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Benchmark soils on alluvial, fluvial and fluvio-glacial formations of the upper-Segre valley

Suelos de referencia en formaciones aluviales, fluviales y fluvio-glaciales de la cabecera del río Segre
Solos de referência em formações aluviais, fluviais e fluvio-glaciais da cabeceira do rio Segre

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ABSTRACT

The upper reaches of the Segre river, flowing through the Pyrenees, offers a variety of geomorphic surfaces that allow us to study soil chronosequences. The objective of this work is to widen the knowledge about the main characteristics and formation processes of some benchmark soils developed on fluvio-glacial, alluvial-fan and terrace materials of Pleistocene and Holocene age related to the Segre river, either siliceous or carbonatic. This knowledge will allow us to identify soil forming processes, commonly found in Mediterranean environments such as carbonate redistribution, clay formation and mobilization and rubefaction, all as functions of parent material and age. Five profiles, ranging from the Lower Pleistocene to the Holocene were classified according to Soil Taxonomy /WRB. The Montferrer profile (Calcic Palexeralf /Calcic Cutanic Luvisol (Chromic) is a deep, partly decarbonated soil, with calcium carbonate accumulation in depth covering glacial features. The Torre del Remei profile (Typic Paleustalf /Cutanic Luvisol) developed on silicic moraines and shows an extreme clay formation and illuviation. The Alp (Typic Haplustalf /Cutanic Luvisol) and Tartera (Petric Calciustept /Petric Calcisol) soils are developed on alluvial fans with calcium carbonate sources. The former is partly decarbonated, whilst the latter is rubefacted on top and shows speleothem-like carbonate pendants with superposition of clay illuviation. The youngest profile, Abellerols, (Typic Calciustept /Typic Calcisol) shows only a partial decarbonation and calcite accumulation at depth. The results show that soil development is determined by the age of the surface and the source of calcite, either in the parent rock or brought by subsurface flow: clay illuviation is extreme in absence of it. Special morphologies of carbonate pendants are indicators of environmental conditions. The coexistence of clay coatings and secondary calcite can be explained by recarbonatation or by spatial differentiation of soil environments in the profile. One of the implications of this research is the inconsistence of using soil development indices based on morphological indicators when soils are formed on different parent materials and are subjected to different geomorphic dynamics.

RESUMEN

La cabecera del río Segre, en sus tramos Pirenaicos, ofrece una variedad de formaciones geomorfológicas que permiten estudiar cronosecuencias de suelos. El objetivo de este trabajo es ampliar el conocimiento sobre las principales características y los procesos de formación de algunos suelos desarrollados sobre materiales fluvio-glaciales, aluviales y de terrazas Pleistocenas y Holocenas relacionados con el río Segre, ya sean silícicos o carbonáticos. Ello permitirá identificar los procesos formadores del suelo propios de ambientes mediterráneos, como redistribución de carbonatos, formación y movilización de arcillas y rubefacción, y relacionarlos con el material parental y la edad. Se clasificaron

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cinco perfiles en materiales con edades desde el Pleistoceno Inferior al Holoceno, de acuerdo con Soil Taxonomy / WRB. El perfil de Montferrer (Palexeralf Cálcico /Calcic Cutanic Luvisol (cromic)) es un suelo profundo, descarbonatado en parte, con acumulación de carbonato de calcio en profundidad superpuesto a rasgos glaciales. El perfil Torre del Remei (Paleustalf típico /Cutanic Luvisol) está desarrollado sobre morrenas silícicas y muestra formación e iluviación de arcilla extrema. Los perfiles de Alp (Haplustalf típico /Cutanic Luvisol) y Tartera (Calciustept pétrico /Petric Calcisol) son suelos desarrollados sobre abanicos aluviales con una fuente de carbonato de calcio. El primero está descarbonatado, mientras que el último está rubefactado en la parte superior y muestra cemento geopetal de carbonatos con morfología de espeleotemas con superposición de iluviación de arcilla. El perfil más joven (Abellerols, Calciustept típico /Typic Calcisol) está descarbonatado sólo en parte y muestra acumulación de calcita en profundidad. Los resultados indican que el desarrollo del suelo se determina por la edad de las superficies y la fuente de calcita, ya sea en el material parental o a través de escorrentía. La iluviación de arcilla es extrema en ausencia de carbonatos. Las morfologías especiales de cemento geopetal de carbonato son indicadores de las condiciones ambientales. La coexistencia de los revestimientos de arcilla y calcita secundaria puede ser explicada por recarbonatación o por diferenciación espacial de los ambientes de suelos en el perfil. Una de las implicaciones de esta investigación es la inconsistencia del uso de índices de desarrollo del suelo basados en indicadores morfológicos cuando los suelos están formados sobre materiales parentales diferentes y están sujetos a dinámicas geomorfológicas distintas.

RESUMO

A cabeceira do rio Segre, ao longo dos Pirenéus, oferece uma variedade de superfícies geomorfológicas que nos permitem estudar cronosequências do solo. O objetivo deste trabalho é ampliar o conhecimento sobre as principais características e processos de formação que alguns solos de referência desenvolveram em materiais fluvio-glaciais e aluviais e em terraços do Pleistoceno e Holoceno relacionados com o rio Segre, sejam de origem silícica ou carbonatada. Este conhecimento permite-nos identificar os processos de formação do solo, típicos de ambientes mediterrânicos como a redistribuição de carbonatos, formação de argila e mobilização e, rubefação, e relacioná-los com o material parental e idade. Procedeu-se á classificação de cinco perfis, que vão desde o Pleistoceno inferior até ao Holoceno recorrendo à Soil Taxonomy /WRB. O perfil de Montferrer (Palexeralf Cálcico /Calcic Cutanic Luvisol (cromic)) é um solo profundo, parcialmente descarbonatado, com acumulação de carbonato de cálcio em profundidade, sobrepondo-se a formações glaciais. O perfil Torre de Remei (Paleustalf típico /Cutanic Luvisol) desenvolve-se sobre formações silícicas e apresenta formação e iluviação de argila extrema. Os perfis de Alp (Haplustalf típico /Cutanic Luvisol) e Tartera (Calciustept pétrico /Petric Calcisol) são solos que se desenvolvem sobre aluviões com uma fonte de carbonato de cálcio. O primeiro está descarbonatado, enquanto o último está rubefactado na parte superior e apresenta um cimento geopetal de carbonatos com morfologia de espeleotemas com sobreposição de iluviação de argila. O perfil mais jovem (Abellerols, Calciustept típico /Typic Calcisol) aparece parcialmente descarbonatado e apresenta acumulação de calcite em profundidade. Os resultados indicam que o desenvolvimento do solo é determinado pela idade das superfícies e fonte de calcite, quer seja do material parental ou transportadas por escorrimento. A iluviação de argila é extrema na ausência de carbonatos. As morfologias especiais de carbonato do cimento de geopetal são indicadoras das condições ambientais. A coexistência de calcite secundária e revestimentos de argila pode ser explicada pela recarbonatação ou diferenciação espacial dos ambientes do perfil do solo. Uma das implicações desta pesquisa é a inconsistência do uso de índices de desenvolvimento do solo com base em indicadores morfológicos, quando os solos são formados por diferentes materiais parentais e estão sujeitos a diferentes dinâmicas geomorfológicas.

KEY WORDS
Pyrenees, soil development, clay illuviation, calcite, decarbonation, micromorphology

PALABRAS CLAVE
Pirineos, desarrollo de suelos, iluviación de arcilla, calcita, descarbonatación, micromorfología

PALAVRAS-CHAVE
Pirenéus, desenvolvimento dos solos, iluviação de argila, calcite, descarbonatação, micromorfologia

1. Introduction

In Mediterranean environments leaching and accumulation of carbonates, clay illuviation and rubefaction are some of the most common morphological soil features which have been widely reported (Yaalon 1997; Torrent and Barrón 2003; Verheye and De la Rosa 2006). Some authors studying these processes have highlighted that a moderate weathering with illuviation of mostly 2:1 clays into B horizons (Xeralfs/Luvisols) takes place in semiarid regions, together with a hematite-induced reddening of the clays due to summer dehydration of free iron oxyhydroxides, carbonate dissolution and reprecipitation (Yaalon 1997). Other authors point out that the red phase corresponds to a climax development, but that as soon as environmental conditions are no longer favourable, this phase is not reached (Verheye and De la Rosa 2006). In this sense, either the soil redness (eg. Torrent and Barrón 2003) or micromorphological (eg. Dorronsoro 1994) indices have been used as age indicators.

In our studies on soils occurring in the right margin of the Ebro valley (NE Spain) with a Mediterranean climate, we observe that rubefaction and clay illuviation occurs at the margins of the Ebro valley (Ubalde et al. 2007) and in soils of the Coastal Catalan System (Empordà and Prades regions: Boixadera et al. 1998; Penedès region: DAAM 2008). With age, an increase of carbonate accumulation was observed on Ebro Terraces (Badía et al. 2009) whilst in the central –most arid- part of the Ebro valley clay illuviation is almost absent (Boixadera et al. 2000).

The Segre river, running from the Puigmal in the Pyrenees (2910 m asl, 1200 mm/y) to La Granja d'Escarp in the Ebro valley (78 m asl, 350 mm/y), has a well developed system of terraces and alluvial fans, well suited to study the effects of parent material, climate, and time on soil development and morphology. This situation is relevant because soils dominated by clay illuviation, carbonate leaching/accumulation or both morphologies are widespread in many areas of the Mediterranean, especially in old surfaces. The Segre river terraces and associated deposits have been studied by several authors (Solé Sabarís 1970; Turu and Peña-Monné 2006; Badía et al. 2009; Calvet et al. 2011).

The upper reaches of the Segre river, flowing through the Cerdanya valley in the Pyrenees, offer a wide range of parent materials, climate, vegetation and land use resulting in high soil diversity. For many years these features have attracted the attention of geomorphologists, geographers and many scholars (Vila 1926, Soutade 1970); and in recent years the soils of the Cerdanya valley have been studied by Boixadera et al. (2008) and Poch and Boixadera (2008).

The objective of this work is to assess the main characteristics and formation processes of some benchmark soils developed on fluvio-glacial, alluvial-fan and terrace materials of Pleistocene to Holocene ages related to the Segre river catchment: either siliceous (clastic) or carbonatic. This knowledge allows the identification of soil forming processes, such as carbonate redistribution, clay formation and mobilization, rubefaction, as functions of parent material and age.

2. Material and Methods

The Segre river follows the Cerdanya valley in a ENE-WSW direction about 20 km until it reaches La Seu d'Urgell, where it turns SW and opens to the Ebro valley. Annual rainfall ranges between 600 and 700 mm in the valley, and between 1000 and 1200 mm on the mountains. Most rainfall occurs in spring and summer, with January the driest month of all. The distribution is different in La Seu d'Urgell, with a higher water deficit during summer. The average air temperatures in the valley are around 2 °C in winter (January), and around 19 °C in summer (July). According to the criteria of Soil Taxonomy (SSS 2010), the moisture regime of the soils is Ustic in most parts of the Cerdanya valley, until an altitude of 1500 m when it becomes Udic; and Xeric in the western part (La Seu d'Urgell, out of La Cerdanya). In all these cases the soil temperature regime is Mesic.

The depression of La Cerdanya is a graben with a ENE-WSW orientation, subparallel to the Pyrenean axis. The Pyrenean Axial Zone was formed during the Miocene, as the result of the activity of a system of normal-slip faults: the Tet and the Cerdanya Faults. The materials forming these structures are mainly granites and metamorphic non-carbonated rocks in the N side and metamorphic (including metamorphic limestones) and calcareous tertiary materials in the S side. During the Quaternary (especially in the recent Pleistocene) a large variety of glacial, periglacial and fluvial geomorphological processes have originated on the area with elevations between 700 and 2900 m. The latest occupation of the Northern valleys by ice was about 15 000 years ago (Calvet et al. 2011). During the Little Ice Age only the upper glacier cirques were occupied by ice. These processes have produced contrasting aspects and shapes of the associated deposits, which are essentially glacial tills, surface formations and river terraces (Gómez Ortiz 1987). Some remarkable features include the morainic ridges on the water divides between valleys (lateral moraines), and moraine ramparts as in Puigcerdá, where glacial tongues merged. The development of glaciers on the south side of the fault trench (area of the Tossa d'Alp) is much poorer, since the moraine debris barely occupied the cirques.

The surface formations covering the slopes are very diverse. The Segre river terraces on the valley bottom are well represented near Bellver and Puigcerdà. Some alluvial fans built by subactual streams, such as Alp, link to the lower terraces (Balasch 2008). Traditionally, four levels of terraces have been described in the area of Puigcerdà (Solé Sabarís 1970).

The vegetation in the valley, below 1600 m belongs to the montane type, dominated by oak forest (*Buxo-Quercetum pubescentis*) and more recently Scots pine (*Pinus sylvestris*). Shrub communities, developed primarily in the more or less steep slopes, belong to alliances *Mesobromion, Xerobromion, Aphyllanthion* and *Ononidion*, depending on pH and soil moisture conditions. Harvested meadows (*Arhenatherion* alliance) occupy the plains. At the bottom of the valley and in areas with high groundwater levels there are patchy remains of willow (*Saponario-Salicetum*), alder (*Alnetum catalaunicae*) and ash groves (*Brachypodio-Fraxinetum*). The current land use is mainly cattle grazing. Irrigation has always played a leading role in these agricultural areas and the landscape reflects this fact e.g. the green colour of the valley bottom in summer is due to irrigation.

Five profiles were selected from a soil survey for further description, analyses and classification (**Figure 1**, **Table 1**). The profile Montferrer was described in a house foundation trench, Tartera and Abellerols in quarry walls and Alp and Torre del Remei in a soil pit. They were described and analyzed according to the methods of Porta et al. (1986). Thin sections were studied according to Stoops (2003). SEM-EDAX analyses were done at the EM service of the Autonomous University of Barcelona. Locations of the five profiles are shown in **Figure 1**.

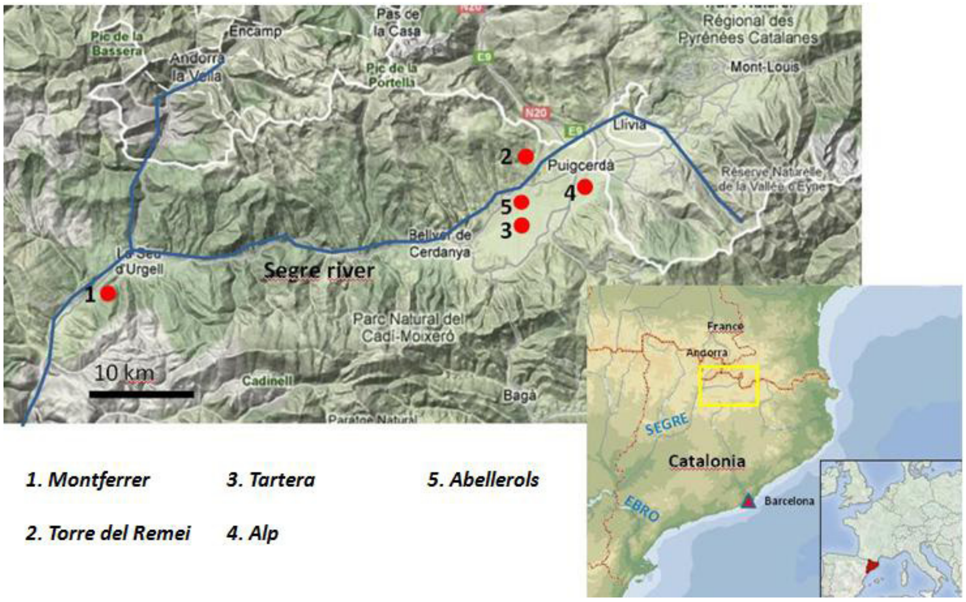

Figure 1. Profile locations in the Cerdanya valley, Catalunya.

Table 1. Location and geomorphic units of the five profiles

Pedon	Altitude (m asl)	Altitude difference from Segre river (m)	Coordinates		Geomorphic unit	Age	Lithology of the parent material
			x	y			
Montferrer	750	50	371051	4689320	Segre Plio-Quaternary terrace (Turu and Peña 2006)	Lower Pleistocene 1800-780 ky	Polygenic gravels (granites, schists) with limestones
Torre del Remei	1130	60	408961	4697018	Glaciofluvial unit T4 (Calvet 2004)	Early Middle Pleistocene (Calvet 2004) 781 ky	Granites and non-calcareous metamorphic rocks
Alp	1115	60*	407744	4693001	Alluvial fan covering the T3 Segre terrace*	Late Middle Pleistocene (Lewis et al. 2009; Peña-Monné et al. 2011) 176 ky	Metamorphic rocks, including some limestones
Tartera	1085	45	404625	4691900	Alluvial fan covering the T3 Segre terrace	Late Middle Pleistocene (Lewis et al. 2009; Peña-Monné et al. 2011) 176 ky	Mostly coarse metamorphic limestones
Abellerols	1080	40	405284	4692858	T2 Segre terrace with distal influence of alluvial fan	Holocene (Solé-Sabarís1970) (max. 12 ky)	Polygenic gravels (granites, meta-morphic rocks and limestones)

*Profile in a proximal position of the alluvial fan, far from the river.

3. Results

Full descriptions of the profiles may be found in Poch et al. (2011). **Table 2** and **Figure 2** contain a summary of the morphological features, and **Table 3** the main physico-chemical characteristics of the profiles.

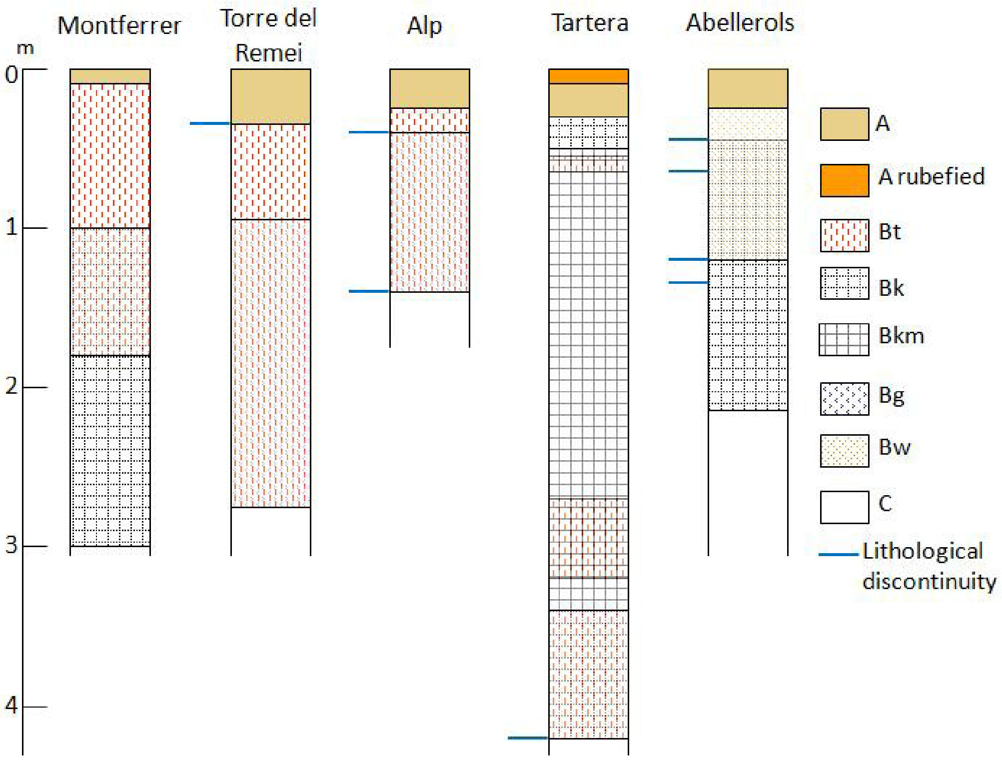

Figure 2. Sketch of the horizon sequence of the studied profiles.

Table 2. Morphology of the studied profiles

Pedon and classification (SSS 2010 / IUSS WRB 2006)	Horizon sequence	Depth (cm)	Munsell colour (moist)	Main morphological features	Diagnostic horizon (SSS 2010)
Montferrer Calcic Palexeralf / Calcic Cutanic Luvisol (Chromic)	Ap	0-10	10YR 5/4	-	Ochric
	Bt	10-100	2.5YR 4/4	Granite regolith	Argillic
	Btk	100-180/200	10YR 8/2	Granite regolith with some calcareous gravels	Calcic
	Bk	>180/200	2.5YR 6/4	Partly cemented; thick silt cappings	(Petro)calcic
Torre del Remei Typic Paleustalf / Cutanic Luvisol	A_1	0-10	10YR 5/4	-	Ochric
	A_2	10-35	10YR 5/4	-	Ochric
	$2Bt_1$	35-95	-	Mottles, generalized clay coatings	Argillic
	$2Btg_2$	95-160	-	Mottles, generalized clay coatings	Argillic
	$3Btg_3$	>160	-	Mottles, generalized clay coatings	Argillic
Alp Typic Haplustalf / Cutanic Luvisol	Ap	0-25	10YR 5/4	Subangular blocky structure	Ochric
	Bt	25-45	10YR 5/4	Coatings related to coarse fragments	Argillic
	$2Btg_1$	45-80	5YR 5/6	Few clay coatings on coarse fragments	Argillic
	$2Btg_2$	80-140	7.5YR 5/6	Clay coatings, mottles	Argillic
	3C	140-163	2.5Y 7/6	Mottles	-
Tartera Petric Calciustept / Petric Calcisol	Ap1	0 – 10	5YR 3/4	Rubefaction	Ochric*
	Ap2	15 – 33	7.5YR 4/4	-	Ochric
	Bk1	30 – 47	-	Hard calcitic pendants, with dissolution features.	Calcic
	Bk2	45 – 50	-	Id.; pisoliths.	Calcic
	Bkmt3	52 – 58	-	Slightly cemented, clay coatings	Petrocalcic
	Bkm4	58 – 77	-	Moderately cemented	Petrocalcic
	Bkm5	77 – 180	-	Moderately cemented	(Petro)calcic
	Bkm6	180 – 280/320	5YR 4/6	Slightly cemented. Mn mottles	Petrocalcic
	Bkmt7	280/320 – 330	10YR 5/6	Moderately-strongly cemented. Clay and calcite coatings	Petrocalcic
	Bkm8	330 – 345	10YR 5/6	Moderately-strongly cemented. Mn mottles	Petrocalcic
	2Bkt9	345 – 420	10YR 5/6	Calcite and clay coatings	Calcic
Abellerols Typic Calciustept/ Typic Calcisol	Ap1	0-8	10YR 3/4	Subangular blocky structure. Leaching	Ochric
	Ap2	8-25	10YR 4/4	Subangular blocky structure. Leaching	Ochric
	Bw	25-46	10YR 4/4	Subangular blocky structure. Leaching	Cambic
	2Bwk1	46-66	10YR 5.5/6	Calcite nodules, coatings and pendants	Cambic
	3Bwk2	66-90/120	2.5Y 6/6	Calcite channel infillings	Calcic
	4Bk3	90/120-132	5YR 6/8 ba, 5YR 3/1 acf	Few calcite pendants	-
	5Bk4	132-202	-	(Calcite in the weathered granite boulders)	-

ba: bands; acf: around coarse fragments; *some associated profiles with mollic horizon (non cultivated).

Table 3. Main physico-chemical characteristics of the studied profiles

Pedon	Horizon sequence	pH$_w$ (1:2.5)	CaCO$_3$ eq (%)	OC (%)	V (%)**	Textural class (USDA)	Sand (%)	Silt (%)	Clay (%)
Montferrer	Ap	7.20	2	3.50	100	Sandy loam	56.9	24.9	18.2
	Bt	7.90	2	0.20	100	Sandy clay loam	66.3	7.4	26.3
	Btk	8.50	42	0.40	100	Sand	79.4	15.7	4.9
	Bk*	8-8.40	1-3	0.03	100	Sand	88.6-95.1	6.1-3.2	5.3-1.7
Torre del Remei	A$_1$	5.70	0	3.92	-	Sandy loam	69.0	24.1	6.9
	A$_2$	5.49	0	0.67	-	Sandy loam	65.9	20.6	13.5
	2Bt$_1$	5.81	0	0.47	-	Sandy loam	67.1	15.1	17.7
	2Btg$_2$	6.59	0	0.14	-	Sandy clay loam	68.9	9.3	21.8
	3Btg$_3$	6.70	0	0.32	-	Sandy clay loam	66.5	12.6	20.9
Alp	Ap	7.80	nd	1.84	100	Sandy loam	54.4	27.5	18.1
	Bt	8.20	nd	0.06	100	Sandy clay loam	49.4	20.3	30.3
	2Btg$_1$	8.20	nd	0.19	100	Sandy clay loam	64.6	9.2	26.2
	2Btg$_2$	7.90	nd	0.15	100	Sandy clay loam	59.1	11.6	29.3
	3C	8.10	nd	0.09	100	Loam	34.8	39.2	26.0
Tartera	Ap1	8.30	5	2.00	100	Loam	52.3	37.4	10.3
	Ap2	8.40	5	1.80	100	Sandy loam	56.6	33.1	10.3
	Bk1	8.40	52	0.80	100	Sandy loam	70.5	23.4	6.1
	Bk2	8.30	34	1.40	100	Sandy loam	59.0	35.4	5.6
	Bkmt3	8.50	41	-	100	-	-	-	-
	Bkt7	8.50	22	0.10	100	Sandy loam	74.9	9.9	15.5
	Bkm8	8.50	41	-	100	-	-	-	-
	2Bkt9	8.70	20	0.10	100	Loamy sand	83.5	8.3	8.2
Abellerols	Ap1	7.40	nd	2.39	100	Sandy loam	61.6	23.4	15.0
	Ap2	8.20	nd	1.48	100	Sandy loam	63.7	21.8	14.5
	Bw	8.50	nd	0.63	100	Sandy loam	64.8	19.8	15.4
	2Bwk1	8.50	6	0.36	100	Sandy loam	60.8	24.7	14.5
	3Bwk2	8.50	16	0.31	100	Sandy loam	61.4	28.2	10.4
	4Bk3	8.50	6	0.12	100	Loamy sand	81.4	14.6	4.0
	5Bk4	8.70	nd	0.25	100	Sand	88.5	8.4	3.1

*2 samples, ** Base saturation percentage., nd: non detectable.
Methods from Porta et al (1986): CaCO$_3$ by calcimetry; OC: Walkley-Black; V: Base Saturation Percentage by NH$_4$-Ac at pH 7; Texture: Discontinuous sedimentation method.

The main morphological features are the carbonatation/limestone dissolution and clay illuviation processes that appear together in some horizons of Montferrer, Alp and Tartera, and the extreme clay illuviation in the highly weathered moraines of Torre del Remei. The main micromorphological features are summarized in Table 4.

Table 4 (I). Summary of the micromorphological descriptions

Pedon	Horizon	Coarse fragments	Micromass	Main pedofeatures
Montferrer	Bt	Schists, quartzites, quartz, mica.	Clay, Mosaic-speckled b-fabric.	Microlaminated clay coatings and infillings, limpid or speckled, occupying 20% in volume.
	Btk	Quartzites, schists and fissurated micas, weathered plagioclases (to sericite).	Mostly sericite. Sericitic-crystallitic b-fabric.	Fe-oxyde coatings on schist fissures and on clay coatings. Amorphous reddish clay coatings. Microlaminated clay coatings. Thick (several mm) silt cappings, sericitic. Micritic coatings on clay and silt cappings, breaking them.
	Bk	Schists, quartzites and metamorphic limestones.	Absent.	Discontinuous cappings of sericitic silt, sometimes broken by micrite. External coatings of micrite, impregnative. Sparite coatings, in palisade. Discontinuous, loose infillings of acicular calcite. Nodules of Fe-oxi-hydroxides.
Torre del Remei	A2	Quartz, quartzites, plagioclases, schists, mica.	Undifferenciated.	Absent.
	2Bt$_1$	Quartz, quartzites, fissured schists, micas slightly opened.	Crystallitic b-fabric, due to mica flakes.	Microlaminated clay infillings and coatings, around pores, coarse fragments and in schist fissures. Fe-oxi-hydroxide hypocoatings.
	2Btg$_2$	Rubefied and fragmented schists, quartz, feldspars, biotite and muscovite, highly weathered.	Microlaminated clay.	All micromass is found as oriented clay infillings and coatings.
	3Btg$_3$	Rubefied and fragmented schists, quartz, feldspars, biotite and muscovite, highly weathered.	Microlaminated clay.	All micromass is found as oriented clay infillings and coatings. Aggregated impregnative nodules of Fe and Mn oxi-hydroxides in the micromass.
Alp	Ap	Schists, quartz.	Brownish mixture of clay, fine silt and organic pigment. Undifferenciated to crystallitic b-fabric due to mica and quartz.	Absent.
	Bt	Schists, quartz and quartzites.	Brownish mixture of clay and fine silt. Mosaic speckled and granostriated b-fabric.	Clay coatings along fissures of coarse gravels.
	2Btg$_1$	Schists, quartz and quartzites.	Clay and Fe-oxides. Mosaic speckled and striated b-fabric.	Generalized microlaminated clay coatings and infillings around packing pores and coarse gravels, some of them argilloturbated.
	2Btg$_2$	Schists, quartz and quartzites.	Clay and Fe-oxides. Mosaic speckled and striated b-fabric.	Generalized microlaminated clay coatings and infillings around packing pores and coarse gravels, some of them argilloturbated. Aggregated nodules of Fe-oxi-hydroxides.
Tartera	Bk1	Limestone fragments, quartz, quartzites, plagioclases.	Clay, fine silt. Crystallitic b-fabric due to mica flakes.	Laminated carbonate pendants, micritic nodules, disorthic or anorthic.
	Bk2	Limestone with dissolution features, quartzites, schists.	Clay, fine silt. Crystallitic b-fabric due to mica flakes.	Pendants of micrite, also of sparitic calcite in palisade, up to 8 mm thick, with an internal banding parallel to the coarse element. Loose infillings of calcite needles.
	Bkmt3	Id.	Id.	Id; clay coatings.
	Bkm4	Id.	Clay and fine silt. Mosaic-striated / crystallitic. (micritic) b-fabric.	id; with fine microlaminated clay coatings alternating with coatings of calcite needles.
	Bkm5	Id.	Micrite. Crystallitic b-fabric.	Id; with sparite nodules; and continuous incomplete infillings of micrite and packed calcite needles.
	Bkmt7	Id.	Id.	Id; with higher amount of clay coatings.
	2Bkt9	id.	id.	Id; with punctuations and aggregate nodules of Fe and Mn oxi-hydroxides on calcite coatings.

Table 4 (II). Summary of the micromorphological descriptions

Pedon	Horizon	Coarse fragments	Micromass	Main pedofeatures
Abellerols	Ap2	Quartz, quartzites, limestones with dissolution features.	Speckled mixture of clay and silt, crystallitic b-fabric due to mica flakes.	Absent.
	Bw	Quartz, quartzites, limestones.	Speckled mixture of clay and silt, crystallitic b-fabric due to mica flakes.	Calcareous spherulites. Queras.
	2Bwk1	Quartz, schists, quartzites, plagioclases with medium linear alteration to sericite.	Speckled mixture of clay and silt, crystallitic b-fabric due to mica flakes or to micrite, depending on the area.	Few microlaminated clay coatings. Micrite hypocoatings on pore walls. Orthic nodules of micrite and of needle calcite.
	3Bwk2	Id.	Fine silt and micrite. Crystallitic b-fabric (micritic).	Hypocoatings of highly packed needle calcite and micrite, up to 2 mm thick. Dense incomplete infillings of needle calcite. Impregnative orthic nodules of micrite. Queras. Very fine (0.1 mm) coatings of microlaminated clay on packed needle calcite coatings.
	4Bk3	Id.	Speckled mixture of clay and silt, speckled b-fabric.	Frequent hypocoatings and nodules of micrite and needle calcite, impregnative, orthic.
	5Bk4	Schists.	Speckled mixture of clay and silt, crystallitic-sericitic b-fabric, also granostriated.	Coatings of microlaminated clay around some coarse fragments. Few micritic hypocoatings on pores.

The micromorphological study of the Montferrer profile reveals that the micromass of the rubefacted horizons is mainly sericite silt, partly coming from the weathering of feldspars, which also forms the silt coatings in the deepest horizons. Clay coatings are generalized, some of them are allophanic with varying Fe contents, evidenced by SEM-EDAX (**Figure 3**). Hydrated Fe-hydroxides coatings are also present in crystalline fan-like form. The recarbonatation of the Btk horizon is very strong, and proceeds mainly from the dissolution of the limestones, breaking down the previous features (**Figure 4**).

The Torre del Remei soil is developed on the frontal moraines of glaciers coming down into the valley, on the south facing side. Their lithology, considering the source area, is mainly granite and schist, without carbonates. They are considered weathered fluvio-glacial formations (Calvet 2004). The soils located on these formations allow us to observe the parent material consisting of gravel and large boulders of gritty granites and schists, highly weathered, that infers the age of the soil, since alteration must have taken place in situ. The attempts to date these surfaces result in high value dispersion due to the weathering degree, which gives low ages to such deeply weathered glacial and glaciofluvial materials (^{10}Be dating, Calvet et al. 2011).

The processes of soil genesis have been primarily formation and mobilization of clay from the alteration of feldspars and micas, as shown by the coatings observed through the microscope in the Bt (argillic) horizons (**Figure 5**). This clay illuviation is a common feature in the soils of the northern part of La Cerdanya that are located in older geomorphic surfaces. In those cases clay illuviation is extreme (Simó 2005). When this accumulation is very intense, it modifies the texture of the horizons so that the loose surface horizons become more sandy, overlying with a sharp boundary on the more clayey horizons. In our case, the abrupt textural change between A and B horizons seems not to be fully due to this process, but to a lithological discontinuity (a new material supplied on the surface), as shown by the different particle size fraction without clay and differences in sand mineralogy between the horizons (Poch et al. 2011).

The Alp soil is also characterized by clay illuviation, remarkably it is not decalcified. The upper B horizon shows clay coatings that continue with depth. The most noticeable micromorphological features are the decarbonated micromass in spite of the high pH that is indicative of a carbonate supply through the overland flow of the alluvial fan, the presence of pressure faces (granostriation) around gravels and sands, and an extreme clay illuviation similar to that of Torre del Remei. Other soils in this unit show pressure faces and development of slickensides (data not presented, Boixadera pers.comm.).

Tartera soil shows a rubefied A horizon, masked by organic matter in some non cultivated profiles

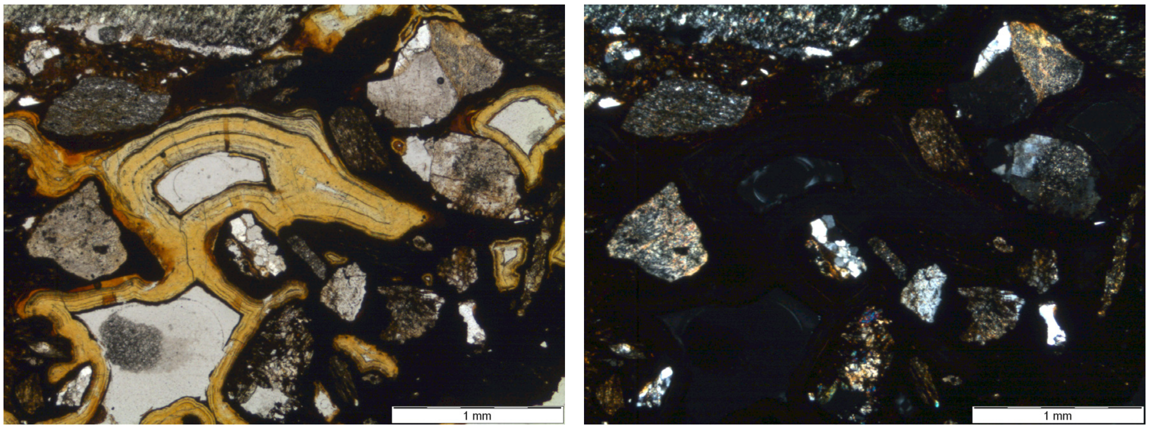

Figure 3. Allophanic coatings (Bt, Montferrer). The anisotropy at the lumen of the pore is an artifact (bubble).

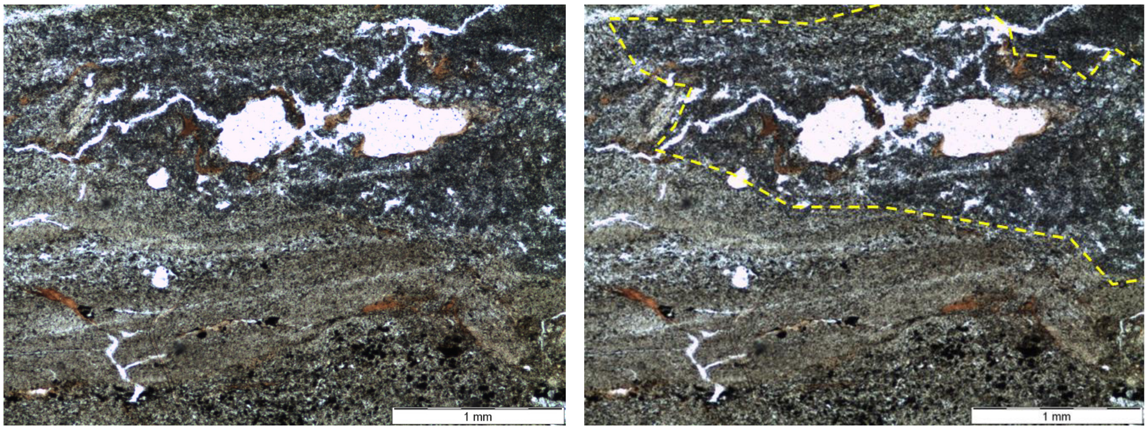

Figure 4. Recarbonatation of a silt capping (Btk, Montferrer). The yellow dotted line shows the recarbonated section by micrite and microsparite. Thin clay coatings are found on the pores of the recarbonated section.

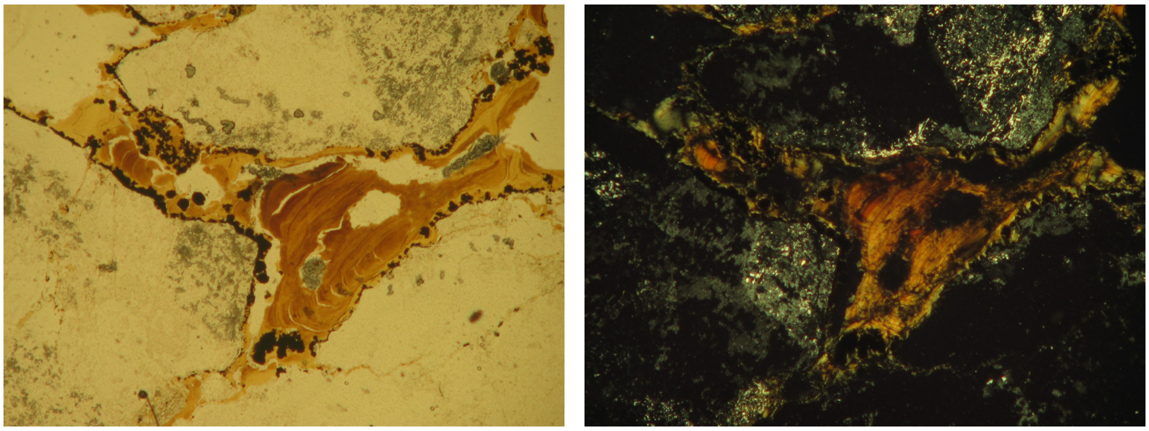

Figure 5. Microlaminated clay infilling and Mn coating (2Bt2, Torre del Remei). PPL and XPL (4.2 mm length).

(data not presented, Boixadera, pers. comm.). Other features are (i) the crystalline nature of calcite pendants underneath the gravels, (ii) the coexistence of clay illuviation together with secondary calcite, and (iii) evidences of dissolution of limestone fragments. These features can be observed both in the field and microscopically. Besides calcitic pendants formed by micrite or by layers of micrite and microsparite, many pendants consist of large calcite crystals, perpendicular to the gravel surface, with interspersed dark reddish layers within the crystals, showing a continuity subparallel to the gravel surface, crossing the crystals (Figure 6). Their morphology is very similar to those of the speleothems, whose laminae have been explained by Paulsen et al. (2003) as annual layers; and by Gradziński et al. (2003) as composed from charcoal and organic particles produced by fires. In our case, in absence of SEM-EDAX evidence, the origin is detrital (clay and fine silt), as shown in thin section, which is in agreement with the formation of the deposit. The large density of bands would then indicate a higher flood frequency in the past, during the period of maximal alluvial fan formation.

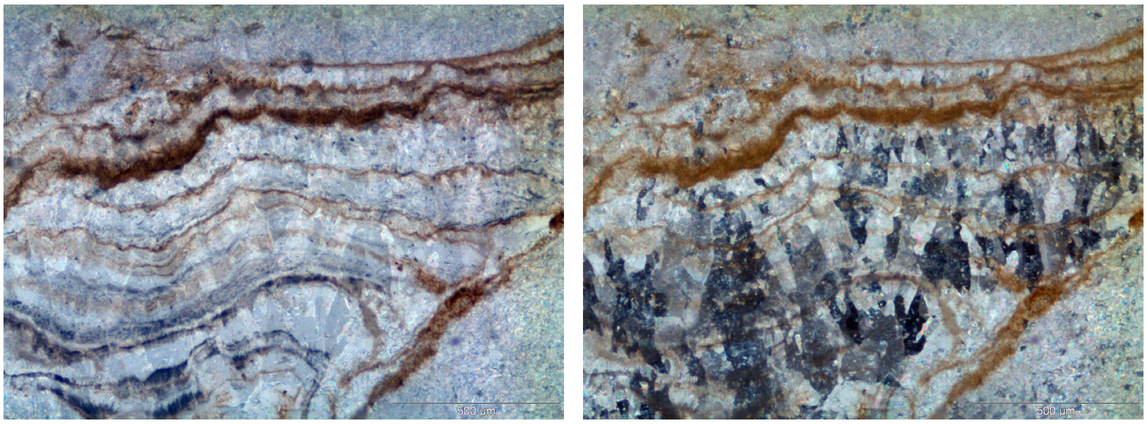

Figure 6. Crystalline banded sparite pendants (Bkm8, Tartera).

The presence of clay coatings in some layers of the deposit allows us to describe Bkt or Bkmt horizons in the field (we propose this suffix order to be coherent with the process chronology). In thin section they appear as clay coatings with different degrees of orientation, mostly covering previous calcite coatings, and more rarely around the voids of cemented masses of secondary calcite (Figure 7).

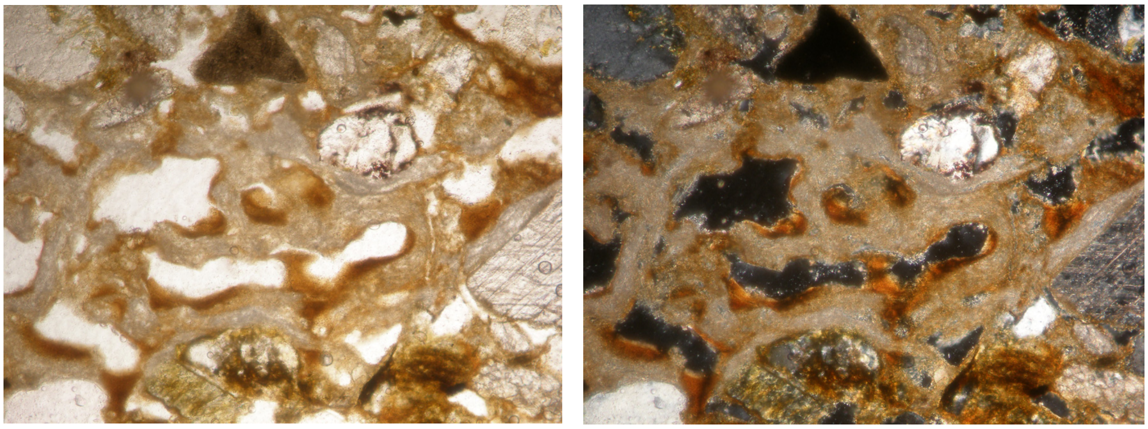

Figure 7. Clay coatings in petrocalcic fragment (Btk7, Tartera) (4.2 mm length).

The Abellerols soil is located in the youngest surface. In spite of the fact that it is a Segre terrace formed by silicatic materials, the presence of some limestone fragments at the top horizons show that there has probably been a supply of carbonates by the distal parts of the alluvial fans at the top. This soil is partly decarbonated in the top 50 cm, although there is some biogenic calcite (biosparite, calcareous spherulites). In the 2Bwk1 horizon there are few clay coatings (Figure 8) coexisting

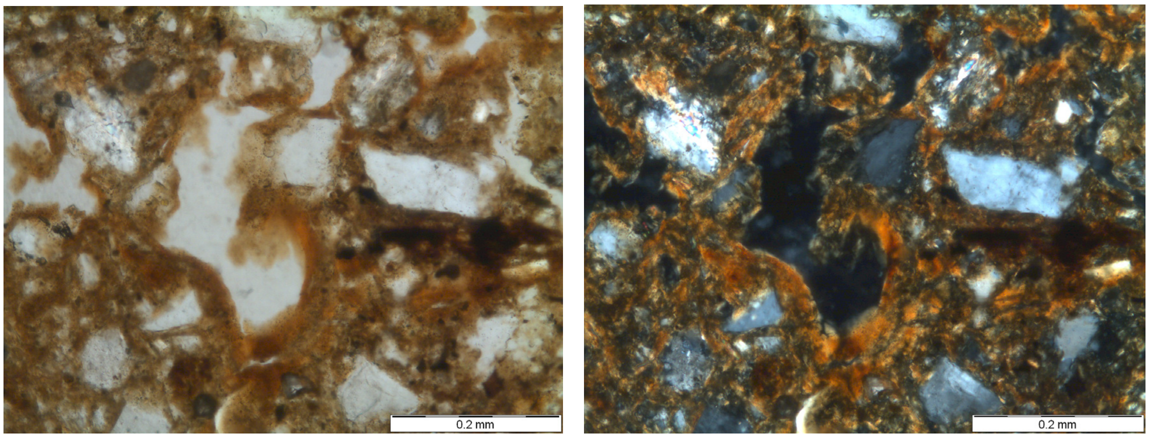

Figure 8. Microlaminated clay coatings. 2Bwk Horizon (46-66 cm), Els Abellerols profile.

with micritic orthic nodules. Calcite accumulation was highest in the 3Bk horizon, with very frequent infillings and coatings of acicular calcite, together with calcite nodules in a cristallitic micritic micromass. In this horizon, clay coatings sometimes covered the calcitic pedofeatures (**Figure 9**).

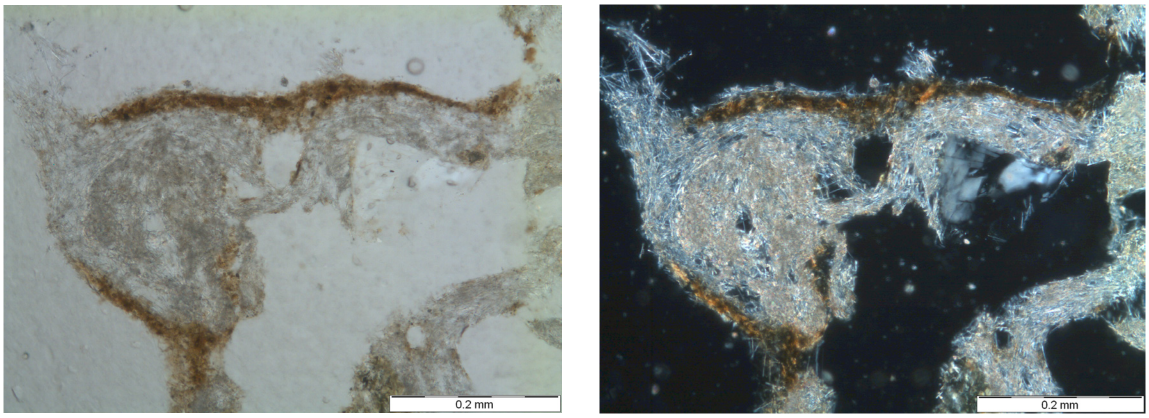

Figure 9. Anisotropic clay coating on a calcite nodule, made of acicular calcite with a micritic nucleus. 3Bk horizon (66-90/120 cm), Els Abellerols profile.

4. Discussion

4.1. Clay illuviation and carbonate redistribution

In three of the studied soils (Montferrer, Tartera, Abellerols) clay illuviation occurred with carbonate accumulation, either before or after (microlaminated clay coatings overlying or underlying secondary carbonates). The absence of such features in the other two soils is explained by the low carbonate supply (Alp), or by the absence of carbonate in the parent material (Torre del Remei).

Alonso et al. (2004) explain clay illuviation on secondary calcite in siliceous Pleistocene river terraces by a combined process of dissolution of formerly coated carbonate crystals and clay illuviation filling the pores. In our case, although limestone dissolution is evident (Montferrer, Tartera), the presence of remains of a decarbonated, rubefacted A horizon allows us to suggest a process of clay illuviation from this horizon, which would accumulate in the pores of the underlying Bk or Bkm horizon, in a process similar to that of the formation of beta horizons (Mathieu and Stoops 1974). In agreement with the concepts of Wieder and Yaalon (1978) and Aguilar et al. (1983), carbonate prevents the dispersion of clay but does not prevent the movement of already dispersed clay (in A horizons) if pores are large enough (Pazos 1990). We have to think about both processes (clay illuviation and calcite redistribution) as alternating, since in some cases, coatings of calcite, mainly acicular, cover the former clay coatings. The origin of dispersed clay is evident in the Montferrer and Abellerols profiles; also the rubefacted, partly decarbonated A horizon is still visible in the Tartera soil. In this case, elluviation takes place in the A horizon and clay floculates in the Bk horizon. Successive episodes of alluvial fan aggradation in the Tartera profile would erode the previous decarbonated

A horizon, and start again the processes in the newly deposited material. In this profile, these flooding episodes of the alluvial fan could supply the fine silt and clay particles that would remain at the surface of the continuously growing sparite crystals of the pendants. Their crystalline nature could then be explained by the fairly constant supply of bicarbonate subsurface water flowing through the coarse, skeleton-supported alluvial fan deposit. The difference in age between Montferrer (the oldest soil) and Abellerols (the youngest soil) is shown only by the thickness of the horizons, suggesting a prevalence of conditions favourable for carbonate leaching down to a given depth during the Quaternary.

4.2. Soil development and surface age

Among the different researches conducted on chronosequences and dating on the terrace systems of the north Ebro tributaries, Lewis et al. (2009) show a positive relationship between surface age and the profile development index (PDI, obtained from morphological properties), and carbonate stage morphology (Gile et al. 1981; Birkeland 1999). In our case, although carbonate morphology of Tartera corresponds to stadium II^+ (continuous pebble coatings, some interpebble infillings), consistent with the terrace age of Lewis et al. (2009) on the Cinca and Gállego rivers, we should not think that the carbonatation process proceeds in the same way, since the progressive alluvial fan aggradation causes this morphology to occur in a much shorter period of time and to be buried by the next material supply. Indeed, older sectors of the same alluvial fan corresponding to an older terrace show identical morphologies (Boixadera, pers.comm.). We must conclude that, in our sequence, the erosion events that might have occurred during the time span of soil development, the different nature of soil parent materials, the diverse soil formation processes –in particular the lateral carbonate supply– and the high weathering prevent the use of a consistent soil development index for all soils. Indeed, some of the features observed correspond to diverse soil formation paths. As examples we showed the formation of amorphous clays in the oldest profile, that could be the result of extreme granite weathering, as it has been observed in spodosols (García-Rodeja et al. 1987). The presence of podzolisation processes in the region, at higher altitudes (Boixadera et al. 2008), supports this idea. Another indication of soil evolution is the presence of vertic features in the Alp and surrounding soils, which would surely mask clay illuviation. All these facts confirm that the use of age indicators should be carefully used, and only when the soil formation process is well determined.

5. Conclusions

In the middle altitudes of La Seu-La Cerdanya valley, calcium carbonate and clay leaching and accumulation are the main soil formation processes. In addition to surface age, soil development is also controlled by parent material characteristics. When calcium carbonate is absent from the parent material (Torre del Remei and Alp), clay illuviation is strong; it couples with mottling phenomena, and leaching of cations are noticeable (Torre del Remei) if $CaCO_3$ is absent in the percolating water.

Profiles Tartera and Montferrer allow us to identify different types of percolation regimes. The existence of alternating morphologies of clay illuviation and calcium carbonate accumulation should be interpreted also in the sense of percolating (clay illuviation) or non-percolating ($CaCO_3$ accumulation) regimes. Special morphologies of carbonate pendants are indicators of environmental conditions. The coexistence of clay coatings and secondary calcite can be explained by recarbonatation or by spatial differentiation of soil environments in the profile.

Reddening of soil materials is more pronounced in calcareous than in non calcareous materials. Mottling is very much related to clay content and it seems to prevent rubefaction (Torre del Remei). Our results are a clear indication that soil development indices based on morphological features could be meaningless if not applied to uniform sequences.

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