How soil forming processes determine viticultural zoning in Catalonia, Spain.

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Abstract
The aim of this paper is to analyze whether the soil forming processes determined in representative vineyard soils, through their effects on soil properties and classification, deserve to be considered in a viticultural zoning based on soil surveys. Many viticultural zoning studies are based on the relationships between grape and wine quality and certain soil properties or different soil forming factors, but there are no studies that consider possible relationships with soil forming processes. The study area produces high quality wines and is located in Priorat and Penedès viticultural areas (Catalonia, Spain). The studied soils belong to representative soil map units, which were determined according to the Soil Survey Manual (SSS 1993), at a 1:5,000 scale. A micromorphological study was undertaken in order to clarify or identify pedogenic processes. The soil forming processes, identified through morphological and micromorphological analyses, had direct effects on soil properties and soil classification. These properties, especially those related to the soil moisture regime, the available water capacity and the calcium carbonate content, had a direct influence on the type of management and quality of grapevine production. We show that the parent material or climate alone cannot be used in viticultural zoning, unless soil forming processes are taken into account.

Key Words
Soil genesis, micromorphological study, soil classification, Soil Taxonomy, vineyard soil, soil survey, viticulture

Introduction
In the last years, viticultural zoning studies have increased significantly in relation to the expansion of the international wine market. Viticultural zoning can be defined as the spatial characterization of zones that produce grapes or wines of similar composition, while enabling operational decisions to be implemented (Vaudour 2003). Among the various environmental factors and for a specific climate, soil is the most important factor on viticultural zoning, due to its direct effect on vine development and wine quality (Gómez-Miguel and Sotés 2003). There are several approaches through soil studies which are oriented to viticultural zoning, but the methods that provide more information are soil survey techniques, since they bring both the knowledge of spatial variability of soil properties and soil classification according to its viticultural potential (Van Leeuwen and Chery 2001). Soil survey methods based on Soil Taxonomy classification (SSS 1999) were useful for viticultural zoning studies at different detail levels (Gómez-Miguel and Sotés 2003; Ubalde *et al*. 2009).

Soil forming processes determine most of the diagnostic horizons and characteristics for the higher categories of Soil Taxonomy, thus the soil genesis is fundamental in order to classify soils and in viticultural zoning based on soil surveys. However, many viticultural zoning studies are based on the relationships between grape and wine quality and certain soil properties or different soil forming factors, namely climate, geology and topography, but there are no studies that consider possible relationships with soil forming processes. This fact may be due to difficulties in determining some of these processes, because soil genesis cannot be observed or measured directly and pedologists could differ about it (SSS 1999). Evidences of some soil forming processes can be detected only by microscopic studies, which require a specific training. Furthermore, some soil forming processes are not adequately addressed by the taxonomic system, especially those related to human activity (SSS 1999).

The aim of this paper was to analyze whether the soil forming processes determined in representative vineyard soils, through their effects on soil properties and classification, deserve to be considered in a viticultural zoning based on soil surveys. To our knowledge, this approach has never been addressed before.

Materials and methods
The study area is located in different protected viticultural areas of Catalonia: Priorat and Penedès. The area is enclosed approximately between 41º 3' N and 41º 48' N and between 0º 40' E and 1º 53' E. The altitude

ranges between 220 m and 550 m. The vineyards are situated on the Catalan Coastal Range, an alpine folding chain formed by both massifs and tectonic trenches. Massifs consist of Palaeozoic slates and granites (Priorat region). Tertiary calcareous rocks outcrop in the tectonic trenches (Penedès region). The climate type is Mediterranean, characterized by a dry warm season during summer, even though there are differences in temperatures and precipitation according to the altitude and distance to the sea. The mean annual precipitation varies from 520 mm in Penedès to 589 mm in Priorat, showing seasonal variations. The Penedès region has an average annual temperature of 14.9 ºC, while that of the Priorat is 12.7 ºC. The soil moisture regime is xeric and the soil temperature regime is mesic (Priorat) or thermic (Penedès) (SSS 1999).

The studied soils belong to representative soil map units, which were determined according to the Soil Survey Manual of the Department of Agriculture of United States (SSS 1993), at very detailed scale (1:5,000). The density of soil observations was 1 observation by cm^2 of map, of which a sixth part corresponded to soil pits and the rest to soil auger holes. Details of the soil survey method are given in Ubalde *et al*. (2009). Moreover, a micromorphological study was undertaken in order to clarify or identify pedogenic processes which were difficult to detect with the naked eye. For the micromorphological study, thin sections were elaborated from undisturbed soil material according to Benyarku and Stoops (2005). Samples were taken from deep horizons, since surface horizons were disturbed by plowing. Generally, 1 or 2 samples were collected for each selected profile. Altogether, in this study, we described a total of 23 thin sections from 19 different profiles and 8 soil map units. The criteria of Stoops (2003) were used in thin section description.

Results and discussion

Soil forming processes in Priorat

The Priorat soils are Entisols, since the identified soil forming processes are not enough developed to determine any diagnostic horizon, except to an ochric horizon. In general, soils developed from granodiorites (Fig. 1) were classified as Xeropsamments, which are characterized by a texture coarser than loamy fine sand and less than 35 % of rock fragments. However, soils developed from very rubefacted granitic regolith (Fig. 2), were classified as Typic Xerorthents. These soils could not be classified as Alfisols, since evidences of illuvial clay is required for an argillic horizon, and in this case, the clay origin was the alteration of biotite. Moreover, these soils cannot be classified as inceptisols because the subsurface horizons maintain the rock structure, and consequently the criteria for cambic horizon are not accomplished. With respect to soils developed from slates, they are classified as Lithic Xerorthents, in spite of presenting a strongly exfoliated rock with intercalations of material enriched in illuvial clay (Fig. 3). There is a subgroup in the Alfisols, named Lithic ruptic-inceptic Haploxeralfs, which are defined by presenting a lithic contact and a discontinuous argillic horizon, horizontally distributed. However, in the studied soils, the thickness of material with illuvial clay was generally lower than 7.5 cm, so the criteria for argillic horizon were not accomplished.

In soils developed from slates, the available water capacity was moderate (56 mm between 0 and 40/50 cm depth), so the water retained by the clay-rich materials among the rock cracks was worth considering (16 mm until 200 cm depth) (Table 1). The presence of redoximorphic features related to clay features would indicate that clay accumulation was causing an alteration in the soil moisture regime. In soils formed from granodiorites, the available water capacity was very low (12 mm between 0 and 40 cm depth). These soils, in addition to shallowness, were composed practically by sand (Table 1), so that there were not particles of silt or clay to retain water. In order to obtain a high quality production, irrigation with low doses applied frequently is needed. The existence of rubefacted granodiorites with neoformed clay resulted in soils with finer textures, increasing three fold the available water capacity (32 mm between 0 and 34 cm depth) in comparison with the non-rubified Xeropsamment. Although irrigation is still necessary, water losses may be smaller. Another soil property improved with clay accumulations was the cation exchange capacity (CEC) of surface and deep horizons. In surface horizons, the CEC increased from 5.1 to 9.1 cmol/kg. This increase represents a substantial improvement of nutrient availability for the vine and the possibilities of development of soil structure and stability of soil aggregates, which is especially important in these soils poor in organic matter (contents lower than 0.5%).

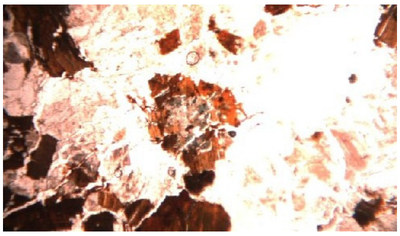

Figure 1. Mineral composition of granitic regolith, with mica alteration in the center of the picture (6.4 mm width, PPL).

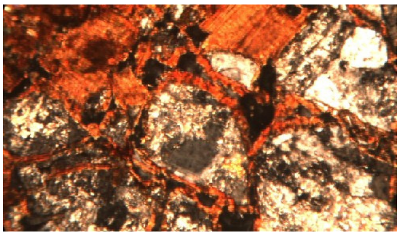

Figure 2. In situ clay neoformation in very rubefacted granitic regolith: microlaminated coatings (1.5 mm width, XPL).

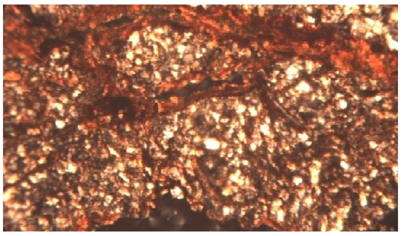

Figure 3. Clay illuviation in slates: clay infillings in cracks and clay coatings in pores (1.5 mm width, XPL).

Table 1. Analytical properties of representative vineyard soils in Priorat region *.

Horizon	Lower depth (cm)	Munsell color (moist)	pH (H_2O 1:2.5)	EC (dS/m)	Organic matter (%)	$CaCO_3$ (%)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 2006)	Bulk density (kg/m^3)	Coarse fragment (%)	Water retention 1/3-bar (%)	Water retention 15-bar (%)	AWC (mm)
Sandy, mixed, mesic, shallow, Typic Xeropsamments																
Ap_1	20	10YR5/4	8.6	0.12	0.1	trace	5.1	91.5	4.9	3.6	Sa	1520	trace	5	3	6
Ap_2	40	10YR5/4	8.6	0.11	0.1	trace	5.2	91.8	6.9	1.3	Sa	1556	trace	5	3	6
C	>160	-	8.4	0.08	trace	trace	4.6	95.5	3.6	0.9	Sa	-	-	4	3	-
Loamy, mixed, active, mesic, shallow, Typic Xerorthents																
Accumulations (34->150 cm depth): Clay coatings on sand grains.																
Ap_1	14	5YR4/5	8.3	0.17	0.5	trace	9.1	71,7	15,9	12,4	SaL	1355	trace	15	7	14
Ap_2	34	5YR4/5	8.4	0.14	0.1	trace	8.8	78,6	12,6	8,8	LSa	1608	trace	12	6	18
C	>150	5YR5/7	8.1	0.18	trace	trace	9.0	85,9	8,6	5,5	LSa	-	-	11	6	-
Loamy-skeletal, mixed, semiactive, mesic, Lithic Xerorthents																
Accumulations (40/50->200 cm depth): Clay coatings on rock cracks.																
Ap_1	15	10YR4/4	7.6	0.26	3.5	trace	12.7	69.5	19.8	10.7	SaL	1569	48	21	8	16
Ap_2	40/50	10YR4/4	7.7	0.22	1.9	trace	12.0	71.1	18.3	10.6	SaL	2105	37	18	8	40
R/Bt	200	2.5Y5/4	7.7	0.21	0.4	trace	15.0	53.6	27.8	18.6	SaL	1920	20	22	11	16

* EC: electrical conductivity; CEC: cation exchange capacity; Textural classes: Sa: sand, LSa: loamy sand, SaL: sandy loam; AWC: available water capacity.

Soil forming processes in Penedès

Most of the Penedès soils are classified as Inceptisols, because of enough carbonate or gypsum accumulations leading to calcic, petrocalcic or gypsic horizons. Generally, they are classified as Typic Calcixerepts, Petrocalcic Calcixerepts and Gypsic Haploxerepts, respectively. However, not all soils with carbonate accumulations could be classified as Calcixerepts, since they did not meet the criteria for a calcic horizon: some soils only showed incipient accumulations, or presented too low $CaCO_3$ content. Generally, these accumulations led to cambic horizons, and soils were classified as Typic Haploxerepts. Even in some cases, where carbonate accumulations were not visible at the naked eye, a cambic horizon could not be determined, and soils were classified as Entisols. Table 2 shows the analytical properties and the description of accumulations in a soil with a well-developed calcic horizon (Typic Calcixerept, Fig. 6), a soil with incipient accumulations of carbonates (Typic Xerofluvent, Fig. 4 and 5), as well as a soil with a gypsic horizon (Gypsic Haploxerept).

The soil forming processes in Penedès were marked by the accumulation of secondary carbonates, which could be highly evolved, as it was indicate by the types of accumulations and their morphology (Table 2). This evolution was reflected in the calcium carbonate content, which could exceed 75%, and in carbonate cementations. The evolution of carbonates in these soils may be a limiting factor for grapevine cultivation. High contents in calcium carbonate can cause a weakening in non-resistant vines, due to iron chlorosis. The main consequences are rickets, foliage destruction, reduced production and even the death of the plant. These problems may be mitigated by the choice of resistant rootstocks, such as 41B and 140R. Furthermore, very intense processes of carbonate accumulation, leading to a micromass cementation, may constitute a limitation for the development of the root system. Moreover, carbonate accumulations in the form of nodules increase the coarse fragment content, and thus reduce the available water capacity. In the deep horizons of a Typic Calcixerept, a loss of 29.7 mm of available water capacity can be quantified, considering a volume of 20% of carbonate accumulations. However, the main implications of carbonate accumulations on vineyard management are related to rootstock selection and ploughing, which should not be too deep to prevent the outcrop of calcic horizons to the surface.

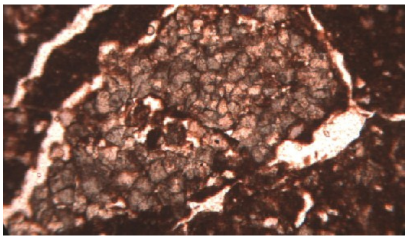

Figure 4. Citomorphic calcite nodules in Typic Xerofluvents:. (1.5 mm width, PPL).

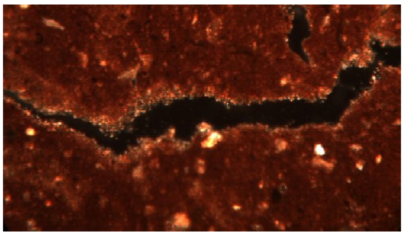

Figure 5. Acicular crystals and microsparite hypocoating in Typic Xerofluvents (1.5 mm width, XPL).

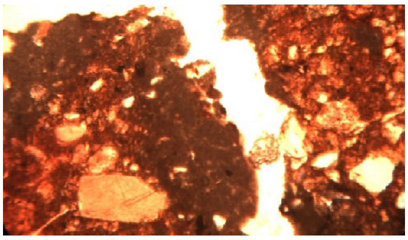

Figure 6. Well-developed carbonate accumulations in Typic Calcixerepts (1.5 mm width, PPL).

Table 2. Analytical properties of representative vineyard soils in Penedès region *.

Horizon	Lower depth (cm)	pH (H_2O 1:2.5)	EC (dS/m)	Organic matter (%)	$CaCO_3$ (%)	Gypsum (%)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 2006)	Bulk density (kg/m^3)	Coarse fragment (%)	Water retention 1/3-bar (%)	Water retention 15-bar (%)	AWC (mm)
Fine, mixed, semiactive, thermic, Typic Xerofluvent																
Accumulations (40-95 cm depth): Microscopic micritic calcite nodules and microesparitic calcite hypocoatings. Whole soil hypocoatings.																
Ap1	12	8.2	0.20	1.6	31	trace	17.5	18.2	40.7	41.1	SiC	1368	0	27	15	20
Ap2	40	8.2	0.25	1.2	33	trace	16.9	18.0	40.6	41.4	SiC	1773	0	27	15	60
Bw	95	8.0	0.66	0.5	31	trace	17.2	11.5	40.8	47.7	SiC	1772	0	27	16	107
Coarse-loamy, carbonatic, thermic, Typic Calcixerept																
Accumulations (30/50->160 cm depth): Macroscopic coatings on pores, geopetal ciment and nodules. Slight carbonate cementation. Microscopic acicular crystals, micrite and microsparite hypocoatings, microsparite and quesparite infillings, micrite and sparite nodules.																
Ap1	15	8.6	0.18	1.4	76	trace	4.5	60.1	29.1	10.8	SaL	1198	46	16	7	9
Ap2	30/50	8.6	0.18	1.2	73	trace	4.4	60.3	28.4	11.3	SaL	1196	37	17	8	17
Bkn	160	8.3	0.60	0.3	69	trace	3.9	60.5	30.9	8.6	SaL	1390	34	13	4	98
Coarse-loamy, mixed, active, thermic, Gypsic Haploxerept																
Accumulations (38-85 cm depth): Gypsum crystals and gypsum coatings on pores.																
Ap1	12/20	7.9	2.29	1.2	31	26	10.2	39.2	55.3	5.5	SiL	1700	5	27	14	34
Ap2	38	7.9	2.29	1.0	30	29	9.2	40.4	56.0	3.6	SiL	1800	10	27	15	43
By	85	8.0	2.33	0.3	25	35	7.5	48.0	46.0	6.0	SaL	1600	5	23	14	64

* EC: electrical conductivity; CEC: cation exchange capacity; Textural classes: SaL: sandy loam; SiL: silt loam; SiC: silty clay; AWC: available water capacity.

Conclusions

In the influence area of the Catalan Coastal Range, a high variety of soil forming processes takes place, in relation to the existing differences in soil forming factors. The soil forming processes, identified through morphological and micromorphological analyses, had direct effects on soil properties and soil classification. These properties, especially those related to soil moisture regime, available water capacity and calcium carbonate content, had a direct influence on the type of management and quality of grapevine production. We showed that the parent material or climate alone cannot be used in viticultural zoning, unless soil forming processes are taken into account.

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