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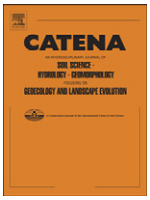

Vertic features in a soil catena developed on Eocene marls in the Inner Depression of the Central Spanish Pyrenees

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ABSTRACT

Scientific interest in marls has expanded in recent years especially in regard to erosion rates, weathering processes and stabilization of the resulting sediments. However, information regarding the properties and evolution of overlying soil is relatively scarce.

This work analyzes the relationship between mechanical properties and standard properties of soils developed on Eocene marls in mountainous regions of the southern Central Spanish Pyrenees. It also examines whether these soils have the vertic features traditionally ascribed to them and how these features may vary along a catena. The water holding capacity of the soils exhibits a typical catena-related trend that increases progressively from low values in upper slope profiles to higher values for the middle slope and valley. The soils have a high percentage of silt-sized particles. Quartz and calcite are the main mineralogical components of the fine earth fraction. Illite represents the major component of the clay fraction. The linear extensibility and Atterberg limits are positively and significantly correlated to clay content. Low liquid limit (usually less than 30%), low soil aggregate stability (lower than 25% in Ap horizons), and high subsidence values ($n > 0.7$) are likely factors in the high dispersivity and sliding risk observed for the soils. These factors also explain the presence of buried soils and lithological discontinuities in lower slope profiles as well as the relatively limited degree of soil evolution, despite a relatively humid climate. Low porosity, mainly of vesicular type, and a poor structure facilitate saturation in the wet season and lead to soil reduction processes, especially within deep soil horizons along lower parts of hillslopes. Simulated wetting and freezing treatments were shown to fracture the unaltered marls into small fragments, demonstrating the soil's susceptibility to physical weathering. Given moderate clay content, absence of smectites and moderate soil extensibility (COLE <0.06 cm cm^{-1} in most horizons), topsoil cracking in lower slope profiles is apparently caused by high rates of evaporation during the dry season. The soils described here did not meet the requirements of vertic horizons but most meet the diagnostic criteria of having a protovertic horizon, despite the absence of swelling and shrinking clays.

1. Introduction

Research on marl-rich watersheds has continued to develop in recent years, with increasing focus on erosion rates and formation of badlands (see review by Gallart et al., 2013). Diverse in their origins, climatic setting and composition, marls can develop soils with unusual chemical and physical soil properties. These soils, traditionally well appreciated (Guerra and Monturiol, 1970), can pose serious management problems in agricultural and engineering land use, because of soil moisture regime and physical properties. Problematic properties include shrinkage and swelling (De Jong et al., 1992; Thomas et al., 2000), high dispersivity and susceptibility to weathering (De Santis et al., 2010; Summa et al., 2007). Shrinkage and swelling drastically increase soil infiltration during dry seasons, but during wet seasons, the soil can remain water-saturated, leading to ponding and mass movement along slopes (Solé et al., 1992). Soil and marl dispersivity can be related to sodium-rich material (Faulkner et al., 2003; De Santis et al., 2010) or clay mineralogy (Kasanin-Grubin, 2013; Pardini, 2003). High weathering and erosion rates of both parent material and soils have been linked to freezing cycles in mountainous areas, which affect shrink–swell processes and surface roughness (Nadal-Romero et al., 2007; Pardini, 2003; Pardini et al., 1996; Regüés et al., 2000; Vericat et al., 2014). These processes, which also naturally vary along catena hillslopes (Faulkner et al., 2003), were found to limit plant colonization of stabilized fine-grained sediments from reclaimed badlands in the southwestern French Alps (Rey, 2009).

A badlands and soil complex with a catenary distribution has been recently described from the Inner Depression of the Central Spanish Pyrenees, an area occupying about 100 km^2 (IGN, 2006). Badlands can

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experience erosion rates of up to 29 mm $year^{-1}$ in upslope areas of the catena (Nadal-Romero et al., 2007). Soils develop above badland sediments in bottom slope areas and in adjacent valleys (Guerra and Monturiol, 1970). Early studies of these areas indicated that they experience only a limited degree of soil evolution, with sequum A–(B)–C, the presence of cracks in summer and a conchoidal structure with depth ("vertisoles topomorfos", as named in Spanish by Guerra and Monturiol, 1970). These studies note that despite solifluction along slopes and flooding in depressions, soils were very fertile, deep and without rock fragments (earning them the local name, "polpar" derived from the Latin, *pulpa*). Most recent reviews describe the expansive properties of these soils and classify them as Vertisols, according to the World Reference Base (Ibarra, 2004). Meanwhile, the National Atlas of Spain, using Soil Taxonomy, indicates that the primary soil types found in the Inner Depression study area are Haplusterts, with inclusions of Calciusterts. Emerging land use pressures (*e.g.*, facilities development and/or greater amounts of animal waste input) are necessitating a better understanding of these unusual soils (García-Ruiz, 2010).

The objectives of this research were to (i) determine the properties of soils developed on Eocene marls, namely soil expansibility and consistency, and relate these to standard chemical, physical and mineralogical soil properties, (ii) determine weathering rates of unaltered marls during wetting and freezing cycles, and (iii) interpret soil changes along a catena to refine current taxonomies for study area soils.

2. Material and methods

2.1. Study area

The study was carried out along a catena within the Val Ancha, located in the Inner Depression of the Central Spanish Pyrenees, south of the town of Gracionépel, and near the city of Jaca (Fig. 1). The bedrock in this Depression is middle Eocene (upper Lutetian to lower Priabonian stage), dominated by massive bluish or blue-gray marls (mudrock), with thin layers of sandstone. The section is interpreted to have formed on a deep marine platform (Montes, 2009). The marl or mudrock is indurated in its unaltered state but is easily weathered, and thus provides a highly erodible regolith for soil development when slope gradients reach sufficiently low values (García-Ruiz et al., 2008; Nadal-Romero, 2011).

The highest soil profile (on the upper slope) develops beneath shrubland cover (*Buxus sempervirens*, *Genista scorpius*, and *Rosa gr. canina*) and is surrounded by bare badlands. Other soil profiles, under cultivation for barley, develop on Holocene colluvium, which accumulated from weathering and erosion of badland marls (García-Ruiz et al., 2011).

The study area has a sub-Mediterranean climate with a mean annual temperature of 11.5 °C, a mean minimum temperature of −9.4 °C and a mean maximum temperature of 35.9 °C. Mean annual precipitation is approximately 810 mm with a seasonal distribution of 28% in autumn, 28% in spring, 26% in winter and 18% in summer. The mean potential evapo-transpiration is approximately 680 mm/year (Thornthwaite method), which results in a relative water deficit during the summer, especially within thin soil profiles and along sun-exposed slopes. In the absence of direct temperature and soil moisture measurements, the soil temperature regime (USDA, 2014) is assumed to be mesic, with an udic or xeric soil moisture regime depending on orientation. Precipitation data were obtained from the Jaca weather station, operated by the Diputación General de Aragón.

2.2. Soil morphology and sampling

This study analyzed five soil profiles (Table 1) developed either on the bluish unaltered Eocene marls (upper slope) or on recent (Holocene) sediments derived from marl erosion (from middle slope to bottom valley). Pits were excavated using a backhoe for each soil profile, except the one located at the top in contact with badlands which was excavated back to expose fresh sediment. The profiles were described in the field according to standard procedures (FAO, 2006), with detailed morphological data recorded at each horizon. Soil samples from each horizon or layer of the soil profiles were collected for laboratory analysis. Undisturbed clod samples were carefully extracted to maintain the original structure and orientation of the soil. These were placed in containers, transported to the laboratory and promptly air-dried. For thin section analysis, unaltered clods were heated at 40 °C, impregnated with epoxy resin under vacuum, mounted on glass slides, and ground down to 30 μm thickness. Thin sections were studied and imaged with a petrographic microscope under plane- and cross-polarized light. Observed pedofeatures were systematically assigned to a hierarchy of soil formation events (Fedoroff et al., 2010). The soils were classified according to the World Reference Base, WRB (IUSS, 2014) and Soil Taxonomy (USDA, 2014).

2.3. Analysis of chemical and physical properties

Samples of thirty-three soil horizons or layers from the five profiles were air-dried and sieved to <2 mm to determine the percentage of gravel (>2 mm) and fine earth (<2 mm). Laboratory analyses were performed on the fine earth fraction. Soil pH was determined potentiometrically from a 1:2.5 (w/v) suspension of soil and water (current pH) and with 1 N KCl (potential pH) (McLean, 1982). Cation exchange capacity (CEC) was determined by NH_4^+ retention after leaching with a neutral solution of 1 N NH_4OAc (Rhoades, 1982). The electrical conductivity (ECe), soluble cations and the sodium adsorption ratio (SAR) were measured on the saturated paste extract (Rhoades, 1982). The total carbonate in the fine earth fractions were assayed volumetrically (calcimeter) using a dissolution procedure (6 N HCl) that evolves carbonate in the sample to CO_2 (Nelson, 1982). Total organic carbon was determined by the wet oxidation method (Nelson and Sommers, 1982), and organic matter content was estimated using the van Bemmelen factor (1.724).

Fine earth fraction particle size distributions were determined by the discontinuous sedimentation method after removal of organic content with H_2O_2 (30%) and clay dispersal with sodium hexametaphosphate (5%) (Gee and Bauder, 1986). Soil aggregate stability (SAS) was assayed for aggregates of 1–2 mm diameter, by the wet-sieving method (Kemper and Koch, 1966). The water coherence test was performed on macroaggregates of 5 cm diameter (Emerson, 1967). Bulk density was obtained by measuring the volume of unaltered soil clods using the water displacement method. Clods were coated in paraffin wax to preserve the structure of the soil samples (natural fabric) and prevent water penetration into clods during immersion (Cornelis et al., 2006). The water contents at wilting point (−1.5 MPa) and field capacity (−0.033 MPa) were measured volumetrically using pressure plate extractors (Richards, 1947). From these values (and the percentage of rock fragments, bulk density and the thickness of each horizon), the available water holding capacity (WHC) for each profile was calculated as the difference between field capacity (FC) and permanent wilting point (PWP), expressed as mm water/1.5 m soil (Badía et al., 2015b). The subsidence index (Porta and López-Acevedo, 2005) was calculated according to the expression:

$$n = (\text{saturation moisture} - 0.2 * (\text{silt} + \text{sand}))/(\text{clay} + 3 * \text{organic matter}).$$

2.4. Mechanical properties

The Atterberg limits (liquid limit and plastic limit) or consistency limits were measured on subsamples sieved to <0.4 mm. The liquid limit (W_L) is determined by applying a small force to soil samples with a moisture gradient by means of a standard Casagrande cup (Andrade et al., 2011). The liquid limit is defined as the gravimetric water content (%), at which 25 blows are required to close a *ca.* 10 mm groove in the soil sample. The plastic limit (W_P) is determined