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# An integrated approach to studying the genesis of andic soils in Italian non-volcanic mountain ecosystems

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ABSTRACT

Over recent decades, andic soils have been increasingly found in non-volcanic mountain ecosystems (NVME) in many parts of the world. In Italy, this type of soil has proved to be greatly affected by aeolian deposits and to be widely distributed geographically.

However, there are still many open questions, especially regarding the genesis of these soils. This paper focuses on five representative pedons taken from NVME. Soil forming processes and relationships between soil and underlying bedrock were investigated by using an integrated approach including geochemical, magnetic, mineralogical, micromorphological and particle size distribution (PSD) analysis. The 5 pedons showed andic character and similar morphology and micromorphology (e.g. silt illuviation, pedorelicts), as well as large differences in terms of soil reaction and clay mineralogy. The analysis of the vertical distribution of C, Al and Fe extracted in pyrophosphate along with related geochemical indices (e.g. $C_p/Al_p$) enabled us to indicate andosolization as the main process of soil formation and to exclude podzolization. With respect to the soil-bedrock relationship, 2 soils showed great similarity to the underlying bedrock along with a clear aeolian particle size distribution footprint, whereas, in the remaining 3 soils, there was a clear soil-bedrock discontinuity and an evident volcanic fingerprint. Some of the soil-bedrock differences related to the geographical settings and latitude.

## 1. Introduction

Andic properties provide soils with distinctive features. Indeed, most Andosols are found in volcanic districts and show excellent properties, such as favorable tilth, friable consistency, low bulk density (typically $< 0.90\ g\ cm^{-3}$), high total porosity, high water-holding capacity, highly stable soil structure, high organic matter storage, high cation exchange capacity, and high phosphate retention, (Shoji et al., 1993; Shoji and Takahashi, 2003). For these reasons, these soils give high chemical and physical fertility to ecosystems (Maeda et al., 1977; Quantin, 1990), supporting a great human presence (Mohr, 1938; Leamy, 1984; Shoji et al., 1993). In spite of their unique positive chemical, physical and biological properties, such soils are incredibly fragile and vulnerable to land degradation processes (Arnalds, 2000; Arnalds et al., 2001; Basile et al., 2003; Terribile et al., 2007; Vingiani et al., 2015).

In recent decades, there has been an increasing number of findings of andic soils (i.e. soils with evident andosolization process) in very different non-volcanic mountain ecosystems (hereafter named NVME) - around the world (Arbestain et al., 2001; Bäumler and Zech, 1994; Bäumler et al., 2005; Caner et al., 2000; Delvaux et al., 2004; Kimble et al., 2000; Zanelli et al., 2006). More specifically, it has been demonstrated that the spatial distribution of these soils is not restricted to volcanic parent materials (e.g. Aran, 1998; Kimble et al., 2000; USDA, 2014; IUSS Working Group WRB, 2015). Indeed, non-volcanic and non-allophanic Andosols in NVME are reported on different types of parent materials and in different climatic regimes including Nepal (Bäumler and Zech, 1994; Bäumler et al., 2005), India (Caner et al., 2000), Austria (Delvaux et al., 2004), North Appalachians (Canada; USA), Kyushu (Japan) and the Alps (Kimble et al., 2000). In all these cases, andosolization (Ugolini et al., 1988; Shoji et al., 1993;) is a major soil forming process regardless of whether these soils meet or do not meet the soil classification criteria for Andosol/Andisol. Therefore, here the term andosolization refers to the well-known soil process forming non crystalline material and having “the accumulation of Fe, Al and dissolved organic carbon in the A horizon with little subsequent leaching of these components to the B horizon and that the formation of the B horizon is dominated by in situ weathering” (Shoji et al., 1993).

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With respect to Italy, Iamarino and Terribile (2008) demonstrated that the spatial distribution of these soils – in NVME - has been greatly underestimated. Mileti et al. (2013) showed that about 82% of the particle size distribution of these soils is explained by fine silt (13 μm) wind materials. In addition, the integration with geochemical and magnetic analysis suggests that a substantial part of the soils in Italian mountain ecosystems have evolved from loess-like sediments, found throughout the country in a broadly dichotomous distribution: autochthonous loess in northern Italy and aeolian volcanic deposits in central and southern Italy. These findings agree with local findings regarding the contribution of both volcanic (Gianfagna and Bigazzi, 2003; Scarciglia et al., 2008; Corti et al., 2012; Frezzotti and Narcisi, 1996; Vingiani et al., 2014) and loess materials (Costantini et al., 2009).

However, Iamarino and Terribile (2008) and Mileti et al. (2013) only report descriptive statistics (mean, CV, standard deviation) - after a strong aggregation for five WRB soil types - of the main chemical, geochemical, grain size, and magnetic properties. Although, in general terms, these papers clarify both the importance of andic soils in Italian NVME and the nature of their parent material, none of these papers, provide a detailed picture of processes (e.g. pedogenesis) at the pedon scale and they do not consider the (complex) relationships between the different soil horizons and those with the underlying bedrock.

Despite these contributions, there are still many difficult-to-solve key open questions about formation and spatial distribution of andic soils in Italian NVME regarding the duration and type of pedogenic processes, mineralogy of the parent material, environmental conditions, influence of vegetation, formation mechanisms of andic features and neoformation of allophane-like minerals and their ecological importance. In this context, we attempted to gain a better understanding of these soils through detailed accounting of their pedogenic processes and their soil-bedrock relationships. Unfortunately, tracing soil parent material in soils can be a rather complex task (Buol et al., 1989; Fitzpatrick, 1983) because, in many cases, the soil parent material no longer exists. Indeed mineral weathering can change soil mineralogy and chemistry. Moreover, soils can undergo different phases of pedogenesis which result in even more complex soil mineral assemblages. In the case of andic soils, the addition of aeolian deposits of different genesis over preexisting soils can further complicate the situation and, therefore, render a true understanding of the soil parent material more difficult.

This analysis focused on five pedons, chosen in order to be representative of the large environmental variability of andic soils in Italian NVME. In order to mitigate the difficulties described above in the analysis of soil-parent material relationships in andic soils, we adopted an integrated approach, using the following methods: (i) chemical analysis (ii) mineralogy, (iii) magnetic susceptibility and (iv) geochemistry analysis of soil fine earth and underlying bedrock, (v) micromorphology analysis and (vi) particle size distribution (PSD) after removal of pedogenic compounds.

## 2. Materials and methods

More specifically, the study was conducted on five benchmark soil profiles (Fig. 1) chosen in order to capture both all the main soil types in NVME and their corresponding landscape units across the Italian latitude gradient, as reported in Iamarino and Terribile (2008). More specifically, the selection was performed by considering that: (i) Silandic and vitric Andosols (24% of all soils) are mainly distributed in South-Central Italy, (ii) Phaeozems (15%) in North-Central Italy; (iii) Aluandic Andosols (7%) have no preferential distribution; (iv) and (v) Cambisols represent the main soil type (46%) and are distributed rather homogeneously throughout the country. Then a pedon was selected from both northern and southern Italy.

Soil profile description and designation of genetic horizons referred to the FAO system (2006). Soils were classified using the World Reference Base (IUSS Working Group WRB, 2015). For chemical, mineralogical, magnetic, geochemical and particle size distribution analysis, we performed a careful sample division in subsamples by using spinning rifflers.

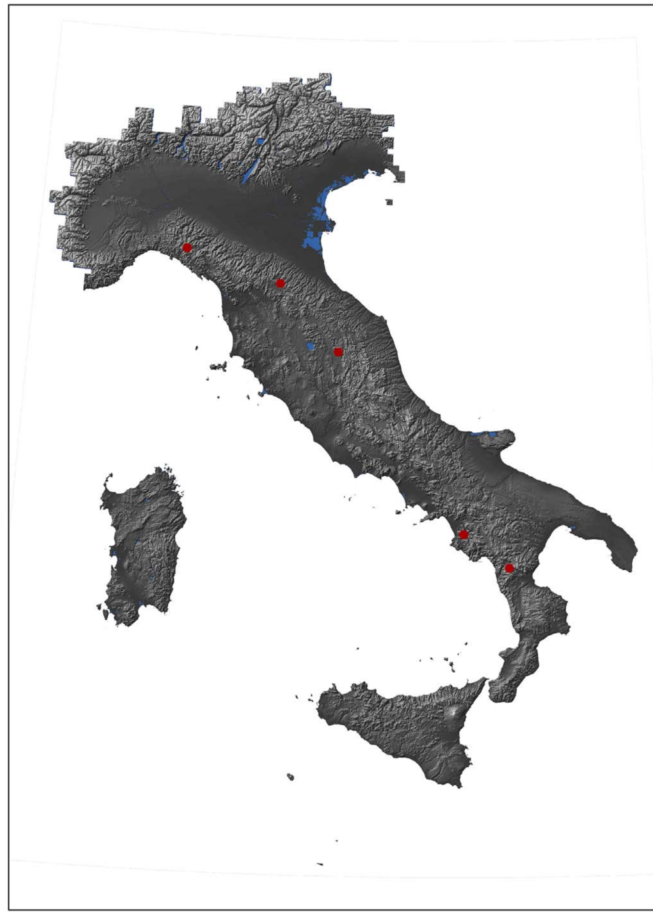

**Fig. 1.** Location of the studied soil profiles.

### 2.1. Chemical analyses

Bulk soil samples were collected for chemical analyses from all soil horizons, air dried and sieved to < 2 mm. Chemical data were produced by the following methods: organic carbon using the Walkley-Black method (Walkley and Black, 1934); pH in $H_2O$ and KCl by the potentiometric method (Soil Survey Staff, 2014). Due to measurements of artefacts induced by variable charge minerals in andic soils (Mizota and van Reeuwijk, 1989), the effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases + acidity (H + Al), with bases being determined by ammonium acetate pH 7 extraction and acidity (H + Al) as released upon exchange by an unbuffered 1 M KCl solution (Soil Survey Staff, 2014). Selective extraction procedures were applied to soil samples in order to assess the different Al, Fe and Si forms. Acid ammonium-oxalate extractable forms ($Al_o$, $Fe_o$ and $Si_o$) were performed in line with Blakemore et al. (1987), bicarbonate citrate Na-dithionite extractable components ($Al_d$, and $Fe_d$), following the Mehra and Jackson (1960) procedure and Na-pyrophosphate extractable complexes ($Al_p$, $Fe_p$, $C_p$) as in Bascomb (1968). As is known, the use of $Al_p$ and $Fe_p$ to separate andosolization from podzolization processes may induce some artefacts, unlike $C_p$ which is also largely used in scientific papers to analyze mobile C pools (e.g. Caner et al., 2011; Toma et al., 2015). Concentrations of elements were measured by the ICP-AES Varian Liberty model 150. Values of $Al_o$ and $Fe_o$ were used to calculate the andic properties index $Al_o + 0.5Fe_o$ (as %) (USDA, 2014; IUSS Working Group WRB, 2015). The allophane