# Holocene Stratigraphy and a Preliminary Geomorphic History for the Palomas Basin, south-central New Mexico

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## Abstract

Holocene alluvial records have been established in many parts of the American Southwest but are lacking in the central Palomas Basin of south-central New Mexico. There, east-draining streams and arroyos feature three widespread main-stem deposits that are inset into one another and have distinct surface characteristics. These are flanked by alluvial fan deposits comparable in age to those on the main-stem. We use five new radiocarbon ages and pre-existing geochronology to compare cycles of aggradation and incision between the axial river, the Rio Grande, and the lower reaches of two of its tributaries. In lower Cañada Honda, an alluvial fan at the mouth of a side drainage experienced soil development during the latest Pleistocene followed by early to middle Holocene aggradation. An adjoining alluvial fan was aggrading at approximately 2600 cal yr BP. After a poorly constrained incision event, an inset main-stem deposit aggraded approximately 600 cal yr BP and grades into an older Rio Grande terrace deposit previously dated at 5000–670 cal yr BP. Synthesizing geochronologic data for the basin, we infer probable incision during 850–550 cal yr BP in Rio Grande tributaries. This incision occurred after a relatively dry interval and during a period of enhanced summer monsoons, consistent with previously established climate-response models. Aggradation appears to have been relatively continuous along high-order tributaries during most of the Little Ice Age (approximately 500–70 cal yr BP) to the present.

## Introduction

Researchers have long recognized that alluvial deposits may record tectonic signals, climatic fluctuations, intrinsic drivers, or some combination of these factors (e.g., Schumm and Hadley 1957; Patton and Boison 1986; Hereford 2002; Wegmann and Pazzaglia 2002). Climate is often favored as a control on cycles of fluvial and alluvial erosion and aggradation because it affects key hydrologic variables such as sediment load and effective discharge (Bull 1991; Hancock and Anderson 2002). At steady state, streams have just enough stream power (a function of discharge and slope) to transmit sediment through their system without net change in their elevation (Lane 1955). Significant variability in any parameter results in changes to channel planform patterns and/or vertical erosion or accumulation of sediment (Mackin 1948; Leopold et al. 1994). Such adjustments may be reflected in longitudinal stream profiles as well as the number and landscape position of allostratigraphic deposits.

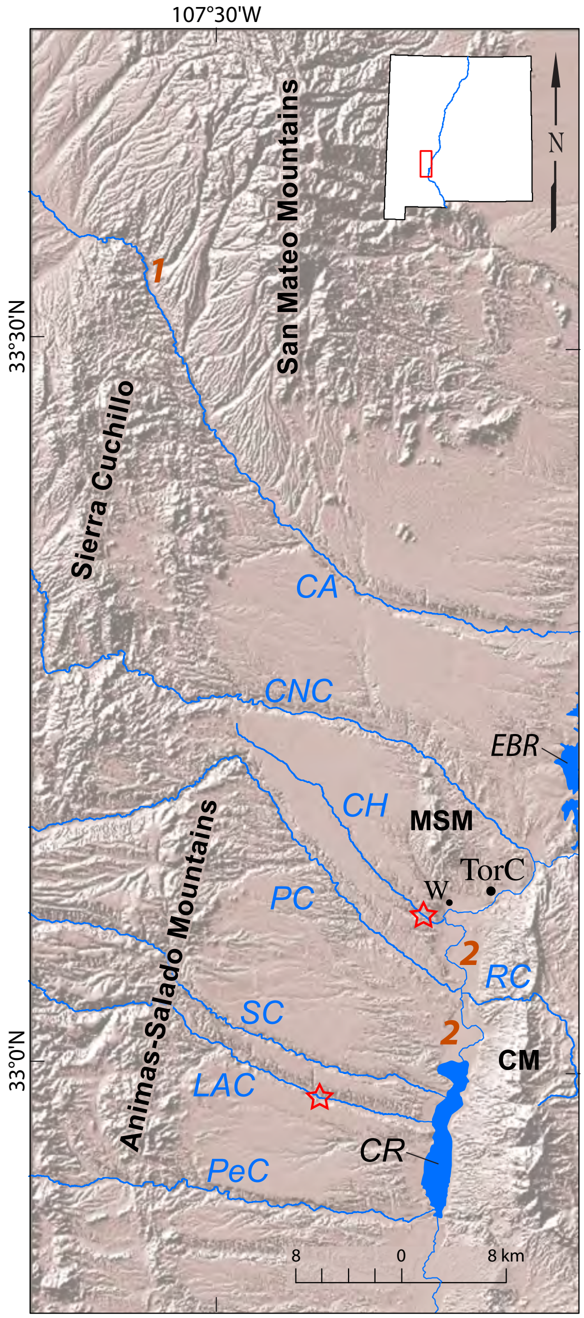



FIGURE 1—Relief map of study area including central and northern Palomas Basin. Abbreviations: Reservoirs—CR=Caballo Reservoir, EBR=Elephant Butte Reservoir. Streams—CA=Cañada Alamosa, CH= Cañada Honda, CNC=Cuchillo Negro Creek, LAC=Las Animas Creek, PC=Palomas Creek, PeC=Percha Creek, RC=Red Canyon, SC=Seco Creek. Mountains—CM=Caballo Mountains, MSM=Mud Springs Mountains. Towns—TorC=Truth or Consequences, W=Williamsburg. Numbers denote previous local studies on Holocene stratigraphy: 1= Monger et al. 2014; 2=Mack et al. 2011. Red stars denote radiocarbon sites of this study.

In the southwestern United States, studies have demonstrated that cut-fill cycles of erosion and aggradation in arroyo systems may be closely related to climatic shifts occurring on centennial to millennial time scales (e.g., McFadden and McAuliffe 1997; Waters and Haynes 2001). In particular, many deposit sequences are thought to record the changing tempo and magnitude of the El Niño/Southern Oscillation (ENSO), the periodic variation of sea surface temperature in the eastern Pacific Ocean that, when strengthened, delivers greater winter moisture to the American Southwest (Graf et al. 1991; Waters and Haynes 2001; Menking and Anderson 2003). Summer precipitation associated with the North American Monsoon (NAM) has also been suggested as a driver of Holocene alluvial-system dynamics (Mann and Meltzer 2007; Mack et al. 2011). Regardless of whether ENSO or NAM dominates during a given interval, there is broad consensus that arroyo cutting in the Southwest can be tied to periods of frequent, high magnitude flooding following prolonged drought (Graf et al. 1991; Hereford et al. 1996; Ely 1997; Waters and Ravesloot 2000; Waters and Haynes 2001; Harvey and Pederson 2011).

Though well-dated in other parts of New Mexico (Mann and Meltzer 2007; Hall 2010), the Holocene alluvial record of intrabasin tributaries has not previously been assessed in the central Palomas Basin (Fig. 1). Here, we present stratigraphic and geochronologic data from two Rio Grande tributaries. We unveil a

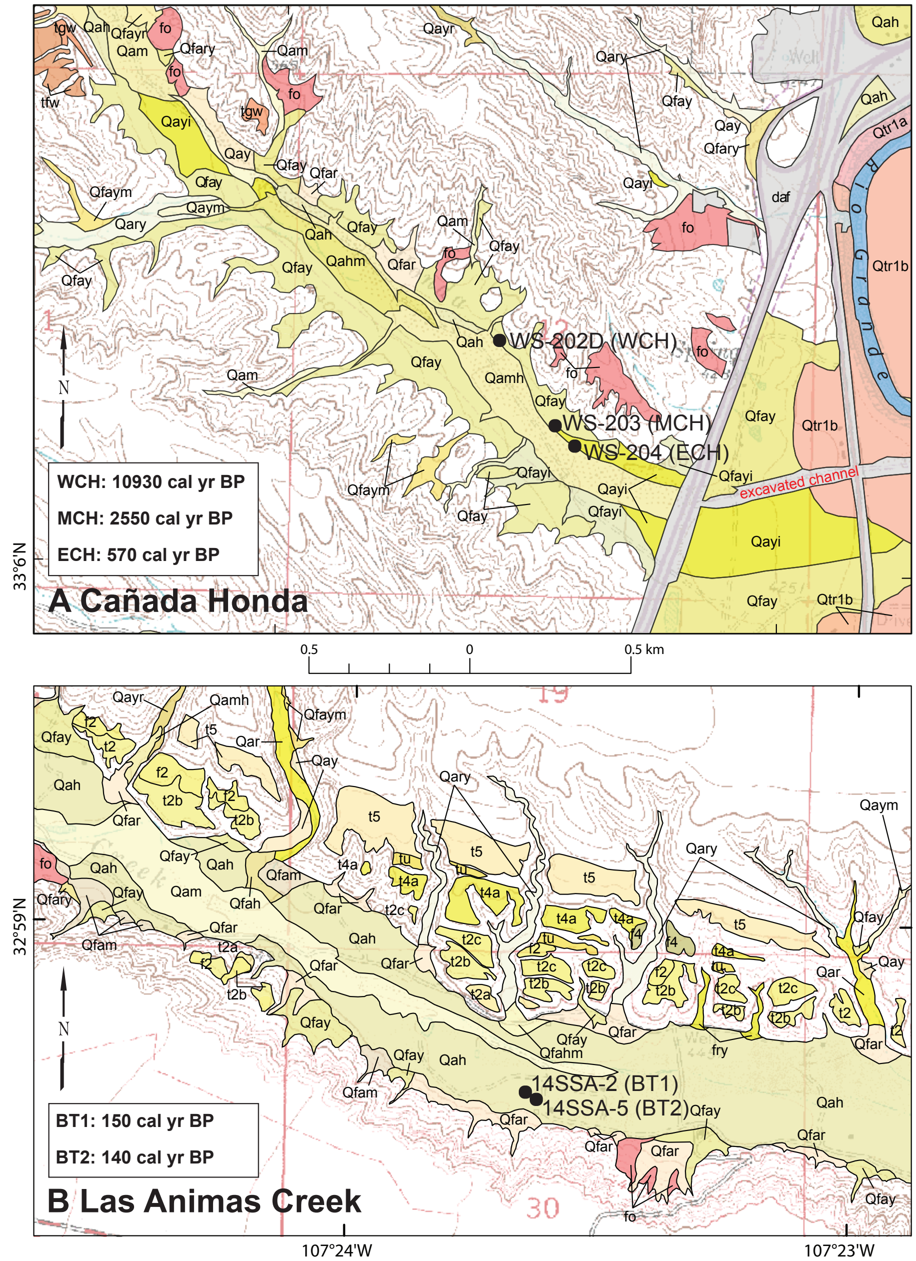



FIGURE 2—Surficial geologic maps of the Cañada Honda and Las Animas Creek study areas. Charcoal radiocarbon samples depicted by black circles; site abbreviations shown in parentheses after sample numbers. Ages given are median ages (Table 1). Unit designations abbreviated from those used in text and previous mapping (Jochems and Koning 2015; Koning et al. 2015). Other abbreviations as follows: r = subequal modern and historical alluvium, fo = older fan alluvium (Pleistocene, not discussed in text), t = Pleistocene terrace deposits (numbered from lowest to highest). Mixed deposits are also mapped (e.g., hm = historical+modern). (A) Cañada Honda study area. Note that Qayi grades into Rio Grande terrace Qtr1b. Mack et al. (2011) mapped this terrace as II, but we interpret it as terrace III based on relative height and surface characteristics. WCH, MCH, and ECH = west, middle, and east Cañada Honda outcrop locales. (B) Las Animas Creek study area. Valley floor is dominated by unit Qah. Sample sites: Bussmann trenches 1 (BT1) and 2 (BT2).

preliminary late Holocene record for deposits in these tributaries, and suggest that their origin lies chiefly in shifting climatic conditions.

## Background

Several studies in New Mexico have demonstrated that landscapes respond to climatic fluctuations (principally in temperature and precipitation) at $10^4$–$10^5$ yr time scales. The foremost study was by Gile et al. (1981), who used geomorphic and stratigraphic relations of the piedmont and Rio Grande in southern New Mexico to suggest the following sequence for climatically induced erosion and sedimentation:

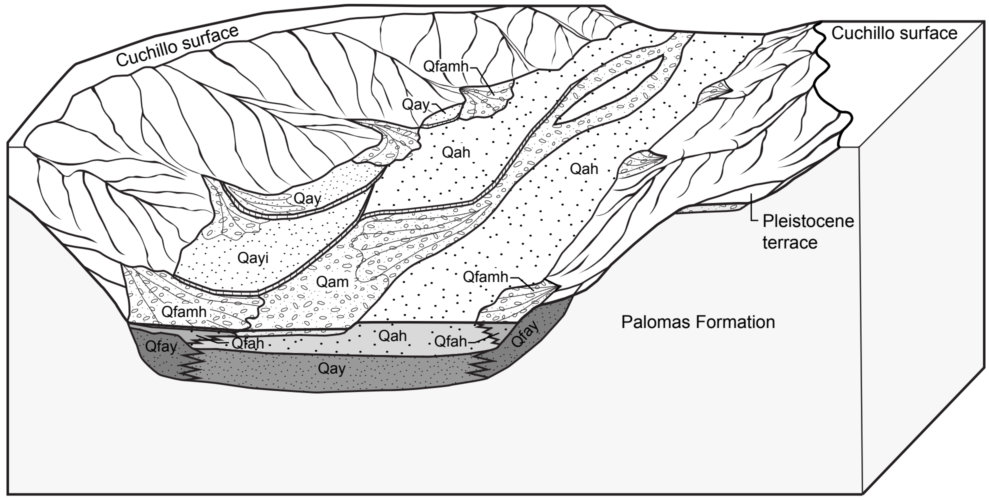
1) During full-glacial periods, desert hillslopes are stable, piedmont sediment yield is low, and high discharges along the axial river derived from glaciated headwaters facilitate downstream incision.

2) During glacial-interglacial transitions, less effective precipitation and reduced vegetation density on local hillslopes results in destabilization of colluvial sediment. This sediment is eroded and transported via piedmont streams to the axial river where discharge is insufficient to transport it, resulting in major aggradation.

3) Quasi-equilibrium once the transition to a full-interglacial period is reached. Another classic climate-response model for the Southwest, proposed by Bull (1991), largely follows that of Gile et al. (1981). Studies in the Rio Grande drainage basin that invoke this model to explain terrace-related alluviation and incision include Dethier and Reneau (1995) along the Rio Chama, Rogers and Smartt (1996) along the Rio Jemez, and Koning et al. (2011) along the Rio Ojo Caliente. McCraw and Williams (2012) infer that terrace formation along Cañada Alamosa in the northern Palomas Basin relates to the climate-related cyclicity described by the Gile et al. (1981) model, but lack age control to demonstrate a conclusive linkage.

Holocene alluvial sequences in New Mexico have formed during the most recent interglacial period, though general tenets of the Gile et al. (1981) model could still apply to their formation over $10^2$–$10^3$ yr intervals (e.g., reduced vegetation permitting erosion of sediment from hillslopes; Gile and Hawley 1968). Many geomorphic studies in the Southwest have found that arroyo incision and backfilling was a common occurrence in the late Holocene, even before the arrival of European settlers (e.g., Hall 1977; Love 1977; Waters 1988; Hall 2010). Mann and Meltzer (2007) emphasize the role of the NAM in incision-backfilling cycles of small- to medium-sized streams, suggesting that sediment accumulation occurs during drier summers with fewer floods and prolonged droughts. High-intensity floods at the beginning of a strengthened NAM, when hillslope vegetation is still sparse from the preceding summer-dry period, facilitate incision of valley floors (e.g., Tucker et al. 2006).

Mack and others (2011) propose a model of landscape response to climate shifts since approximately 12500 cal yr BP that emphasizes the ratio of sediment supply relative to stream discharge, where higher ratios favor aggradation and lower ratios favor incision (Lane 1955; Blum and Tornqvist 2000). Their model predicts net erosion along the axial river during winter-wetter and summer-warmer conditions, and aggradation along the axial river during times of enhanced summer NAM. The latter prediction arises from the argument that transverse tributaries incise when floods become more frequent and intense due to a strengthened NAM, transporting copious sediment to the axial river prompting




**Unit Explanation**

Valley Floor

- Qam — Modern alluvium (ca. AD 1950–2015)
- Qah — Historical alluvium (<600 cal yr BP)
- Qayi — Inset younger alluvium (~500 –1000 cal yr BP)
- Qay —Younger alluvium (latest Pleistocene -late Holocene)

Alluvial fans

- Qfamh — Modern alluvium (ca.AD 1950–2015)
- Qfah — Historical alluvium (<600 cal yr BP)
- Qfay —Younger alluvium (latest Pleistocene –late Holocene)

FIGURE 3—Schematic illustration of late Quaternary stratigraphy of lower transverse drainages in the central Palomas Basin. Unit designations as in Figure 2. Note buttressed relationships and interfingering of main-stem tributary alluvium with side-fan deposits. The Cuchillo surface marks the constructional top of the Palomas Formation and has been dated to >780 ka (*Mack et al. 1993, and Mack et al. 1998*).

FIGURE 4—Exposure of historical alluvium. The lower 60–70 cm is clast-supported, imbricated, sandy gravel in very thin to thin, tabular beds. The overlying brown pebbly sand fills a swale. The age of this unit is probably near the youngest part of the 500–50 year age range. Hammer for scale.

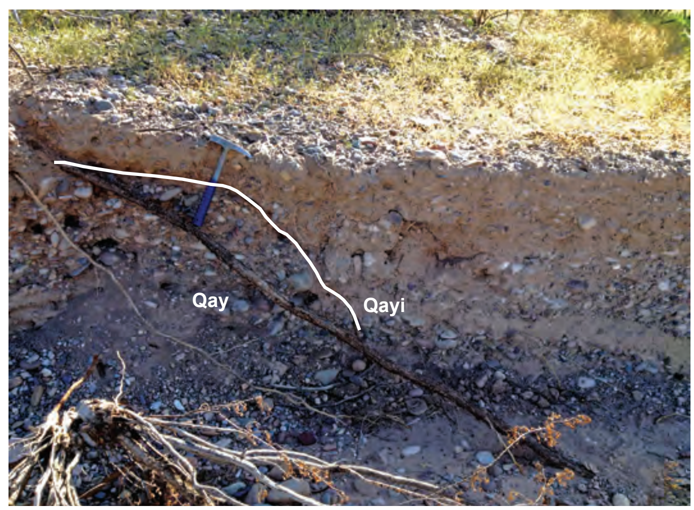



FIGURE 5—Buttress unconformity between Qay and Qayi deposits at the middle Cañada Honda site. Unit Qay grades laterally northwestward into Qfay (Figure 6). On Figure 2A, Qay is subsumed into unit Qfay because it forms a narrow polygon that is not mappable at 1:12,000. Hammer for scale.

it to aggrade. Conversely, a reduction of NAM intensity and magnitude would cause aggradation in transverse catchments (Mann and Meltzer 2007), decreasing sediment supply to and permitting incision along the axial river. Wet winter conditions resulting in a high snowpack would bolster this tendency.

## Setting

### Palomas Basin

The Palomas Basin is an east-dipping half-graben within the Rio Grande rift. The rift's axial river and namesake, the Rio Grande, flows near its eastern margin (Fig. 1). The basin is flanked by north-trending mountain ranges exposing Precambrian through Tertiary bedrock. The basin itself is filled by Neogene gravel, sand, and mud of the Santa Fe Group, deposited on piedmonts and by the ancestral Rio Grande (e.g., Seager and Mack 2003; Mack et al. 2012). The Palomas Formation constitutes the upper part of the Santa Fe Group and outcrops extensively in the central Palomas Basin (Lozinsky and Hawley 1986a, 1986b; Jochems and Koning 2015). Nine large canyons with drainage areas >220 km$^2$ and numerous small arroyos flow east to southeast across the Palomas Basin before draining into the Rio Grande or its reservoirs (Fig. 1).

The climate of the Palomas Basin is arid, with the summer months (June through August) experiencing average temperature


FIGURE 6—Annotated photographs depicting late Holocene stratigraphy at the middle and east Cañada Honda sites. Charcoal sample locations shown by dashed rectangles. (A) Middle Cañada Honda site. Distalmost Qfay alluvium with sandy gravel overlying finer silty sand. A stage I to I+ calcic horizon has overprinted the upper sandy gravel. This unit grades eastward into Qay. Backpack for scale. (B) An inset late Holocene deposit (Qayi) at the east Cañada Honda site. The surface soil has less visible calcium carbonate accumulation than seen in the upper photo. Person is 1.9 m tall.

highs of 93–96° F and average lows of 63–67° F (Western Regional Climate Center 2015). Average yearly precipitation is 25.5 cm, over half of which (13.7 cm) falls during NAM summer storms in the months of July through September (Xie and Arkin 1997; Barron et al. 2012). Vegetation regimes in the basin range from Chihuahuan scrubland-steppe at lower elevations (<1,600 m above sea level, ASL) to lower piñon-juniper above 1,800 m ASL

### Rio Grande

As the master river of the Palomas Basin, the late Quaternary history of the Rio Grande is relevant to that of its tributaries. After approximately 800 ka, strengthened glacial-interglacial cycles coupled with integration of Lake Alamosa in the northern Rio Grande rift resulted in net incision along the Rio Grande, punctuated by periods of aggradation (Gile et al. 1981; Wells et al. 1987; Connell et al. 2005; Mack et al. 2006; Machette et al. 2013). The resulting post-800 ka incision in Rio Grande tributaries carved canyons in the Palomas Formation up to 90 m deep, flanked by terrace sequences interpreted to be middle to late Pleistocene in age (McCraw and Williams 2012; Koning et al. 2015). Valley floor deposits have been interpreted as Holocene based on their weak soil development and landscape position (Cikoski and Koning 2013; Jochems and Koning 2015), and clearly grade to Rio Grande deposits at most tributary mouths (e.g., Jochems and Koning 2015).

Incision and backfilling continued after the last glacial maximum, resulting in four latest Pleistocene–Holocene terrace deposits that line the modern floodplain of the Rio Grande in the Palomas Basin. Mack and others (2011) mapped these terraces and determined that their ages fall between approximately 12,400 and 260 cal yr BP using radiocarbon dating of calcium carbonate nodules/filaments, charcoal, and gastropod and bivalve shells. These deposits consist primarily of mud, clayey fine sand, and gravelly sand with stage II carbonate morphology observed in buried soil horizons of older deposits. The natural flood regime of the Rio Grande was interrupted by the construction of Elephant Butte Dam in 1916, and the width and location of the modern channel are now primarily controlled by flood-related deposition on transverse alluvial fans (Mack et al. 2008).

### Study Tributaries

The two study tributaries, Cañada Honda and Las Animas Creek, flow eastward across the Palomas Basin before draining into the Rio Grande and Caballo Reservoir, respectively (Fig. 1). Cañada Honda is a short (26 km) ephemeral stream that heads at approximately 1,300 m ASL in the western part of the basin, 25 km northwest of the town of Truth or Consequences. It flows through Plio-Pleistocene basin fill of the Palomas Formation except for the upper 1–2 km of its profile, where it heads in outcrops of Oligocene rhyolite and basaltic andesite (Jochems 2015). Draining an area of approximately 60 km$^2$, Cañada Honda is nearly uninhabited but has been subject to grazing activity since at least the early to mid-20th century (J. Beaty, pers. comm., 2015).

Las Animas Creek heads on the Continental Divide in the Black Range at 2,750 m ASL (Fig. 1). This stream flows across late Eocene–Oligocene volcaniclastic rocks, felsic tuff, rhyolite, and basaltic andesite as well as a minor amount of Paleozoic carbonates and Miocene basin fill before entering the Palomas Basin 30 km southwest of Truth or Consequences (Harrison et al. 1993). It drains an area of 340 km$^2$ and is unusual among local tributaries for having several reaches that experience flow almost year-round (Davie and Spiegel 1967). This flow and the shallow aquifer of the Las Animas valley floor sustain a vegetation community of grass interspersed with cottonwoods and local stands of Arizona sycamore (*Platanus wrightii*). The valley of Las Animas Creek has been intermittently inhabited since at least the 12th century (Nelson et al. 2006), and has experienced a mix of grazing and farming activity since the settlement era. Anecdotal evidence suggests a shallow channel and swampy valley floor in the late 19th century, but incision in the main channel starting around AD 1910 and a lowered water table in the 1920s (B. Bussmann, H. Chatfield, local residents, pers. comm., 2014).

Stream gage data is not available for the study tributaries. However, Mack and others (2008) estimatd flood peak discharges during a summer 2006 monsoon event at 180 m$^3$/s and 970 m$^3$/s for nearby Palomas Creek and Red Canyon, respectively (Fig. 1). Additionally, a peak discharge of 563 m$^3$/s was measured for Percha Creek, south of Las Animas Creek, in August 1999 (USGS NWIS database 2015).

## Methods

We mapped late Quaternary deposits along Cañada Honda and Las Animas Creek at 1:12,000 scale. Mapping included both field investigations and detailed placement of contacts using photogrammetry software (StereoAnalyst for ArcGIS 10.1, an ERDAS extension, version 11.0.6). Deposits were distinguished using criteria that included relative landscape position, surface characteristics (degree of desert varnishing based on color of surface clasts, calcium carbonate accumulation, and eradication of original bar-and-swale topography), and degree of soil development (e.g., presence of Bt or Bk horizons). Both main-stem deposits and alluvial fan units emanating from side canyons were mapped in tributaries. Additionally, we mapped alluvial fan and Rio Grande terrace deposits at the mouth of Cañada Honda. The latter were correlated to the terrace stratigraphy of Mack et al. (2011).

In Cañada Honda, detrital charcoal for radiocarbon analysis was collected where cut-banks of the modern drainage have exposed older deposits. In Las Animas Creek, detrital charcoal was collected from two trenches (termed the Bussmann trenches) dug approximately 2 m below the modern floodplain. A total of five samples were submitted and analyzed by mass spectrometer at Beta Analytic Inc., Miami, FL. A charcoal sample was collected from each of the trenches in Las Animas Creek and the remainder were collected from cut-banks along Cañada Honda. In Table 1, we present both conventional ($^{14}$C yr BP) and calibrated (cal yr BP) ages where present = AD 1950. Ages were calibrated using Calib7.1 (Stuiver and Reimer 1993) and the IntCal13 dataset of Reimer et al. (2013); calibrated results at 95% probability are given. Median ages discussed in the text were calculated from the medians of the entire calibrated age ranges for each sample and rounded to the nearest 10 yr. Conventional radiocarbon ages were uniformly assigned conservative analytical errors of ± 30 $^{14}$C yr BP due to low (<30$^{14}$C yr BP) 1 σ errors.

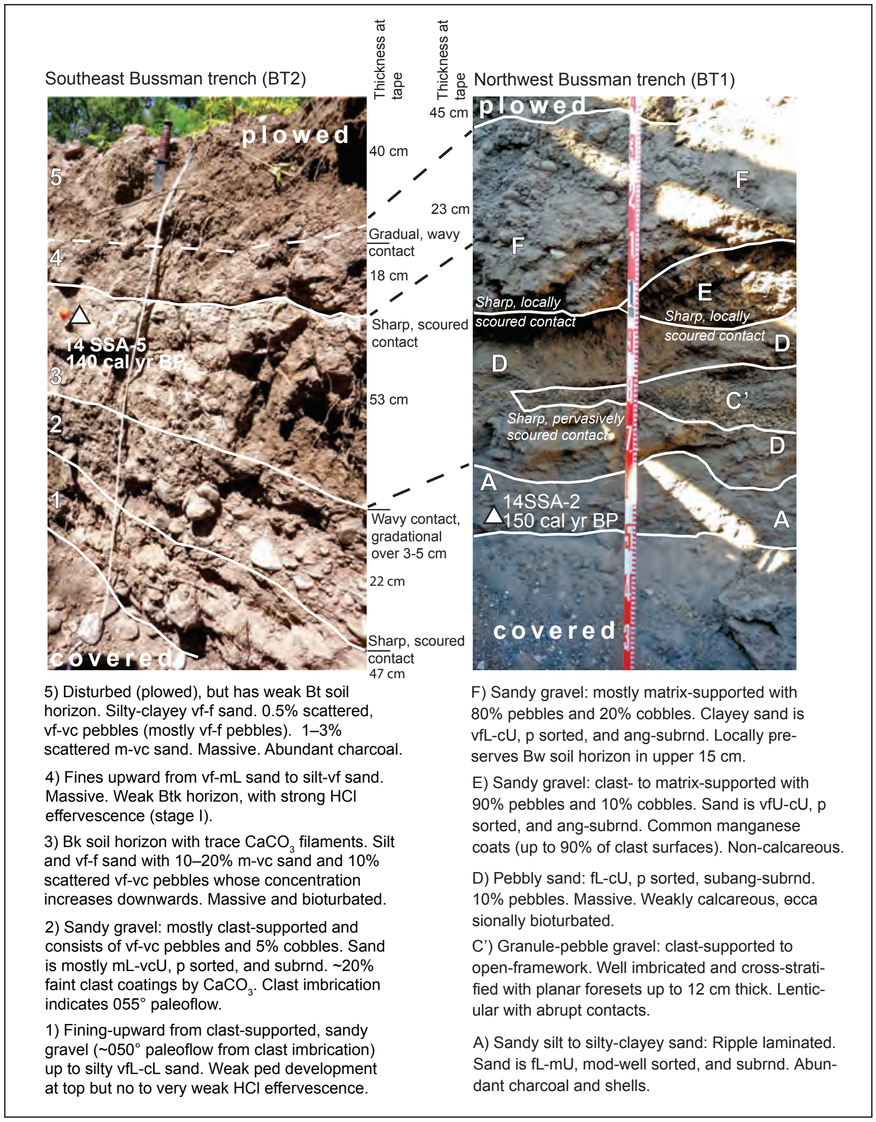



FIGURE 7—Annotated photographs showing stratigraphy of Qah deposits in two 2 m-deep pits in lower Las Animas Creek (labeled Bussmann trenches BT1 and BT2 in Fig. 2B).

## Results: Holocene stratigraphy

### Valley Floor

Mapped units in the study tributaries are denoted by designations implying the type of deposit and its relative age. For example, the Qay deposit consists of valley floor alluvium that is younger than (i.e., inset below) valley margin terraces (not discussed here), but older than historical alluvium of Qah. Deposits denoted by the letter "f" are found in alluvial fans (e.g., younger fan alluvium of Qfay).

The Cañada Honda and Las Animas Creek study areas consist of valley floor deposits flanked by alluvial fans (Figs. 2–3). The valley floor is underlain mainly by Qay and modern-historical sandy gravel (Qamh). Most of Qay has been removed by erosion. Remnants of Qay are typically located adjacent to the toes of alluvial fans (Qfay) and, because of their narrowness, are generally subsumed into Qfay at 1:12,000-scale mapping. Where present, Qay has a slope that approximately parallels the modern stream and grades laterally into Qfay. Coarse modern-historical sandy gravel is usually associated with valley floor channels inset into older units (Figs. 4).

Depending on the texture of the Palomas Formation that is being eroded, Qay sediment ranges from gravelly to sandy. Gravel is mostly clast-supported and imbricated. Locally, there are minor grain-supported, slightly clayey beds inferred to be debris flows. Finer Qay sediment is comprised of brown to light brown (7.5YR 5/2–6/3), massive, slightly silty sand with minor lenses of sandy gravel. Local buried soils feature calcic horizons with stage I to II carbonate morphology. The surface soil of Qay generally has a stage I to I+ calcic horizon, except where eroded.

In lower Cañada Honda, the Qfay-Qay allostratigraphic package is inset by a younger deposit, Qayi (Fig. 5). This deposit consists of grayish brown to pale brown (10YR 5/2–6/3) sand and silty sand interbedded with subordinate, lenticular beds of sandy gravel (Fig. 6). Near the surface, <20% of clasts have calcium carbonate coats, mostly on their undersides.

In Las Animas Creek, historical and modern alluvium underlie the valley floor, with Qah more widespread than modern deposits (Fig. 2B). Modern alluvium is generally coarse sand and gravel within a 1–2 m-deep channel inset into historical alluvium. The historical alluvium is comprised of interbedded floodplain deposits and channel fills (Fig. 7). Floodplain deposits consist of brown to dark grayish brown (7.5–10YR 4–5/3 to 10YR 5/2) silt and very fine- to medium-grained sand with minor clay. These fine-grained deposits are massive, ripple-laminated, or internally bedded (very thin to thin). Buried soils are common and characterized by ped development, faint clay films on ped faces, and/or stage I carbonate morphology. Channel fills consist of sandy gravel and pebbly sand with occasional cross-stratification. Clasts locally exhibit partial coatings of calcium carbonate and are clast-supported, imbricated, and comprised of pebbles with minor cobbles and

| Sample # | Lab #[a] | Deposit | Material Dated | UTM N[b] | UTM E[b] | Conventional Age ($^{14}C$ yr $BP_{1950}$)[c] | 2σ Calibrated Age Range (cal yr $BP_{1950}$)[d] | Median Age (cal yr $BP_{1950}$)[e] | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|---|---|---|---|
| *Cañada Honda* | | | | | | | | | |
| WS-202-D1 | Beta-406473 | Qfay | charcoal | 3665387 | 284572 | 9590±30 | 3011106-10763 (1.000) | 10930 ± 170 | -21.6 |
| WS-203 | Beta-406477 | Qfay | charcoal | 3665180 | 284659 | 2480±30 | 2390-2385 (0.004)<br>2723-2432 (0.996) | 2550 ± 170 | -22.4 |
| WS-204 | Beta-406474 | Qayi | charcoal | 3665150 | 284689 | 540±30 | 634-596 (0.308)<br>561-514 (0.692) | 570 ± 60 | -10.8 |
| *Las Animas Creek* | | | | | | | | | |
| 14SSA-2 | Beta-406475 | Qah | charcoal | 3651443 | 276327 | 180±30 | 297-255 (0.207)<br>224-136 (0.569)<br>114-106(0.009)<br>99-81 (0.024)<br>78-74 (0.005)<br>33-0 (0.186)[f] | 150 ± 150 | -24.7 |
| 14SSA-5 | Beta-406476 | Qah | charcoal | 3651415 | 276364 | 110±30 | 269-211 (0.286)<br>200-188 (0.020)<br>148-12 (0.694) | 140 ± 130 | -26.3 |

Table 1—Summary radiocarbon geochronology for Cañada Honda and Las Animas Creek study areas

[a]*All samples dated by AMS analysis, Beta Analytic Inc., Miami, FL.*

[b]*Coordinates given in UTM Zone 13S, NAD83.*

[c]*Conservative error of ± 30 14C yr BP1950 is given for all samples due to 1σ < 30 14C yr BP1950 in each case.*

[d]*2σ calibrated age ranges calculated as relative probability using Calib 7.1 (Stuiver and Reimer 1993) and IntCal13 calibration curve of Reimer et al. (2013).*

[e]*Median age reported by averaging entire age range and rounding to nearest 10 yr. Error is difference between median and end values of range.*

[f]*33-0 cal yr BP range implies possibility of post-1950 age (including modern) indicating the influence of $^{14}C$ from above-ground nuclear weapons testing.*

FIGURE 8—Photographs illustrating differences between geomorphic surfaces in lower Cañada Honda. A) Surface of the main-stem Qah deposit depicted in Figure 4. Note bar-and-swale relief (10–35 cm) and the non-varnished nature of the gravel. B) Surface of a Qfay deposit with bar-and-swale relief of <20 cm, weak clast varnishing (note the lesser amounts of gray clasts), and a relatively smooth profile. Backpack for scale in both photographs

FIGURE 9—Photograph illustrating prevalent gullying of hillslopes along lower Las Animas Creek. Similar gullying is observed along other transverse drainages in the central and northern Palomas Basin, especially Cañada Alamosa. The photograph shows the north-facing slope at a location 4 km upstream of the Bussmann trench sites (Fig. 2B).

5–10% boulders. Historical alluvium commonly features a surface with moderate bar-and-swale relief here and in Cañada Honda (Fig. 8A).

### Valley Margins

Steep slopes flanking valley margins typically exhibit gullying and erosion, particularly in the larger drainages of the Palomas Basin (Fig. 9). This erosion has exposed packages of modern and historical fan alluvium. This sediment is lithologically similar to that observed in valley floors, and is either incised into Qfay (Fig. 10A), forms a telescoped lobe near the toe of Qfay (Fig. 10B), or overlies Qfay as a sheet.

Qfay deposits consist of interbedded sandy gravel and pebbly sand. Beds are lenticular to tabular and convex-up in exposures transverse to the fan axis (Fig. 11). The gravel is clast- to matrix-supported, locally has an open framework, and is composed of pebbles with minor cobbles (Fig. 12). The sand is brown to grayish brown (10YR 4/3 to 5/2–3; 7.5YR 5/3) or light

A

B

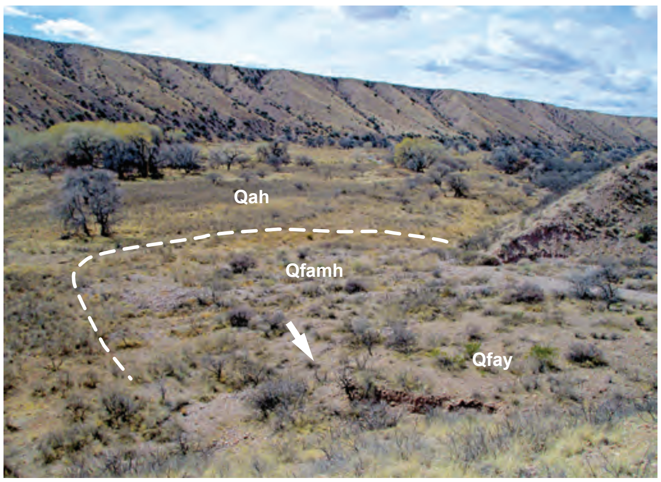



FIGURE 10—Photographs illustrating toe-cuts on Qfay alluvial fans in Las Animas Creek. A) Backpack at base of a 2 m-tall toe-cut. Qah in foreground. B) Approximate 2 m-tall scarp in foreground (arrow). Behind this scarp, a telescoped Qfamh fan lobe is actively prograding onto historical alluvium (Qah) on the valley floor. White dashed line shows the toe of Qfamh..

brown (7.5YR 6/3), and fine- to very coarse-grained. Locally, finer-grained sediment is present as massive, muddy, very fine- to medium-grained sand interbedded with minor lenticular beds composed of pebbles.

Qfay surfaces have distinctive characteristics (Fig. 8B). These surfaces display no or subtle bar-and-swale topographic relief (0–30 cm) and are commonly eroded. Clasts on higher surfaces with minimal reworking are weakly varnished. Where not subjected to intensive surface erosion, the Qfay surface is generally underlain by a soil with a 0–20 cm thick A horizon, Bt horizon with local clay argillans, and a calcic soil up to 80 cm thick featuring stage I to I+ carbonate morphology (rarely, stage II). Buried soils are locally present as well that include calcic and cambic (Bw) horizons (unit E, Fig. 11). Unless buried by younger fan sediment (e.g., Qfamh; Fig. 10), the toes of Qfay fans are commonly cut by the main-stem channel with the resulting scarp generally 1–3 m tall.

### Radiocarbon Ages

Radiocarbon samples taken from deposits in the central Palomas Basin yield early to late Holocene ages (Table 1). These results are in agreement with field relationships indicating that Qah and Qayi deposits post-date Qay and Qfay deposits, including the observations that Qayi is inset into Qfay and Qay across the basin (Fig. 5) and that Qfay and Qay display a higher degree of soil development (e.g., Fig. 11).

Figures 6 and 11 show the stratigraphic context of charcoal sample sites in the west, middle, and east Cañada Honda exposures. There, the lower part of Qfay returned a median age of 10930 cal yr BP (sample WS-202-D1 in Fig. 11), and distal Qfay sediment returned an age of 2550 cal yr BP (sample WS-203 in Fig. 6A).

The youngest of the Cañada Honda samples (WS-204) returned a median age of 570 cal yr BP (Table 1). The difference in age between Qfay and Qayi in the middle and eastern Cañada Honda exposures is therefore approximately 2,000 yrs. Part of that interval represents deposition of the upper part of Qfay. The remainder is incorporated in an incision-related lacuna related to the buttress disconformity between the Qfay-Qay allostratigraphic package and Qayi (Fig. 5).

The valley floor of Las Animas Creek is dominated by Qah deposits underlying the modern floodplain, which spans nearly the entire width of the canyon. Charcoal samples from Qah returned probable 2σ calibrated age ranges of 224–136 and 148–12 cal yr BP (Table 1).

## Discussion

### Aggradation and Incision in the Palomas Basin

Using stratigraphy and radiocarbon age control, we make several interpretations regarding latest Pleistocene landscape stability, early to middle Holocene aggradation, and late Holocene geomorphic responses. The earliest part of our record is preserved at the west Cañada Honda exposure, where alluvial fan sediment coarsens upward to sandy gravel (units D and E, Fig. 11). Unit A is interpreted to represent latest Pleistocene alluvial fan deposition based on the 10930 cal yr BP median age of unit D in addition to the fact that unit D is underlain by Bt and stage II calcic horizons. Though lacking direct age control, we suggest that sediment in the upper part of the Qfay deposit reflects mostly continuous deposition in the early to middle Holocene. This inference is based on the gradational contact between units D and E and cumulic calcium carbonate accumulation in unit E. Unit E also coarsens upward on the east side of the west Cañada Honda site, but the underlying units B through D there were stripped by erosion (Fig. 11). These stratigraphic relations indicate that the active stream was eroding the east side of the alluvial fan sometime during the early Holocene after deposition of unit D. Later in the early to middle Holocene, aggradation occurred across practically the entire fan, likely accompanied by fan progradation based on the upward-coarsening texture of unit E.

The fine-grained unit at the base of the middle Cañada Honda exposure is interpreted as distal fan sediment, although clast imbrication in the upper part is consistent with a main-stem deposit (Fig. 6A). The median age of 2550 cal yr BP thus indicates alluvial fan and main-stem deposition at that time. This interval of aggradation could coincide with a hiatus in sedimentation on alluvial fans from low-order Cañada Alamosa tributaries between approximately 3000 and 2500 cal yr BP, as interpreted by Monger et al. (2014) in the northern Palomas Basin.

Incision occurring between 850 and 550 cal yr BP in the middle reaches of Cañada Alamosa (Monger et al. 2014) could possibly have occurred in the upper reaches of Cañada Honda and low-order drainages elsewhere in the central Palomas Basin. More work is needed to conclusively demonstrate this event, which deeply dissected side-fans of low-order tributaries in the northern Palomas Basin. Main-stem floodplain sediment along Cañada Alamosa, correlative to unit Qah in the central basin, has been dated to <550 cal yr BP (Monger et al. 2014).

The 570 cal yr BP median age at the east Cañada Honda site, near the top of unit Qayi, coincides with the end of the 850–550 cal yr BP incision episode interpreted from Cañada Alamosa and the axial Rio Grande. Two different explanations for this concurrence are possible: 1) basin-wide incision ending approximately 600 cal yr BP; or 2) aggradation at the east Cañada Honda site concomitant with incision in the upper reaches of this canyon.

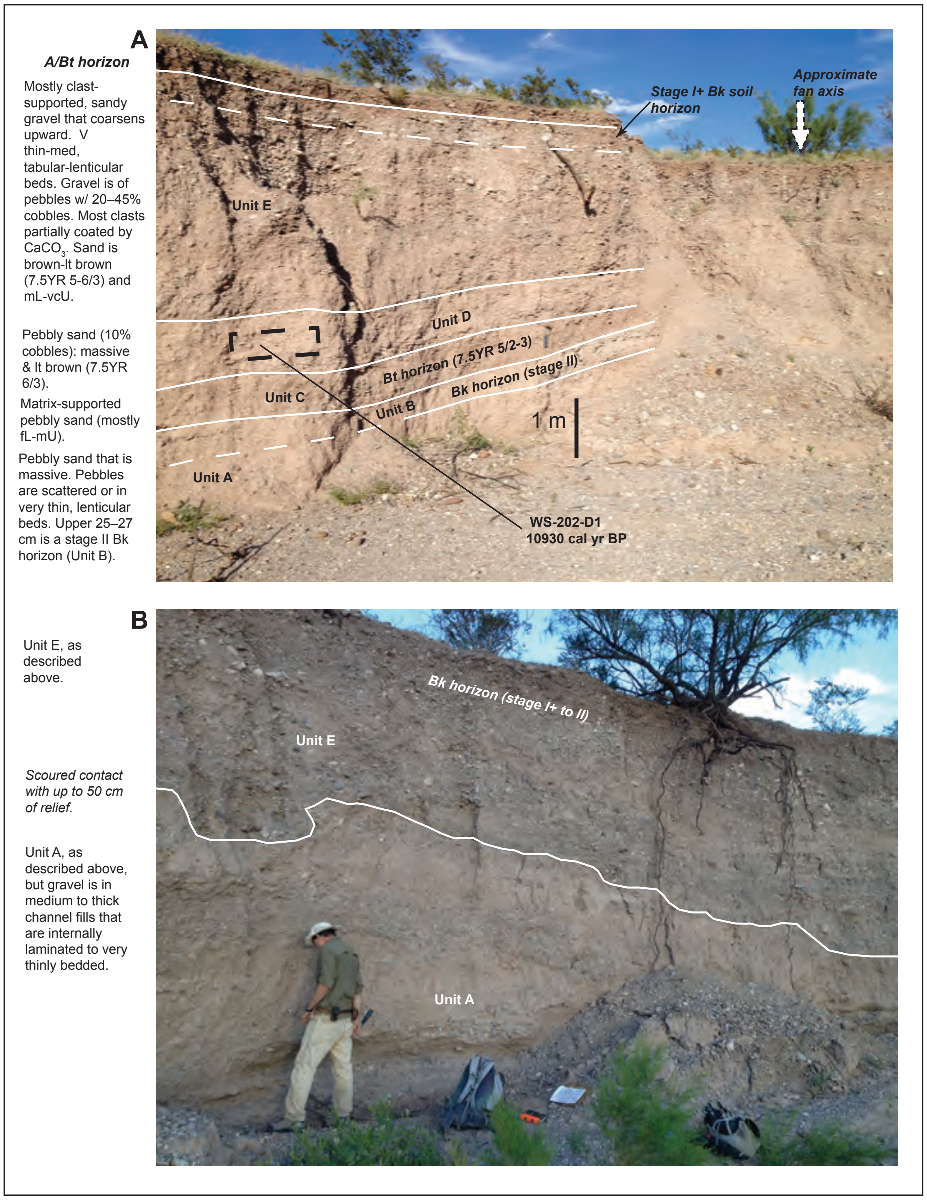



FIGURE 11—Annotated photographs depicting the stratigraphy and lithology of Qfay deposits at the west Cañada Honda site. Person in lower photograph is 1.9 m tall. Charcoal sample location shown by dashed rectangle. View is to the northeast in both photographs. The top photograph is west of the fan axis and the lower photograph is east of the fan axis. Units A and E correlate between the two photographs.

Simultaneous intra-drainage aggradation and incision implied by the latter explanation has been invoked in the large Rio Puerco watershed, a Rio Grande tributary in central New Mexico (Friedman et al. 2015).

At the mouth of Cañada Honda, Qayi grades into Rio Grande terrace III. Aerial photographs suggest similar surface features and elevations, in which case our median age of 570 cal yr BP for Qayi could also represent a minimum age for terrace III. If accurate, this scenario implies Rio Grande incision shortly thereafter. In the Truth or Consequences area, shells at the top of the next lowest terrace (IV), have been dated at 510–260 cal yr BP (Fig. 13; Mack et al. 2011). To the south, charcoal from the base of terrace IV returned an age of 550–510 cal yr BP (Mack et al. 2011). We thus argue that Rio Grande incision occurred approximately 550 cal yr BP.

Two Palomas Basin alluvial records reveal that historical valley floor aggradation occurred in tributary arroyos at approximately the same time as terrace IV sediment was deposited (<550–260 cal yr BP) on the Rio Grande valley floor (Fig. 13). Aggradation is dated to <600 cal yr BP in Cañada Alamosa (Monger et al. 2014), and the upper 2 m of historical deposits in Las Animas Creek are dated to <300 cal yr BP. There is no direct age for the Qah deposit in Cañada Honda, but the lack of soil development and the 570 cal yr BP median age of the older Qayi deposit restricts Qah deposition to <500 cal yr BP following an incision event at approximately 550–400 cal yr BP. The <260 cal yr BP incision of Mack et al. (2011) on the axial Rio Grande may correspond to post-Qah incision in lower Cañada Honda or Las Animas Creek. The precise timing of the latest incision event in lower Cañada Honda is not known but likely occurred in the past 150–100 years based on surface characteristics of unit Qah. The latest incision of Las Animas Creek occurred after AD 1910 based on previously discussed anecdotal evidence.

## Comparison with Southwest Arroyo Records

Acknowledging that our five radiocarbon ages produce considerable uncertainties for some intervals (e.g., 2500–700 cal yr BP), we draw tentative comparisons between our aggradation-incision record in the central Palomas Basin and other Southwest locales (Fig. 14). The following episodes of broad synchronicity are allowed: 1) soil formation in the latest Pleistocene; 2) early to middle Holocene aggradation; 3) alluviation or stability at approximately 3000–2500 and 1800–1500 cal yr BP; 4) incision 1000–550 cal yr BP (but during different intervals within this time frame); 5) alluviation approximately 500–250 cal yr BP; and 6) incision near the boundary of the 19th and 20th

FIGURE 12—Left: Exposure of Qfay alluvium on the north side of Las Animas Creek. Pink ruler is 15 cm long. Here, Qfay is comprised of very thin to medium, tabular to lenticular beds of pebbly sand and sandy gravel. The latter is mostly clast-supported and contains 5–10% grain-supported, clayey deposits that are likely debris flows. The top soil is approximately 30 cm thick, contains a higher proportion of fine sand and silt, and exhibits a very weak calcic horizon (stage I).

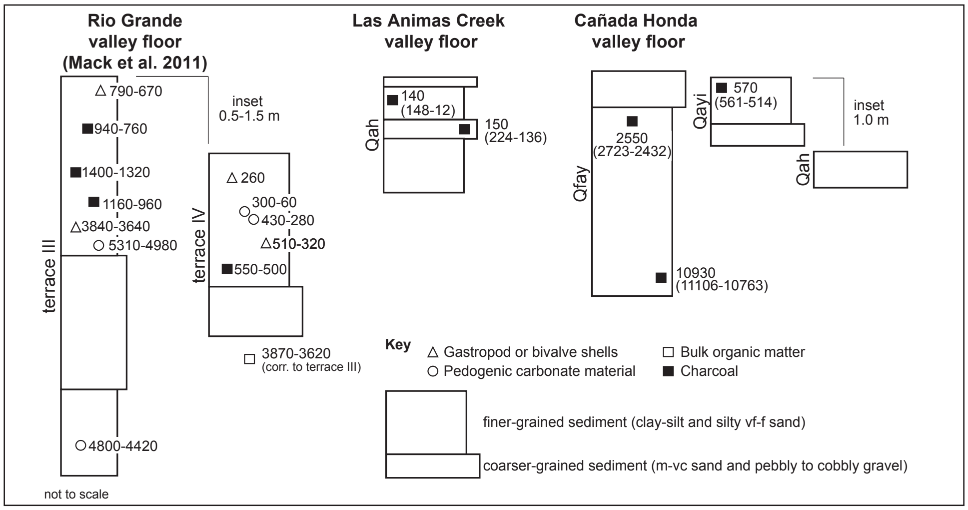


FIGURE 13—Summary of late Holocene stratigraphy and geochronology established in the central Palomas Basin. All dates are from radiocarbon analyses; ages in parentheses are highest probability age ranges from 2σ calibration (see Table 1). *Rio Grande valley floor deposits modified from Mack et al. (2011).*

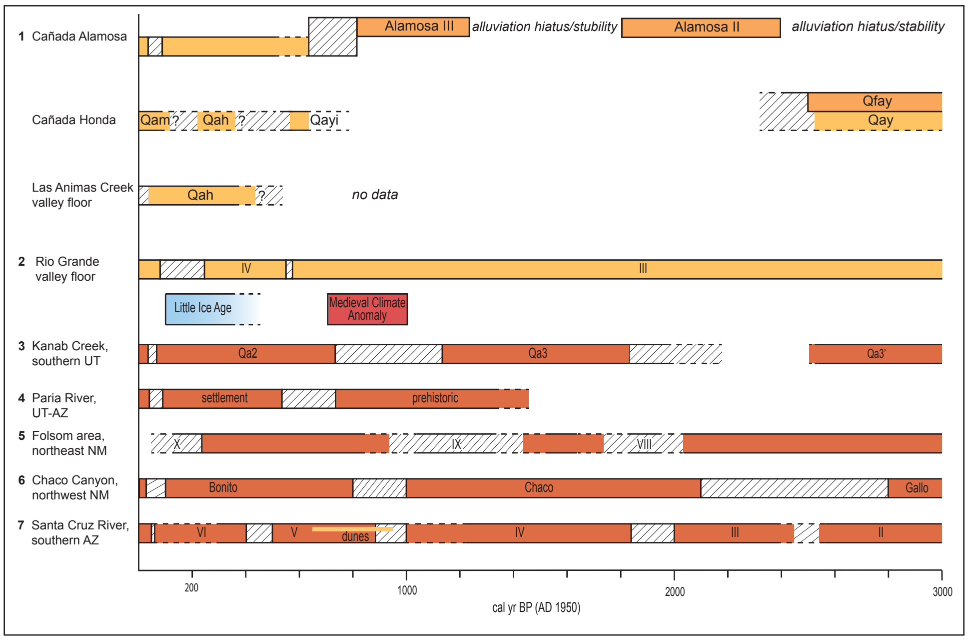


FIGURE 14—Comparison between Palomas Basin Holocene alluvial and fluvial records, and aggradation-incision records from streams and arroyos around the Southwest. Tan and orange bars represent axial stream and side-fan sedimentation, respectively. Hachured bars represent inferred periods of incision. Dashed lines indicate less constrained intervals. *References: 1) Monger et al. 2014; 2) Mack et al. 2011 (note minimum age of terrace III re-interpreted at 570 cal yr BP); 3) Nelson and Rittenour 2014; 4) Hereford 2002; 5) Mann and Meltzer 2007; 6) Hall 1977 and 2010; and 7) Waters 1988.*

centuries. Note that our dataset is incomplete for aggradation at 1800–1500 cal yr BP and interpretation 3 is therefore based on other records (Fig. 14).

The precise timing and nature of late Holocene aggradation events differ between localities in the Southwest (Fig. 14). For example, aggradation approximately 1800–1000 cal yr BP interpreted in other regional records is not strongly supported in Palomas Basin tributaries, although it is inferred for the Rio Grande valley floor (Mack et al. 2011). Instead, at least 1,000 years of relative stability, probably associated with an incised channel, allowed some degree of soil development in the Alamosa II deposit of the low-order Cañada Alamosa tributary fan investigated by Monger et al. (2014). This interval also coincides with deposition followed by the formation of paleosols on the middle to late Holocene Rio Grande floodplain at El Paso, Texas (Hall and Peterson 2013).

## Comparison with Paleoclimate Records

Based on the above discussion, we believe that incision likely occurred 850–550 cal yr BP in the Palomas Basin. If correct, this incision would have occurred during dry conditions but relatively strengthened summer monsoons (Fig. 15). Low overall precipitation from 900–700 cal yr BP and a relatively enhanced NAM between 900 and 550 cal yr BP are inferred from speleothem and foram climate proxy records, respectively (Poore et al. 2005, 2011; Asmerom et al. 2007). More broadly, several workers interpret a shift from wet to dry climate at approximately 1000 cal yr BP in the Southwest and Great Plains, which initiated stream valley incision and eolian sand deposition (Hall 1990; Blum and Valastro 1994; Mason et al. 2004; Lepper and Scott 2005; Hanson et al. 2010), although Hall and Penner (2013) suggest this shift occurred approximately 1400 cal yr BP. The 850–550 cal yr BP interval also coincides with declining ENSO-related sedimentation in Lake Pallcacocha, Ecuador (Moy et al. 2002), and the end of a wet period suggested by the El Malpais tree-ring record in northwest New Mexico (Stahle et al. 2009). Note that approximately 550 cal yr BP is approximately concurrent with greater precipitation (Pink Panther Cave speleothem), a weakened NAM (Gulf of Mexico forams), and greater ENSO-related sedimentation in Lake Pallcacocha (Fig. 15), all suggestive of winter-dominant precipitation. Consequently, our inferred 850–550 cal yr BP incision event began during a dry period with a relatively strong NAM and ended with the arrival of winter-dominant precipitation and a weakened NAM.

Available records show a distinctive paleoclimate signature during the Little Ice Age (LIA) approximately 500–70 cal yr BP (Fig. 15). Cooler and wetter conditions are observed in proxy records across the Southwest during this interval (e.g., Armour et al. 2002; Reheis et al. 2005; Castiglia and Fawcett 2006). In northern Mexico and southwestern New Mexico, Lake Palomas and Lake Cloverdale experienced high levels during this time,

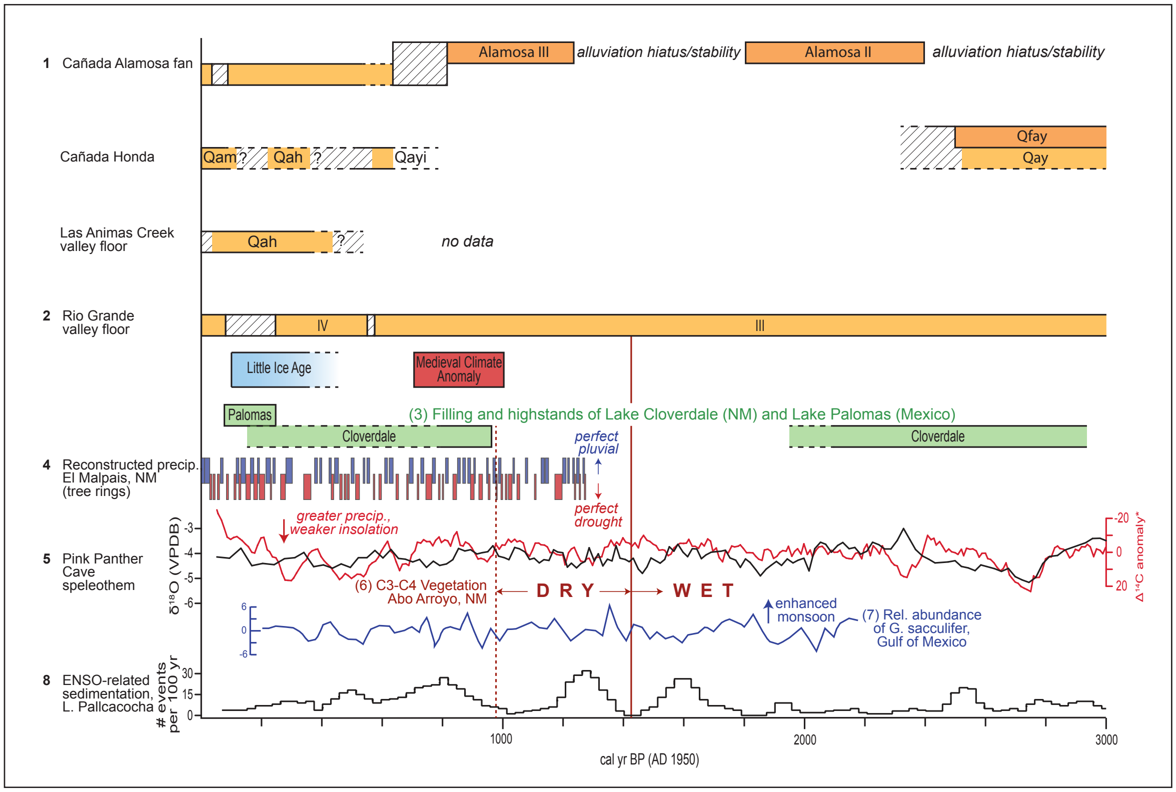



FIGURE 15—Comparison between Palomas Basin Holocene alluvial and fluvial records and regional and hemispheric climate records. Boxes and hachures as in Figure 14. *References: 1) Monger et al. 2014; 2) ) Mack et al. 2011 (note minimum age of terrace III re-interpreted at 570 cal yr BP; 3) Krider 1998 and Castiglia and Fawcett 2006; 4) Stahle et al. 2009; 5) Asmerom et al. 2007; 6) Hall and Penner 2013; 7) Poore et al. 2005; and 8) Moy et al. 2002.*

and greater precipitation is indicated by the Pink Panther Cave speleothem with an exception of drier conditions approximately 300 cal yr BP (Fig. 15; Krider 1998; Castiglia and Fawcett 2006; Asmerom et al. 2007). Multi-year drought also prevailed in the Southwest during the mid-18th century, as supported by tree-ring and soil records showing sustained periods of low reconstructed precipitation and flow in the Rio Grande, as well as a shift from woodland to Chihuahuan desert scrub vegetation (Van Devender 1990; Grissino-Mayer 1996; Monger et al. 1998; Stahle et al. 2009; Woodhouse et al. 2013). Wet LIA conditions in the 19th century are supported by tree-ring and pluvial lake records (Fig. 15). Deposition of Las Animas Creek Qah alluvium coincided with at least the latter part of the LIA (Fig. 15), perhaps facilitated in part by reduced vegetation on hillslopes due to drought in the 1600s and 1700s.

### Comparison with Climate-Response Models

The study area tributaries provide a natural test of the Mann and Meltzer (2007) and Mack et al. (2011) climate-response models because they are closely linked to the axial river floodplain (e.g., Mack et al. 2008). Our data allows for widespread 850–550 cal yr BP incision, though more work is needed for verification. If real, this erosion would have occurred during a relatively dry period with enhanced summer monsoons after approximately 900 cal yr BP following wetter conditions. That incision occurred during these climatic conditions is consistent with the aforementioned models. Drier climate would have reduced vegetation density and enhanced erosion on hillslopes, while strong, periodic flooding would have provided the stream power necessary to flush sediment from low-order drainages (e.g., Hooke 2000).

We also interpret that the axial Rio Grande incised at approximately 550 cal yr BP. Paleoclimatic records suggest winter-dominant precipitation at this time (Fig. 15). This observation is consistent with the Mack et al. (2011) model because it implies that the Rio Grande would have had a higher water to sediment ratio, favoring incision. Increased vegetation density in tributary catchments, combined with fewer strong summer monsoons, could have allowed aggradation in the headwaters of low-order drainages.

The most recent incision event on the Rio Grande occurred after 260 cal yr BP but is otherwise unconstrained, meaning that Rio Grande incision could have been in- or out-of-phase with the lower reaches of Cañada Honda and/or Las Animas Creek. At Las Animas Creek, aggradation could have occurred as a response to multi-year droughts in the mid-1700s, following the Mann and Meltzer (2007) and Mack et al. (2011) models. Rio Grande incision at 150–100 cal yr BP would also be consistent with the models, given strong LIA conditions in the 19th century (Fig. 15), but out-of-phase with aggradation occurring at Las Animas Creek.

## Conclusions

The resolution of our alluvial record from south-central New Mexico precludes detailed correlation with alluvial or climate records extending from the mid-Holocene to approximately 1,000 years ago. However, incorporating data and interpretations from other studies with our <1,000 year chronology permits the following conclusions:

1) Multiple alluvial deposits can be differentiated on both the valley floors and alluvial fans of east-flowing drainages in the central Palomas Basin. These deposits have unique surface characteristics consistent with relative ages inferred from inset relationships.

2) An incision event that occurred in Cañada Alamosa at 850–550 cal yr BP may also have occurred in tributaries in the central Palomas Basin, with one deposit (Qayi) implying concomitant upstream erosion and downstream aggradation in Cañada Honda.

3) The 850–550 cal yr BP incision event occurred during a time of enhanced summer monsoons superimposed on

overall aridity, consistent with climate-response models proposed by Mann and Meltzer (2007) and Mack et al. (2011).

4) Incision occurred on the Rio Grande approximately 550 cal yr BP during a period of winter-dominated precipitation, also consistent with the climate-response models.

5) LIA aggradation was common across the Southwest and formed Qah deposits in the study area after approximately 500 cal yr BP.

## Acknowledgments

The focus and scope of this manuscript were greatly improved by reviews from Dr. Steven Cather, Dr. Stephen Hall, and Dr. Grant Meyer. We thank landowners Bill Bussmann and Las Palomas Land & Cattle Company for access to their properties. Leo Gabaldon assisted with the drafting of figures. We are grateful for financial and logistical support from the Geologic Mapping Program at the New Mexico Bureau of Geology and Mineral Resources supervised by Dr. J. Michael Timmons. Finally, we are grateful to Dr. Dave Love for assisting in charcoal collection and field descriptions of the geomorphic units described in this manuscript.

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