearly colluvial from limestone and calcareous crust fragments. Our interpretation is that several periods suitable for rubefaction (warmer temperatures) have occurred during the Quaternary.

The polygenetic nature of red Mediterranean soils has been reviewed by Fedoroff and Courty (2013). According to them, clay illuviation, rubefaction and carbonate dissolution are assumed to take place during the wet interglacials, while carbonate accumulation would occur during drier periods. According to Fedoroff (1997) clay illuviation is a unlike feature under our present climate conditions, because the illuviation process only takes place in the more humid borders of the Mediterranean basin. The clear microlamination of the clay coatings in Aspres and Ventalló soils – absent in Holocene Armentera and Closes profiles - points to past, more humid climates. These features, which are not always present in red Mediterranean soils (Reynders 1972; Bresson 1974; Lamouroux et al. 1978) could have been preserved thanks to the accretional character of the parent material (Ventalló soils) subjected to a discontinuous genetic process (erosion/accretion); and to a period of rubefaction due to Fe release by mineral weathering and clay illuviation (**Table S2**). In the Aspres soils the same feature has been preserved across the climatic fluctuations of late Pliocene and Quaternary because no inputs of external material have reached these soils, or in such amounts that the soil is able to incorporate them into the profile without apparent profile retardation or simplification (Johnson and Watson-Stegner 1987).

Wagner et al. (2014) presented an account about the pedogenetic process operating in the Western Mediterranean. They concluded that the area experienced a subtropical climate since Early Pliocene, and highlighted significant differences among the areas they studied (Balearic Islands and Granada basin).

The Fe index (**Table 8**) shows a great range of values in B horizons (5.2 to - 52.8) reflecting the very different degrees of weathering and of pedogenetic development. This index encompasses both the degree of pre-weathering of substrates as well as the differences within the parent material, and its distribution may indicate different pedogenesis and weathering (Wagner et al. 2014). Our data are more similar to the Granada basin than to the Balearic Islands as reported by Wagner et al. (2014). This could reflect less favourable conditions for weathering (lower temperatures and more seasonal rainfall than in the Balearic Islands).

Fedt/Fet of B horizon, as well as Fedt and (Fedt-Feox)/Fet increase also with the age of the soils, in agreement with the findings of Arduino et al. (1986).

Ortiz et al. (2002) identified periods of strong pedogenesis in the Granada Basin and showed situations where soil characteristics were used to date landforms. In our case the available data support the idea that pedogenic characteristics of the landforms indeed help interpret their history and therefore are a very useful proxy (Fedoroff and Courty 2013).

## 7. Conclusions

The diagnostic features of the studied soils are clearly related to the landforms (soil-landscape units) where they are located, both in terms of identifying soil forming processes and defining soil types. These relationships have been established for the study area, and allow us to build up a good soil-landscape model. These facts also help to improve soil correlation, both in the field and in the office.

Carbonate translocation, clay illuviation and rubefaction are the main soil forming processes operating in the area. They are expressed in different manners according to the geomorphic surfaces, age, accretional / erosional evolution and finally human influence.

The non-calcareous status of almost all of the Aspres soils developed on Pliocene landforms with no inputs other than calcareous dust, seems to demonstrate that rainfall has been able, and is able at present, to remove the calcareous additions from the soil. However, in medium textured, well drained soils on Holocene – more recent - landforms, rainfall is not able to fully leach or even to mobilize the carbonates from the calcareous parent material to a significant extent. This fact strongly restricts the expression of cambic horizons.

A cambic horizon may be only identified in soils with a calcic horizon on older surfaces; while the cambic horizon of the Closes series is a special case due to the drainage of a previous lacustrine, sodium-rich environment, linked to a water table. The illuvial horizon of the Closes variant, in spite of the sodicity, does not qualify as a natric horizon. The soils of the Pleistocene surfaces are polycyclic, with several (at least 2) cycles of erosion / colluviation associated with alternations of clay illuviation and recarbonation plus rubefaction. The oldest Pliocene soil does not express such phenomena because it did not receive a significant input of new materials during its formation.

# 8. Acknowledgements

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