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# Pedogenetic interpretations of particle-size distribution curves for an alpine environment

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ABSTRACT

The Qilian Mountains are generally capped by a productive silty soil layer wherever the environment allows. As Holocene loess is prevalent across the Qilian Mountains, we assume that at least some of these fine sediments are derived from loess deposition and that soils across the region may be genetically linked. To test these hypotheses, nine pedons in different landscapes within a typical alpine watershed of the Qilian Mountains were sampled. We also collected fine earth samples from glacier surfaces and crevices of glacial debris in the moraine zone. The particle-size distribution (PSD) is used as a proxy for identifying aeolian fractions in soils. The PSD curves of all of the fine-earth fractions examined are polymodal, although three modal sizes of roughly 16 μm, 35 μm and 80 μm are found in almost all sediments in varying proportions. These modal sizes have been identified as three sources of aeolian sediments in different transport systems. The composition and thickness of loess sediments are related to local site conditions and may be related to the paleoenvironmental history of the site. Clastic debris and vegetation cover serve as dust traps during different stages of soil formation in this alpine environment, and soils grow upward with accumulating loess sediment. Our study demonstrates that PSD curves can be used to determine the origins (and especially aeolian origins) of soils. Furthermore, this study provides insight into the pedology, ecology and paleoenvironmental history of loess-affected ecosystems in alpine areas of the Qinghai-Tibetan Plateau.


## 1. Introduction

Many high-mountain regions are capped by a silty surface soil layer whose origin lies far beyond the weathering capacity of basement rocks (Küfmann, 2003; Clark and Duffy, 2006; Lawrence et al., 2011; Munroe et al., 2015). There is increasing evidence that a substantial proportion of clay and silt fractions of alpine soils have been derived from wind-blown dust, especially since the Last Glacial Maximum (Dahms, 1993; Muhs and Benedict, 2006; Lawrence et al., 2013). Tracing the aeolian origins of soils in alpine environments is particularly important, as these fine mineral (and sometimes organic) particles may contribute significantly to alpine ecosystems through the addition of various types of bio-essential elements and through improvements in water and nutrient holding capacity levels (Litaor, 1987; Field et al., 2009; Lawrence et al., 2011; Herckes et al., 2006; Neff et al., 2008). Ecosystem studies would benefit from an accurate assessment of aeolian fractions in soils using various tools that have been proposed for identifying dust additions to soils (Chadwick et al., 1999; Reynolds et al., 2001; Lawrence et al., 2013).

The particle-size distribution (PSD) has long been used to make pedogenetic interpretations of soils (Litaor, 1987; Simonson, 1995). For example, many pedological studies of periglacial environments have applied soil PSD to source soil parent materials and to interpret pedogenic processes (Navas et al., 2008; Abakumov, 2010; Strauss et al., 2012). PSDs are traditionally determined using the pipette and sieve method and are typically represented as clay, silt and sand fractions. These granulometric fractions carry pedological and geological information and records of soils, which are often interpreted in combination with mineralogical and geochemical results (Litaor, 1987; Muhs and Benedict, 2006; Tate et al., 2007). The laser diffraction method constitutes an alternative means of measuring PSDs that generates considerably more detailed particle-size information at a much faster rate (Vandenberghe, 2013). In loess and other sediment studies, laser methods have routinely been used for decades to identify PSD parameters as effective proxies for tracing source regions, inferring sedimentary histories and reconstructing paleoclimates (Liu, 1985; Sun et al., 2002, 2004; Stanley and Schaetzl, 2011; Vandenberghe, 2013). Recent studies show that detailed PSD curves generated using laser methods could provide valuable information for interpreting soil origins and especially for identifying aeolian deposits in soils (e.g., Tate et al., 2007; Schaetzl and Luehmann, 2013; Hirmas and Graham, 2011; Crouvi et al., 2013; Lawrence et al., 2011; Miller and Schaetzl, 2012; Mileti et al., 2013).

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PSD curves of windblown sediments typically appear with a primary characteristic modal size resulting from sorting processes (Pye, 1995). This modal size provides excellent information on sedimentologic origins (Tate et al., 2007; Vandenberghe, 2013). In addition, when mixed with other sediments or soil materials, the characteristic modal size persists in most cases (Luehmann et al., 2013; Sun et al., 2004; Hobbs et al., 2011). This suggests that detailed PSD curves may reflect the genetic complexities of sediments derived from multiple sources.

In this study, we collected three samples from glacier surfaces, five samples from moraine debris crevices and nine soil profiles from different landscapes and geological settings within a typical alpine watershed of the Qilian Mountains. Field morphological features including the massive stone-poor silty surface soil layer, widespread lithological discontinuity in soil profiles and well-preserved loess-like soils as well as abundant cryoconites on glacier surfaces represent extensive additions of aeolian dust to this alpine mountainous region. Our primary goal was to identify genetic links between these sediments and to extrapolate their origins in relation to well-documented deposits in the larger region by examining and referencing detailed particle-size data. In addition, we attempted to identify dominant soil forming processes and their ecological implications by interpreting PSDs in relation to local site conditions.

## 2. Materials and methods

### 2.1. Study area

The study area is located in the central region of the Qilian Mountains — the northeast border of the Qinghai-Tibetan Plateau (Fig. 1a). The Qilian Mountains are surrounded by vast arid lands with the Taklimakan Desert to the west, the Badain Jaran and Tengger Deserts to the east, the Gobi Desert to the north and the Qaidam Desert to the south (Fig. 1a). Climatic patterns around the Qilian Mountains are mainly driven by contrasting wind systems, i.e., high altitude Westerlies, the East Asian Summer Monsoon (EASM) and the cold-dry Winter Monsoon. Precipitation patterns are mostly related to the EASM, as 89% falls from May to September (Bourque and Mir, 2012). During the winter and spring, the Siberian-Mongolian high pressure cell drives the low altitude cold-dry Winter Monsoon north, resulting in heavy dust storms (Nottebaum et al., 2014). It has been documented that loess deposition became a prevalent phenomenon within the Qilian Mountain area since the early Holocene. However, loess deposition was absent during the Late Pleistocene, when high wind speeds and low temperatures prevented the development of vegetation as effective dust traps (Küster et al., 2006).

Our sampling sites are situated within a small watershed (Hulugou). Based on meteorological data recorded at 2980 m asl in this basin (Fig. 1b), the mean annual temperature is 1.1 °C, the mean annual precipitation level is recorded as 447 mm, and the annual potential evaporation level is recorded as 1102 mm (Chen et al., 2015). The mean annual precipitation level increases with increasing altitude over a gradient of roughly 200 mm $km^{-1}$, and the mean annual temperature decreases at a rate of roughly 5.6 °C $km^{-1}$ (Chen et al., 2014). The terrain in the Hulugou watershed is complex, presenting a clear vertical zonality of landscapes from 2960 m to 4820 m (Chen et al., 2014) (Fig. 1b). Glaciers are restricted to the summits of high mountains (above 4500 m) followed by the cold desert zone (3900–4500 m) with steep terrain. The alpine meadow/shrubby meadow zone (3300–3900 m) and subalpine steppe zone (2960–3300 m) are characterized by heavily undulating and hummocky terrain. Marsh meadows and coniferous forests are limited along the north-facing hillslope (Fig. 2d).

### 2.2. Field sampling

During our fieldwork, sediment and soil profiles were examined according to their geomorphological positions, landscapes and geological settings (Table 1). The main sampling route is located along the north-facing hillslope, and our sampling sites cover nearly all landscape types. Three cryoconites (C1–C3) were collected from the glacier surface (Shiyi glacier) (Fig. 2a) at altitudes of 4527 m to 4599 m. Fine earth (D1–D5) was also gathered from glacial debris (Fig. 2b) of the moraine zone with an altitudinal gap of approximately 100 m from 4064 m to 4424 m. Soil profiles were excavated and sampled according to pedogenic horizons, and soil morphological features were examined in the field (Supplemental Table 1). Six soil profiles were sampled along the north-facing hillslope. Among these, sites S3 and S4 are located in concave positions, while the others are geomorphologically stable. A gravelly lithological discontinuity is present in soil profiles S1, S2, S5 and S6 but is absent in profiles S3 and S4 within 120 cm (Fig. 2). Three sites (S7, S8 and S9) were sampled on the south-facing hillslope. S8 and S9 were easily identified as weakly weathered loess in the field. S7 is distinctive from the other soil profiles in terms of color and texture due to the presence of red mudstone. The surface soil horizon of S7 is characterized by a more yellow-tinted hue compared with the coloring of deeper soil horizons (Fig. 2).

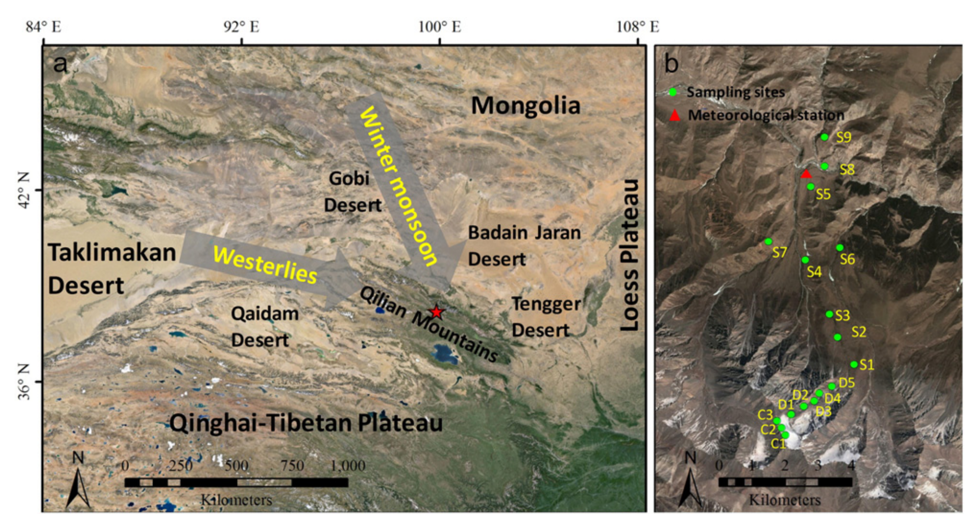


**Fig. 1.** The Qilian Mountains are located on the northeastern margin of the Qinghai-Tibetan Plateau and are surrounded by vast arid lands (a). Sampling sites along the Hulugou watershed (b).