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A morphological approach to evaluating the nature of vineyard soils in semiarid Mediterranean environment

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Abstract

La Mancha (Central Spain) is one of the most extensive vineyard regions in the world, and 'Valdepeñas' is a representative Protected Denomination of Origin (PDO) in this region. However, what are their main soil types? what kind of horizons are the most common? and what is the role of the geomorphological positions in their pedodiversity? After describing and sampling 90 soil profiles in this area, Alfisols, Inceptisols and Entisols were mainly identified in Soil Taxonomy terms; in other words, Luvisols, Cambisols, Regosols, Leptosols and a highly significant proportion of Calcisols according to FAO-UNESCO-ISSS. The accumulation of carbonate, the thickness of which varies from a diffuse or powdery form to crusted forms, appear sometimes like polycyclic. The presence of red soils, with or without a calcic or petrocalcic horizon, indicates the most representative edaphic stages in this region. Consequently, the morphological signature is calcic or petrocalcic, followed by argillic and/or cambic horizons, under ochric horizons. It can be concluded that the nature of soils in Valdepeñas can be considered a differential factor to bear in mind for quality viticultural production.

Highlights

- There are unknown conceptual zones in support production of wine.
- A comprehensive study in a local case was performed due to its traditional production of vineyards.
- This study highlights the importance and uniqueness of the calcic and petrocalcic horizons.
- A disconnect exists between some tradicional viticultural zones with low reputation and the real value of their soils.

KEYWORDS

argillic, calcic, carbonate accumulations, La Mancha, petrocalcic horizons, red soils, soil survey, vineyard, viticulture

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1 | INTRODUCTION

The effect of soils, climate and topographic factors on grape composition has been addressed several times (Tramontini et al., 2013; White, 2020; White et al., 2007). However, the contribution of soil to the character of wine has been ignored, especially prior to the 1980s, with the climate being thought to play the most important role in the quality and quantity of wine production. This trend has evolved more recently and, nowadays, the importance of soil properties on wine production has been much more widely studied, as noted by Van Leeuwen and de Rességuier (2018), who acknowledged a specific effect of soil on terroir expression. Indeed, it has been found that different soils, under the same climate, cause differences in the composition of the wine, as also reported by Willwerth et al. (2010).

The wine industry is showing great interest in the mechanisms by which the soil and, in general, the terroir, affects the quality of wine by studying the behaviour of the vine on a specific soil (Lanyon et al., 2004). In fact, according to De Andres et al. (2007), wine-growers are showing increasing interest in determining the effects of soil composition, fertility, texture and so forth on wine quality.

Production has grown notably worldwide in terms of both quantity and quality since the end of the last century (de Luca, 2011), and viticultural research has contributed to this increase. This rise has focused on the creation of new viticultural areas, with specific characteristics, or on expanding annual production in traditional viticultural areas, such as Castilla–La Mancha (Central Spain; Pillet, 2007), and other regions in Mediterranean Europe (Costantini & Barbetti, 2008; Coulouma et al., 2006).

The Mancha region covers a wide extension of the Central Iberian plateau, representing the largest (and probably one of the oldest) delimited wine region in the whole of Europe, occupying about 500,000 hectares (MAGRAMA, 2017). With a total production of 17 million hectolitres, the region accounts for almost 52% of the total national production (Directorate-General for Agriculture and Rural Development, 2018). Within this region, the Valdepeñas Protected Denomination of Origin (PDO) has been considered to be one of the traditional wine producing zones, with around 22,000 ha of extension.

Given the tendency to perform a territorial study for zoning purposes, there is a need to respect the coherence between soil use and the typological information of this soil. To determine whether the geographic area of the PDO Valdepeñas has functional and significant pedological characters, the current study aimed to perform a detailed identification of the macromorphology and pedodiversity properties in terms of the geomorphological features.

2 | MATERIALS AND METHODS

2.1 | Characteristics of the study area: Geomorphic and climatic settings

The research area (Figure 1) is located in the province of Ciudad Real (La Mancha region), covering the six municipalities (Alcubillas, Moral de Calatrava, San Carlos del Valle, Santa Cruz de Mudela, Torrenueva and Valdepeñas) completely and four partially (Alhambra, Granátula de Calatrava, Montiel and Torre de Juan Abad). This territory is made up of a large

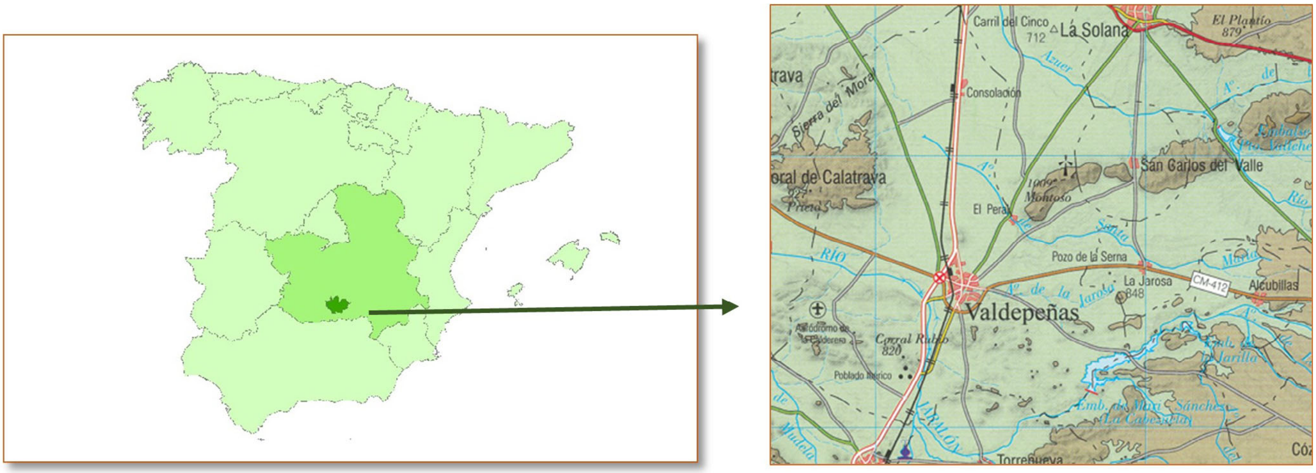

FIGURE 1 Map showing the geographical location of the study area

FIGURE 2 Typical flat or almost flat relief (with red soils) on which residual reliefs stand out

plain, on which some mountain ranges and their associated reliefs stand out (as shown in Figure 2), within the geographical context located in the connection zone between Campo de Montiel and Campo de Calatrava. Two geological domains can be distinguished. The Hercynian basement that includes metasedimentary rocks (quartzites, shales and slates mainly). The other domain includes sedimentary basins (between Miocene and Plio-Quaternary), with limestones, conglomerates, sandstone-lime, sands, silts and clay-rich materials of reddish colours (ITGE 2008–2009–2018, Pillet, 2007). The geomorphology of the region is conditioned mainly thus by the existence of a series of Pliocene-Quaternary basins, which are bounded by sierras constituted by Palaeozoic rocks. Within the basins the landscape is very smooth, which means topography is predominantly a flat plateau.

The mountain ranges and their associated reliefs mainly comprise quartzites, sandstones, schists and shales. From these mountains (or the isolated hills) it is common to find glacis developed on the sedimentary fill. Additionally, dolines and dejection cones appear as a result of quaternary deposits of a carbonated clay nature. Another type of surface is the one related to the courses of the rivers, as valley bottoms, terraces and alluvial fans (ITGE, 1988, 2009, 2018). Finally, small areas appear with granite or volcanic rocks.

From a climatic point of view, the region is semiarid, with an average annual temperature of about 12–14°C, with an average temperature of 25°C in the warmest month and 6°C in the coldest. The frost period is 4–5 months. Precipitation has an average value of around 450 mm annually, with an average duration of the dry period of 4–5 months.

2.2 | Soil identification and sampling

This study was conducted as part of the 'Mapa de suelos de la DO Valdepeñas' (Soil map of the PDO Valdepeñas) project, funded by the 'Denominación de origen Valdepeñas' (Valdepeñas' denomination of origin). A comprehensive and harmonized analysis have been carrying out of the different soil coverings, the pedotaxa and their spatial distribution (during more than 30 years). After the preparation and design of the survey, the different phases of the methodology are as follows: The fieldwork, sample laboratory analysis, soil classification, soil unit and zoning definition.

In order to perform an accurate soil survey of the area, which involves soil genesis and mapping, it is necessary to first know the soils' landforms, geology, associated plant communities, and other features. In Mediterranean regions, boundaries are sharp in general (where soils change over a few metres) although sometimes they are gradual. For that matter, images showing trees, buildings, roads, land uses and rivers are commonly used as a base map to locate boundaries accurately. Data layers, especially geological data, along with global positioning systems are used to accurately locate soil units and map boundaries. This is how, based on previous knowledge about the soils of the region, entire polypedons have been classified and grouped according to their properties for interpretative output as vector maps (polygons). This way, rather than making a large number of observations on a regular grid pattern to state the soil type, a limited number of strategically located points in the landscape were selected. Moreover, aerial photographs (conventional panchromatic in black and white photography) were used. That allowed us to separate small areas of soils having a different bedrock, physiography, or major land resource area. Finally, extensive anthropogenic activities and farmers opinion were considered.

More than 100 profiles were opened at different landscape points (Figure 3). In each soil horizon, soil samples were collected to perform physicochemical and chemical analyses. Besides, undisturbed samples were collected to determine soil bulk density.

Therefore, an 'inductive' method was used, followed by a 'deductive' phase. Thus, the study territory was subdivided into major physiographical environments. Subsequently, units based on the nature of the parent materials, slope, erosion, landform, land use and the opinion of local farmers, were established. After this phase, 90 geo-referenced soil profiles were excavated to a 1.5–2 m depth for full description according to FAO Guidelines (FAO, 2006), Soil Survey

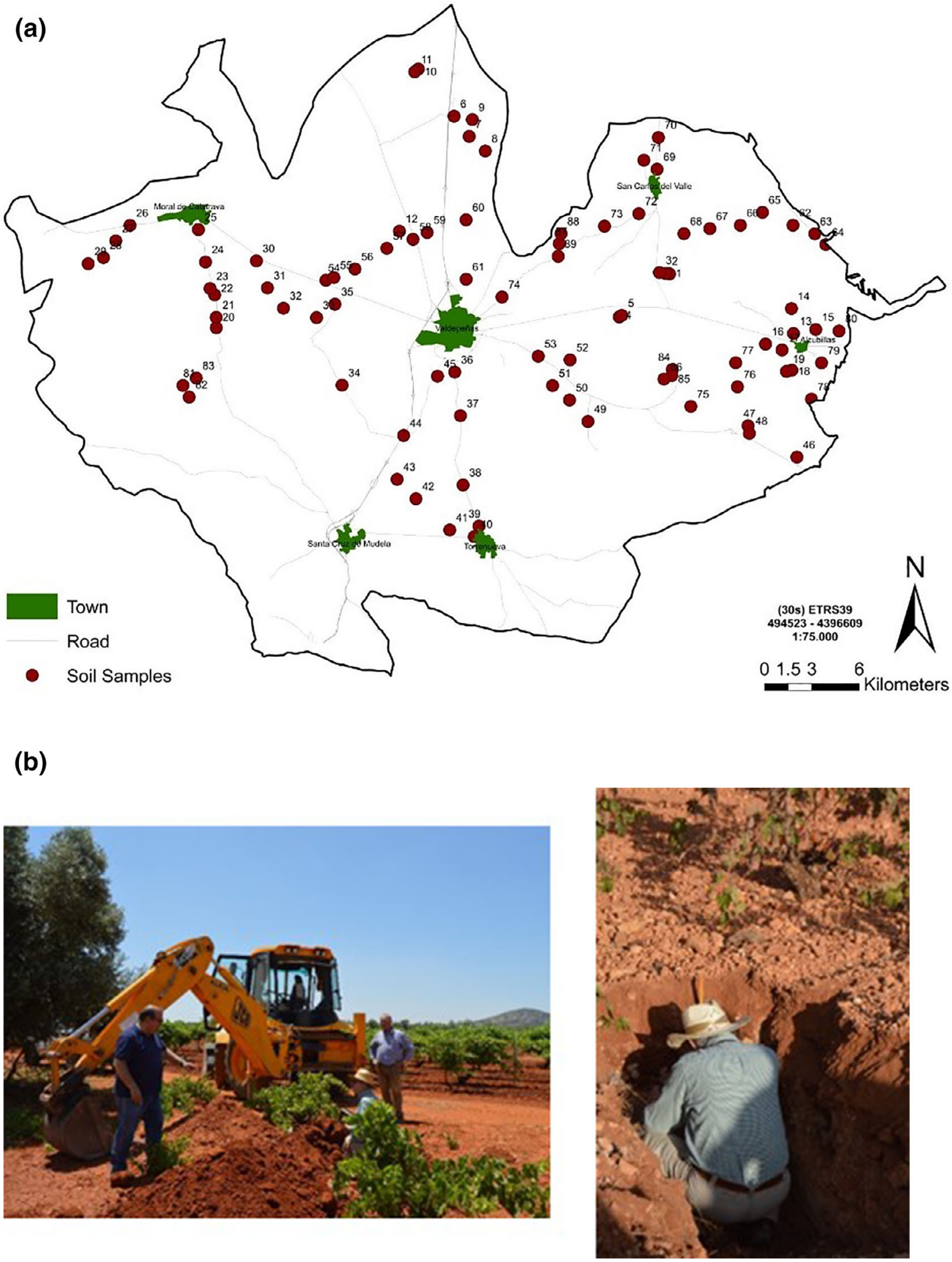

FIGURE 3 (a) Spatial distribution of soil profiles sampled. (b) Opening a soil profile and its description

Staff (1993) and Schoenberger et al. (2012). Figure 3 shows the distribution of these soil profiles, which were sampled separately from horizon to horizon until the parent material was reached (García-Navarro et al., 2019). Approximately, 150 pits were manually drilled to control substantial morphological changes of the soils in landscape.

2.3 | Laboratory methods

The collected soil samples (from February to December 2018) were transported to the Soil Analysis Laboratory of the University of Castilla La Mancha. After drying in an open-air space for 6–7 h, samples were passed through a 2 mm mesh sieve. The soil samples were kept in a plastic bag and preserved in the laboratory till chemical analysis.

Chemical and physicochemical analyses of fine earth samples were performed according to standard procedures as follows: Soil texture was determined using the hydrometer method (Gee & Bauder, 1986) with three replicates. Soil pH was potentiometrically measured in H_2O and in 0.1 M KCl using a 1:2.5 soil:water suspension. Electrical conductivity was measured using an electrical conductivity (EC) meter in a 1:5 soil: water extract. Calcium carbonate was measured using the calcimeter Bernard method. The active calcium carbonate equivalent or 'active lime' was determined using the NH_4-oxalate method, as described by Drouineau (1942). The method of Olsen et al. (1954) was used to estimate available P. Soil organic matter was determined as described by Anne (1945). Exchangeable cations were determined using an ammonium acetate extraction method (Thomas, 1982) and determined by atomic absorption spectrometry. Kjeldahl method (Bremner & Mulvaney, 1982) was used to assess total nitrogen content. All samples were extracted and analysed in triplicate.

3 | RESULTS AND DISCUSSION

3.1 | Soil macromorphology and properties

The macromorphological analysis of the 90 profiles described and sampled showed that, in general, the morphological features of soil profiles in the PDO Valdepeñas show a sequence of A_p-B_t-C_{km}, A_p-B_t-C_k, A_p-B_w-B_{km}, A_p-B_w-C_k, A_p-C_{km} horizons or simply A_p-B_w-C or A_p-C (García-Navarro et al., 2019). Table 1 shows general and

TABLE 1 General and pedological characteristics of the investigated soils

		Rhodoxeralf			**Haploxerept**			**Calcixerept**		**Calcixerept**	
		A_p	**B_t**	**C**	**A_p**	**B_{w1}**	**B_{w2}**	**A_p**	**C_k**	**A_p**	**C_{km}**
Coordinates UTM (30 s)		0471649*x* − 4288817*y*			0451175*x* − 4292707*y*			0485021*x* − 4283927*y*		0443146*x* − 4294682*y*	
Depth (cm)		0–12	12–69	>69	0–18	18–59	>59	0–36	>36	0–15	>15
Coarse elements (%)		38.9	26.7	23.2	34.0	61.4	42.7	35.5	54.9	31.2	n.d.
Sand (%)		55.7	33.6	29.7	38.2	41.7	31.7	39.7	33.7	55.7	n.d.
Silt (%)		12.0	4.6	4.5	37.5	30.0	38.0	37.4	36.7	32.0	n.d.
Clay (%)		32.3	61.8	65.8	24.3	28.3	30.3	22.9	29.6	12.3	n.d.
Texture		Loam-clay-sandy	Clay	Clay	Loam	Loam-clay	Loam-clay	Loam	Loam-clay	Loam-clay	n.d.
Organic matter (%)		1.5	0.9	n.d.	1.2	1.0	n.d.	1.7	1.4	1.2	n.d.
P (mg/kg)		10.4	10.6	n.d	9.5	9.8	n.d	12.2	11.9	9.6	n.d.
Total nitrogen (%)		0.05	0.03	n.d.	0.04	0.05	n.d.	0.06	0.05	0.08	n.d.
C/N ratio		13.8	8.5	n.d.	12.6	12.2	n.d.	12.2	11.1	12.4	n.d.
pH (water 1:2.5)		8.2	7.7	7.4	8.4	8.4	8.5	8.7	8.8	8.5	n.d.
Electrical conductivity (dS m^{-1})		0.13	0.10	0.12	0.31	0.30	0.27	0.14	0.11	0.11	n.d.
$CaCO_3$ content (%)		0.0	0.0	0.0	16.8	19.3	12.0	38.5	61.5	5.4	33.8
Active limestone (%)		n.d.		n.d.	8.3	9.6	10.4	19.0	19.2	n.d.	7.9
Cation exchange complex ($cmol^+$/kg)	Ca^{2+}	19.3	20.0	n.d.	18.6	11.8	n.d.	16.2	17.9	16.7	n.d.
	Mg^{2+}	0.7	0.5	n.d.	0.7	0.5	n.d.	0.5	0.7	9.5	n.d.
	K^+	0.1	0.1	n.d.	0.3	0.3	n.d.	0.1	0.1	0.2	n.d.
	Na^+	0.1	0.1	n.d.	0.1	0.1	n.d.	0.1	0.1	0.1	n.d.
S (sum of cations)		20.2	21.6	n.d.	19.8	12.6	n.d.	16.8	18.7	17.5	n.d.
Base saturation (%)		100	91.4	n.d.	100	100	n.d.	100	100	100	n.d.

Note: Great groups, according to Soil Survey Staff (2014).
Abbreviation: n.d., not determined.

pedological characteristics of some representative investigated soils (Rhodoxeralf, Haploxerept and Calcixerept).

It can be seen from Figure 4 that the presence of epipedions other than ochric cannot be verified (some are close to a mollic type). The importance of this ochric horizon, which becomes clear (according to Soil Taxonomy) as it fails to meet the definition for any of the other seven epipedons (because it contains too little organic carbon, or is both massive and hard, or harder when it is dry etc.), can be deduced from the data. The argillic horizon with a frequency of 54 cases, while the cambic horizon is found only in 15 cases. The diagnostic calcic and petrocalcic horizons occur in 29 and 35 cases, respectively (64 cases in total, which reveals a high percentage of soil profiles).

For combinations between horizons (Figure 5), it should be noted that argillic and calcic horizons are common in 14 cases, while argillic and petrocalcic horizons are found in eight cases, followed by calcic and petrocalcic in four cases. Cambic with calcic or petrocalcic appear in three cases each, and, finally, argillic with calcic and petrocalcic combinations appear in two cases and cambic combined with argillic appears in only one case. The take way from Figure 6 is that distribution is uneven, although the predominance of argillic horizons stands out, which shows the development of highly evolved pedogenetic processes into the area.

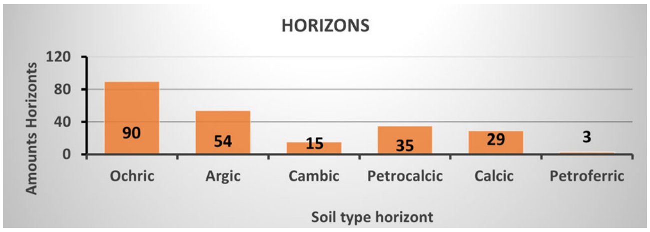

FIGURE 4 Frequency of different diagnostic horizons found in PDO Valdepeñas

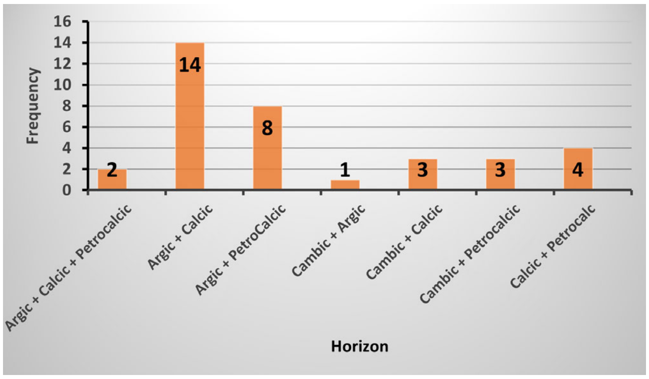

FIGURE 5 Combinations of different diagnostic horizons found in PDO Valdepeñas

Table 1 shows the main features and properties of four selected and representative soil profiles. As can be seen, the textures are predominantly loam, loam-clay and loam-clay-sandy. A clear increase in clay content, typical of argillic horizons, can be observed in some soil profiles, for example profile 1 (32.3% in A_p horizon vs. 61.8% in B_t horizon). The content in organic matter thereof varies between 1.2% and 1.7% in surface horizons. The total N status ranged, in general, from 0.03% to 0.08%, and there is no optimal value. Moreover, the extracted available phosphorus content varied from 3.4 to 20.1 ppm, thus indicating that the soils studied were poor in P content. The pH values varied from 7.4 to 8.8 (neutral to moderately basic); no strongly acidic soils were found. The EC ranged from 0.11 to 0.31 dS m^{-1}, thereby indicating that all the soil samples analysed showed low salt content. A high variation of carbonate content was also found (0%–38.5% in A_p horizons; 12.0%–61.5% in deep horizons). A similar trend was observed for active limestone, with values in the range 0%–19.2%. All soils are saturated or near saturated, with Ca being the main cation in the exchangeable complex. Saxton (2002a, 2002b) reported that soil Ca creates 'a favourable medium for root exploration, uptake of minerals and growing a healthy vine'. Similarly, Seguin (1986) speculated that the main influence of Ca on wine quality was as a result of its beneficial effect on soil structure, particularly in clay soils, as is the case here.

Based on their morphological and analytical data, García-Navarro et al. (2019) concluded that the soil orders identified are mainly Alfisols, Inceptisols and Entisols, according to Soil Taxonomy (Soil Survey Staff, 2014), which correspond to the soil groups Luvisols, Calcisols, Cambisols, Regosols and Leptsols according to FAO-UNESCO-ISSS (2014). Calcisols represent a significant proportion (about 40%, Table 2).

3.2 | Linking geomorphic features, soil types and their pedogenesis

The relationship between formative factors and taxons has been addressed by several authors (Bockheim et al., 2014), and soils are known to be strongly linked to the landforms upon which they develop (Schaetzl & Anderson, 2005).

With regard to the nature of bedrocks, the experience obtained during the selection and opening of the 90 soil profiles in the study area allows us to conclude the difficulty in classifying the parent material type in this site. Thus, at any one moment, unconsolidated

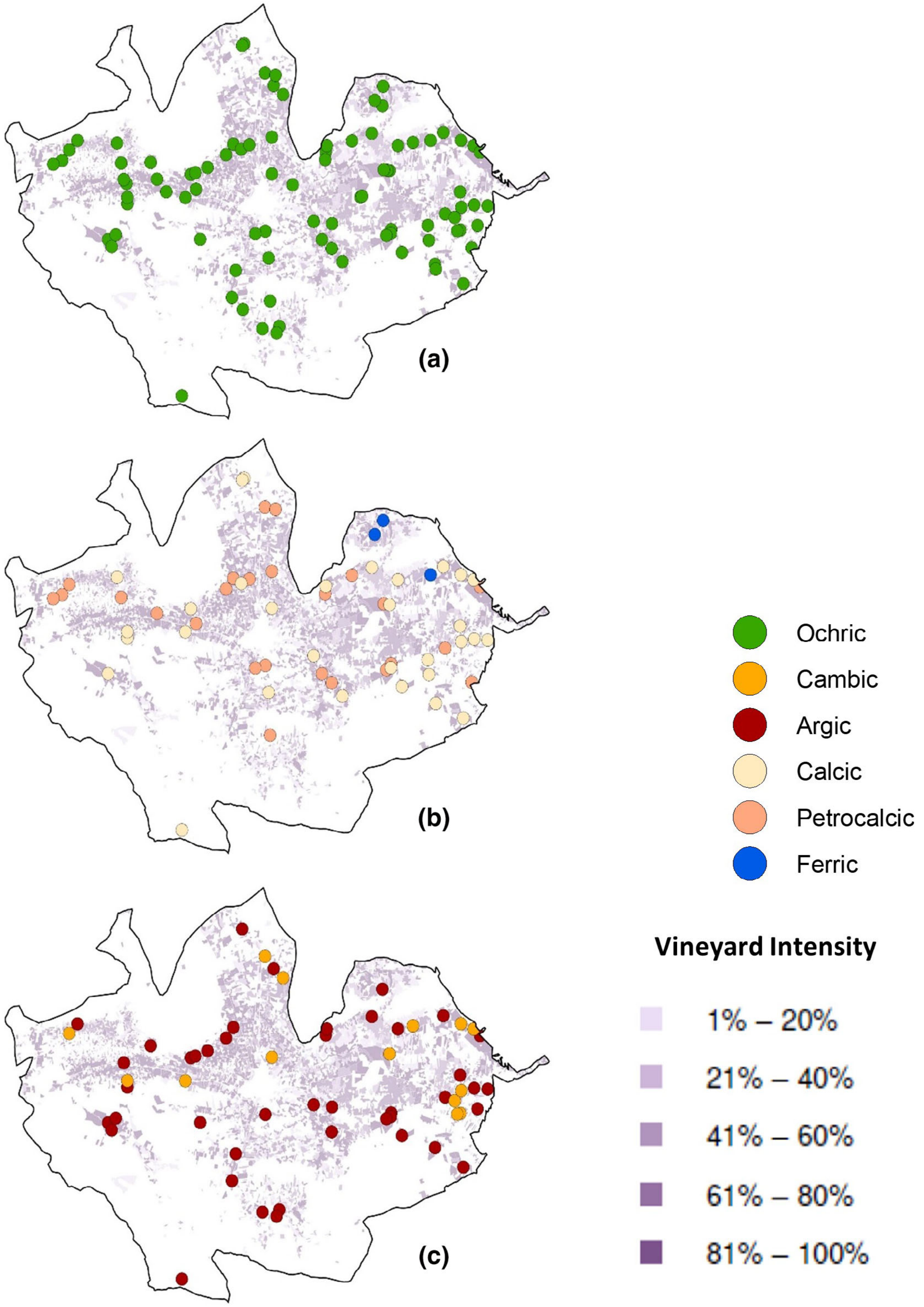

FIGURE 6 The spatial distribution of epipedions (a) and endopedions (b, c) found in the profiles analysed

contrasting soil material may differ in texture, pore-size distribution, mineralogy, bulk density and so forth, although some of the differences may not be readily observable in the field. For instance, is difficult to determine whether some deposits are alluvium or to distinguish certain mud flow deposits. Consequently, we decided to classify the parent material of many profiles as 'calcareous carbonate sedimentary material', according to Neuendorf et al. (2005) and Schoeneberger et al. (2012).

The vineyard soils examined appear to be linked to the micro-landforms upon which they develop. The

TABLE 2 Brief summary of collected soil profiles, including soil types

Reference soil groups	Principal qualifiers	Number of soil profiles	% Relative to total	
Leptosol	Haplic	2	2.2	2.2
Regosol	Haplic	3	3.2	4.3
	Colluvic	1	1.1	
Cambisol	Haplic	6	6.4	6.4
Calcisol	Leptic	1	1.1	37.5
	Haplic	8	8.7	
	Petric	23	25.5	
	Endogleyc	1	1.1	
	Luvic	1	1.1	
Luvisol	Leptic	1	1.1	48.6
	Haplic	12	13.2	
	Gleyic	1	1.1	
	Calcic	21	23.3	
	Cutanic	9	9.9	

FIGURE 7 Typical smooth topography with red soils (Alfisols according to soil taxonomy, Luvisols according FAO-UNESCO-ISSS), developed on glacis in the Moral de Calatrava zone

degree of pedogenetic development is determined by the balance between morphogenesis and pedogenesis, which basically depends on the stability conditions of natural environments. In those surfaces in which the Palaeozoic materials appear, the residual reliefs (with scarps) are spaces in which runoff favours erosion rather than the formation and evolution of soils, thus generating lithic soils or soils with a minimum depth of solum (Gerrard, 1992). In these same Palaeozoic areas, on the back of the slope (backslope), the dragging and transport of material predominates, thus resulting in the presence of poorly developed soils. The dragged materials tend to accumulate preferentially at the base of the slopes of these hills (footslope), thus allowing the formation of red soils since the humidity increases as the flow rate decreases. Obviously, the vineyards rarely appear on sloping surfaces, especially if, as is the case here, hard lithologies emerge on these surfaces (quartzites, quartzite sandstones, shales etc.). In these types of zones, according to several authors (Birkeland, 1999; Gerrard, 1992; Huggett & Cheesman, 2002; Mausbach & Wilding, 1991), the greatest imbalances are due to losses from erosion on slopes prevailing over soil formation.

In contrast, it is frequent to find vineyards on flat or almost flat surfaces with slopes between 0% and 3%, and some in higher topographies (generally less than 10%), just where the erosion/formation ratio is less than 1, or where deposition gains occur, for example, in foothills and floodplains (Buol et al., 2011). In this sense, the existence of a smooth topography makes pedogenesis prevail, thus allowing soils to reach a good degree of development (Figures 7 and 8), with well-differentiated diagnostic horizons (argillic and calcic/petrocalcic).

The iconic soils of Valdepeñas are probably so-called red soils (Alfisols or Luvisols), with clayed texture and sometimes showing a superficial stone phase (Figure 9a), which are soils formed at the expense of ancient geological materials (shales, schists and sandstone quartzites). This is typical of many zones in Castilla–La Mancha (Jiménez-Ballesta et al., 2018; Jiménez-Ballesta, Bravo, Amorós, Pérez-De-Los-Reyes, García-Giménez, et al., 2020). Many studies have been carried out in the world on the genesis of red soils on carbonate rocks (e.g. Durn, 2003; Fedoroff & Courty, 2013; Jiménez-Ballesta, Bravo, Amorós, Pérez-De-Los-Reyes, García-Pradas, & García-Navarro, 2020). These studies are more widespread in the Mediterranean and temperate regions. Red soils with calcic or petrocalcic horizons (Figure 9b), developed on limestone or derived carbonatic sediments, are much more common. In both cases, soil development occurs as a result of long periods of exposure to fersialitic weathering of old surfaces (one of the pedogenetic processes proposed by Bockheim & Gennadiyev, 2000; Jiménez-Ballesta, Bravo, Amorós, Pérez-De-Los-Reyes, García-Pradas, & García-Navarro, 2020). Some of these soil profiles were found to be relatively thick, with argillic horizons, (argilluviation). Reddish hues (rubefaction) are associated with the presence of haematite, an iron oxide common to calcareous or non-calcareous soils. These processes are not rare if we consider that the majority of the slopes in which the profiles are found are less than 5%, which implies surfaces with a certain geomorphological stability that are conducive to pedogenesis.

FIGURE 8 (a) Typical flat landscape showing vineyard with a stony cover due to erosion and/or drag linked to geological processes and mechanisation by ploughing, which raises fragments of deep horizons (C_{km}). Small elevations corresponding to inselbergs can be seen in the distance. (b) Red soil showing a laminar structure in the clay horizon and laminar calcium carbonate accumulation. The geomorphological position is in terminal areas of lying glacis only. The laterality and continuity of all the accumulation is frequently ruled out

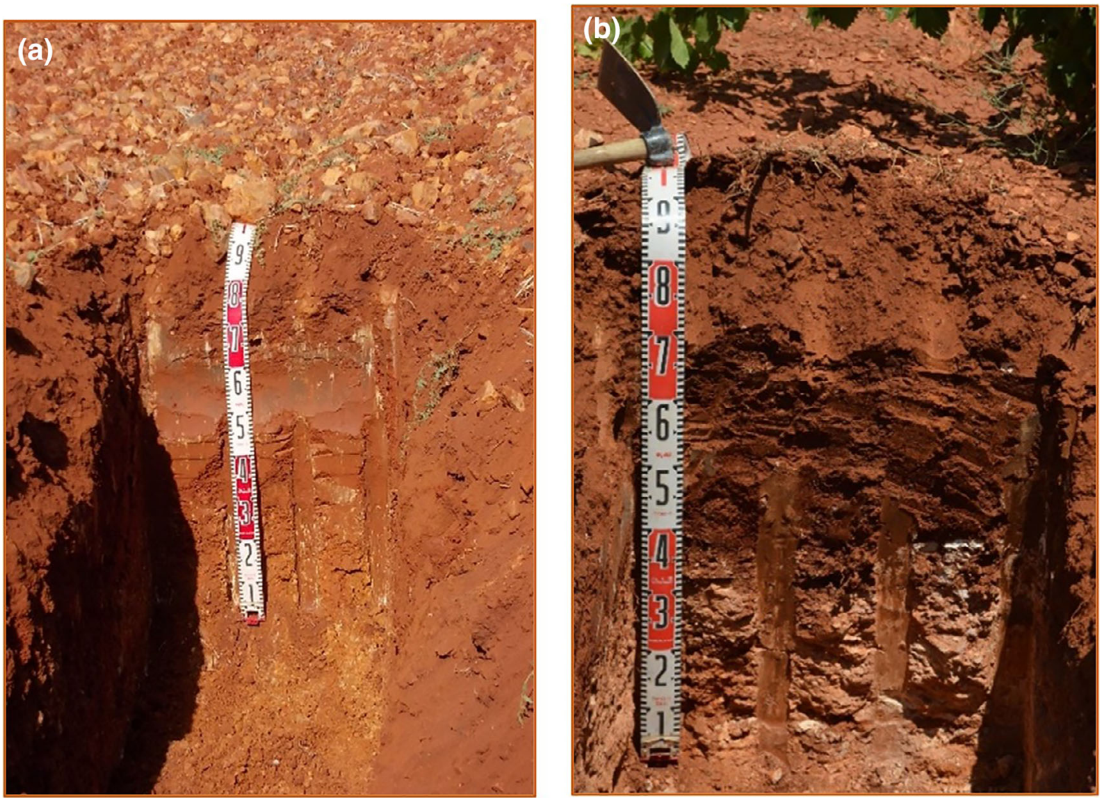

FIGURE 9 Clayed red soils, showing (a) surface stone phase and redox depletion at the bottom of the soil profile. (b) Petrocalcic horizon

Despite the mostly dominant flat or almost flat landforms in the territory of PDO Valdepeñas, a remarkable pedodiversity can be appreciated. Indeed, the geomorphological positions are generally stable surfaces such as glacis and terraces, floodplains, and foothills, among others. Over these surfaces, lengthy periods allowed for pedogenic processes to occur, which then led to very evolved soils. Under these Mediterranean conditions, the effective mineral weathering, dissolution and leaching of calcium carbonate occur and, at this point, the migration of clay can take place too. In addition, during the hot summer period, soil desiccation happens, and this causes the development of red dehydrated oxidised iron compounds (mainly haematite) within the soil profile. This is how the most widely known pedological fingerprint of Mediterranean climate conditions has been formed: The so-called red Mediterranean soils (Verheye & de la Rosa, 2005; Yaalon, 1987).

The typical feature of soils developed over calcareous materials in the Mediterranean climate, as happens in the study area, is the presence of a significant amount of $CaCO_3$ (Table 2). The formation process of these soils after mineral weathering is decarbonisation by loss of abundant $CaCO_3$ from the parent material by washing. This process fundamentally depends on the amount of (rain) water that infiltrates into the soil and the initial $CaCO_3$, the content of the soil, and substrate. But given the scarcity of rainfall in the area (around 400–500 mm per year), $CaCO_3$ does not disappear on this profile and, therefore, accumulates in-depth, originating calcic or petrocalcic horizons. The dispersion of the clay is linked to this process, as a consequence of the wetting of the dry soil, leads to the dispersion of clay, causing clay migration that generally results in the formation of the argillic horizons, (argilluviation). Consequently, a common phenomenon in the mentioned soils is that they show a clay 'skin' of illuviation on faces of structural elements, in edges, in the pores and in root canals. The third, and final evolution, is the result of a slow and prolonged weathering that is expressed by a red colour (2.5–5 YR), mainly due to the formation of haematite (Boero & Schwertmann, 1989).

Thus, it can be seen that the characteristic feature of pedogenesis in the Valdepeñas region is the red soil formation process and the presence of calcic or petrocalcic horizons, which appear in sufficiently stable surfaces, thus allowing prolonged pedogenesis. In this sense, and according to Targulian and Sokolova (1996) red soils with calcic or petrocalcic horizons may be referred to as 'soil memory' (pedomemory or pedorecord) in this region and can be perceived as the compilation and interaction of past environmental conditions in conservative surfaces (Arnold et al., 1990; Targulian & Goryachkin, 2004).

Exceptionally, small spatial environments (10–20 ha) with a very different character from the starting materials are also found. One is granite materials, on which Inceptisols or Entisols (Soil Taxonomy), in other words, Cambisols and Regosols (FAO-UNESCO-ISSS), have developed. Others are the presence of soils formed at the expense of starting materials of a volcanic nature, with the morphology fitting those mentioned above. All these soils represent a singularity within the territory under consideration (Figure 10).

3.3 | The common presence of calcium carbonate accumulations

Calcic and petrocalcic horizons are formed in most soils of the PDO Valdepeñas region, as also occurs in many

FIGURE 10 Inceptisols and Entisols (soil taxonomy), Cambisols and Regosols (FAO-UNESCO-ISSS), in small spaces on granite parent materials in the Pozo de la Serna zone

regions of the world (Dhir, 1995; Khandkikar et al., 2000; Monger et al., 2005). The precipitation of secondary carbonate, with varying thickness, and these horizons are one of the most remarkable morphological features in the soils of Valdepeñas, where accumulations range from diffuse or powdery (frequently as pseudomcellyum forms) to crusted forms, which are sometimes polycyclic. Consequently, calcium carbonate accumulations in the soils studied varied from slight filaments to prominent nodules and plugged horizons. Indeed, many of the soils showed horizons with a white colour below a depth of about 70–80 cm due to different types of calcium carbonate accumulations ranging from imperceptible accumulations (the minority) to massive or laminar, agatiform, nodular (compact or diffuse), breccia, powdery accumulations or pseudomycellyium forms. In fact, we have observed such accumulations ranging from extremely hard to extremely soft, passing through various intermediate forms, thus suggesting that these soils are likely to be calcic or petrocalcic horizons. In any case, they are related to stable geomorphical surfaces.

The precipitation and consequent accumulation of calcium carbonate in soil is a complex phenomenon that is quite common in soils from arid or semiarid regions (Gile, 1999; Gile, 1993). Indeed, there is a considerable debate regarding the origin of the pedogenic carbonate, otherwise known as pedogenic calcrete or caliche (Alonso-Zarza & Wright, 2010). The accumulation of calcium carbonate in the lower horizons of the soil profiles implies washing (or eluviation) the upper part. Calcic carbonate accumulation appears immediately below the argillic or cambic horizon, as shown in Figure 11. Shallow petrocalcic horizons directly under ochric horizons (Figure 12) are relatively common. This horizon can function as a water store (when crushed) by retaining the winter and spring rain. However, the cemented petrocalcic horizon acts as a root-restricting subsoil horizon (Duniway et al., 2007).

Different photographs showing these types of accumulations in the form of calcic or petrocalcic horizons can be found in Figure 13. Some morphological features of carbonates are that they exhibit polycyclic and polyphase development, with calcite cementing detrital grains of quartz, feldspar, and others, seen as floating textures or individual nodules. This may be related to phases of soil formation, erosion or reworking. The appearance of

FIGURE 12 Shallow petrocalcic horizons

FIGURE 11 A generic decarbonation process, together with clay illuviation and, above, the evidence of intense red colours, show an advanced weathering stage. Some soils have been able to form on pre-weathered pedosediments that have undergone strong weathering

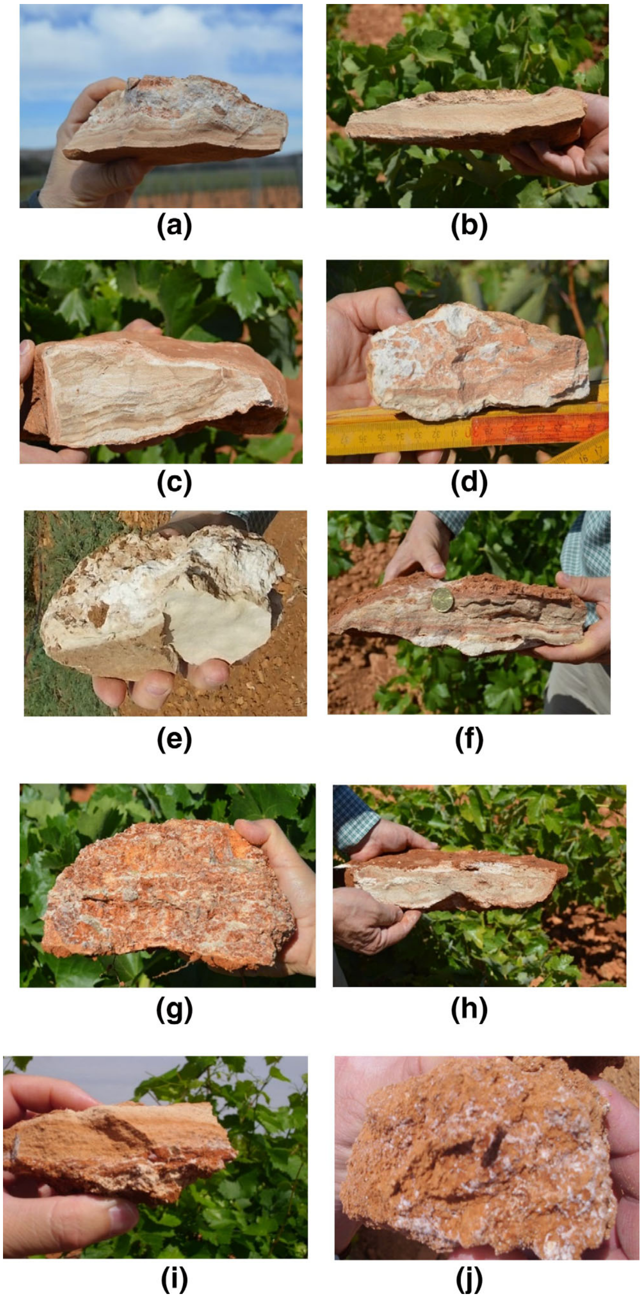

FIGURE 13 Field photographs of well-developed pedogenic carbonate accumulations (C_{km}). Laminar agatiform crust structure in (a–d, f, i); successive salmon coloured lamination (a–d, f, i); brechoid and nodular calcrete (a, e, j). The figures (a–d, f–i) showed variations in the accretion phases; (g) and (i) represent hypocoatings inside the soil matrix; appearance of voids in (e). Finally, in (c) and (j) calcitic particles occur as a coating around grains

well-developed nodules in the argillic horizons should be interpreted as being due to a process of aridification after the mobilisation of carbonate and clay.

The formation of a laminar layers (a–d,f,h,i of Figure 13) is attributed to the restriction of downward soil water movement and precipitation of carbonates in the accumulated soil water (Gile et al., 1966); appearance of the laminar agatiform crust structure, showing successive salmon coloured lamination (a–d,f,i); brechoid and nodular calcrete (a,e,j); variations in the accretion phases of the petrocalcic horizon (a–d,f,g–i); hypocoatings inside the soil matrix and around the soil pores or cracks and irregular sexquioxidic clay impregnation (g,i); (e) the appearance of voids; calcitic particles occur as a coating around grains (c,j).

Accumulations that lead to the presence of petroferric contacts are less frequent. Indeed, soils with an apparent petroferric horizon exist (Figure 14), but only in the lower part of the inselberg, the zone affected by water accumulation and percolation, which allows and favours both iron oxide and carbonate accumulation and cementation in the subsurface. Generally speaking, the petroferric contact is known to be associated with tropical and subtropical settings, which is why we suggest its presence here. Indeed, in the area studied such petroferric accumulations are usually only a few centimetres thick.

3.4 | Stoniness in vineyards

Although petrocalcic horizons appear to be both root- and water-restricting, (Ruellan, 2002), there is evidence that these horizons may absorb soil water and may therefore be potential water sources for plants. Field experiments by Hennessy et al. (1983) indicated that petrocalcic horizons have the potential to rapidly absorb and retain large volumes of soil water, with a measured field capacity of 0.36 m^3/m^3, although Duniway et al. (2007) reported that cementation by $CaCO_3$ dramatically alters the water-holding characteristics of soils.

For centuries, human activities have produced changes in soil status as a result of land use and/or land cover changes, including disturbance (increasing the A_p horizons in detriment to Ah horizons), fertilisation and, lastly, irrigation. These factors have resulted in significant modifications, especially in the biota, increasing erosion and compaction. As such, anthropogenic impacts have generated a new frontier in Pedology or, at least, certain soil changes during pedogenesis, as reported by several authors (Brantley et al., 2006; McKenzie et al., 2004; Richter, 2007).

In this sense, another distinctive character of some soils in the PDO Valdepeñas is that many of them have a stony phase (more or less thick), linked (or not) to a petrocalcic phase (from which they come) due to breakage effects promoted by farmers. This means that the fragments of petrocalcic horizons are currently on the surface. In areas close to the quartzitic hills, stony phases based on heterometric quartzite fragments appear next to them (Figure 15). With the aim of linking the effects of

FIGURE 14 Soil profile showing petroferric contact, and details of this contact

FIGURE 15 Details of some stony phases linked to petrocalcic horizons and quarzitic hills

stoniness on vineyard productivity and quality, Pérez-de-los-Reyes et al. (2020) pointed out their protective role against soil erosion and in the conservation of soil moisture.

3.5 | Implications of the nature of the PDO Valdepeñas soils in the vineyard

Regarding the morphology of the studied soils (depth of the horizons, structure of the limestone crusts, fertility of the soils, rainfall in the area etc.), it can be stated that the viticulture of the area should be focused on the production of quality wines since no excess of vigour is expected and the plants will achieve a good balance between exposed leaf area and production (Smart & Robinson, 1991). The root system will explore surface horizons and, in some cases, can penetrate fissured petrocalcic horizons (see Figures 11, 12 and 14) that can store winter rainfall and make it available to plants at the most critical summer days. Indeed, according to Winkler (1974) and Morlat and Jacquet (2003), the soil supports the root system, from where water and other nutrients are absorbed, which is crucial for grapevine growth and yield. Additionally, soil structure and soil chemical composition can influence grapevine composition and, consequently, wine quality as Mckenzie and Christy (2005) stated.

Most soils in PDO Valdepeñas are characterised by a moderate to deep soil profile that presents clay illuviation horizons (as B_t horizon in Rhodoxeralf profile, Table 1). As a general rule, there are deep soils with good drainage and good water retention properties (all of them with important properties since they can affect grapevine performance [White, 2009]). It is important to note that PDO Valdepeñas is located in the middle of the semiarid Mediterranean area, (where grapevines are subjected to excessive heat and water stress), which makes proper soil water storage capacity essential. That being said, Roby et al. (2004) stated that the best grape quality is obtained under moderate water stress conditions during the maturation period.

Soil textural classes present a relatively homogeneous pattern; a loamy and clay loam (just the textural class commonly considered highly suitable for agriculture) is the most prevalent in most of the PDO Valdepeñas soil. However, Winkel et al. (1995) suggest that loamy soils may produce high-quality wines.

The consequence of hardness (caused by the existence of petrocalcic horizons) on vine performance is due to the direct effect on the distribution and functional capacity of the root system to extract water and nutrients. Keller (2010) stated that compact and shallow soils can obstruct root access to oxygen, water and nutrients, limiting root growth and development. It is also worth mentioning that nutrient and water uptake occur mostly within 50 and 100 cm on the soil profile for grapevines. However, these petrocalcic horizons are located in the deep part of the soil profiles, so they do not always affect root growth. Conversely, petrocalcic horizons entail a certain level of retention in the movement of percolating water. The conclusion is that, in these semiarid regions, their existence increases vine performance (either yield or quality).

Seguin (1986) argues that soil pH does not have much influence on the quality of wines, since quality wines are produced on acidic, neutral and alkaline soils, although there are limits to the acidity and alkalinity of the soil tolerable by vines. In that regard, none of the 90 soil profiles studied has a pH outside of normal ranges. In soils with pH above 8.0, iron, manganese, copper and zinc availability are reduced (Davidson, 1991). Most of the soils studied are developed on carbonate materials, so deficiencies in Ca and Mg do not exist; only those with high pH (>8.3), associated with elevated concentration of very fine carbonates, may cause severe lime-induced chlorosis (iron or zinc deficiency Bravo et al., 2015; Amoros et al., 2017), although that circumstance is usually corrected by the farmer. Tramontini et al. (2013) stated that wines from clay soils showed high sugar accumulation and anthocyanin concentration; therefore, it is expected that an important part of the soils in the area under study, having argillic horizons, have these characteristics in this regard.

In light of the above, the pedological substrate in the PDO Valdepeñas comprises singular soil typologies appropriate for wine production. These soils make up complex systems, which are not always the best or the most productive farms. Vines are resilient plants that extend their roots in all directions to find nutrients and water (Morlat & Jacquet, 1993). Considering the soils described in this article, which have traditionally been used for vineyards, this study highlights the importance and uniqueness of the calcic and petrocalcic horizons that can characterise, in part, this singular viticultural environment 'terroir' (Van Leeuwen & de Rességuier, 2018).

4 | CONCLUSIONS

In this study, soil types in a traditional vineyard region, namely, the PDO Valdepeñas, have been identified in terms of the main geomorphological features. The main soils are Alfisols, Inceptisols and Entisols, according to Soil Taxonomy (which correspond to Luvisols, Calcisols, Cambisols, Leptosols and Regosols, according to FAO-

UNESCO-ISSS system). Lithic soils (Entisols), the lower levels of which lead to evolved soils of the Alfisol type, frequently with calcic or petrocalcic horizons, dominate in the inselberg formations. These soils have undergone a Mediterranean fersialitic weathering type, thus resulting in red colour due to the accumulation of free iron oxides (iconic red soils). Depending on the topography, this soil type may not form, thus meaning that cambic horizons appear (with or without calcium or petrocalcic). As such a cambic horizon may not always appear, thus passing from the surface horizon A_p directly to a C or R horizon. Secondary carbonate, the thickness of which varies from a diffuse or powdery form (frequently as pseudomcelia) to crusted forms (sometimes polycyclics), is also observed.

All the situations in the area studied have occult-type superficial diagnostic horizon. Profiles with argillic and calcic/petrocalcic horizons are also widespread, followed by cambic upon calcic/petrocalcic horizons. As such, the dominant pedological processes are argiluviation, calcification/decalcification and rubefaction.

The chemical, physicochemical and morphological properties of these soils, associated with the profile position in the landscape, suggest a strong influence of the calcareous parent material (followed by metamorphic materials in order of importance) on soil formation. The maintenance of soil organic matter by proper soil management should therefore be ensured to improve their status.

We conclude that the nature of the soils in the PDO Valdepeñas can be considered to be distinctive for viticultural production by providing basic supportive microenvironments for vineyards, although these effects can, and should, be improved by farmers.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Raimundo Jiménez-Ballesta: Conceptualization (equal); investigation (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Sandra Bravo:** Formal analysis (equal); investigation (equal); software (equal); writing – review and editing (equal). **Jose A. Amorós:** Investigation (equal); methodology (equal); writing – review and editing (equal). **Caridad Pérez-de-los-Reyes:** Investigation (equal); methodology (equal); writing – review and editing (equal). **Jesús García-Pradas:** Formal analysis (equal); methodology (equal). **Monica Sánchez:** Investigation (equal); methodology (equal). **Francisco J. Garcia-Navarro:** Formal analysis (equal); investigation (equal); methodology (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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