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Pedogenesis, permafrost, substrate and topography: Plot and landscape scale interrelations of weathering processes on the central-eastern Tibetan Plateau

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ABSTRACT

Weathering indices (WI) and pedogenic oxides ratios (POR) were used to describe patterns of weathering intensities and pedogenesis along climatic gradients, mainly affected by varying influences of the Asian and Indian Monsoon. These climate settings induce particular soil moisture (SM) conditions, in turn closely related to permafrost state, substrate, and topography. Nine sites including a total of 30 soil profiles were examined along an eastern and a western transect across the central-eastern Qinghai–Tibet Plateau. Additionally, differences between four soil groups were analysed. According to our knowledge, the presented study is the first attempt of a comprehensive application of different WI and POR to substrates of currently permafrost-affected soils. It provides an evaluation of various tools in terms of chemically describing and differentiating the related processes to distinct environmental settings in low-weathering regions. We found that weathering trends along the climatic gradients could be clearly outlined by WI, whereas POR rather account for small scale variations, describing significant differences of pedogenesis between continuous and discontinuous permafrost conditions. Pyrophosphate soluble iron (Fep) proved to be useful for differentiating permafrost and ground water influenced soils, showing a strong correlation to total organic carbon ($r = 0.89$). The chemical index of alteration (CIA) is the most suitable WI, whereas Ca-free CPA is more easily biased by salinity variations of topsoils at sites with negative water balance, thus pretending lower weathering intensities. Regression analyses for WI and POR with main independent variables underline the specific characteristics: climatic parameters best explain WI, while SM is dominant for POR. The ratio (Fed-Feo)/Fet proved as the most appropriate POR with 64% explained variation by a multiple linear regression model, implying significantly lower iron release with higher SM and pH values. Variation of Fep can be explained by 63% with soil acidity being most important, followed by SM. Importantly, the presented research provides tools for investigating past and future stability or respective degradation processes of permafrost ecosystems on the Tibetan Plateau and may be applicable to other permafrost-affected environments.

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1. Introduction

Pedogenesis and the state of soil development are considered to be important predictors for total soil organic carbon (TOC) and nitrogen contents of permafrost-affected soils on the Tibetan Plateau (Baumann et al., 2009). Soil development is closely associated with specific weathering intensities under distinct environmental conditions (Brady and Weil, 2008; Jenny, 1994). Hence, the presented research provides an approach to evaluate and differentiate pedogenesis by soil chemical properties in relation to their main influencing factors.

Chemical weathering processes release iron and other elements contained in primary minerals of bedrocks and sediments. Depending on various soil characteristics, such as soil moisture (SM), soil temperature (ST), soil acidity, and redox conditions, distinct pedogenic oxides (PO) are formed under a particular timeframe (Kämpf et al., 2011). By extracting fractions of PO with specific degrees of crystallisation, it is possible to determine intensity, duration, quality, and direction of pedogenic processes (McKeague, 1967; Mehra and Jackson, 1960; Schlichting and Blume, 1962; Schwertmann, 1964). Several pedogenic oxides ratios (POR) have been successfully applied to describe and relatively date geomorphological units (e.g. Aniku and Singer, 1990; Arduino et al., 1984; Mirabella and Carnicelli, 1992; Torrent et al., 1980) as well as soil weathering

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Abbreviations: WI, weathering indices; PI, Parker index; KN, Kronberg & Nesbitt Index; CIA, chemical index of alteration; CIW, chemical index of weathering; PIA, plagioclase index of alteration; CPA, chemical proxy of alteration; PO, pedogenic oxides; POR, pedogenic oxides ratios; MAT, mean annual air temperature; MAP, mean annual precipitation; SM, soil moisture; ST, soil temperature; TOC, total soil organic carbon; SG, soil group; RG, Regosols; CM, Cambisols; GL, Gleysols; PF, permafrost-affected soils.

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chronosequences and palaeosols (e.g. Buero and Schwertmann, 1987; Dahms et al., 2012; Diaz, 1989; Mahaney and Fahey, 1980; McFadden and Hendricks, 1985; Rezapour et al., 2010; Sauer et al., 2010; Torrent et al., 2007). However, only few soil surveys systematically investigated PO in periglacial environments and under the scope of current soil formation (Melke, 2007).

Weathering indices (WI) have been primarily developed for sedimentary geology (e.g. Cullers, 2000; McLennan, 1993; Yang et al., 2004). Many studies have adopted these tools for analysing and describing geomorphological units, loess layers and palaeosols (e.g. Bäumler, 2001; Bäumler and Zech, 2000; Buggle et al., 2008, 2011; Gallet et al., 1998; Kühn et al., 2013; Wagner, 2005). Weathering intensities have been investigated in arctic permafrost and glaciated areas (Bäumler, 2001; Melke, 2007; Wagner, 2005), whereas only little research has been done in dry permafrost areas like the Tibetan Plateau. Due to the cold and arid climate, low chemical weathering intensities are expected in periglacial environments (Brady and Weil, 2008; Fedo et al., 1995; McLennan, 1993).

The Tibetan Plateau extends over more than 2.4 million km^2 on an average altitude of 4000 m a.s.l., representing the largest high-altitude and low-latitude permafrost area on earth. It proved to be particularly sensitive in terms of global warming (Qiu, 2008) and land use changes (Yang et al., 2009). About 54% of the plateau's surface is directly influenced by permafrost (Cheng, 2005). Over the past decades, permafrost degradation processes can be more frequently observed with corresponding changes in soil moisture–temperature regimes (e.g. Cheng and Wu, 2007; Jin et al., 2000; Kang et al., 2010; Yang et al., 2010, 2011; Zhang et al., 2003) and desertification processes (Wang et al., 2011; Xue et al., 2009; Yan et al., 2009). Soil's properties are accordingly altered, reassigning their role in ecosystem functioning (Chapin et al., 2000; Vitousek, 1997). This leads to instability and erosional features mainly triggered by widespread occurring loose sediments and sparse vegetation, which in turn is a result of lower soil moisture contents as a consequence of permafrost degradation (Baumann et al., 2009). Consequently, decreasing soil organic carbon contents can be observed (Dai et al., 2011).

Distinct climate gradients are evident across the research area (An et al., 2001), exhibiting clearly differing mean annual air temperature (MAT) and mean annual precipitation (MAP) as independent variables for soil weathering. Together with the above-described prerequisites and processes, the altering permafrost-affected ecosystems on the Tibetan Plateau provide an ideal compound to examine the use of POR and WI to describe weathering processes on both landscape scale and plot scale. In accordance to our present knowledge, this is the first study systematically analysing interdependencies of PO and WI in substrates subjected to current soil formation in permafrost environments across climate transects.

The primary objective of this study is to investigate the influence of permafrost on weathering intensity and pedogenesis. We hypothesise that:

(1) SM is a key variable for pedogenesis and weathering processes, mainly determined by permafrost characteristics, substrate, and topography.
(2) SM content is interrelated to distinct precipitation–temperature ratios and thus to specific permafrost distribution, caused by varying influences of monsoon systems between the eastern and western transect as well as along each transect.
(3) Intensity of weathering and pedogenesis can be described by WI, PO fractions and POR. These indicators are in turn all essentially related to independent moisture parameters showing clear differences along climate transects and specifically between continuous and discontinuous permafrost. By consideration of other independent parameters, WI and POR can be evaluated with regard to their validity in comparable environments.

2. Materials and methods

2.1. Environmental settings

Data presented in this paper were gathered during field work on the central-eastern Tibetan Plateau in the years 2006, 2007 and 2009 along an eastern and western transect, which both are north–south oriented (Fig. 1, Table 1). Sites on the eastern transect (EAST) extend along 98.5°E and range from 34.3 to 35.3°N in the region between the settlements of Huashixia and Yushu, whereas the western transect (WEST) stretches along 92.2°E and ranges from 31.4 to 34.7°N between Wudaoliang and Nagqu.

MAT ranges from −3.5 to −5.7 °C on the eastern transect and from −0.2 to −5.6 °C on the western transect. Mean annual precipitation (MAP) varies from 458 to 521 mm (EAST) and 285 to 510 mm (WEST) with 80% of the rainfall occurring during the summer months. Thus, two major climatic trends are evident in the research area: the subtropical East Asian Monsoon transporting comparably warm and moist air from the eastern lowlands to the eastern Tibetan Plateau during summer months decreasing westwards, and the Tropical Indian Monsoon influencing the Tibetan Plateau from the south (Domrös and Peng, 1988). The east–west oriented mountain ranges are important barriers for these airmasses. During the cold and dry winters, extratropical westerlies occur together with the prevailing Mongolian–Siberian high pressure system. Temperature and precipitation generally decreases from SE to NW, locally strongly influenced by topography and elevation. This explains the differences between sites E1 and E2 of EAST: they are geographically located next to each other but have pronounced climatic differences, which is caused by the Anyêmaqên Mountain Range located in the east. Site E2 is in lee position, showing lower rainfall with higher temperatures compared to E1, where an east–west stretching furrow between the Anyêmaqên and Bayan Har Mountains locally leads to higher rainfall and lower temperatures. Site E3 is located southwards close to Bayan Har pass, explaining the lower MAT and higher MAP. Similar situations occur in WEST, with the Tanggula Mountains being the most eminent climatic divide. Evaporation ranges on average for the whole Tibetan Plateau between 1204 and 1327 mm (Wang and French, 1994), reaching 1478 mm in the headwaters of Yangtze River (Hu et al., 2009), 1264 mm in the headwaters of Yellow River around Maduo (Zhang et al., 2010) and 1770 mm in the area around Amduo (Feng and Zhu, 2009). Gao et al. (2006) provide evaporation values ranging from 1500 to 2300 mm for Nagqu County rising from SE to NW. Hence, evaporation far exceeds precipitation in the whole research area.

Permafrost characteristics and distribution are closely linked to climatic patterns (Ping et al., 2004; Wang and French, 1994, Fig. 1). Active layer thickness averages around 1–2 m, increasing from northwest to southeast and with decreasing altitude (Cheng and Wu, 2007; Wang et al., 2000). EAST is characterised by discontinuous and unstable permafrost conditions with a widespread vertical disconnection in the area around Huashixia. In these cases, soils freeze seasonally to a depth of 2–3 m with the upper limit of permafrost located in 4–7 m depth (Jin et al., 2000). This vertical freezing-gap is non-existent with higher elevation, as can be observed for the Bayan Har Shan site (E3). The western transect extends from continuous ice-poor permafrost in the area around Wudaoliang (W1/W2), to sporadic island permafrost in the region around Nagqu (W6/W7). Permafrost degradation, also caused by former construction activities, lead to the formation of numerous small depressions, where surface water accumulates or thermokarst lakes are formed (Niu et al., 2011). Moreover, desertification is a major consequence of permafrost degradation frequently observable in the research area (Xue et al., 2009).

Glacial aeolian loess-like sediments and sediments dominated by silt and fine sand fractions, being mainly of local origin (Feng et al., 2011), cover most slopes and terraces providing the main parent material for pedogenesis (Schlütz and Lehmkuhl, 2009). Soil formation is closely

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