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An eolian deposit–buried soil sequence in an alpine soil on the northern Tibetan Plateau: Implications for climate change and carbon sequestration

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ABSTRACT

The accumulation of eolian dust plays an important role in the development of alpine soils on the northern Tibetan Plateau. However, little is known either about the nature of soil-forming processes in the region, or about the magnitude of soil organic and inorganic carbon (SOC and SIC) storage. Here we report the results of an investigation of a typical profile, consisting of a series of buried soils developed within eolian deposits, situated at an altitude of 4951 m in the Amdo zone of the northern Tibetan Plateau. Bulk density, pH, SOC and SIC content, grain-size distribution, magnetic susceptibility and mineralogical composition were measured at high resolution, and AMS ^{14}C dating was used to provide a chronology. Based on all of the analytical data we conclude that this alpine accretionary soil profile contains three buried soils beneath the present surface soil layer. The deepest and oldest soil is the basal paleo-weathering crust (Ferralsol) which underwent active soil formation from 5540 to 7615 yr. BP, or even earlier. The other soils, which are developed within the overlying eolian dust deposits, are Luvisols and they document the occurrence of two intervals of more humid conditions than the present day: from ~3455 to 5540 yr. cal BP and from ~2000–2500 yr. cal BP. Microscopic analysis of coarse particles from the profile reveals that high values of magnetic susceptibility at the base of the profile reflect the presence of coarse magnetite grains present as inclusions within quartz grains derived from the weathering of granitic gneiss. In addition, the magnetic susceptibility profile reflects the effects of winnowing of the eolian fraction by wind activity, and not the production of fine magnetic grains during pedogenesis. SOC is the dominant form of carbon in this alpine soil and the SOC density and average accumulation rate values within the entire interval of eolian deposits are 19.67 kg C m^{-2} and 3.55 g C m^{-2} $yr.^{-1}$, respectively. These remarkably high values indicate that this alpine accretionary soil is characterized by highly efficient SOC burial, and therefore that such soils are an important terrestrial CO_2 sink. Likewise, the buried soil plays an important role in SOC storage. Finally, the characteristics of the buried soils indicate a long-term climatic trend towards aridity in the study region. This natural trend has promoted the processes of desertification and grassland degradation on the northern Tibetan Plateau, and these processes may have been exacerbated by human activity.

1. Introduction

The Tibetan Plateau has one of the largest distributions of alpine meadow in the world, with a total area of alpine soils of about 29.8×10^6 ha (Lin and Feng, 2015). The alpine meadow on the Tibetan Plateau plays a very important role in cattle rearing, soil conservation, environmental protection, and carbon cycling (Wang et al., 2007; Ohtsuka et al., 2008; Baumann et al., 2009). Our previous investigation has confirmed the eolian origin of the parent materials for the alpine soils at Amdo in the northern Tibetan Plateau (Lin and Feng, 2015), highlighting the importance of eolian dust inputs for the development of alpine soils in the region. However, very little is known about alpine soil-forming processes in the region, including the nature of the dust accumulation processes, temporal variation in pedogenic conditions, and the history of soil development (e.g. Yaalon and Ganor, 1973).

In regions where thick eolian deposits accumulate, variations in soil-forming factors, especially climate, result in the formation of loess–paleosol sequences (Liu, 1985; An, 2014). Consequently, the morphology and various other properties of loess–paleosol sequences can be used as tools to infer past climate changes (Birkeland, 1984; Dahms, 1998; Jacobs and Mason, 2004; Orlova and Zykina, 2002; Muhs et al., 2004; Zech et al., 2013). In the Chinese Loess Plateau in particular, numerous studies have demonstrated the utility of the loess–paleosol sequences as archives of climate change and past dust deposition cycles (Liu, 1985; Derbyshire et al., 1997; Bäumler, 2001; An, 2014). On the Tibetan Plateau, however, the characteristics of eolian deposits and related buried soils, and their paleoclimatic significance, are still not well understood (Caine et al., 1982; Saijoa and Tanaka, 2002; Kaiser et al.,

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2009; Lehmkuhl et al., 2014; Zhang et al., 2015). Such deposits and the related soils could potentially be used as a natural laboratory for improving our understanding of temporal trends in alpine soil development, and in addition they could be useful for assessing the causes of alpine soil degradation on the Tibetan Plateau (Cui and Graf, 2009; Miehe et al., 2014).

Soil organic carbon (SOC), the major component of soil organic matter (SOM), plays an extremely important role in the process of alpine soil development (Wallace, 1994; Bockheim and Koerner, 1997). In addition, in cold regions SOM constitutes a major part of the global carbon pool (Lal and Kimble, 2000b; Johnson et al., 2011). In recent years, the role of soil in terrestrial ecosystems, and in particular carbon capture in soils, SOC budgets and SOC turnover have become a focus of research attention (Schlesinger, 1990; Harden et al., 1992; Eswaran et al., 1993; Nieder and Benbi, 2008; Chaopricha and Marín-Spiotta, 2014; Munroe, 2014; Lehmann and Kleber, 2015). However, despite the increased interest in soil carbon dynamics and their impact on global carbon cycles during the past decade, the characteristics of SOC storage in eolian soil sequences have received relatively little attention (Luo et al., 2000; Ni, 2002; Wang et al., 2002; Tao et al., 2007; Yang et al., 2008; Baumann et al., 2009). In particular, in the case of alpine soils, the relationship between eolian processes and SOC burial, and the mechanisms of organic carbon sequestration, are poorly understood. Soil inorganic carbon (SIC) is also an important component of total C pool in soils (Lal and Kimble, 2000a, 2000b; Rasmussen, 2006; Tan et al., 2014) and the characteristics of the SIC pool in alpine soils are also poorly known.

On the Tibetan Plateau, eolian processes are active and ongoing (Owen et al., 1992; Lehmkuhl et al., 2000; Bäumler, 2001; Feng et al., 2014; Lin and Feng, 2015). Here, we extend our earlier work on eolian dust contributions to the formation of alpine soils on the northern Tibetan Plateau (Lin and Feng, 2015). A typical sequence of buried soils developed within eolian deposits at Amdo, on the northern Tibetan Plateau, has been investigated in detail with the objectives of: (1) improving our understanding of alpine soil-forming processes; (2) characterizing the features of buried soils; (3) quantifying the SOC and SIC pool; and (4) reconstructing the temporal variation of pedogenic conditions.

2. Materials and methods

2.1. Study area

The study area is in the Amdo region, on the northern Tibetan Plateau (Fig. 1). The Amdo–Cona down-faulted valley (4550–4700 m above sea level), with an approximate east–west orientation, is a major feature of the geomorphology of the region. The piedmont of the Tanggula Mountains borders the Amdo–Cona valley to the south, while to the south of the valley is a wide undulating and planar erosion surface at approximately 5000 m (Fig. 1; Feng and Zhu, 2009; Lin and Feng, 2015).

Amdo town (4700 m, a.s.l.) has an average annual precipitation and evaporation of 411.6 mm and 1770 mm, respectively. The annual average temperature is −3 °C. The average temperatures of the hottest (July) and coldest (January) months are 7.9 °C and −15 °C, respectively (Guan and Chen, 1984). The soils in the area (surface Cambisol, buried Luvisols and Ferralsol; ISSS, 1998; see below) do not contain permafrost within their profiles. The predominant vegetation is alpine meadow, mainly comprising *Kobresia humilis*, with lesser amounts of *Carex moorcroftii*, *Leontopodium nanum*, *Potentilla anserina L.*, *Oxytropis latibracteata Jurtz* and *Androsace tanggulashanensis* (Sun et al., 2011).

2.2. Field sampling and soil profile description

Soil profile A6B is located at 32.14227° N, 91.64014° E, altitude 4951 m (measured using a handheld GPS). It is situated on the top of a gently rising hill on the planar erosion surface near Amdo Town (Figs. 1, 2). The site is identical to that of soil profile AS6 previously reported by Lin and Feng (2015). In the previous investigation, bulk samples were collected at a 5-cm-interval from soil profile AS6. In the present study we collected samples at a 1-cm-interval from the top to the bottom of the profile. The sample numbers were specified as AS6B-depth (cm). Profile AS6B (Fig. 2) is described as follows:

0–68 cm: eolian deposits, consisting of silty sand (no particles >2 mm in diameter, except at the base of the profile; Lin and Feng, 2015). From 0

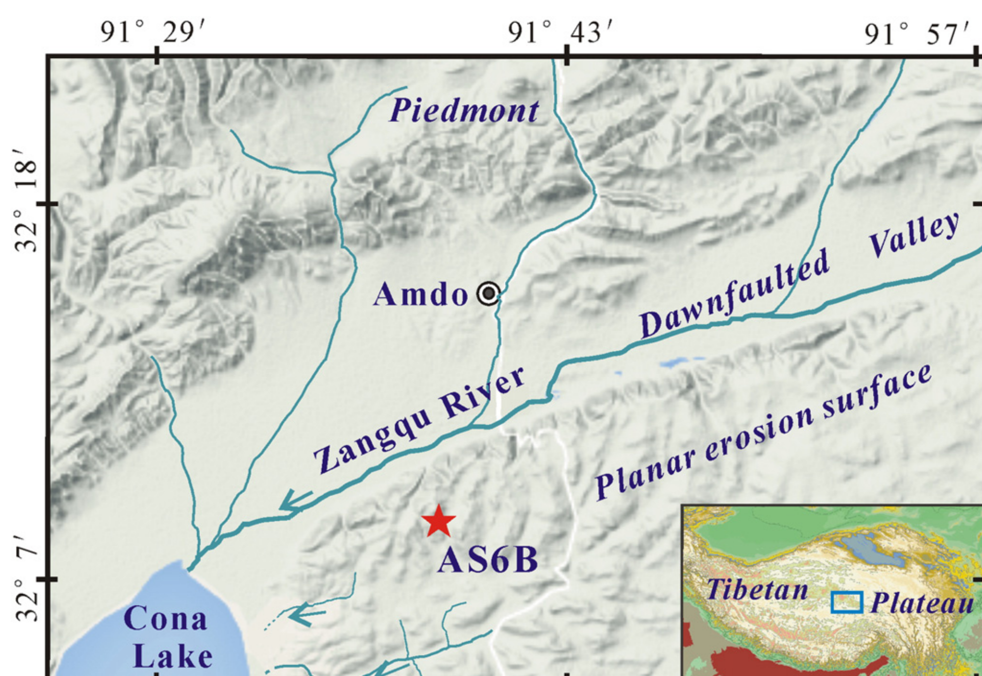

Fig. 1. Topography of the study site. Inset map shows location of the study area within the Tibetan Plateau.