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 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 850–350 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.

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
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.


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 1935; 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
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 km² 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...
Based on their weak soil development and landscape position (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 rift resulted in net incision along the Rio Grande, cycles coupled with integration of Lake Alamosa in the northern Rio Grande rift resulted in 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 km², 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 km² 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) estimated flood peak discharges during a summer 2006 monsoon event at 180 m³/s and 970 m³/s for nearby Palomas Creek and Red Canyon, respectively (Fig. 1). Additionally, a peak discharge of 563 m³/s was measured for Percha Creek, south of Las Animas Creek, in August 1999 (USGS NWIS database 2015).

Methods

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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 varnish 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 (14C 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 14C yr BP due to low (<3014C yr BP) analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low analytical errors of ± 30 14C yr BP due to low
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 brown to gray (10YR 5/4–5/3; 7.5YR 5/4–5/3) and occasionally contains gray to dark gray (7.5YR 5/2–4; 7.5YR 4/3–3/2) matrix.

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

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Lab #</th>
<th>Deposit</th>
<th>Material</th>
<th>UTM N°</th>
<th>UTM E°</th>
<th>Conventional Age (14C yr BP1950)</th>
<th>2σ Calibrated Age Range (cal yr BP1950)</th>
<th>Median Age (cal yr BP1950)</th>
<th>δ13C (‰)</th>
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<tbody>
<tr>
<td>Cañada Honda</td>
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<tr>
<td>WS-202-D1</td>
<td>Beta-406473</td>
<td>Qfay</td>
<td>charcoal</td>
<td>3665387</td>
<td>284372</td>
<td>9590±30</td>
<td>3011106-10763 (1.000)</td>
<td>10930 ± 170</td>
<td>-21.6</td>
</tr>
<tr>
<td>WS-203</td>
<td>Beta-406477</td>
<td>Qfay</td>
<td>charcoal</td>
<td>3665180</td>
<td>284659</td>
<td>2480±30</td>
<td>2390-2385 (0.004)</td>
<td>2723-2432 (0.996)</td>
<td>2550 ± 170</td>
</tr>
<tr>
<td>WS-204</td>
<td>Beta-406474</td>
<td>Qayi</td>
<td>charcoal</td>
<td>3665150</td>
<td>284689</td>
<td>540±30</td>
<td>634-596 (0.308)</td>
<td>561-514 (0.692)</td>
<td>570 ± 60</td>
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<tr>
<td>Las Animas Creek</td>
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<tr>
<td>14SSA-2</td>
<td>Beta-406475</td>
<td>Qah</td>
<td>charcoal</td>
<td>3651443</td>
<td>276327</td>
<td>180±30</td>
<td>99-81 (0.024)</td>
<td>78-74 (0.005)</td>
<td>150 ± 150</td>
</tr>
<tr>
<td>14SSA-5</td>
<td>Beta-406476</td>
<td>Qah</td>
<td>charcoal</td>
<td>3651415</td>
<td>276364</td>
<td>110±30</td>
<td>269-211 (0.286)</td>
<td>200-188 (0.020)</td>
<td>140 ± 130</td>
</tr>
</tbody>
</table>

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

Coordinates given in UTM Zone 13S, NAD83.

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

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).

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

33-0 cal yr BP range implies possibility of post-1950 age (including modern) indicating the influence of 14C from above-ground nuclear weapons testing.
soil development (e.g., Fig. 11). Qfay and Qay display a higher degree of
depositions post-date Qay and Qfay deposits, including the
are in agreement with field relationships indicating that Qah and
yield early to late Holocene ages (Table 1). These results
Radiocarbon Ages
generally 1–3 m tall.
commonly cut by the main-stem channel with the resulting scarp
fan sediment (e.g., Qfamh; Fig. 10), the toes of Qfay fans are

cambic (Bw) horizons (unit E, Fig. 11). Unless buried by younger
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
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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).

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
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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 geo-
morphic 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.
Through 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,
within the upper part 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 concur-
rence 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.

Figures 6 and 11 show the stratigraphic context of charcoal
sample sites in the west, middle, and east Cañada Honda expos-
sures. 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 2350 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 allostrati-
graphic 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).
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**

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

**Records**

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.
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 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).
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 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 350 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.

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