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Chronosequence development and soil variability from a variety of sub-alpine, post-glacial landforms and deposits in the southeastern San Juan Mountains of Colorado

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ABSTRACT

Surficial processes acting on post-glacial alpine and sub-alpine landscapes vary at small temporal and spatial scales and are thus often difficult to conceptualize in the context of large-scale landscape evolution models. Soils developing in this setting can thus provide valuable information about landform genesis, sedimentology and age. Relatively few post-glacial chronosequences have been examined in these settings however, particularly for the variety of landforms and parent materials that exist within alpine and sub-alpine environments. Here, we examine a chronosequence of relatively young, post-glacial landforms with varying parent materials and climate histories. We dug and described 39 soil pits in the upper Conejos River Valley of Colorado on a variety of deposits and landforms, including alluvial fans, terraces, colluvium, glacial till, and terminal moraines, and compared soil properties with radiocarbon ages from the area. Our results suggest that some typical chronosequence soil properties (e.g., pH, structure, color) do not correlate with time over short time scales. However, extractable iron ratios (Fe_o/Fe_d) show a relatively strong correlation with age across late-Pleistocene and Holocene time scales and maximum profile clay content shows a weak but statistically significant relationship with age. Both of these trends are stronger when examined across a single parent material. Differences in initial parent material texture and dust inputs seem to be the most significant complicating factors over post-glacial time scales. Soil property development through time is most inconsistent in cumulic alluvial fan soils. This observation may indicate that alluvial fans are more responsive to sub-basin scale processes as opposed to fluvial terraces that are more likely respond to processes active across the entire basin. These differences would explain why stratigraphically similar alluvial fans are mantled by soils with varying development. Nonetheless, horizonation, clay content, and extractable iron ratios provide a useful tool for correlating young deposits, assigning ages, and interpreting the geomorphic history of complex post-glacial environments.

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1. Introduction

Accurate chronologies are key elements of geomorphic mapping and the interpretation of surface morphology. Soil chronosequences have long been used to provide inexpensive relative ages of landforms and deposits, which in turn allows for the investigation of landscape evolution where numerical age dating is limited. In addition, soils can yield important information relating to incision and sedimentation rates (e.g., Birkeland et al., 2003; Leigh and Webb, 2006), landscape response to climate change and anthropogenic impacts (Eppes et al., 2008; Johnson et al., 2013; Layzell et al., 2012b, e.g., McFadden and McAuliffe, 1997), as well as alluvial response to intrinsic variability (Eppes and McFadden, 2008). Despite their importance as tools for investigating and reconstructing the geomorphic history of landscapes, few soil chronosequences have been created for the post-last glacial maximum (LGM) deposits of alpine and sub-alpine environments in the Rocky Mountains (e.g., Birkeland et al., 1987).

Developing soil chronosequences in alpine and subalpine environments is complicated by the overall young age of soils (e.g., Birkeland et al., 1987), which have typically only begun forming in the last 15 cal. kyr BP, since glacial retreat. In fact, few existing alpine chronosequences have attempted to discern variability in soil development at sufficiently short time scales to differentiate post-LGM deposits. The lack of established chronosequences is likely because it is not clear if traditional indicators of soil age such as color change and the presence of illuvial clays can be sufficiently differentiated between these relatively young deposits. Additionally, post-LGM climates have been shown to be quite variable (e.g., Jiménez-Moreno et al., 2008; Johnson et al., 2013), which further complicates chronosequence development.

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Post-LGM chronosequences are also complicated if soils are examined across multiple parent materials with different textural characteristics (e.g., sediment size and sorting). Soil chronosequences are typically developed for an individual sequence of landforms including ground moraines (Egli et al., 2001a, 2001b, 2003a), moraines (Berry, 1987; Birkeland and Burke, 1988; Douglass and Mickelson, 2007; Egli et al., 2003b; Mellor, 1986; Taylor and Blum, 1995), loess (Birkeland, 1984b), fluvial terraces (Bain et al., 1993; Engel et al., 1996; Eppes et al., 2008; Layzell et al., 2012a; Leigh, 1996, e.g., McFadden and Weldon, 1987; Shaw et al., 2003), alluvial fans (e.g., McFadden et al., 1989; Mills and Allison, 1995; Ritter et al., 1993) and colluvial deposits (Pollack et al., 2000). In alpine and subalpine areas, however, moraines, alluvial fans, colluvium and valley bottom terraces are found in close proximity to one another and are closely related in terms of form and process (i.e., fans typically grade to terraces). Therefore, if certain soil–age relationships are observable in a small region across multiple landforms and deposits then questions regarding geomorphic relationships can be addressed. For example, alluvial fan and terrace chronologies can be compared in order to identify the source and timing of sedimentation. Such information could also compliment ongoing work in Critical Zone Observatories (e.g., Anderson et al., 2011; Leopold et al., 2011) and inform discussion about soil production (Anderson et al., 2011; Dethier and Lazarus, 2006; Riggins et al., 2011).

This study aims to examine age-dependent soil properties across a variety of post-glacial deposits and landforms in a major, subalpine to alpine drainage basin of the southern Rocky Mountains, USA. Developing this cross-landform chronosequence will provide insights into key pedogenic processes and thresholds acting in these relatively understudied environments. Although this approach challenges fundamental chronosequence assumptions, our data shows statistically significant trends between key soil properties and age despite variation in parent materials, climate and vegetation histories. Additionally, the creation of a multiple-landform relative dating tool for alpine areas will provide geomorphic researchers with a method for better understanding aggradational histories and landscape-scale processes in high elevation environments where datable material is scarce.

2. Study area

2.1. Geography

The Conejos River Valley is located in the southeastern San Juan Mountains in the southern Rocky Mountains (Fig. 1). The Conejos River has four distinct reaches: glaciated headwaters, a glaciated trunk valley, an unglaciated trunk valley, and an alluvial plain where the river flows into the San Luis Valley. The river flows north from its headwaters in the center of the range before flowing east out into the Rio Grande, draining approximately 2300 km^2. The study area for the chronosequence described herein comprises the upper portion of the glaciated Conejos River valley (~35 km in length) plus 6 glaciated tributaries (Rito Azul, North Fork, Middle Fork, Adams Fork, South Fork, and Lake Fork; Fig. 1). Platoro Reservoir (3050 m elevation), which was built in 1951, approximately divides the study area in half. Throughout the field area, the main Conejos River and its tributaries can be further divided into separate sub-reaches. Each sub-reach is characterized by a broad glacial valley, with widths ranging from 300 to 1000 m, separated by steeper canyon reaches, approximately 5 km long, where valley widths range from 50 to 100 m. This pattern of alternating steep and shallow reaches resembles a series of cyclopean steps (Johnson et al., 2010).

During the LGM, the Conejos River basin was covered by the southern extent of the San Juan ice cap, which glaciated all but the highest peaks in the upper Conejos River Valley (Atwood and Mather, 1932). Large valley glaciers extended more than 40 km from the center of the ice cap carving out large U-shaped valleys. In the eastern San Juan Mountains, the glaciers carved deeply into soft volcanic bedrock leaving a high relief landscape where peaks rise to nearly 4000 m and valley floors lie as much as 1000 m below. The volcanic bedrock formed at ~30 ma and is thought to be associated with the end of the Laramide orogeny (Lipman et al., 1970; Lipman, 1974). The eastern San Juan Mountains appear to have been tectonically inactive since the main period of Rio Grande Rift extension ended between 10 and 5 ma (Morgan et al., 1986).

2.2. Climate

Climate in the San Juan Mountains is typical of alpine and subalpine microclimates in the Southern Rocky Mountains and is also strongly influenced by the North American Monsoon (Adams and Comrie, 1997) and El Niño Southern Oscillation (ENSO) cycles. Precipitation in the area also originates from mid-continental troughs and the subtropical jet stream. A nearby SNOTEL station monitors modern climate at roughly the mean elevation of the field area (although not in the field area) where annual temperature is ~1 °C while average annual precipitation is ~75 cm (2/3 of which is winter; 60 cm of snow cover through winter months is typical). Most moisture falls either during the winter months or during the North American Monsoon, which runs from mid-July through August. Maximum river discharge occurs in the late spring (May and June) as temperatures warm and snowpack melts. Since these climate records are recorded at an elevation similar to the middle of the field area, the actual conditions are probably slightly cooler and wetter throughout the upper portion of the valley and warmer and drier throughout the lower portion of the field area. Vegetation varies with altitude but is typically coniferous forest (*Picea engelmannii* and *Abies lasiocarpa*) in the lower field area and alpine tundra in the upper field area (Johnson et al., 2013). Throughout the field area, areas of open grass exist, regardless of elevation, and these were used for soil profile examine to control for differences in vegetation.

Climate is known to have changed in the San Juan Mountains since the LGM (Ariztegui et al., 2007; Carrara and Andrews, 1976; Carrara et al., 1984, 1991; Fall, 1997; Guido et al., 2007; Jiménez-Moreno et al., 2008; Johnson et al., 2013). In particular, there are two paleoclimate records derived from bog cores sampled within 25 km of the field area (Johnson et al., 2013) and within the field area (Deal, 2014). These records provide relatively high-resolution, corroborating, post-LGM records of climate for the field area. Both records provide evidence that cold LGM temperatures lasted until about 16 cal. kyr BP followed by warming until 14–13 cal. kyr BP. A cold Younger Dryas is well-evidenced in both records as is a cold period around 8200 +/− 400. The remainder of the first half of the Holocene was relatively warm and stable. The second half of the Holocene was generally colder with increasing climate switching frequency after 5 cal. kyr BP and again after 3 cal. kyr BP. Records conflict as whether climate was dominantly warm or cold during the latter half of the Holocene (Johnson et al., 2013).

2.3. Quaternary geology

The landforms and deposits of the upper portions of the Conejos River Valley have been mapped at a 1:24,000 scale (Johnson et al., 2010; Layzell, 2010; Layzell et al., 2012b). The most prominent geomorphic features and deposits found within the study area are glacial till, alluvial fans, stream terraces, and colluvium. The expression of landforms and deposits varies in the field area above and below the bedrock constriction that now constitutes the dam for Platoro Reservoir, however the general stratigraphy found in the field area can be correlated (Fig. 2). LGM terminal moraines mapped by Atwood and Mather (1932) lie outside the study area, but are discussed as they provide valuable comparisons for the younger soils in the field area.

Our calculations, based on the timing of deglaciation in the western San Juan Mountains (Guido et al., 2007), indicate that glaciers likely retreated through the field area between 12 and 14 cal. kyr BP. This

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