Post-glacial landscape response to climate variability in the southeastern San Juan Mountains of Colorado, USA

Bradley G. Johnson a,⁎, Martha Cary Eppes b, John A. Diemer b, Gonzalo Jiménez-Moreno c, Anthony L. Layzell d

a Environmental Studies Program, Davidson College, Box 7056, Davidson, NC 28035-7056, USA
b Department of Geography and Earth Sciences, University of North Carolina Charlotte, McEnery 324, 9201 University City Blvd, Charlotte, NC 28223–0001, USA
c Departamento de Estratigrafía y Paleontología, Facultad de Ciencias, Universidad de Granada, Avda. Fuente Nueva S/N, 18002 Granada, Spain
d Department of Geography, University of Kansas, Lawrence, KS 66045, USA

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ABSTRACT
Geomorphic mapping in the upper Conejos River Valley of the San Juan Mountains has shown that three distinct periods of aggradation have occurred since the end of the last glacial maximum (LGM). The first occurred during the Pleistocene–Holocene transition (~12.5–9.5 ka) and is interpreted as paraglacial landscape response to deglaciation after the LGM. Evidence of the second period of aggradation is limited but indicates a small pulse of sedimentation at ~5.5 ka. A third, more broadly identifiable period of sedimentation occurred in the late Holocene (~2.2–1 ka). The latest two periods of aggradation are concurrent with increases in the frequency of climate change in the region suggesting that Holocene alpine and sub-alpine landscapes respond more to rapid changes in climate than to large singular climatic swings. Soil development and radiocarbon dating indicate that hillslopes were stable during the Holocene even while aggradation was occurring in valley bottoms. Thus, we can conclude that erosion does not occur equally throughout the landscape but is focused upslope of headwater streams, along tributary channels, or on ridge tops. This is in contrast to some models which assume equal erosion in headwater basins.

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Introduction

The timing and nature of climate-related landscape evolution are not well-understood (e.g., Ballantyne, 2002; Dixon et al., 2009) despite an increased focus on ‘Critical Zone’ processes over the last decade (Riebe et al., 2001; Roering et al., 2001; von Blanckenburg, 2005; Marston, 2010). This uncertainty is amplified in alpine and subalpine areas where few post-last glacial maximum (LGM) landformst have been precisely dated. Mountainous environments that were glaciated during the LGM are often dominated by large, paraglacial landforms (Ballantyne, 2002; Marston, 2010) yet Holocene landforms, including talus slopes, rock glaciers, small alluvial fans, and small terraces, are common in alpine areas (e.g., Matsuoka and Sakai, 1999; Curry and Morris, 2004; Johnson et al., 2007, 2010). The majority of previous work on Holocene landscape evolution has focused on processes of periglacial activity (Benedict, 1966, 1970; Janke, 2005), talus production (Curry and Morris, 2004), recent glaciation (e.g., Benedict, 1973), paraglacial sedimentation (Church and Ryder, 1972), and transport of materials by rock glaciers (Outcalt and Benedict, 1965; White, 1971; Janke, 2007; Janke and Frauenfelder, 2008). The majority of these studies focus on Late Glacial landscapes. Yet, determining the climatic conditions during which erosion and aggradation occur in the Holocene is more analogous to landscape response to modern climate change. Furthermore, many studies of fluvial systems make inferences about sediment-supply fluctuations from the contributing alpine portions of their basins without determining the erosional history of those basins.

Understanding landscape evolution in mountainous environments requires local records of erosion, aggradation, and paleoclimatic change. In the absence of regional paleoclimate records, authors generally compare records of erosion and sedimentation with global paleoclimate records (e.g., Wells et al., 1987; McDonald et al., 2003). However, robust regional paleoclimate records are critical to understanding the influence of climatic forcing on local landscapes. Having a local climate record is especially important when examining landscapes in the southern Rocky Mountains because climate is the result of complex interactions between Southwest climate to the south and Rocky Mountain climate to the north (Mann and Meltzer, 2007). To summarize, the evolution of alpine and sub-alpine landscapes is not well understood from previous work because 1) the timing and evolution of post-LGM landscapes is poorly constrained, and 2) regional paleoclimate records are not always available to compare with landscape evolution records.
In the southern San Juan Mountains, a series of small, Holocene alluvial fans and terraces inset into larger post-glacial landforms has been identified. These fans and terraces imply that erosion and aggradation after the LGM were episodic and related to changes in climate because the area has been tectonically inactive during this time (Lipman, 1974). It is our goal to document the timing of these periods of landscape evolution in the uppermost part of the Conejos River Valley, southern Colorado, and compare the landscape record with a paleoclimate record derived from a core extracted from the nearby Cumbres Bog (Johnson, 2010). Comparing these two records provides a direct link between climatic conditions and post-LGM landscape change. Documenting source area landscape evolution might also aid researchers examining water supply and quality as well as sedimentation rates in large dryland basins whose headwaters are in alpine regions (e.g., San Luis Basin) by increasing understanding of sediment supply and discharge from contributing drainages like the Conejos River. In turn, this leads to better prediction of water use and sedimentation in populated basins throughout the western North America.

Field area

The field area is located in the southeastern San Juan Mountains of southern Colorado (Fig. 1). The site is at the intersection of a variety of climatic and geologic regimes. To the immediate east is the arid San Luis basin, which is the uppermost section of the Rio Grande Rift and is bounded to its east by the Sangre de Cristo Mountains. To the immediate north and west is the majority of the San Juan Mountains with the central Rocky Mountains lying farther to the north. To the west and southwest is the desert southwestern extension of Basin and Range with numerous mountain ranges bounded by flat, dry valleys and playas, while the Jemez Mountains and Sonoran Desert lie to the south.

The eastern San Juan Mountains are characterized by high elevations with relatively low local relief. Valleys typically lie at ~2900 m and peaks are as high as 3900 m. Mapping by Atwood and Mather (1932) showed that the San Juan Mountains were covered by the second largest alpine ice mass in the continental United States during the LGM, after only the Yellowstone ice cap. The area contained two separate ice domes that were connected by individual valley glaciers, with an ice mass centered along the Continental Divide, which runs through the area. The area is characterized by typical evidence of alpine glaciation including U-shaped glacial valleys, erratics in high-elevation valleys and plateaus (~3350 m), and large volumes of glacial sediment in mountain valleys.

The research presented here focuses on deposits in the uppermost Conejos River Valley, an area that lies entirely above 3050 m. During the LGM, only ridge tops (~3800 m and higher) were exposed above the San Juan Ice Cap (Atwood and Mather, 1932). The main valley of the upper Conejos River trends north and is fed by four major tributaries (Fig. 1). The lowest extent of the field area is marked by the Platoro Reservoir, which was created when the Conejos River was dammed in 1951. Post-LGM incision has cut V-shaped notches into the Conejos’s U-shaped glaciated valley floor in many locations (Johnson et al., 2010).

Figure 1. A shaded-relief map of the Upper Conejos River Valley created from a 10 m digital elevation model. The three main tributaries to the Conejos River are labeled and the contour interval is 100 m. Platoro Reservoir, which marks the downstream limit of the field area is located in the upper right (NE) corner. Cumbres Bog is located ~40 km south of the field area at Cumbres Pass (37°1.3′N, 106°27.0′W).
Methods

The surficial geology of the Conejos River valley was mapped upstream of Platoro Reservoir in the southern San Juan Mountains of Colorado. Mapping was completed at a 1:24,000 scale with key sections of valley bottom mapped at a 1:12,000 scale. Landforms were identified and differentiated in the field and then described for morphology, sedimentology, soil development and stratigraphic relationships (Johnson, 2010). Seventeen soil pits were dug throughout the area and an additional 22 pits were dug downstream of Platoro Reservoir by Layzell (2010) plus another two on recessional moraines outside the field area. These soil pits were described using methods described in Birkeland (1999) and Schoeneberger et al. (2002) with the goal of creating a chronosequence that would expand the usefulness of radiocarbon dating in the area. Soil profile horizonation, color, and extractable-iron ratios (McKeague et al., 1971; Alexander, 1974; McFadden and Hendricks, 1985) were shown to be related to the age of the soil (Johnson, 2010). In particular, Fe ratios showed good correlation with age ($r^2$ of 0.68, $p<0.001$, Johnson, 2010; Layzell, 2010). Thirteen samples for radiocarbon dating were taken from hand-dug soil exposures and were extracted at depths greater than 30 cm. Samples generally consisted of pieces of charcoal <0.5 cm in diameter.

A ~7 m core obtained from Cumbres Bog (~3100 m asl) contains a proxy record of paleoclimate for the southern San Juan Mountains (Johnson, 2010). Cumbres Bog lies ~40 km south of the upper Conejos River Valley. The small basin containing the bog is elevated slightly above the Conejos River, which is incised into the valley floor just ~3 m thick and overlie glacially polished bedrock surfaces. Sediment comprises sub-angular to sub-rounded cobbles and boulders in a matrix of silty-sand. Soil color ranges from brown to dark brown (10YR 2/1 to 10YR 4/4) while soil horizonation is typically A–AB–B (Fig. 2). Extractable-iron ratios vary from 0.3 to 0.52 (unitless). Well-developed B horizons, low extractable-iron ratios (Johnson, 2010), similar features downstream (Layzell, 2010), and the timing of glacial retreat in the western San Juan Mountains (Guido et al., 2007) suggest that this till was deposited between 12 and 14 ka. Upslope from the glacial valley bottoms are large alluvial fans (Paf1) that either grade to the valley floor or slightly above it (Fig. 3). These large fans comprise gravels, cobbles, and boulders in a sandy matrix. Soil color varies from dark gray to brown (10YR 3/2 to 10YR 4/4) and typical horizonation (A–AB–Box–Ab) reflects the cumulus nature of the soils. The extractable-iron ratio was only determined for one pit on a large alluvial fan and it was 0.53. The fact that the fans overlie the till and grade to an elevation slightly above the level of the till implies that formation began immediately after deglaciation. Fan thickness (~5 m), along with soil color and horizonation, indicates that the fans remained active into the early Holocene. This idea is supported by radiocarbon dates from colluvial deposits (Pfcol, 9765–9908 cal yr BP and 9500–9634 cal yr BP; see Table 2 for all dates) that grade to these large alluvial fans. The colluvial radiocarbon samples were taken from unforested areas of large continuous slopes with roughly uniform gradient. The early Holocene ages are supported by soil development on colluvial slopes. Soils are similar in color (10YR 3/2 to 2.5Y 5/3) and horizonation (A–AB–Box–C) to the glacial and alluvial deposits described above. Extractable-iron ratios vary from 0.39 to 0.35. The Pleistocene till and glacial outwash along with Pleistocene to early Holocene colluvium and alluvial fans comprise the vast majority (>80%) of the surficial deposits in the Conejos River Valley.

Throughout the field area, the Conejos River has incised into the floor of the glacial valley (Johnson et al., 2010). The incision has eroded through Pleistocene depositional features leaving till and alluvial fans grading to till 1–5 m above the stream and exposing bedrock in many areas. Although the incision is commonly 1–5 m, in steep tributary reaches the river is incised as much as 100 m below the old glacial valley bottom. For example, the Adams Fork tributary, formerly a hanging valley, now grades to the modern Conejos Valley floor isolating the Pleistocene glacial deposits (Pgd) and alluvial fans (Paf1) of the upper Adams Fork well above the modern channel (Fig. 3).

The incision of rivers and streams throughout the area resulted in Holocene units being consistently inset into the larger, older alluvial fans (Paf1), till (Pgt), and colluvium (Pfcol). Small Holocene alluvial fans and fluvial terraces are common throughout the field area. Along incised reaches of the Conejos River, there is one dominant Holocene fluvial terrace unit (HF2) that is elevated 1–2 m above the modern channel. The deposits of this unit are composed of clast-supported, sub-rounded and rounded gravels and pebbles in a sand and silt matrix. Soil color varies from dark brown to light brown (10YR 3/2 to 10YR 5/4) and horizonation is generally A–AB–B. Weakly developed, buried A horizons occur locally. Extractable-iron ratios vary from 0.57

Results

Landform sedimentology, stratigraphy, soils, and landscape evolution

The landscape of the upper Conejos River Valley is dominated by LGM-aged features such as glacially carved cirques and arêtes, as well as moraines and glacial outwash formed in association with the Conejos Glacier. Valley floors are U-shaped in cross section and are mantled by thin deposits of till (Pgt, Johnson et al., 2010) emplaced during glacial recession. These glacial deposits are 1–3 m thick and

Table 1: Raw and calibrated radiocarbon dates from Cumbres Bog Core.

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Depth (cm)</th>
<th>Cumulative depth</th>
<th>$^{14}C$ age, $^{14}C$ yr BP</th>
<th>+/− $^{14}C$ yr BP</th>
<th>Calibrated range, cal yr BP$^a$</th>
<th>Material</th>
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<tr>
<td>CB2-6</td>
<td>60.5</td>
<td>60.5</td>
<td>1530</td>
<td>40</td>
<td>1379–1405</td>
<td>Wood</td>
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<tr>
<td>CB2-7</td>
<td>63</td>
<td>156</td>
<td>2250</td>
<td>25</td>
<td>2200–3222</td>
<td>Stern</td>
</tr>
<tr>
<td>CB2-8</td>
<td>86</td>
<td>274</td>
<td>4280</td>
<td>40</td>
<td>4838–4880</td>
<td>Leaf</td>
</tr>
<tr>
<td>CB2-9</td>
<td>53.5</td>
<td>346.5</td>
<td>7490</td>
<td>30</td>
<td>8244–8362</td>
<td>Bulk sediment</td>
</tr>
<tr>
<td>CB2-10</td>
<td>39</td>
<td>435</td>
<td>10,090</td>
<td>50</td>
<td>11,474–11,862</td>
<td>Peat</td>
</tr>
<tr>
<td>CB2-11</td>
<td>55.5</td>
<td>546.5</td>
<td>12,300</td>
<td>40</td>
<td>14,110–14,746</td>
<td>Bulk sediment</td>
</tr>
<tr>
<td>CB2-12</td>
<td>50</td>
<td>648</td>
<td>15,130</td>
<td>40</td>
<td>18,054–18,552</td>
<td>Bulk sediment</td>
</tr>
</tbody>
</table>

$^a$ Calibrated using CalPal-Online from quickcurve2007 version 1.5.
to 0.67. The Holocene terrace unit has been dated to 1171–1262 and 1869–1933 cal yr BP (Table 2). The ages were derived from samples of charcoal found at two vertically sequential locations in the same outcrop (Fig. 4). The same terrace unit downstream was dated by Layzell (2010) to 994–1066 cal yr BP. Small, Holocene alluvial fans (Haf2), inset into the larger alluvial fans (Paf1), grade to the Holocene
terrace (Fig. 5). The small alluvial fans are comprised of clast-supported gravels to boulders in a sandy matrix. Soil color varies between browns and light or yellow-brown (10YR 2/2 to 10YR 4/3) while horizonation is generally A–Bw–Ab although more established B horizons appear locally. Extractable-iron ratios vary from 0.60 to 0.70. These small alluvial fans have been dated to 2009–2120 cal yr BP although Layzell (2010) has dated similar alluvial fans to 2125–2285 cal yr BP.

An additional alluvial fan that is set stratigraphically between the ~2 ka fans and the Pleistocene fans was dated at 5319–5449 cal yr BP. The fan is along an incised tributary to the Conejos River but grades to an elevation above the late Holocene terrace level. The channel that the alluvial fan lies in is narrow (<4 m wide), and incision after ~5 ka (to the level of the late Holocene terraces) and again after ~1 ka (to the modern stream level) eroded the majority of the landform leaving only the section that was described and dated. While only one alluvial fan of this age has been identified in the area, the timing of deposition does match a series of terraces and alluvial fans downstream of Platoro Reservoir (See Table 2, Layzell, 2010).

### Table 2

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Location</th>
<th>14C Age 14C yr BP</th>
<th>± 14C yr BP</th>
<th>Calibrated range, cal yr BP</th>
<th>Material</th>
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<td>190</td>
<td>25</td>
<td>29–279</td>
<td>Charcoal</td>
</tr>
<tr>
<td>CVS2</td>
<td>Middle Fork Hft2</td>
<td>1250</td>
<td>30</td>
<td>1171–1262</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5158b</td>
<td>South Fork Hft2</td>
<td>1130</td>
<td>30</td>
<td>994–1066</td>
<td>Charcoal</td>
</tr>
<tr>
<td>CVS1</td>
<td>Middle Fork Hft2</td>
<td>1950</td>
<td>30</td>
<td>1869–1933</td>
<td>Charcoal</td>
</tr>
<tr>
<td>SJ-7-07-4B</td>
<td>Adams Fork Hft2</td>
<td>2100</td>
<td>30</td>
<td>2093–2120</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5159b</td>
<td>South Fork Haf2</td>
<td>2160</td>
<td>30</td>
<td>2125–2285</td>
<td>Charcoal</td>
</tr>
<tr>
<td>CVS3</td>
<td>Main Fork Haf1</td>
<td>4650</td>
<td>30</td>
<td>5319–5449</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5597b</td>
<td>Lake Fork Hft1</td>
<td>4690</td>
<td>30</td>
<td>5350–5470</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5154b</td>
<td>Lake Fork Haf1</td>
<td>6790</td>
<td>30</td>
<td>7608–7666</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5155b</td>
<td>Lake Fork Hft1</td>
<td>7610</td>
<td>30</td>
<td>8396–8422</td>
<td>Charcoal</td>
</tr>
<tr>
<td>5157b</td>
<td>South Fork Hft1</td>
<td>8060</td>
<td>30</td>
<td>8912–9016</td>
<td>Charcoal</td>
</tr>
<tr>
<td>SJ-7-07-3Char</td>
<td>Adams Fork Phcol</td>
<td>8520</td>
<td>30</td>
<td>9500–9634</td>
<td>Charcoal</td>
</tr>
<tr>
<td>CVS6</td>
<td>Adams Fork Mouth PHcol</td>
<td>8810</td>
<td>30</td>
<td>9765–9908</td>
<td>Charcoal</td>
</tr>
</tbody>
</table>

b. From Layzell (2010).

**Paleoclimate**

The core taken from Cumbres Bog extended 12 m down from the surface of the peat mat that covers the surface of the bog. Each drive of the corer was 1 m in length and the sediment recovered was generally within 3% of the drive length indicating very little compression. The first 4 m of the core were unconsolidated peat containing little or no clastic material. The 5th meter of the core was open water containing no sediment and very little organic material indicating that the 4 m thick peat mat is floating. These top 5 m were watery and were not preserved in stratigraphic order and therefore were not described. The bottom 7 m of the core, discussed herein, comprise sediments from below the lake floor and these were recovered in 1 m sections. Generally, sediment in the upper 3 m of the described core is organic-rich and is made up of finely laminated muddy sediment (<1 mm thick) with varying amounts of organic matter. The next 3 m of the core are composed of finely laminated muds (<1 mm thick), which become progressively less organic-rich down section. The basal 1 m of the core comprises thinly bedded (~1 cm) muds that are rhythmically...

**Figure 4.** A cut-bank exposure of the Holocene fluvial terrace (Hft2) unit where charcoal fragments were sampled for radiocarbon dating (CVS1 and CVS2, see Table 2 for details). The sediment comprises gravels and sands, and soil texture varies from sandy loam to loam. The inset image shows a detailed view of the soil profile.
bedded overlying cm-scale graded beds composed of sands and muds interpreted as varves. A more detailed assessment of the core can be found in Johnson (2010) but relevant results are presented here. Radiocarbon dates taken from throughout the core presented an age model for its entire length (Table 1). Sections between dates were interpolated and at the bottom of the core, the age model was extrapolated based on the sedimentation rate of the nearest section. The same was done at the top, where the projected age of the top of the core is remarkably near modern age. Sedimentation rates in Cumbres Bog remained between 0.2 and 0.4 mm/yr for 6 of the 7 intervals bracketed by the age data. The exception is between 2.3 and 1.4 ka, where the sedimentation rate is 1 mm/yr. A strong age model is provided by the generally consistent sedimentation rate and small radiocarbon age errors (Table 1). This slightly higher sedimentation rate led to an increased sampling interval since sampling was done by depth. Therefore, all trends in the core were reexamined by sampling at equal age intervals and all trends discussed below were found to be persistent regardless of sampling style.

Pollen was examined as ratios between species known to be indicative of climate in mountainous areas of the western United States (e.g., Andrews et al., 1975; Jiménez-Moreno et al., 2008). *Pinus/Artemisia* and *Picea/Artemisia* ratios were found to be the best proxies for climate in the core (Fig. 6). Since Pine currently grows at elevations below Cumbres Bog, abundant Pine pollen is an indicator of warmer periods when Pine could have grown at higher elevations. Similarly, *Picea* tends to be dominant at lower elevations. Alternatively, high *Artemisia* percentages indicate either the expansion of tundra near the bog or an increase in transported *Artemisia* pollen from lower elevations (due to decreased forest around the bog). Thus, when both ratios are high, climate is interpreted as being warm.

Both pollen ratios indicate that temperatures were colder than those of the Holocene from the LGM through about 14 ka with the exception of a short, warm interval at 15.5 ka (Fig. 6). After 14 ka, pollen indicates that temperatures rose rapidly until the onset of the Younger Dryas (12.8 to 11.5 ka) when temperatures cooled and stayed cool through 11.5 ka. Climate between 11.5 ka and 6 ka was characterized by a relatively warm interval during which temperature variations occurred over 1000–2000 yr periods. After 6 ka, climate not only became slightly colder but also became more variable in terms of frequency and magnitude of temperature oscillations (Fig. 6, Johnson, 2010). Specifically, climate changes in the second half of the Holocene occurred more frequently (400 yr periods) and at greater magnitudes than changes that occurred in the first half of the Holocene (Fig. 7).

The magnetic susceptibility (MS) record from the core varied to a greater degree during the Pleistocene (0–300 SI units) than during the Holocene (−1.5–2.5 SI units). Generally high MS values during the Pleistocene are indicative of the high clastic content in the sediment of that age. The highest MS values are present in layers where the sand content is high. After 12 ka, MS values decreased to near 0 SI units and remain relatively constant through 5.5 ka. Between 5.5 ka and the present, MS values fluctuated between 1.5 and −1.5 on roughly 500 to 1000 yr time scales. During this period, MS values appear to correlate inversely with organic content, implying that MS could indicate changes in the organic content of the sediment.

![Figure 5](image-url) A detailed geologic map of the surficial deposits of a valley-bottom section of the Upper Conejos River Drainage (Johnson et al., 2010) showing typical stratigraphic relationships between Holocene alluvial fans and Pleistocene–Holocene alluvial fans. The highlighted section was taken from the Adams Fork and is ~1 km in length. Map units include late-Holocene fluvial terrace (Hft2), late-Holocene alluvial fan (Haf2), late-Pleistocene–early-Holocene fluvial terrace (Pft1), late-Pleistocene–early-Holocene alluvial fan (PaF1), late-Pleistocene–early-Holocene colluvium (PfCol), late-Pleistocene till (Pgt), and Tertiary bedrock (Tbr). The map units are described briefly described in the results and more fully described in our previous work (Johnson, 2010).
Figure 6. Paleoclimate proxies from the Cumbres Bog core plotted against an age model derived from seven radiocarbon dates from throughout the core (Johnson, 2010). Pollen ratios were calculated as *Pinus*/*Artemisia* (Pi-A/Pi + A) and *Picea*/*Artemisia* (P-A/P + A).
Clay percentages vary considerably in the Pleistocene section of the core (bottom 3 m; nearly 0–100%). Although our method has a high error (the Spectrex LPC calculates a low clay percentage by mass when measuring samples rich in fine sands), the maximum values are indicative of the clay-rich nature of the core bottom. After the Younger Dryas (4.3–4.8 m depth), clay values were low and varied much less than during the Pleistocene, implying fairly stable sources of clastic material.

Discussion

Radiocarbon ages in the field area clustered around three periods of accelerated sedimentation. The first period occurred between 9 and 10 ka and included colluvial deposition and downstream alluviation that underlies early Holocene terrace landforms. A second period of accelerated sedimentation occurred around 5.5 ka, although deposits of this age are poorly preserved in the area upstream of Platoro Reservoir but commonly underlie alluvial terraces farther downstream (Table 2). A third cluster of ages occurs between 1.1 and 2.2 ka and is represented by inset alluvial fan and terrace deposits. The early Holocene period is likely the stabilization period for the landscape after deglaciation, while the mid- and late-Holocene periods must represent periods of reactivated landscapes.

Paraglacial landscape evolution

The comparison of landscape evolution and regional paleoclimate records indicates how the subalpine landscapes of the southern Rocky Mountains responded to climate forcing since the LGM. Immediately following deglaciation, sedimentation rates were likely extremely high in valley bottoms because adjacent hillslopes probably had limited vegetative cover. Unstable hillslopes combined with glacial meltwater should have favored active transport of sediment on hillslopes (creating alluvial fans) and in valley bottoms (flushing sediment out of the system). Relatively cool climate conditions during the Younger Dryas were associated with development of alluvial fans as well as transport of downstream sediment out of the system preventing valley floor aggradation. Assuming that deglaciation was complete by 12 ka (as per Animas Valley cosmogenic dates from Guido et al., 2007), the 9500–9634 and 9765–9908 cal yr BP ages and well-developed soils on hillslope colluvium suggest that slopes in the San Juan Mountains study area took ~3000 yr to stabilize following deglaciation. We believe that soils on colluvial hillslopes, which are neither cumulic nor eroded, provide evidence that the colluvium was deposited during the last stages of paraglacial sedimentation (before 9.5 ka), after which at least lower elevation hillslopes stabilized. The
stabilization of hillslopes during the paraglacial adjustment period likely involved complicated interactions between the compaction and cementation of loose sediment via weathering processes, the decline of slope angles through erosion, and the reestablishment of vegetation over time (Ballantyne, 2002; Marston, 2010). The high sedimentation rates on hillslopes during the 3 ka paraglacial period likely led to the large alluvial fans (Paf1, Johnson et al., 2010) visible in the field area today. However, there are no significant, continuous fill terraces implying either that Conejos River discharges were sufficient to transport sediment out of the upper Conejos River Valley or that runoff was insufficient to transport most sediment beyond alluvial fans.

Early Holocene climate implications

Hillslope stabilization, which began in the early Holocene, is accompanied by an overall lack of depositional landforms in the field area up until ~5.5 ka. While it is possible that alluvial fans and terraces were deposited between 10 ka and 6 ka and subsequently eroded, it is more likely that no significant deposition occurred. Our Cumbres Bog climate record indicates that climate was warm during the first half of the Holocene, and varied with lower frequencies and magnitudes than the climate did in the late Holocene (Fig. 7). These observations correspond well with other regional paleoclimate records, which suggest warm, and sometimes wet, climate between 10 ka and 6 ka in the southwestern U.S. (Markgraf and Scott, 1981; Carrara et al., 1984, 1991; Feiler et al., 1997; Vierling, 1998; Jiménez-Moreno et al., 2008).

The local landscape stabilization during this time period suggests that San Juan Mountain landscapes were unresponsive to warm regional temperatures and climate variability occurring over longer, 2000–3000 yr timescales. This interpretation is generally in agreement with similar research at lower elevations in northeastern New Mexico which found a combination of stability and incision during the early Holocene (Mann and Meltzer, 2007).

Mid-Holocene landscape evolution and climate forcing

The first discrete period of observed Holocene deposition in the field area is an alluvial fan dated at 5.4 ka. This mid-Holocene alluvial fan is inset into, and therefore younger than, the large Pleistocene alluvial fans. The late-Holocene alluvial fans (1–2.2 ka) are, in turn, inset into the mid-Holocene fan with very little of the mid-Holocene fan preserved. While this is the only alluvial fan of mid-Holocene age identified in the Conejos headwaters, downstream of the field area a terrace, dated to around 5.4 ka (Layzell, 2010), crops out consistently above the modern channel and is associated in some locations with additional alluvial fans. The wide distribution of the terrace unit downstream, combined with the erosion of the alluvial fan we dated, indicates that the unit was generally poorly preserved upstream of Platoro Reservoir. The poor preservation is likely the result of narrow width of the tributary gully which resulted in near-complete removal of older material during the period of incision after ~5 ka.

The timing of this mid-Holocene alluvial fan and terrace formation correlates with a drop in temperatures indicated by the pollen record in the Cumbres Bog core and with the earliest period of Holocene glacial activity in the Front Range noted by Benedict (1973). This period also corresponds with a change in the frequency of major climate shifts in the core record (2000–3000 yr before 6 ka, 1000 yr between 6 ka and 3 ka, for both Alluvial fans and streams). It is difficult to determine the relative importance of change in temperature or change in frequency of climates to cause short periods of aggradation during the Holocene. Both mechanisms are likely to force changes in vegetation that could destabilize hillslopes and it is likely that erosion and subsequent deposition were responding to both factors.

Late-Holocene landscape evolution and climate forcing

Alluvial fans and streams terraces were widely deposited along tributary channels in the headwaters of the Conejos River between ~2.2 ka and ~1 ka (Haf2 and Hft2). Again, the late-Holocene units correlate with terraces and alluvial fans of similar age and morphology downstream of Platoro Reservoir (Layzell, 2010). Other authors working in the region also note aggradation between 2 and 1 ka (Mann and Meltzer, 2007). The resolution of our pollen record makes it possible to recognize at least three and perhaps four warm/cold cycles fluctuations during this period. From the pollen record, we infer that it is not warm or cold periods alone that initiate the strongest Holocene responses from this landscape but rather it is the rapid changing of the climate. The period of rapid climate change that is documented in the core may reflect an increase in El Niño–Southern Oscillation (ENSO) strength after 6 ka and again after 3.5 ka (Rodbell et al., 1999; Bacon et al., 2010). A strengthened ENSO cycle could provide additional winter snowpack and spring runoff during warm cycles (El Niño) and a higher frequency of summer storms and rain events during cold cycles (La Niña). Thus, high discharge values basin-wide may cause sediment mobilization and downstream aggradation to occur. Research elsewhere suggests that an intensified ENSO cycle favors extreme summer storms which in turn caused aggradation on alluvial fans in the Sonoran Desert (Bacon et al., 2010). Furthermore, earlier research documented a decrease in the periodicity of depositional patterns in arroyos after ~6.8 cal ka BP in northeastern New Mexico (Mann and Meltzer, 2007). These observations support the idea that rapid changes in climate may destabilize surfaces because vegetation and other ecological responses are slower and may involve destabilization of landforms (Knox, 1972).

Colluvial stability and sediment sources

It is somewhat surprising that colluvium (PHcol) in the Conejos River Valley, which generally lies near the angle of repose and is unconsolidated, would be stable despite extreme summer monsoon rains (Adams and Comrie, 1997). Long-term stability is supported by radiocarbon ages of the colluvium and by the lack of buried soil horizons, the strong A–AB–Box–C horizonation (Fig. 2), and relatively low extractable-iron ratios. The long-term stability of colluvium during the Holocene is in contrast to many published models for hillslope erosion (Dixon et al., 2009), which assume that weathering of colluvium, and underlying bedrock, is constant and steady through time. Although it is unknown as to whether this is a local phenomenon or can be expanded to other regions, the stability of these hillslopes is an important insight into alpine and sub-alpine landscape evolution.

The fact that lower hillslopes have remained stable for nearly the entire Holocene is not to say that all slopes in the basin were completely inactive. However, consistently well-developed soil profiles also indicate that neither significant aggradation (which would produce buried soils within the profile) nor erosion (which would produce weakly developed profiles) has occurred since the hillslopes stabilized. That said, the steep slope of the landscape makes it likely that a small amount of sediment is transported downslope from the ridge tops to the valley bottom while the hillslopes remain in steady state.

The most recent period of deposition presents a paradox whereby sedimentation isaggrading valley bottoms (Haf2 and Hft2) despite stability on adjacent hillslopes. The three most likely sources of sediment in the system are tributary headwaters, ridge-top colluvium, and previous generations of alluvial fans and terraces (Fig. 8). If the sediment mainly comes from tributary stream headwaters, this would imply that tributary streams are eroding headward. This is supported by the presence of rills near stream headwaters. Alternatively, the aggrading sediment may be reworked from previous generations of
alluvium within the existing fluvial system. For example, the mid-
Holocene (~5.5 ka) alluvial fan formed within channels incised into
Pleistocene alluvial fans and the late Holocene fans are slightly
downstream. Thus, the late-Holocene fans may have formed when
high discharge caused by increased ENSO strength (Bacon et al., 2010)
eroded sediments from the mid-Holocene fan surfaces and deposited
them on the late-Holocene fans formed at the mouths of stream
channels. This mechanism would explain the poor preservation of
mid-Holocene fans. It is also possible that sediment is eroded from the
ridge tops. Ridge-top soil, derived directly from bedrock, was not
examined and may be easily eroded because of a lack of vegetation on
ridge tops combined with increased snowpack. Whatever the source
of sediment for late-Holocene aggradation, it is clear from soil profiles
and radiocarbon ages erosion is not occurring basin-wide but is
focused as in localized zones of rapid erosion.

Regional implications

Questions remain about the causes of hillslope destabilization,
erosion, and subsequent deposition. A number of mechanisms have
been suggested for different climatic regimes. At lower elevations in
northeastern New Mexico, valley fill indicates that incision occurs
during periods of wet summers while aggradation occurs during
periods of summer drought although more complicated mechanisms
are difficult to access (Mann and Meltzer, 2007). In Nevada, a shift in
climate toward drier and warmer conditions at 2.5–1.3 ka correlated
to hillside erosion and subsequent deposition (Miller et al., 2001).
Once hillslopes and alluvial surfaces restabilized, the primary
landscape response (after 1.9 ka) was for streams to incise. Desert
alluvial fans in the Sonoran Desert aggraded between 3.3 and 2.3 ka
due to an increase in effective moisture caused by a strengthened El
Niño–Southern Oscillation in the late Holocene (Bacon et al., 2010).
It is interesting that all three of these studies found periods of
aggradation during the late Holocene, a period that is characterized
in our record by rapid climate fluctuations. Yet the mechanisms noted
in each study vary slightly. Nonetheless, the collective evidence
supports the idea that an important factor in regional aggradation is
rapid changing of climate.

Conclusions

Landscapes in alpine and sub-alpine regions of the southern San
Juan Mountains underwent a 3 ka paraglacial adjustment period
immediately following the LGM. This adjustment was characterized
by the aggradation of large alluvial fans and widespread colluviation,
followed by the eventual stabilization of hillslopes and fans at ~9.5 ka.
The landscape appears to have remained relatively stable from ~9.5 ka
until a mid-Holocene period of sediment mobilization at ~5.5 ka. The
core extracted from Cumbres Bog indicates that sedimentation at this
time corresponds with a period of cooling in the region. This period of
aggradation is likely not well expressed in the field area because of
more recent incision in the narrow tributary channels where deposition occurred. In contrast, a more extensive set of terraces
dated to ~5.5 ka in age was found farther down the Conejos River
Valley (Layzell, 2010). The most significant sedimentary event to
occur in the Conejos River Valley during the late Holocene occurred
between ~2.2 ka and ~1 ka ± 0.1 ka. This period of deposition
corresponds not with a cold period but with a period of rapid climate
oscillation between warm and cold temperatures.

The results of this study provide some of the first evidence that
Holocene alpine and sub-alpine landscapes responded mainly to
changes in climate and not to persistent, generally cool climates.
Future work should focus on determining whether this result is
specific to regions affected by ENSO cycles or if other regional climate
mechanisms (e.g., PDO, Asian Monsoon) play a similar role in the
landscape evolution of high-elevation landscapes of other areas.

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