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Plio-Pleistocene incision history of the Rio Ojo Caliente, northern Española Basin, and overview of the Rio Grande system in northern New Mexico

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PLIO-PLEISTOCENE INCISION HISTORY OF THE RIO OJO CALIENTE, NORTHERN ESPAÑOLA BASIN, AND OVERVIEW OF THE RIO GRANDE SYSTEM IN NORTHERN NEW MEXICO

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ABSTRACT.—The Rio Ojo Caliente, a tributary to the Rio Chama in the Española Basin, exhibits a well-preserved flight of Plio-Pleistocene terrace deposits. Ten terraces identified along the Rio Ojo Caliente consist of several meters of river gravels deposited onto straths cut on Precambrian and Tertiary rock. Strath heights range from 3 to 165 m above the river and correlate to straths beneath dated terraces along the Rio Chama and Rio Grande. River gravels at ~270 m above the Rio Ojo Caliente directly underlie the 3.65 Ma Black Mesa basalt, representing topographic inversion of a southwest-flowing ancestral Rio Grande. Two topographically lower terraces are associated with the ~1.6 Ma Guaje pumice (~160 m) and 0.62 Ma Lava Creek B ash (~110 m). These three surfaces constrain a variable incision history with rates, using basal strath heights, that average 65 m/m.y. from 3.65 to 1.6 Ma, 30 m/m.y from 1.6 to 0.62 Ma, and 175 m/m.y. from 620 ka to present.

New longitudinal profile data support and expand the hypothesis of Wells et al. (1987) that increased incision in the Española Basin since ~600 ka involved piracy of the San Luis Basin drainages by Española Basin drainages in the middle Pleistocene. Likewise, we concur that major knickpoints in the longitudinal profile of the Rio Grande and its tributaries upstream from the Rio Chama represent young transients due to the integration of the two basins. The pattern of knickpoints and convex profiles in the mainstem and tributaries could represent a passing transient wave of incision. South of the mainstem knick-zone, tributary knickpoints occur within convex profiles at progressively higher elevations; north of the mainstem knick-zone, tributaries have

simpler concave profiles. Bedrock strength is a strong factor in localizing knickpoints, but does not fully explain this pattern.

INTRODUCTION

The Rio Grande is the main river system that drains the southern Rocky Mountains. Its headwaters are in the San Juan Mountains of Colorado, and it follows the Rio Grande rift southwards towards the Gulf of Mexico (Fig. 1). Apparently the Rio Grande did not reach the Gulf of Mexico as a through-going drainage system until the Quaternary, when internally drained basins and/or alluvial plains became integrated (Pazzaglia and Hawley, 2004; Smith, 2004); integration may have been driven, in part, due to the increased discharge from capture of the San Luis Basin (Pazzaglia and Hawley, 2004). The rift itself and the southern Rocky Mountain province existed as tectonic entities long before the present drainage system was established. The drainage evolution and incision history of the Rio Grande provides an important record of the tectonic, geomorphic, and climatic history of the Rocky Mountain/Colorado Plateau region in the Quaternary.

The Colorado Plateau/Rocky Mountain landscape evolved from a precursor Laramide to Oligocene landscape which consisted of a partially internally drained continental plateau that may have been at elevations similar to today (Wolfe et al., 1998) or that was progressively uplifted by plateau forming events in the Laramide, Oligocene, and Neogene (Morgan and Swanberg, 1985; Sahagian et al., 2002). Regardless of the paleoelevation history, there is considerable room for further understanding of the interactions of neotectonics and climate change in shaping the modern topography. One approach is to work backwards from today, using river profiles, preserved river terraces, and improving geochronological constraints, to improve the understanding of the landscape evolution. We take it as an axiom that both global climate changes in the Quaternary (Molnar, 2001; Peizhen et al., 2001) and regional tectonic changes (Machette et al., 1998; Chapin et al., 2004) affected the Rocky Mountain/Colorado Plateau region. The term "tectonics" in this paper is used very broadly to refer to a wide range of processes that affect topography: slip on faults, volcanism, epeirogenic uplift (rock uplift and/or surface uplift), and the isostatic effects of any of these processes. Investigations need to address the interaction of these two forces, their potentially different spatial and temporal scales, and any feedback effects, as recorded by changing incision history and drainage evolution.

The highly dissected landscape that we observe today in the northern Rio Grande rift of New Mexico is the result of relatively high rates of Plio-Pleistocene river incision. High standing features capped with volcanic rocks resistant to erosion such as Black Mesa, Taos Plateau, Cabezon, and Mesa Prieta form an inverse topography showing us the general floodplain elevation 2 to 4 million years ago. Based on these relationships, the incision rate in north-central New Mexico has averaged 60-90 m/my over the last 2-4 m.y. (Hallet, 1994; Hallet et al., 1997; Wisniewsky and Pazzaglia, 2002). However, additional age control on inset river terraces suggests that the incision rate has been markedly variable through time, at least in some areas. The preservation of terraces allows us to unravel the incision history and explore the controls on regional incision.

The primary purpose of this paper is to introduce new river terrace data collected along the Rio Ojo Caliente in the summer and fall of 2003 (Newell et al., 2003; Koning, 2004), and to understand these data in the context of previous studies in the region. New data presented in this paper include terrace mapping, terrace correlations, and the measurement of longitudinal river profiles for all major rivers and tributaries in the Española and southern San Luis Basins. As a secondary goal, within the context of this new compilation of data related to Quaternary landscape evolution, we explore ideas about the possible controls on river incision, and discuss future research needs to test various hypotheses.



FIGURE 1. The Rio Grande-Chama river system, showing the location of the study area, major geographic features, and rivers and tributaries draining northern New Mexico and southern Colorado superimposed on a regional digital elevation model; modified from Chalk Butte Inc. (1995). Letters along the rivers correspond to the knickpoints shown on the river longitudinal profiles. BM = Black Mesa.

DEVELOPMENT OF MODERN DRAINAGES AND TOPOGRAPHY

Miocene extension and magmatism formed the N-S trending Rio Grande rift as a series of half graben basins that extend from central Colorado (Arkansas graben) to southern New Mexico, where the rift transitions to the wider Basin and Range province. The rift follows and helps define the highest topography of the Rocky Mountains (Eaton, 1986); this high topography may have formed diachronously via crustal shortening in the Laramide and magmatic upwelling in both Oligocene and Neogene times (Roy et al., 1999). Early extensional deformation due to collapse of high topography began in the Oligocene and some consider this to be the beginning of Rio Grande rift formation (Smith et al., in press). Numerous Laramide reverse faults were reactivated as Miocene normal faults (Karlstrom et al., 1999). Some workers postulate two stages of rifting (Morgan and Swanberg, 1985); others suggest that the rift developed progressively with discrete periods of major subsidence, as recorded by sediment thickness (Lozinski, 1994; Mack et al., 1994). Renewed Miocene epeirogenic uplift is indicated by tilting of the Ogallala Formation (McMillan et al., 2002; Leonard, 2002). By Miocene time, the rift was established as a series of structural basins that may have alternated between being integrated via an axial river, versus being internally drained when the river terminated in fluvial fans within a basin (Pazzaglia and Hawley, 2004).

Thus, as a general concept, different reaches of the present axial river system have different ages and fluvial histories that shifted diachronously from aggradation to general incision in the Pliocene, and it was not until the Quaternary that the Rio Grande became fully integrated (Wells et al., 1987; Mack et al., 1997). The Pliocene- Quaternary can be thought of as a time of incision and relief generation in the Rockies. It was the time of integration (or re-integration) of the Española and San Luis Basin drainages, as discussed in this paper. It is also a time of global climate change and onset of northern hemisphere glaciations since ~3.5 Ma (Droxler et al., 2003); global increases in sedimentation rates and implied increases in erosion rates have also been attributed to this climate change (Peizhen, et al., 2001). Displacement rates on normal faults has waned since the Pliocene, but many structures are still active (Machette et al., 1998). Pliocene- Quaternary magmatism shows resurgence in terms of basaltic volcanism starting at about 5 Ma in both the rift and along the Jemez lineament (Chapin et al., 2004).

Wells et al. (1987) hypothesized that a through-flowing Rio Grande between the San Luis and Española Basins was established between 300 and 700 ka when the San Luis drainages were captured by the headwaters of the ancestral Rio Grande. Their evidence for the capture event was based on interpretation of geomorphic features including convexity in river profiles, barbed river planforms, and river terrace relationships. Age control was based on tephra in San Luis Basin lake sediments and inferred ages of terrace gravels based on soil development. The zone of capture was hypothesized to be a broad divide near the present day Red River – Rio Grande confluence, where a zone of knick-

points, or knick-zone, exists in the modern profile where the Rio Grande is entrenched into the Servilleta Basalt flows. Wells et al. (1987) identified 6 fluvial terraces along the Rio Grande, downstream from the knick-zone. Their oldest fluvial terrace was estimated to be post- 1 Ma based on soil development (argillic horizon development and stage III-IV soil carbonates) and inset relationships with the highest regional geomorphic surface containing Tsankawi Pumice (1.12 Ma).

Dethier et al. (1988), Gonzales and Dethier (1991) and Dethier and Reneau (1995) greatly expanded the geomorphic investigations of the Española Basin through terrace mapping, terrace correlation and terrace dating. Gonzales and Dethier (1991) identified two periods of aggradation and three periods of incision since the Miocene, four pre-Quaternary surfaces, and at least seven Quaternary surfaces (terraces) in the basin. They also hypothesized that many basalt flows in the basin were erupted into and along ancestral river valleys and represent proxies for past base levels. Their Quaternary terraces were correlated and discriminated primarily on the basis of topographic position due to the general lack and/or preservation of diagnostic soils on most terrace deposits. Age control was developed for many of these deposits based on association with lower Bandelier tuff (~1600 ka), Lava Creek B tephra (620 ka; Sarna-Wojcicki and Davis, 1991), and a series of gastropod amino-acid racemation and radiocarbon ages.

Gonzales and Dethier (1991) also analyzed faulting in the basin and concluded that some faults, including the Pajarito and Embudo faults, were active in the Pliocene - Quaternary. They concluded that river system evolution in terms of aggradation and incision cycles were due to the interaction of climate, periodic inputs of volcanic material, and tectonic activity. Dethier and Reneau (1995) expanded on the terrace mapping and chronology of Gonzales and Dethier (1991), identifying approximately 20 Quaternary river terraces and lacustrine deposits along the Rio Grande and Rio Chama. Based on local age control, Dethier and Reneau (1995) inferred a differential incision history with rates < 50 m/m.y. from mid-Pliocene to mid-Pleistocene, jumping to > 200 m/m.y. after the mid-Pleistocene (~620 ka). These compare to incision rates in the Rocky Mountain region that, based on occurrences of Lava Creek B tephra, ranged from <20 to 300 m/ m.y. since ~620 ka, which exceed early-middle Pleistocene rates by a factor of 2 to 5 (Dethier, 2001). Within White Rock Canyon, landslide, lacustrine, and river terraces were hypothesized to represent Rio Grande damming events in the late Pleistocene (Dethier and Reneau, 1995; Dethier and Reneau, 1996; Reneau and Dethier, 1996). The ages of these deposits were identified to range from >50 ka to 12 ka, which roughly correlate to high stands of regional Pleistocene lakes, and the authors attributed the damming events to late Pleistocene pluvial periods. Local base-level changes due to damming events and lake formation in White Rock Canyon and potential affects on river aggradation and incision were hypothesized. In general, these authors called on Quaternary climatic factors (pluvial - interpluvial cycles) as the primary driver for river incision/aggradation, although Quaternary volcanic and tectonic activity were not ruled out as potentially important factors.

NEW DATA FROM THE RIO OJO CALIENTE

Terrace mapping was conducted along the Rio Ojo Caliente, located within the northwestern Española Basin (Fig. 1). This paper summarizes these new data in the context of studies of well-dated terraces along the Rio Chama (Dethier et al., 1988; Gonzalez and Dethier, 1991; Dethier and Reneau, 1995) and studies of knickpoints and drainage integration in the Rio Grande system (Wells et al. 1987). The terrace and incision data are integrated with ideas generated from ongoing mapping in the Rio Chama area and Albuquerque basin (Connell, 2002; Koning, 2004). We also provide new longitudinal river profiles of the Rio Grande and Rio Chama and their major tributaries within the Española and San Luis Basins (Fig. 1).

Longitudinal River Profiles

Longitudinal river profiles were constructed for the major trunk rivers draining the southern San Luis Basin and Española Basin and their primary tributaries. Profiles were constructed by plotting distance versus elevation data along the center of the active river channel, as collected from USGS 1:24,000 topographic maps with a contour interval of 20 ft. The main trunk river in the basins is the Rio Grande, and its largest tributary in the region is the Rio Chama. Longitudinal profiles for the Rio Grande and all major tributaries are shown in figure 2. Perhaps the most fundamental observation (Fig. 2) is that the Rio Chama has a simple concave profile, with several very small amplitude knickpoints, and upstream the Rio Grande has a higher gradient and has a prominent knick-zone, comprised of several knickpoints and convex sections.

Rio Grande System

A prominent knick-zone is evident on the Rio Grande profile starting 42 km upstream from the confluence of the Rio Chama (Fig. 3, A-D). This knick-zone is a composite of four individual knickpoints (A-D) that in total constitute ~450 m of elevation change over ~80 km of river reach. The downstream knickpoint (in Precambrian rocks; A in Fig. 3) appears relatively sharp, whereas, the three upstream knickpoints (in Tertiary basalt; B, C, and D in Fig. 3) are rounded in profile. Are these knickpoints fixed at bedrock- or structurally controlled "waterfalls" perhaps due to base-level fall and differential incision as a function of rock type, or are they transient incision waves that are migrating north following some tectonic or drainage reorientation event?

Analysis of the tributary profiles at and south (downstream) of the Rio Grande knick-zone (Fig. 3) indicates that knickpoints also exist in the side stream tributaries in the section between the Rio Chama confluence and knickpoint (D) in the Rio Grande. The Rio Embudo, which enters just below the first Rio Grande knickpoint (A) has a complex profile with a prominent knickpoint (E) ~16 km above the confluence. The Rio Pueblo de Taos, which has its confluence just downstream from the second Rio Grande knickpoint (B) is also convex and has a knickpoint (G) closer (~5 km) to its confluence with the Rio Grande. The Rio Hondo, which joins the Rio Grande ~ 12 km upstream from knickpoint (B), has a simpler, steep and slightly concave profile (Mitchell, 2000). The Red River, which joins the Rio Grande just below the third Rio Grande knickpoint (C), has a generally steep profile that is slightly convex overall.

In contrast, above the Rio Grande knick-zone (A – D, Fig. 3), the tributary profiles are different. The Rio Costilla is concave

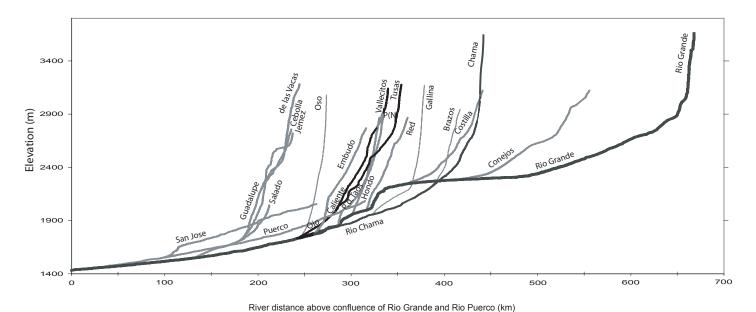


FIGURE 2. Longitudinal river profiles for the Rio Grande and its major tributaries from the confluence of the Rio Puerco (south) to the headwaters of the Rio Grande (north); tributaries of the Rio Chama are shown by thin gray lines and tributaries for the Rio Grande are shown as thick gray lines.

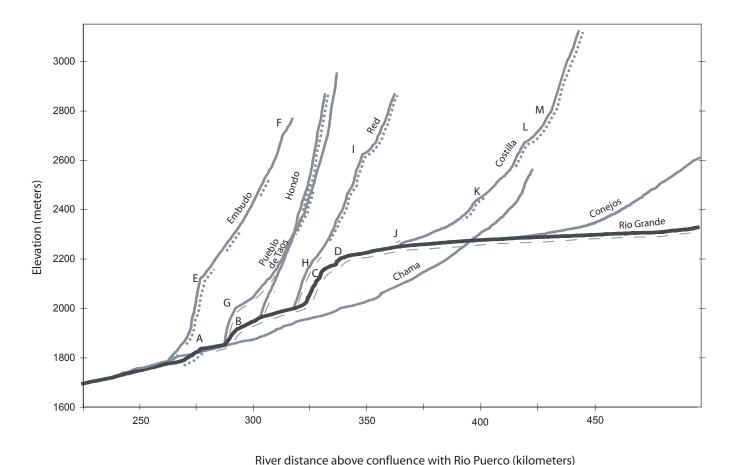


FIGURE 3. Longitudinal profiles for the Rio Grande and its major tributaries through the knickpoint reach of the Rio Grande. Major knickpoints identified by capital letters and bedrock type underlying knickpoints delineated by a dotted pattern for Precambrian basement and by bars for Tertiary basalts.

over most of its length and appears graded to the gentle upstream profile of the upper Rio Grande. It does show a slight convexity near its confluence with the Rio Grande, as it cuts through Taos Plateau basalts. Similarly, except for its mountain reaches, the Conejos River is concave and graded to the gentle upstream profile of the upper Rio Grande. It is important to note that the gentle upper Rio Grande is still well entrenched into the Taos Plateau basalts as it flows through the southern San Luis Basin. In summary the knickpoint reach (A-D, Fig. 3) of the Rio Grande is characterized by convex or steep profile tributaries below the knick-zone (A-D) transitioning to concave, graded profiles above the knickpoint (D). Also, the knickpoint in the Rio Embudo is farther upstream than the knickpoints in the Rio Pueblo de Taos and Red River.

The type of bedrock in the vicinity of the knickpoints was identified on the river profiles (Fig. 3). The downstream knickpoint of the Rio Grande (A of Fig. 3) as well as the knickpoint on the Rio Embudo (E of Fig. 3) are underlain by Precambrian basement rocks. The three upper knickpoints of the Rio Grande (B - D of Fig. 3), the knickpoint on the Rio Pueblo de Taos (G of Fig. 3) and the convex reach of the Red River (H of Fig. 3) pass through basalts of the Taos volcanic field.

Rio Chama System

The Rio Chama and its tributaries are different in longitudinal profile than the Rio Grande (Fig. 4). Our observations suggest that the Rio Chama system does not show the prominent knick-zone that characterizes the Rio Grande system in northern New Mexico. However, under close examination, the Rio Chama profile that on average is smooth and concave, displays minor knick-points and reaches with slightly convex profiles. Aside from the Rio Ojo Caliente, which shows a relatively gentle profile graded to the Rio Chama, the smaller tributaries including the Rio Oso, Rio Tusas, Vallecitos River, and the Rio Brazos generally have steep profiles with numerous convex reaches with small amplitude knickpoints (f, g, h-i, j, n, s-t, etc. of Fig. 4).

Unlike the knickpoints on the Rio Grande, the small knickpoints on the Rio Chama are underlain by soft Cenozoic and Mesozoic sedimentary rocks, and can be generally associated with formation changes. The knickpoints on the tributary streams are generally underlain by Tertiary volcanics (Rio Oso) or Precambrian basement rocks (Tusas, Vallecitos, and Brazos), and the presence of knickpoints is likely due to rock strength changes. Interestingly, the Rio Ojo Caliente, which in the study area passes

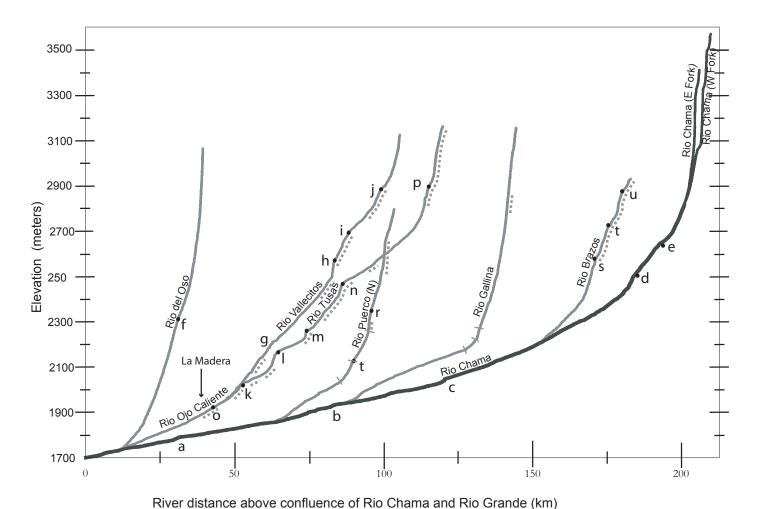


FIGURE 4. Longitudinal profiles for the Rio Chama and its major tributaries from the Rio Chama confluence with the Rio Grande (south) to the head-waters of the Rio Chama (north). Major knickpoints identified by lower-case letters and bedrock type underlying knickpoints delineated by a dotted pattern for Precambrian basement.

through the Tertiary Santa Fe Group, has a short box canyon section comprised of Precambrian basement; and its profile does not show a defined knickpoint in these hard rocks (o, Fig. 4).

Quaternary Terraces

Profiles represent today's river gradient, whereas past river levels and gradients are preserved in abandoned terraces. Terrace mapping was conducted along the Rio Ojo Caliente near the town of La Madera, New Mexico (Fig. 1). Ten Quaternary terraces were identified and mapped (Figs. 5 and 6) and their strath elevations above the active river channel were measured (Table 1). Terraces were identified as Q1 – Q10, with Q1 being the lowest topographically, and Q10 being the highest. Straths were cut into either the Tertiary Santa Fe Group or the Precambrian basement. In some cases, such as with Q10, a terrace strath was not exposed and only remnant river gravels were present, so an estimated elevation was assigned. Terrace tread heights were also recorded to aid in correlation with other regional terrace mapping reported in the literature (Gonzalez and Dethier, 1991; Dethier and Reneau, 1995). Terrace deposits were composed of several meters of poorly to

unconsolidated, moderately-well to well rounded gravels and cobbles, comprised predominantly of quartzite. Soils on most terrace treads were very poorly developed and not diagnostic for correlation, with one exception. A well-developed soil profile was identified on the tread of Q9, comprised of a moderately well developed argillic horizon, and a stage II-III soil carbonate horizon (Machette, 1985). Terrace correlations were done primarily using topographic height above the active river, and by mapping semi-continuous straths. Within the map area (Fig. 5), terraces Q1 – Q6 are paired east and west of the Rio Ojo Caliente. To the west of the map area, two surfaces topographically equivalent to Q7 and Q9 were observed, suggesting that these terraces are also paired, at least locally. Q8 and Q10 were not observed west of the Rio Ojo Caliente in the vicinity of the map area.

In addition to the new mapping near La Madera, terrace mapping was conducted along the Rio Ojo Caliente between La Madera and the confluence with the Rio Chama, and along the Rio Chama for 4 km upstream of its confluence with the Rio Grande (Koning and Manley, 2003; Koning, 1994). In the lower reaches of the Rio Ojo Caliente, the terrace deposit of Q2 is dis-

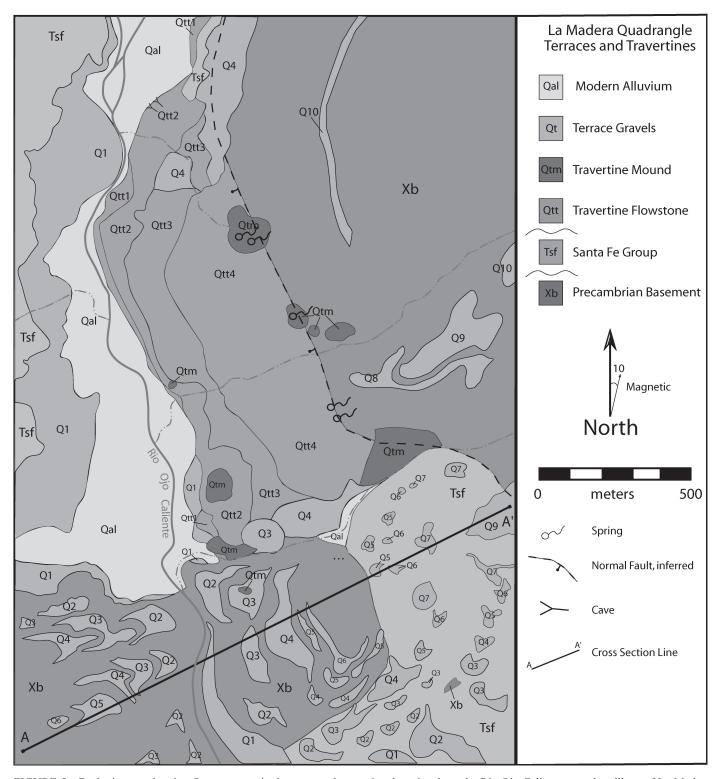


FIGURE 5. Geologic map showing Quaternary paired terrace and travertine deposits along the Rio Ojo Caliente near the village of La Madera, NM. Terrace number (Q1 - Q10) indicates topographic position, with Q1 being lowest and Q10 highest.

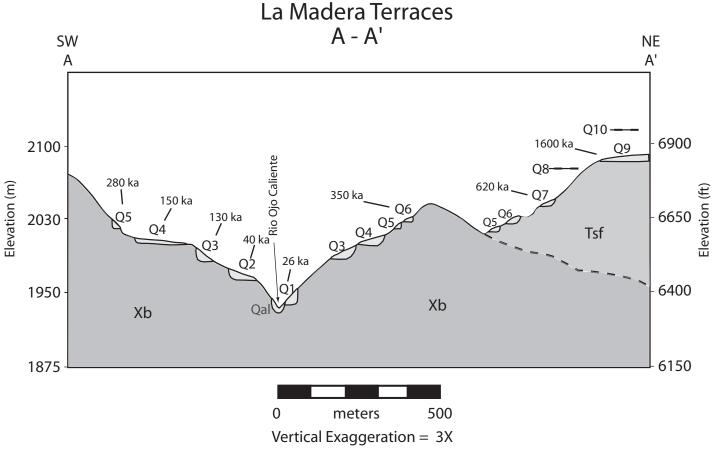


FIGURE 6. Geologic cross-section A-A' showing Quaternary terrace deposits mapped along the Rio Ojo Caliente near La Madera, NM. Local age control assigned based on correlations with Dethier and Reneau (1995) and Gonzales and Dethier (1991).

tinct in that it contains large basalt boulders derived from Black Mesa (Fig. 1), and Q3 is locally comprised of a subset of three slightly inset terrace straths. The mapped elevation of these terrace straths, supplemented with heights measured by Jacob staff for most terraces, was used to calculate the elevation above the current river channel. A perpendicular line between the mapped strath location and the current channel trend was used to pick the river channel elevation off of 1:24,000 USGS quadrangles with a 20 ft. contour interval; therefore, terrace correlations shown in figure 7 are projected into a vertical plane parallel with the present-day river channel axis.

Dethier et al. (1988), Gonzales and Dethier (1991) and Dethier and Reneau (1995) reported age control on terraces mapped and correlated along the Rio Grande in and near White Rock Canyon, and along the Rio Chama near the confluence with the Rio Grande, near the confluence with the Rio Ojo Caliente and slightly upstream from this confluence. Their best age control was derived from the occurrence of basal Bandelier Tuff Guaje pumice (~1600 ka) and Lava Creek B tephra (620 ka) within terrace deposits; amino acid racemation ages were also used for age control (last 400 ka) from fossil gastropods found in terrace and lacustrine sediments, and radiocarbon ages were obtained in the younger terraces. Extending the terrace correlations along the Rio Ojo Caliente downstream to the Rio Chama, we can compare

the Rio Ojo Caliente terraces to the dated terrace sequence along the Rio Chama. We were able to correlate our terrace sequence along the Rio Ojo Caliente and Rio Chama to this well studied and dated terrace sequence as shown in Table 1. The terraces

TABLE 1. Rio Ojo Caliente and Rio Chama Fluvial Terraces

Terrace	Strath Height (m above river²)	Mean Strath Height (m)	Approximate Age (ka) ³
Black Mesa ¹	268.3	268.3	3650
Q10	152-164	160	na
Q9	134-142	137	1600
Q8	113-128	120	na
Q7	82-122	109	620
Q6	67-98	84	350
Q5	67-82	67	280
Q4	55	55	150
Q3	30-61	46	130
Q2	14-49	29	40 - 100
Q1	3-12	6	26 - 40

¹Ancestral Rio Grande gravels located beneath Black Mesa basalt

²Projected height above Rio Ojo Caliente or the Rio Chama

³Approximate ages assigned based on correlation to terrace chronology reported by Dethier and Reneau (1995) na – not available

along the Rio Ojo Caliente downstream to the Rio Chama and subsequently downstream to the confluence with the Rio Grande (approximately 50 km) were correlated based primarily on strath height above the active channel. In some cases, the physical and sedimentological characteristics of the terrace fill and the overlying soil are used, as noted above, but distinguishing characteristics are limited. Due to the well exposed and relatively continuous nature of the terrace straths and deposits, we were able to correlate most of the terraces longitudinally; however, the correlations are preliminary and future work is needed to better characterize the sedimentology and soils, and if possible date the deposits. Figure 7 shows the terrace correlation from La Madera downstream to the confluence with the Rio Grande. In the upper reaches of the Rio Ojo Caliente, the terrace surfaces roughly parallel the current river profile. Near the confluence with the Rio Chama, the terraces older than Q2 appear to deviate from the river profile; downstream from the confluence, these surfaces return to a parallel configuration. Downstream from the confluence with the Rio Grande the surfaces appear to show some deviation again; the reason for these deviations is still under investigation, and further work is necessary to confirm and improve the correlations in these areas.

The highest river gravels were found underlying the Servil-

leta Basalt flows topping Black Mesa along the Rio Ojo Caliente ~10 km north of the Rio Chama confluence. The clasts are imbricated, with imbrications averaging S35°W, roughly parallel with the trend of Black Mesa. Gravels underlying this flow are also reported in May (1980), Gonzales and Dethier (1991), and Koning and Manley (2003). Dethier and Reneau (1995) reported an Ar-Ar age for the basalt flow of 3.65 Ma, providing a minimum age for the river gravels. These gravels have a provenance consistent with the southernmost San Luis Basin and Peñasco Embayment (Koning and Manley, 2003; Koning, 1994). However, at the southernmost end of Black Mesa, the clast compositions suggest some input from the Rio Chama system and paleocurrent directions are more variable (Koning and Manley, 2003). The basalt flow likely filled the lowest part of the paleovalley containing the ancestral river systems at 3.65 Ma. The fact that these flows are now the highest features in the landscape is an excellent example of inverted topography due to resistance to erosion of the basalts. Continuations of this ancestral river may have flowed under what is now the Pajarito Plateau as suggested by river gravels within strata underlying the Bandelier Tuff in some canyons (Griggs, 1964; Waresback and Turbeville, 1990; Turbeville, 1991; Dethier, 1997) and by gravels intersected in drill core on the Pajarito Plateau (Vaniman et al., 2002).

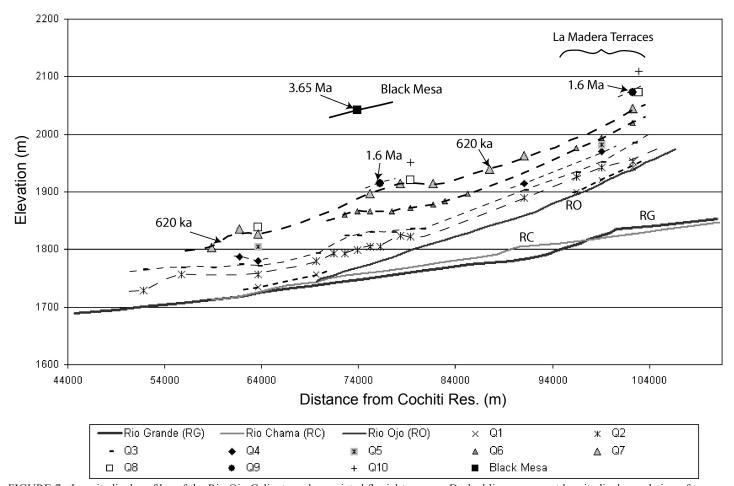


FIGURE 7. Longitudinal profiles of the Rio Ojo Caliente and associated fluvial terraces. Dashed lines represent longitudinal correlation of terrace straths. Age control from correlation to Dethier and Reneau (1995) indicated on selected terraces (Table 1).

Incision Rates

Based on the measurements of terrace strath elevation and the correlation of terrace surfaces to local age control, the average incision rate over the last 3.65 Ma for the Rio Ojo Caliente- Rio Chama system is 74 m/m.y. But, based on the average terrace strath elevations above the current river channel, rates were variable through this time, and the average incision rate was ~65 m/my from 3560 - 1600 ka, ~30 m/my from 1600 - 620 ka, and ~175 m/my from 620 ka to the present (Fig. 8). These three intervals are constrained by radiometric ages of the Black Mesa basalt, the Guaje pumice, and the Lava Creek B tephra, respectively. These rates fall within the range of other regional incision rates reported in the literature (Dethier, 2001; Wisniewski and Pazzaglia, 2002; Pazzaglia and Hawley, 2004). Between 620 ka and present there are 6 terrace surfaces along the Rio Ojo Caliente that we have correlated to age control that is based primarily on gastropod amino-acid racemation ages (Gonzalez and Dethier, 1991; Dethier and Reneau, 1995). Utilizing these ages, the incision rate over the last 620 ka has varied between 90 and 1600 m/m.y. (Fig. 8), although the very rapid incision rates only apply for short periods of time on the order of thousands to tens of thousands of years. The degree to which this highly variable incision rate over this period is real, versus due to dating uncertainties of the terrace deposits, is unknown. Also note that the current river is flowing on alluvium of an unknown thickness; therefore, all of the incision rates are calculated to present river level, not to the buried bedrock strath (c.f. Pederson et al., 2002) and hence are minimum estimates of bedrock incision averaged over the time period in question.

Quaternary Travertines

Quaternary travertine deposits mapped along the Rio Ojo Caliente near La Madera (Fig. 5) provide a potentially powerful tool for further understanding differential incision over the last ~ 400

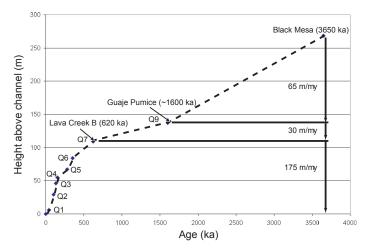


FIGURE 8. Graphical representation of the average incision rate calculated from the terrace straths and correlation to age control from Dethier et al. (1988), Gonzales and Dethier (1991), and Dethier and Reneau (1995).

ka. Travertine deposits originate from springs that issue along a normal fault between the Tertiary Santa Fe Group and the Precambrian basement in the map area. Travertine forms modern and ancient spring-mound deposits, large platforms of flowstone that are topographically equivalent to fluvial terrace gravels, and, importantly, has cemented fluvial terrace gravels of different ages, including the modern channel.

DISCUSSION

The combined data from analyses of river longitudinal profiles, terrace deposits, and incision rates in the Española and San Luis Basins aid us in interpreting the evolution of drainages during the integration of the ancestral Rio Grande in the Quaternary. On the basis of barbed river planforms and other geomorphic features, Wells et al. (1987) hypothesized that the internally drained San Luis Basin was captured and integrated into the Española Basin establishing a through-flowing Rio Grande between the two basins. Based on river terrace relationships, dated tephra (Bishop Ash) in the Hansen Bluffs lacustrine deposits of the San Luis Basin (Fig. 11), and paleontological evidence in these lacustrine deposits, the river integration event and formation of the knickpoint occurred sometime between 300 - 700 ka, with the 600 - 700 ka timeframe being most probable (Rogers, 1984; Rogers et al., 1985; Wells et al., 1987; Mitchell, 2000; Pazzaglia and Hawley, 2004). Prior to integration, the northeastern Española basin would have been drained by the ancestral headwaters of the Pleistocene Rio Grande near the present day Red River (Rogers, 1984; Rogers et al., 1985; Wells et al., 1987; Pazzaglia and Hawley, 2004). Based on the longitudinal profile of the Rio Chama system (Fig. 4) and its flight of terrace deposits, we propose that prior to the integration event, that the Rio Chama was the northwestern headwaters to the Plio-Pleistocene Rio Grande.

Knickpoints on river longitudinal profiles can be due to some event that results in a net change in base level or can be due to a rivers response to bedrock control (Knighton, 1993). The knick-zone on the Rio Grande has been described as a relatively young feature attributed to the drainage integration event in the Pleistocene (Wells et al., 1987). Individual knickpoints in the Rio Grande system can to a first order be attributed to bedrock changes or control, but the pattern of knickpoints in the Rio Grande and tributaries (Fig. 3) suggests the possibility of a more complex story. The profile convexities on the Rio Embudo (E, Fig. 3), Rio Pueblo de Taos (G, Fig. 3), and Red River (H, Fig. 3) could result from to simple bedrock control, tributary response to base-level drop on the Rio Grande, or possibly a wave of incision propagating northward. The absence of a convex profile on the Rio Hondo has been interpreted as a result of the Rio Hondo's ability to keep pace with base level fall and thus never forming a knickpoint (Kelson and Wells, 1989; Mitchell, 2000). Unlike the Rio Embudo and Rio Pueblo de Taos that have headwaters in Paleozoic sedimentary rocks, the Rio Hondo has headwaters in the Precambrian basement and has basin-area discharge properties that result in a higher effective stream power (Kelson and Wells, 1989). These factors underscore the need to understand how tributary discharge scales with basin area and bedrock prop-

erties before over interpreting the Rio Grande knickpoints. Our data are insufficient at present for any unique interpretation, but the patterns of convexities and knickpoints is noteworthy and worth further, more quantitative, analysis in the future.

The cause for the proposed 300 - 700 ka integration/knick-point formation has been a point of ongoing debate. Wells et al. (1987) argue the case for both climatic changes due to Pleistocene glaciation cycles and tectonic controls related to the Rio Grande rift or regional epeirogenic uplift. If river integration occurred at approximately 600 ka, then it corresponds with the apparent dramatic increase in incision rate (from 30 to 175 m/my) preserved by river terraces along the Rio Chama – Rio Ojo Caliente system. It may be that onset of rapid incision in the Chama system could be driven by increased incision in its downstream reaches because of the river integration event. Alternatively drainage capture of the San Luis Basin and increased regional incision in the Rockies may both have been a response to external forcing such as climate and/or tectonics.

Regional incision rates have varied substantially since the apparent onset of general basin dissection between 3.5 and 5 million years ago (Dethier et al., 1988; Gonzalez and Dethier, 1991; Dethier and Reneau, 1995; Pazzaglia and Hawley, 2004; Koning, 2004). Incision in the Española basin has also varied substantially (Fig. 8). Regional studies in the Rio Grande rift and the Rocky Mountains have identified similar ranges of incision rates and the case has been made for both climatic forcing (Wells et al., 1987; Dethier et al., 1988; Dethier and Reneau, 1995; Dethier, 2001; Pazzaglia and Hawley, 2004) and tectonic controls (Wells et al., 1987; Dethier et al., 1988; Pazzaglia, 1989; Formento-Trigilio and Pazzaglia, 1996, 1998; Wisniewski and Pazzaglia, 2002; Newell et al., 2003). Here we briefly revisit the debate by placing the new data collected in this study in the context of Plio-Pleistocene climate change and regional tectonism over the same period.

Starting in the Pliocene the global climate began to generally cool, and the Northern Hemisphere transitioned to a climate marked by swings between glacial and interglacial periods by the late Pliocene (Droxler et al., 2003). Looking specifically at the last 850 ka of global climate (Fig. 9; modified from Karner et al., 2002), based on marine oxygen isotopes, we have superimposed the apparent ages of river terraces in the Española Basin and the average incision rates over this period. The age of terrace deposits appear, in most cases, to roughly correlate with the transition from glacial (pluvial) to interglacial (interpluvial) periods. This is consistent with the hypothesis that during climatic transitions from wet to dry, sediment loads drop, followed by incision and the abandonment of terrace deposits (Bull, 1991). Also, the jump in average incision rate from 30 m/m.y. to 175 m/m.y. appears to correlate with a climatic shift to large swings in glacial-interglacial periods on a ~100 k.y. cycle (Fig. 9). However, data are insufficient to explore the impact of global climate on variability in local incision rates. Figure 9 places average incision rates along the Rio Ojo Caliente and Rio Chama in the context of climate variability; however, it is important to note that variability of local incision rates, in terms of periods of fast and slow incision, on the Rio Ojo Caliente and Rio Chama are not necessarily consistent

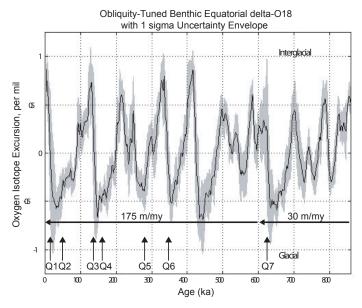


FIGURE 9. Global climate oscillations between glacial and interglacial periods over the last 800 k.y. based on marine oxygen isotopes. The Española Basin terrace chronology and average incision rates are superimposed on the record; modified from Karner et al. (2002).

with fast and slow periods of incision on other regional drainages (Frankel and Pazzaglia, 2004; Pazzaglia and Hawley, 2004).

Along with major changes in climate, regional magmatism was on the increase over the Plio-Pleistocene. Figure 10 shows the distribution of dated volcanic rocks in New Mexico (Chapin et al., 2004). Note that over the last five million years, volcanism, dominated by mafic volcanics, appears to have increased. This mafic magmatism has occurred within certain zones in the Rio Grande rift and along the Jemez lineament, a broad structural feature marked by Neogene and Quaternary magmatism and tectonism that crosses the Rio Grande rift in the northern Española Basin (Fig. 11). A closer look at several fields in northern New Mexico (NMBGMR, 1998) indicates that magmatism over the last 5 Ma has occurred in different locations at different times. Periodic magmatism in the Rio Grande rift and along the Jemez lineament may be associated with gentle doming that drives, in part, incision in the Española Basin. In support of this hypothesis, Wisniewski and Pazzaglia (2002) attributed Quaternary convexup river and terrace profiles along the Canadian River to doming along the Jemez lineament.

The Quaternary travertine deposits mapped along the Rio Ojo Caliente may hold more answers related to the forces driving incision. Travertines near La Madera, NM offer an opportunity for additional age control on terraces younger than \sim 400 ka using U-series dating. Field relationships suggest that travertine cemented terrace gravels and large travertine surfaces, or terraces, are roughly coeval with fluvial terraces. Travertine deposition may also be linked to climate variation and tectonic pulses. The model for travertine deposition in the Colorado Plateau and Rio Grande rift (Crossey et al., 2003) links deeply sourced CO_2 gas charged fluids related to magmatism to mixing with shallow

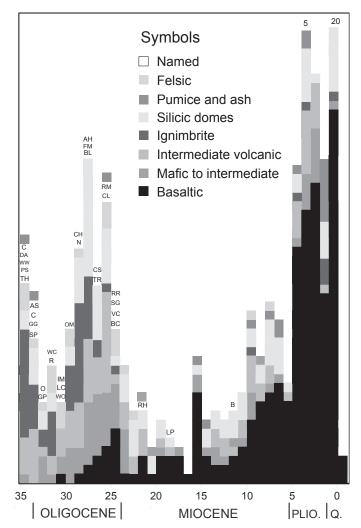


FIGURE 10. Bar graph showing the distribution and frequency of volcanism in New Mexico since the Cretaceous; note the large increases in volcanism in the Plio-Pleistocene; modified from Chapin et al. (2004).

aquifers along flow-paths focused along basement penetrating faults. Acquisition of the required calcite load is accomplished by dissolution of calcium bearing minerals along the flow path and deposition of carbonate occurs after surface discharge and CO₂ degassing at springs. Pulses in magmatism and related seismicity could add the required gases and fluids to drive travertine accumulation, or alternatively, gases and fluids are always present in the system and high discharge at springs during wet (pluvial) periods is required for large accumulations. Also, the oxygen isotopic signature of banded Quaternary travertine flowstone has been shown to preserve a meaningful record of climate variability on a local scale (Obrien, 2002; Matsuoka et al., 2001). Future work on the La Madera travertines including U-series dating, stable isotopic analysis, and fluid inclusion analysis will help to provide data to resolve the incision history and the complex interaction of climate and tectonism on the system.

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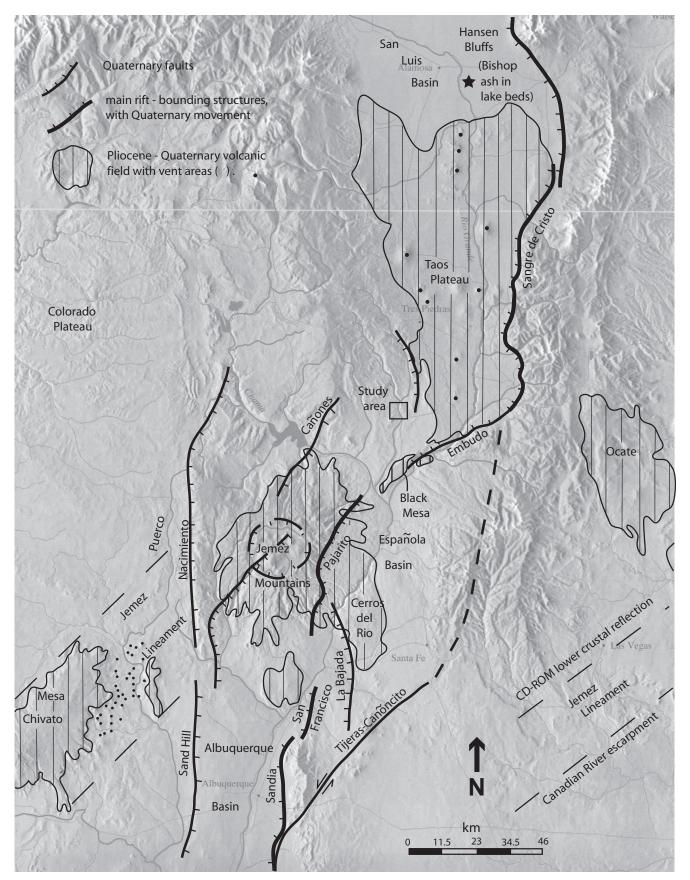


FIGURE 11. Major regional neotectonic and volcanic features of the Española and San Luis Basins, northern New Mexico and southern Colorado superimposed on a digital elevation model for the region; modified from Chalk Butte Inc. (1995).

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