



# Liquid and plastic limits of clayey, organic C-rich mountain soils: Role of organic matter and mineralogy



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## ABSTRACT

The soil liquid (LL) and plastic limit (PL), and their difference PI (plasticity index) are physical properties related with the soil mechanical behavior, determined on the <0.425 mm soil fraction, and used in different fields of earth and soil sciences. They are known to depend on soil organic matter (SOM) and/or clay content, but these soil properties are generally determined on the <2 mm fraction (fine earth). Furthermore, these dependencies can be affected by many qualitative aspects, such as the specific surface area (SSA) and the equivalent basal spacing (EBS) of clay minerals, and clay aggregation. The aims of our research were therefore i) to investigate the role of clay and SOM contents in a set of clay- and organic C-rich mountain soils, considering both the <2 mm and <0.425 mm fractions; ii) to assess the effect of the mineralogical composition (type of minerals, EBS and SSA) and clay aggregation in the <0.425 mm fraction. The relationships observed between Atterberg limits and the clay and organic C amounts evidenced the importance of considering the <0.425 mm soil fraction instead of the fine earth. The relative role of clay and organic C contents in the <0.425 mm fraction was comparable for LL, while in the case of PL the most relevant variable was TOC. Therefore, in a first stage of increasing water content, the role of SOM is fundamental (i.e. in the semisolid state and plastic interval), then the interactions among clay particles dominate. No clear relationship was instead observed with the mineralogical composition, although SSA and EBS were both correlated positively with LL and PI. The aggregated clay amount was positively related with LL and PI, and EBS. This, together with the relationships with EBS and SSA, evidenced that a role of clay exists in determining the soil mechanical behavior, but it seems to be more related to the interactions among clay particles occurring in the soil, than to the simple mineralogical composition. The findings suggested that, while PL seems to be more controlled by the organic fraction, LL and PI are more influenced by SOM and clay minerals and their interactions.

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## 1. Introduction

In earth sciences, the plastic limit (PL) and liquid limit (LL) were defined by Atterberg (1911) as the soil gravimetric water contents (%) needed for the transition of the <0.425 mm fraction from the solid to plastic state, and from the plastic to liquid state, respectively. The detailed methods description is provided by ASTM and BSI standard methods (BSI, 1990; ASTM D 4318–10e1, 2010), and by McBride (2002).

*Abbreviations:* LL, liquid limit; PL, plastic limit; PI, plasticity index; SOM, soil organic matter; MIF, mineral intensity factor; SSA, specific surface area; EBS, equivalent basal spacing; BS, base saturation; TC, total C; TOC, total organic C; AC, aggregated clay; SEE, standard error of the estimate; VIF, variance inflation factor.

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Atterberg limits are relevant for a wide range of purposes such as soil classification in engineering (Atterberg, 1911; Casagrande, 1932), soil mechanics (Haigh, 2012; Haigh et al., 2013; Zbik et al., 2015), agricultural soil management and plant growth (Keller and Dexter, 2012; Abbaspour-Gilandeh and Sedghi, 2015; Zolfaghari et al., 2015a), and natural hazard assessment (Yalcin, 2007; Ramezanpour et al., 2010; Diaz-Hernandez et al., 2015), with a particular focus on sloping areas (Summa et al., 2010; Stanchi et al., 2013, 2015).

In agricultural and forest soils, LL and PL have been often related with soil organic matter (SOM) and clay contents (e.g. De La Rosa, 1979; De Jong et al., 1990; Mbagwu and Abbeh, 1998; Schmitz et al., 2004). However, as pointed out by Blanco-Canqui et al. (2006) and Zolfaghari et al. (2015b), the studies on Atterberg limits and related soil properties often gave contrasting results; dependencies were not always observed and, when present, they could be affected by a large number of additional characteristics such as SOM type, hence land

use, and soil mineralogy. Moreover, soil databases normally report the chemical properties of the fine earth fraction (i.e. <2 mm), which is the standard fraction for analytical purposes (e.g. van Reeuwijk, 2002; Soil Survey Staff, 2014a).

Stanchi et al. (2015) found no correlation between LL, PL and the clay fraction content, while they observed a positive relationship with organic C on a dataset of mountain forest soils in the Aosta Valley (N-W Italy), particularly in SOM-enriched soil horizons such as A, Bs, and Bh. They therefore concluded that SOM was the dominating property controlling LL and PL in the mountain topsoils of the study area, and that its effect in deeper soil horizons was visible only when the organic C amount was above a certain threshold (around  $20 \text{ g kg}^{-1}$ ). This predominance of SOM seems reasonable, considering that the clay fraction of the studied soils was relatively scarce (always <20%), as often observed for alpine soils and it showed a small inter-sample variation. Keller and Dexter (2012) found that LL and PL were well related with both SOM and texture in a dataset of agricultural topsoils (i.e. tilled layer) from EU and USA, where the correlation with clay was stronger for LL than PL, even if the reasons were not clear. In addition, they concluded that PL was not affected by clay contents lower than 35%, confirming that a linear correlation cannot always be foreseen.

Mineralogical characteristics may play some role in determining the soil mechanical properties. Depending on the charge density of exchangeable cations that provide strong hydrophilic sites for solvent sorption (Schoonheydt and Johnston, 2006), several water layers may be incorporated in the interlayer of phyllosilicates with low layer charge, such as smectites. When instead the layer charge is higher, as in illites, or the interlayer is occupied by Mg-octahedral sheets or stable Al polymers, as in lithogenic or pedogenic chlorites (Tolpeshta et al., 2010), the amount of water that can be sorbed is much lower. As layer charge affects the interlayer distance, an index that may help understanding the effects of mineralogy on soil mechanical properties is the equivalent basal spacing (EBS), a global evaluation of the interlayer distance suggested by Schmitz et al. (2004). Badia et al. (2015) studied the relationships between Atterberg limits and soil mineralogy in illite-rich soils using either semi-quantitative mineralogical analysis or EBS, and found that the least plastic soils had abundant quartz and carbonates. Hajjaji et al. (2010) observed a good correlation between LL, PL and EBS for sediments taken from stratigraphic sequences in Tunisia. Furthermore, different clay minerals have a different specific surface area (SSA), which may vary depending on the formation pathway and environment, globally affecting the colloidal behavior and the water sorption capacity. Dolinar (2012) observed a direct relationship between the Atterberg limits (LL, PL) and the SSA. Keller and Dexter (2012) speculated that the mechanical behavior of soils at water contents higher than the liquid limit might be more controlled by SSA than the one in the plastic range. Among the qualitative aspects related with the clay fraction, Keller and Dexter (2012) highlighted the role of the aggregated clay particles that can actually behave as silt-sized grains in soils, hence reducing its plasticity. Some indirect effect of soil aggregation was observed also by Blanco-Canqui et al. (2006), who explained differences in soil consistency with variations in SOM amount and the effects it had on structure. Also Zolfaghari et al. (2015b) remarked that clay aggregation and SOM quality might need further investigation with respect to Atterberg limits, and this might be particularly true for the surface soil horizons where the influence of the organic component is more pronounced.

Therefore, despite some general consensus on the influence of the clay fraction and organic matter on the soil liquid and plastic limits, some points still need to be addressed by research. First, while LL and PL are determined on the <0.425 mm soil fraction, the other soil properties (e.g. texture, SOM content) generally refer to the fine earth soil fraction (i.e. <2 mm). In addition, the role of clay mineralogy in organic matter-rich soil horizons such as non-agricultural soils (e.g. mountain forest topsoils), potentially prone to natural hazards, is still poorly

studied, as a large part of the research focuses on agricultural soils, sediments or stratigraphic sections.

In particular, little is known about mid-altitude mountain soils located in geographical regions where even small changes in temperature and precipitation largely affect snowfall frequency and amount, thus altering the precipitation regime (Terzago et al., 2013) with potential effects on natural hazards frequencies. We therefore investigated a set of forest soils (Ligurian Alps, NW Italy), that are relatively rich in both the clay fraction and SOM, with the aim of evaluating the relationships among LL, PL, and these soil properties from both the quantitative and the qualitative point of view. In particular we investigated:

- 1) The relative effect of clay and organic matter. We hypothesized that LL and PL might be better correlated with the properties of the <0.425 mm soil fraction than those of the fine earth;
- 2) The relationships between the mineralogical composition and aggregation of the clay fraction, and LL and PL in the <0.425 mm size range.

## 2. Materials and methods

### 2.1. Description of the study area

The study area is located in the Ligurian Alps (NW-Italy, Fig. 1) at elevation ranging from 800 to 1600 m a.s.l., at the boundary between Piemonte and Liguria Regions, 30 km far from the Mediterranean Sea. It is particularly interesting for the combination of environmental factors, as it is located at the convergence of the Mediterranean, European, and Alpine biogeographic regions (Cornara et al., 2014).

The average annual temperature ranges between 4 and 7.5 °C, decreasing with altitude and with local variability with slope aspect. The annual precipitation is around 1000–1200 mm, with spring and fall maxima, and summer minima (Biancotti et al., 1998). The soil moisture regime is always udic, while the temperature regime varies from mesic (below 1300 m a.s.l.) to frigid (above 1300 m a.s.l.). Forests cover a large part of the territory and are dominated by beech (*Fagus sylvatica* L.), chestnut (*Castanea sativa* Mill.), larch (*Larix decidua* L.), fir (*Abies alba* Mill.), and Scots pine (*Pinus sylvestris* L.). The soils of the area develop on a wide range of parent materials, from pelitic and metapelitic sedimentary (or weakly metamorphosed) rocks to hard and coarse grained quartzite. Pelitic and metapelitic rocks allow the development of relatively clay-rich soils that are therefore characterized by both high SOM contents, which are typical of forest soils, and fine texture (with both lithogenic and pedogenic layer silicates). Quartzite instead supports the development of coarser textured soils. A detailed description of soils, vegetation cover, and geology of the area is provided by Catoni et al. (2016). We selected 11 soil samples on varying parent material (Table 1): 2 were on quartzite or metamorphic porphyroids, 3 on limestone-dolostone, and 6 on the Helminthoides Flysch unit formed by both calcareous and non-calcareous weakly metamorphosed siltstones and claystones discontinuously interbedded by sandstones. Topsoils (0–10 cm) were collected, then air dried and sieved at 2 mm (fine earth fraction).

### 2.2. Chemical and physical analyses

On the <2 mm fraction, the total C (TC) contents were determined by dry combustion with an elemental analyzer (NA2100 CE Instruments, Rodano, Italy). The content of inorganic C was measured with the TIC-solid module of a TOC analyzer (Vario TOC132 Elementar, Hanau, Germany). The total organic C (TOC) content was computed as the difference between C measured by dry combustion and carbonate-C. Soil particle distribution was determined by the pipette method with Na-hexametaphosphate after pre-treatment for SOM oxidation with  $\text{H}_2\text{O}_2$  (Gee and Bauder, 1986). As TOC is linearly related to SOM, it was considered as an indicator for SOM content in further statistical analyses. The exchangeable amounts of elements (Ca, Mg, K and Na)

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