The Compass: Earth Science Journal of Sigma Gamma Epsilon

Volume 84 | Issue 4 Article 4

1-31-2013

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Recommended Citation

Layzell, Anthony L. and Eppes, Martha C. (2012) "Holocene Pedogenesis in Fluvial Deposits of the Conejos River Valley, Southern Colorado," *The Compass: Earth Science Journal of Sigma Gamma Epsilon*: Vol. 84: Iss. 4, Article 4.
Available at: https://digitalcommons.csbsju.edu/compass/vol84/iss4/4

HOLOCENE PEDOGENESIS IN FLUVIAL DEPOSITS OF THE CONEJOS RIVER VALLEY, SOUTHERN COLORADO

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ABSTRACT

Relatively few geomorphic studies have examined Holocene-aged soils developed in alluvial deposits in the Rocky Mountains. Here, we present a soil morphological investigation from a suite of fluvial terraces in the glaciated portion of the Conejos River Valley, southern Colorado. The surficial geology of 25 km of the glacial valley was mapped in detail. Within three separate sub-reaches (Platoro, Lake Fork and South Fork) a total of thirteen soil pits and exposures were excavated and described on alluvial deposits. Soil samples were analyzed for particle size and extractable iron.

Soil horizonation (A/C to A/B/2C), structure (fine sub angular to medium angular blocks), clay content of the B horizon (8.0% to 22.8%) and Fe_o/Fe_d (0.39 to 0.80) illustrate trends with relative terrace deposit age in individual sub-reaches. However, only Fe_o/Fe_d ratios displayed similar rates of development between all sub-reaches highlighting the usefulness of this metric for determining accurate rates of pedogenesis and relative age for Holocene-aged deposits in sub-alpine environments. Results indicate that clay content and structure developed in alluvial deposits of similar ages vary between sub-reaches. Clay contents were found to be lower in the Platoro sub-reach (e.g. 13.1% at Platoro and 20.0% at South Fork on Qt1 deposits). This variation is attributed to heterogeneity in the nature of the inherited parent material and potential variability in aeolian dust contributions throughout the Holocene.

KEY WORDS: Holocene soils, soil chronosequences, soil chemistry, pedogensis.

INTRODUCTION

Soil chronosequences are important tools for investigating and reconstructing the geomorphic history of fluvial systems. Soils develop under the influence of several environmental factors including climate, organisms, relief, parent material and time (Jenny, 1994). A soil chronosequence is a series of soils for which weathering characteristics vary primarily as a function of time. Analysis of time-dependent soil properties therefore provides a relatively inexpensive way to determine relative deposit age and to correlate landforms of different ages (e.g. Mills, 2005). Furthermore, soil chronosequences may also yield important information relating to incision and sedimentation rates (Birkeland *et al.*, 2003; Leigh and Webb, 2006), as well as the response of fluvial systems to extrinsic factors, such as climate (McFadden and McAuliffe, 1996; Eppes *et al.*, 2008), and intrinsic variability, such as differences in rock type (Eppes and McFadden, 2008).

Fluvial terraces facilitate chronosequence studies due to their relative ease of correlation and temporal juxtaposition (i.e. higher terraces are typically older than lower terraces). Soils on fluvial terraces have been investigated in a variety of different physiographic environments across the Unites States including the Pacific Coast Ranges (McFadden and Weldon, 1987), the Sierra Nevada Mountains (Alexander, 1974), the Colorado Front Range (Birkeland *et al.*, 2003), the Blue Ridge Mountains (Leigh, 1996), the eastern Piedmont (Engel *et al.*, 1996; Layzell *et al.*, 2012a) and the Atlantic Coastal Plain (Howard *et al.*, 1993; Shaw *et al.*, 2003). In particular, these chronosequence studies have found a variety of different soil properties that show trends with time including rubification, clay content, B horizon thickness and extractable iron. These studies also highlight some variability in the type of soil properties that develop over time in different physiographic regions. This study therefore aims to identify the particular soil properties that develop primarily as a function of deposit age in subalpine environments. Despite their usefulness in geomorphic studies, relatively few soil chronosequence studies exist for Holocene-aged fluvial deposits in the Rocky Mountains. The lack of research in this area is likely due to the relatively young age of Holocene soils. It is unknown whether typical time-dependent soil properties display sufficient differential development at this temporal scale. Therefore, this study hopes to provide important insights into how soils develop in hereunto understudied subalpine settings

Geomorphic Setting

The study area lies on the southeastern edge of the San Juan Mountains in Southern Colorado (Fig. 1). The Conejos River, a tributary of the Rio Grande, originates in the San Juan Wilderness and flows east into the San Luis Valley. The Conejos River can be divided into four distinct reaches: glaciated headwaters; a glaciated trunk valley; an unglaciated trunk valley and an alluvial plain. The study area comprises the upper portion of the glaciated trunk valley, approximately 25 km in length. Research in the study area was focused primarily on three sub-reaches; Platoro, Lake Fork and South Fork, where the greatest proportion of terrace deposits were present (Figs. 1 and 2). Each sub-reach is characterized by a broad glacial valley, with valley widths ranging from 300 to 1000 m, separated by steeper canyon reaches, where valley widths are 50 to 100 m.

METHODOLOGY

A total of thirteen soil exposures were excavated and described on fluvial deposits in the field area according to Soil Survey Staff (1993) and Birkeland (1999). Descriptions from hand-excavated soil pits were supplemented by descriptions of natural exposures (e.g. fluvial cut banks) in order to determine spatial variability and for

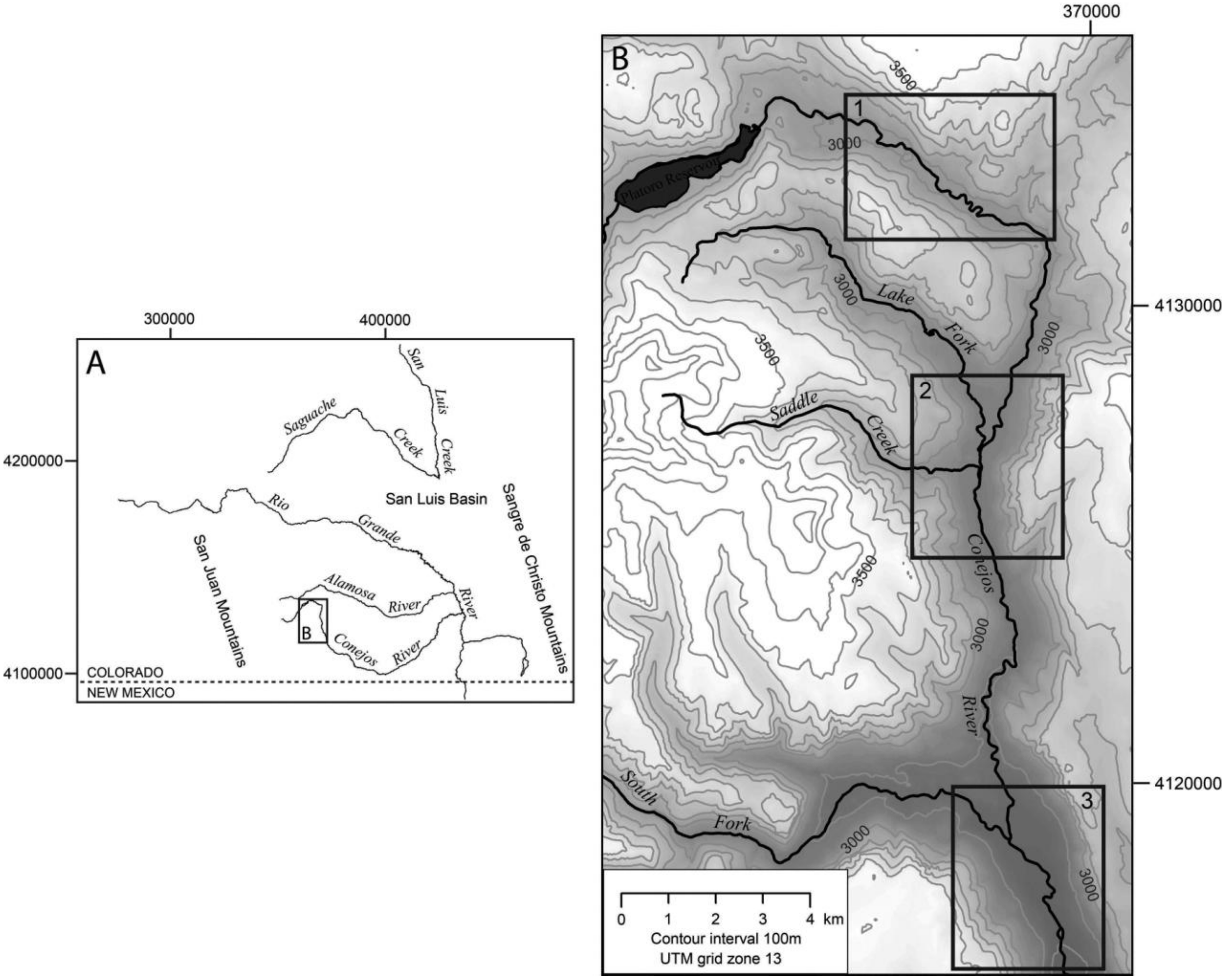

Figure 1. Study area location in the San Juan Mountains, southern Colorado. Regional map A shows major rivers in the upper Rio Grande watershed. Study area map B shows valley sub-reach locations: 1) Platoro; 2) Lake Fork; 3) South Fork. Modified from Layzell *et al*., 2012b.

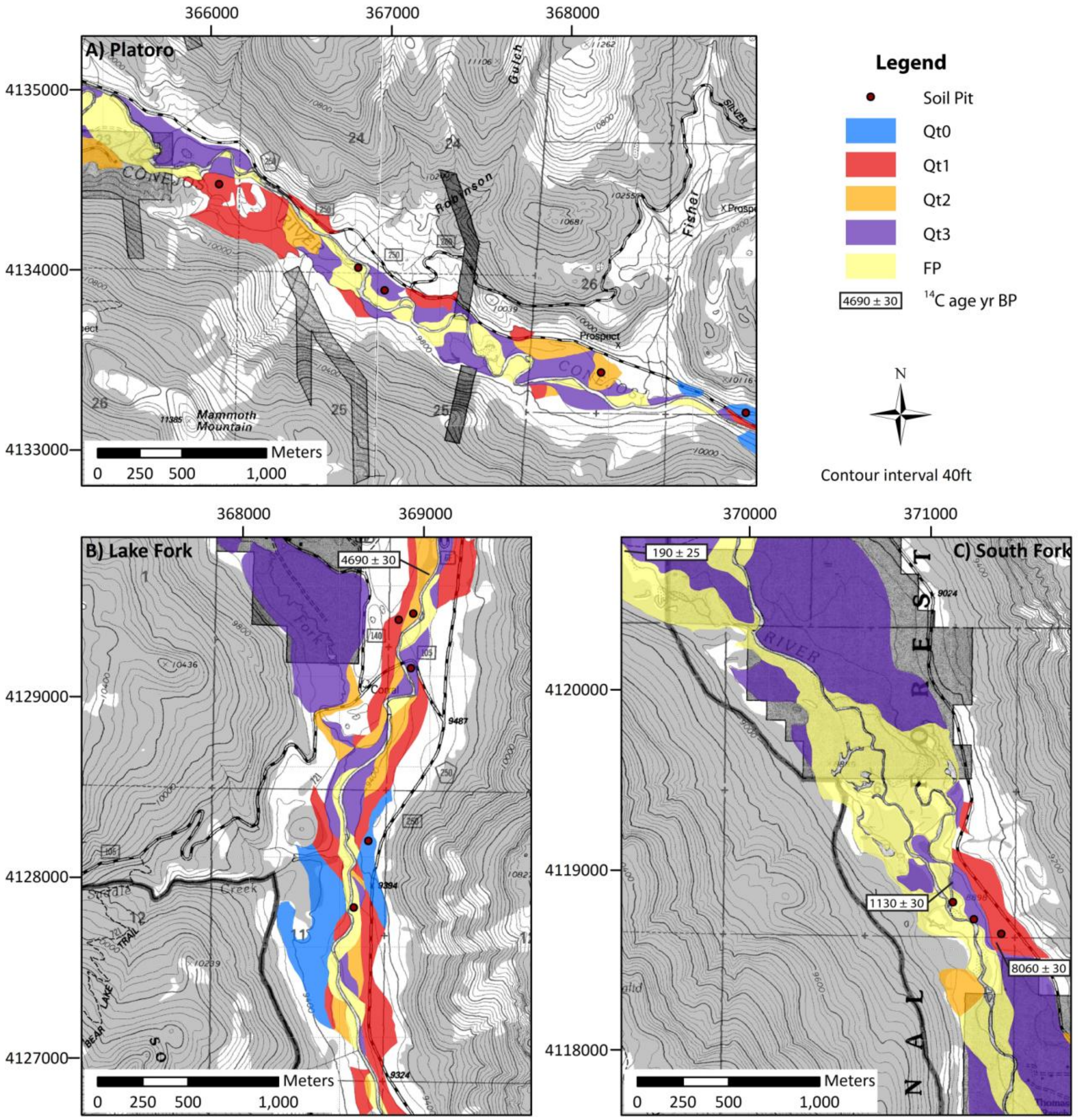

Figure 2. Surficial geologic map of valley sub-reaches showing terrace (Qt0-3) and floodplain (FP) deposits and soil pit locations.

further correlation of map units. Analysis of soil morphology included descriptions of geomorphic surfaces, horizon thickness and boundaries, color, structure, gravel content, consistence, roots and pores, texture, clay films, as well as sedimentary descriptions. Each soil profile was sampled by horizon. All samples were sieved in the field and the <2 mm fraction analyzed for particle size (pipette method) and extractable iron (oxalate and dithionite-citrate methods). Extractable iron analyses were performed on samples from horizons with the greatest evidence of weathering (B horizons) for each terrace unit. The dithionite-citrate method (Fe_d) (Mehra and Jackson, 1960) determines the total secondary or free iron not included in silicate minerals. This includes crystalline oxides (e.g. hematite, goethite), amorphous hydrous oxides (e.g. ferrihydrite) and organic bound iron (Birkeland, 1999). The oxalate extraction method (Fe_o) (McKeague and Day, 1966) determines the amount of amorphous hydrous oxides and organic bound iron. The ratio of Fe_o/Fe_d, sometimes termed the iron activity ratio, therefore negates the difference in the initial Fe_o content of the parent material and emphasizes the formation of crystalline iron oxides due to weathering processes. Horizon and profile development indices were calculated for different soil properties based on Harden (1982).

Chronological control is provided by radiocarbon (^{14}C) ages determined by the University of Georgia Center for Applied Isotope Studies using an accelerator mass spectrometer. Terrace and floodplain deposits are dated by four ^{14}C dates from charcoal (Fig. 2).

RESULTS AND DISCUSSION

Detailed field mapping identified a suite of four terraces (Qt0-3), a modern floodplain (FP), three alluvial fan units, colluvial hillslope deposits, morraines and undifferentiated glacial till (Qgu) (Figs. 2 and 3). Here we focus on soils developed in terrace and floodplain deposits.

Figure 3. Photograph of typical terrace sequence in the Conejos River Valley: Qt0-3, terrace units; FP, modern floodplain; Qgu, undifferentiated glacial deposits.

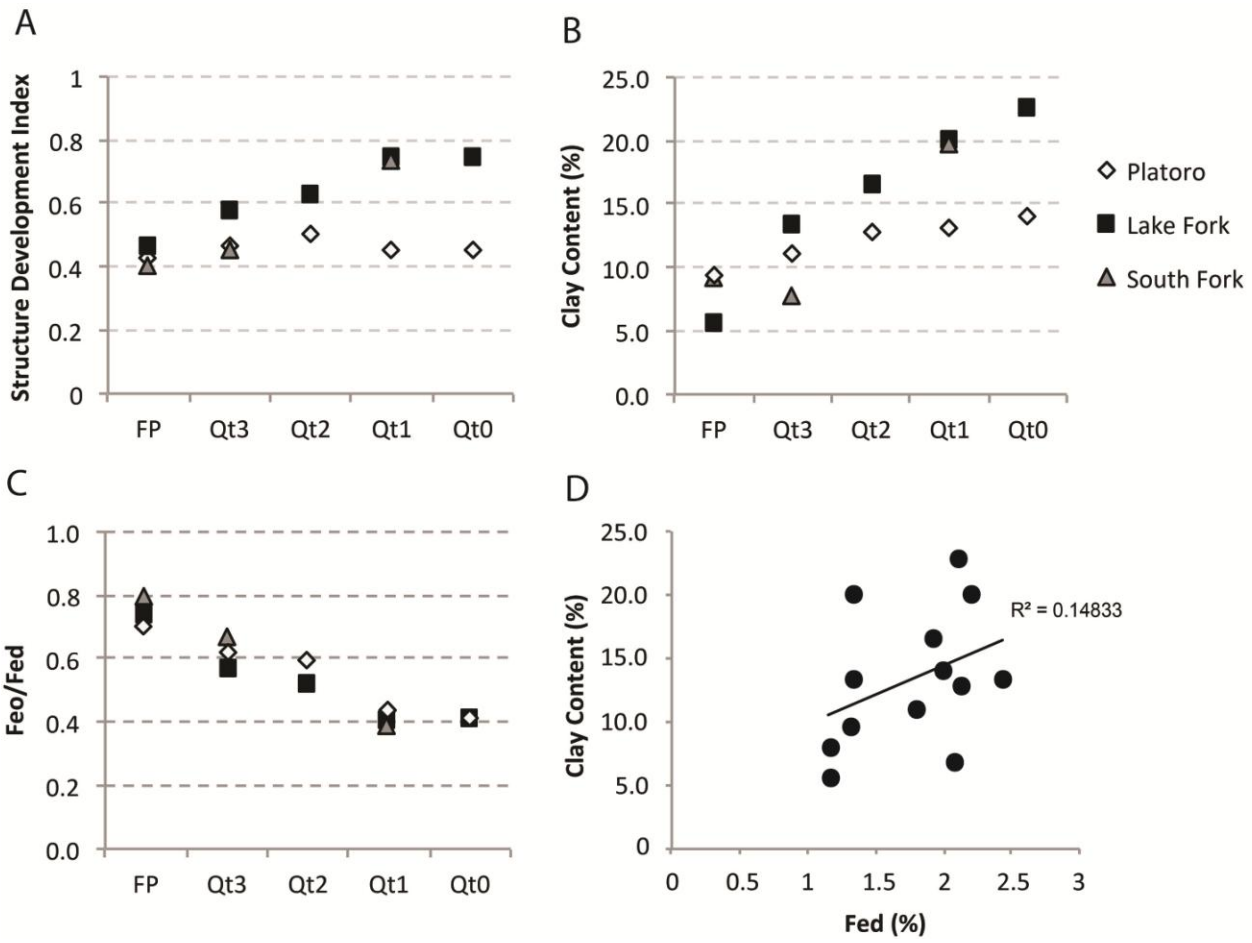

Figure 4. Chronosequence plots of soil properties from alluvial deposits: **(A)** soil structure, **(B)** clay content in the B horizon, **(C)** iron activity ratio (Fe_o/Fe_d). Plot D shows the relationship between Fe_d and clay content.

Soil morphologic trends

Soil morphological properties exhibit trends as a function of age in the Conejos River Valley. Soil profiles on terrace deposits show increased horizon development with age (Table 1). Profiles typically increase slightly in horizon complexity from A-AB/C horizonation on the floodplain to A/Bw-B/2C on younger surfaces (e.g. Qt3) to A/B/2C on older units (e.g. Qt0-1). The A horizons in all soils are similar and are typically characterized by horizon thickness of 8-30 cm, very dark to dark brown colors (10YR 2/2-10YR 4/3), silty loam textures and weak structure.

Soil structure in the B horizon notably increases with relative terrace age. Structure typically changes from fine sub-angular blocks (FP and Qt3) to medium angular blocks (Qt0-1) (Table 1). Quantifying changes in structure by converting field observables into a horizon development index, based on Harden (1982), shows a general positive trend with relative terrace age (Fig. 4A). Maximum soil structure index values range from 0.42 on floodplain deposits to 0.75 on Qt0 units.

Clay content in the B horizon shows positive trends with relative age of terrace deposit (Fig. 4B). Clay content typically increases with depth from A to B horizons in all units, highlighting the influence of alluvial processes (Table 2). B horizon clay content for terrace soils ranges from 5.6% on floodplain deposits (FP) to 22.8% on Qt0.

While soil morphological properties exhibit trends with time in individual sub-reaches, results also indicate that soils of similar ages vary between sub-reaches. For example, soil structure (Fig. 4A) and clay content (Fig. 4B) is less developed on older units in the Platoro sub-reach. Maximum percent clay on Qt0 units was 22.8% at Lake Fork but only 14.0% at Platoro.

Soil chemistry trends

Soils developed in Quaternary deposits usually redden progressively with time as pedogenic iron oxides accumulate in the soil. While changes in color hue were not readily observable in the field (Table 1), analysis of pedogenic iron content revealed trends with relative terrace age.

Changes in pedogenic iron formation due to weathering processes are reflected in the iron activity ratio (Fe_o/Fe_d) (Fig. 4C). Maximum values of Fe_o/Fe_d in each sub-reach were found in the youngest floodplain soils, which indicate a relatively low degree of iron crystallinity compared to older deposits. Fe_o/Fe_d ratios also show consistent trends between sub-reaches, decreasing from between 0.71 and 0.80 in floodplain soils to between 0.39 and 0.41 in Qt0 soils. The declining trend in Fe_o/Fe_d has been documented in other studies (e.g. Shaw *et al.*, 2003; Eppes *et al.*, 2008) and attributed to the conversion of amorphous hydrous oxides to more stable crystalline forms over time.

A close relationship has been shown to exist between pedogenic iron oxide (Fe_d) and the clay content in soils (McFadden and Hendricks, 1985). However, terrace soils in the Conejos River Valley do not display this close relationship (i.e. no statistical correlation: $r = 0.3119$, $p = 0.632$), although a weak positive trend is identifiable ($R^2 = 0.14833$) (Fig. 4D). McFadden and Hendricks (1985) suggest that a low degree of correlation between Fe_d and clay content in Holocene soils may indicate the influence of nonpedogenic factors. For example, low correlations may reflect variation inherited from parent materials or from inputs of aeolian dust.

Contrasting soil development between sub-reaches

Soil development on Qt3 units is similar throughout the study area. This observation indicates a synchronous spatial and temporal formation for this unit. However, in the uppermost sub-reach (Platoro), soil morphological properties (e.g. structure and clay content) on Qt0-2 terraces exhibit less development than similar soils developed in other sub-reaches (Lake Fork and South Fork). Therefore, influence of time on soil development may have been moderated by other soil forming factors in the Platoro sub-reach.

We interpret the observed variability in soil morphological properties to be due to differences in inherited parent material. Clay content of the soil is an important factor in the formation of blocky structure (Birkeland, 1999). The lower clay content measured in Platoro soils therefore explains the weaker soil structure observed in Qt0-2 terrace units. Parent material texture can have a significant influence on soil formation. Therefore, lower clay contents in Platoro soils may be representative of the nature of the inherited alluvium. Pedogenic clay formation is more rapid in finer-textured material because the greater surface area per unit volume facilitates increased weathering rates as well as the retention of clay particles (Birkeland, 1999). It is therefore feasible that the alluvial parent material at Platoro is coarser because fluvially deposited sediments typically fine downstream.

Alternatively, different clay contents may reflect differences in aeolian dust contributions. Post-glacial aeolian dust has been identified as a significant factor in pedogenesis in sub-alpine environments (e.g. Owens and Slaymaker, 1997). In the San Juan Mountains, dust has been shown to contribute fine silt and clay sized particles to the A horizon over time (e.g. Lawrence, 2009). Similarities in A horizon properties for all terrace units (Table 1) and observed decreases in silt content with depth (Table 2) indicate that dust is an important input to Conejos River Valley soils. The low degree of correlation between Fe_d and clay content in terrace soils further suggests that clay may be largely inherited from dust inputs rather than from the weathering of primary mineral grains (e.g. McFadden and Hendricks, 1985). While pedogenic clays are typically sourced from both dust influx and the weathering of primary grains, the rates of clay accumulation from each process can be significantly different (Birkeland, 1999). These observations are consistent with other studies on soils that are continually enriched with aeolian dust (e.g. McFadden and Weldon, 1987; Owens and Slaymaker, 1997; Muhs and Benedict, 2007).

CONCLUSION

Fluvial terraces preserved in the Conejos River Valley facilitate investigation into the relationship between soil development and time in a sub-alpine setting. In this study, certain soil characteristics change systematically as a function of time. In particular, soil horizonation, structure, clay content of the B horizon and Fe_o/Fe_d illustrate trends with relative terrace deposit age in individual sub-reaches. However, only Fe_o/Fe_d ratios displayed similar rates of development between all sub-reaches highlighting the usefulness of this metric in determining accurate rates of pedogenesis and relative age for Holocene aged deposits in sub-alpine environments. Soil development on Qt3 units is similar throughout the study area suggesting a synchronous spatial and temporal formation. However, significant variability in the development of soil structure and clay content was found to exist on older deposits (Qt0-2) in the Platoro sub-reach. We conclude that the observed variability is a function of differences in the inherited parent material. Similarities in A horizon properties, documented decreases in silt content with depth and the lack of correlation between Fe_d and clay content confirm that dust has been an important input in the Conejos River Valley throughout the Holocene.

Tables 1 and 2 are provided as separate Excell files to this manuscript.

Table 1. Field descriptions of soil morphological properties.

Table 2. Particle size (<2 mm) data for alluvial deposits.

ACKNOWLEDGEMENTS

This research was funded through the US Geological Survey National Cooperative Mapping Program (USGS Award G09AC00131), the University of North Carolina at Charlotte Geology Scholars Award and the Chama Institute of Art and Science. Special thanks are extended to Jeremy Poplawski and Ben Rote for their assistance in the field, as well as Claire Chadwick, Mike Murphy and Arezou Eslaminejad for their help with laboratory analyses.

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