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QUATERNARY EVOLUTION OF THE RIO GRANDE NEAR COCHITI LAKE, NORTHERN SANTO DOMINGO BASIN, NEW MEXICO

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Abstract—Quaternary base-level change in the northernmost Santo Domingo basin records the effects of damming and knickpoint migration upstream in White Rock Canyon and the influence of middle Pleistocene climate change. Quaternary changes were superimposed on complex base-level responses to changes in upstream sediment delivery, volcanism in the western Cerros del Rio and movement along the La Bajada fault zone in the late Pliocene and early Pleistocene. During Quaternary time, the Rio Grande cut the modern White Rock Canyon, initially transporting large quantities of sediment into the northernmost Santo Domingo basin, then incising this fill and underlying bedrock, stranding a series of inset, mainly fill terraces. Two principal pulses of aggradation, separated by >40 m of incision, can be distinguished in the surficial geologic record near the southern end of White Rock Canyon: an early Pleistocene episode (Q_1) that began with eruption of the upper Bandelier Tuff and another episode (Q_2) in middle Pleistocene time. Base-level lowering of ~60 m, punctuated by relatively brief periods of aggradation (Q_3 and Q_4), dominated geomorphic changes in the northernmost Santo Domingo basin from about 300 ka to present. Middle and late Pleistocene incision records decreased sediment load or increased stream power that resulted from upstream drainage evolution and pluvial/interpluvial cycles of increased amplitude.

INTRODUCTION

During Quaternary time, the Rio Grande cut the modern White Rock Canyon, initially transporting large quantities of sediment into the northernmost Santo Domingo basin, then incising this fill and underlying bedrock, stranding a series of inset, mainly fill terraces. Quaternary events were guided by the late Pliocene position of the Rio Grande as it ended a period of aggradation, late Pliocene faulting and Plio–Pleistocene volcanism. Despite the proximity of the Cochiti Lake area to the La Bajada fault zone (Fig. 1) and deformation of the oldest terrace, faulting appears to have affected sediment production only indirectly. Quaternary sedimentation and base-level change in the northernmost Santo Domingo basin were dominated by extrabasin effects: (1) erosion and transport of the Bandelier Tuff, which completely filled White Rock Canyon at 1.61 and 1.22 Ma (ages from Izett and Obradovich, 1994); (2) removal of one or more basalt knickpoints exposed during cutting of the Canyon; (3) formation and subsequent erosion of landslide dams and associated lake sediment (Reneau and Dethier, 1996a); and (4) variable, but increasing stream power or decreasing sediment load in middle Quaternary time, most likely driven by climate change. Episodic changes in vegetation, hillslope erosion and stream power during pluvial/interpluvial cycles undoubtedly influenced rates of downcutting and sedimentation patterns along the Rio Grande and its tributaries, modulating transport of sediment to the northern Santo Domingo basin. This paper documents the aggradation and incision history of the northern part of the Santo Domingo basin, using evidence preserved in the Cochiti Dam quadrangle and upstream along White Rock Canyon into the southern Española basin.

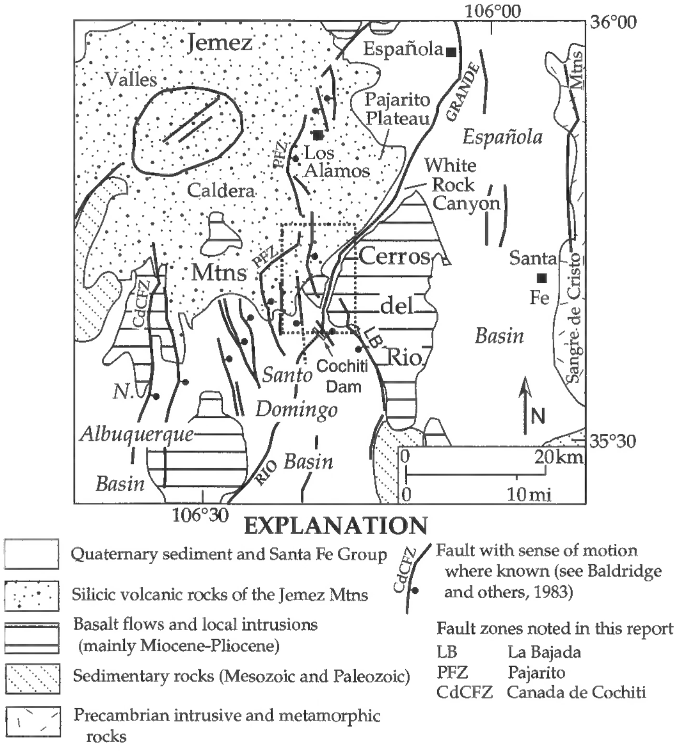

FIGURE 1. Map showing regional geology and location of northern Santo Domingo basin and White Rock Canyon. Dashed rectangle outlines Cochiti Dam 7.5' quadrangle.

SETTING

Location and climate

The northern Santo Domingo basin extends south from southern White Rock Canyon, where it is bounded by the La Bajada escarpment to the east and the Jemez Mountains to the west. The Rio Grande flows in an narrow meander belt 200–300 m below the canyon rim in White Rock Canyon and is flanked by extensive high terraces in the vicinity of Cochiti Lake and by lower terraces in the southern Cochiti Dam quadrangle. Elevations in the area range from about 1600 to over 2145 m. Comparison to nearby areas in the Española basin suggests that the mean annual temperature near Cochiti Lake is about 10.5°C and precipitation is about 30 cm, split about equally between relatively gentle winter precipitation and more intense monsoonal precipitation during July and August. Present climate is thus semi-arid. Vegetation ranges from mixed piñon/juniper woodland in the higher elevations to communities dominated by grasses and sagebrush at elevations below about 1650 m.

Bedrock geology and structure

The Santo Domingo basin represents a complex transitional zone between the Albuquerque basin to the southwest and the Española basin to the northeast. Portions of the area have been mapped by: (1) Smith et al. (1970), who emphasized volcanic rocks; (2) Kelley (1977), who focused on sedimentary rocks and structure; and (3) Smith and Kuhle (1998 a, b), who used new 1:24,000 geologic mapping and limited subsurface data to suggest revisions to hydrostratigraphic models of the Santo Domingo basin. Erosion of the northern basin has exposed mainly late Cenozoic sedimentary rocks and sediment deposited by the ancestral Rio Grande and by channels draining piedmonts to the east and west. Interlayered with the sediments are Pliocene and early Pleistocene basalts and evolved rocks derived from the Cerros del Rio volcanic field and early Pleistocene silicic tuffs erupted at the Valles caldera in the Jemez Mountains. The La Bajada fault zone, which strikes northwest through the study area, offsets the lower Bandelier Tuff by about 100 m at White Rock Canyon, but extends <1 km west of the Rio Grande. Buried Pliocene volcanic rocks in the hanging wall of the fault suggest that post 2.7-Ma offset to the southeast may exceed 300 m (Smith and Kuhle, 1998a). West of the Rio Grande, the Pajarito fault and subparallel splays closer to Cochiti Lake drop the upper Bandelier Tuff down to the east about 30–120 m (Smith and Kuhle, 1998a). The La Bajada fault zone apparently does not displace middle Pleistocene deposits east of the Rio Grande. Aby (1997), however, suggested that the Pajarito fault zone deforms middle, and possibly, late Pleistocene terraces to the west of the Rio Grande.

METHOD

Field mapping and measurements reported here were collected on the Cochiti Dam 7.5-minute and adjacent quadrangles during field studies sponsored by the U.S. Geological Survey's Middle Rio Grande Basin Project and by the New Mexico Bureau of Mines and Mineral Resources STATEMAP Project (Smith and Kuhle, 1998b). Terrace nomenclature in this paper replaces preliminary terrace assignments for the Cochiti Dam area given in Dethier et al. (1988; Figs. 2, 3). The reader should note that in referring to deposits beneath terraces, this report uses the height of the top of the axial gravel above present grade; elevations listed for Q_1–Q_4 in Dethier et al. (1988) referred to the height of terraces above present grade.

Field measurements

My geologic mapping in the Cochiti Dam quadrangle used traditional field and air-photo analysis techniques. Location and elevation control was provided by inspection of the 1:24,000 topographic map, supplemented by older maps and GPS measurements in areas of altered or inundated topography near Cochiti Dam and Cochiti Lake. Topographic uncertainty is thus ±6 m and locally greater, particularly where grading during dam construction or inundation by Cochiti Lake has obscured original topographic and geologic relationships. I measured stratigraphic sections and fault offsets using a hand level and local topographic control. Gravels occur in a variety of stratigraphic settings and are categorized by rock type. I use "axial lithologies (gravel)" here for mixtures of resistant clasts dominated by Precambrian quartzites transported by the Pliocene and Pleistocene Rio Grande from northern New Mexico; axial deposits younger than about 1.2 Ma include significant numbers of rounded boulders composed of vesicular basalt. Piedmont deposits include a western facies rich in silicic and intermediate volcanic rocks from the southern Jemez Mountains and an eastern facies characterized by granitic rocks transported from the southern Sangre de Cristo Range by the ancestral Santa Fe River and other piedmont drainages. Rounded boulder gravel rich in intermediate volcanic rocks (dacitic and andesitic?) is present in Quaternary deposits and was probably eroded from the Cochiti Formation (Smith and Levine, 1996) and the Puye Formation (Waresback and Turbeville, 1990) by east-flowing tributaries of the ancestral Rio Grande.

Ages derived from radiometric and amino-acid racemization techniques

Age control near the southern end of White Rock Canyon is provided by local stratigraphic relationships, Ar/Ar dating of basaltic rocks and silicic tuffs, and amino-acid racemization ratios (AARs) in gastropods contained in some Quaternary deposits (Table 1). At several sites early Pleistocene deposits overlie basaltic rocks dated at about 2.5 Ma. Stratigraphic relationship of deposits and surfaces to the lower and upper Bandelier Tuff, dated at 1.61 and 1.22 Ma, respectively, provide the most useful time lines. Several dated flows of andesite, trachyandesite, and dacite are younger than the lower Bandelier Tuff and provide stratigraphic markers along the eastern margin of the Rio Grande. Fall and reworked layers of San Diego Canyon tuff (1.85 Ma), pumice of the Valles Rhyolite (South Mountain(?) tuff and El Cajete pumice) and the far-traveled Lava Creek "B" ash (0.62 Ma) are also present locally between White Rock Canyon and Santo Domingo Pueblo to the south.

Gastropods collected at seven sites from beneath two terraces were analyzed using techniques described by Dethier and McCoy (1993). Several gastropod species were analyzed from each of the sites to aid comparison to AAR-age relationships developed from nearby areas (Dethier and McCoy, 1993). I derived a preliminary AAR-age relationship using the genus Succinea for the northern Santo Domingo basin, based primarily on the parabolic curve presented by Dethier and McCoy (1993) and on the slightly higher temperatures in the Cochiti Dam area.

GEOLOGY AND AGE OF QUATERNARY ALLUVIAL DEPOSITS

Field relationships, radiometric ages, and age estimates derived from gastropod AARs permit separation of five Quaternary terraces that cap alluvial deposits along the Rio Grande north of Cochiti Dam (Figs. 2, 3). Alluvial fills overlie erosion surfaces cut on late Pliocene and early Pleistocene volcanic rocks. Age/elevation relationships (Table 1) show that late Pliocene base level was only slightly higher than at present. Levels rose by <80 m in the early Pleistocene and began falling again after 1.2 Ma, most rapidly after ~300 ka. The highest terrace (Q_1) is: (1) extensively preserved, but only south of the La Bajada fault zone; (2) poorly defined by elevation above the Rio Grande, partially because of faulting; and (3) apparently much steeper than the lower terraces. Calculated slope for the terrace (0.035) is likely a minimum estimate, because the data include at least two downfaulted sections; other areas may also have been deformed. Younger terraces are apparently undeformed, more closely follow the present course of the Rio Grande, and their slopes are less than that of Q_1, although more than that of the predam Rio Grande; younger terraces are reasonably well defined by elevation.

Q_1 terrace and underlying deposits

High surfaces and underlying deposits mapped as Q_1 represent the peak of Quaternary aggradation in the northern Santo Domingo basin. The best-exposed deposits record somewhat different histories (Fig. 4). Preserved Q_1 remnants on both sides of the "big bend" in the Rio Grande (Fig. 2) are 100–115 m above the Rio Grande and consist of alluvial fills 15–30 m thick that include immense blocks of upper Bandelier Tuff flow units and locally overlie the tuff. The upper surface of Bandelier Tuff is pervasively fractured and disrupted in some exposures, making it difficult to identify the contact between the tuff and overlying sediment. Section 96-40 portrays the southern end of a segment of the early Pleistocene paleocanyon mapped by Reneau and Dethier (1996b). The exposed section suggests that near the big bend, the ancestral Rio Grande flowed in this paleocanyon before the eruption of both units of the Bandelier Tuff and after eruption of the upper Bandelier Tuff. Splays of the La Bajada fault zone locally offset the Q_1 terrace (Fig. 2). Southwest of the big bend, section DN-96-74 exposes ~25 m of coarse alluvium above the upper Bandelier Tuff, including clasts of tuff <5 m in diameter. Near the Tetilla Peak Overlook (Fig. 2), major areas of the Q_1 terrace cover a coarse alluvial fill 20–40 m thick that overlies a laterally extensive basal zone consisting of rounded boulders of intermediate volcanic rock. Most of the fill near section 96-27 is rich in axial lithologies and pumiceous material. The southeastern Q_1 remnant is preserved west of a fault that parallels the La Bajada zone and may be displaced by a northwest-striking fault, but field evidence for significant displacement is not compelling. With the exception of remnants near the town of Cochiti Lake, subangular blocks of basalt <3 m in diameter are exposed beneath and on each of the Q_1 terraces. The remnants east of the town overlie axial gravel that locally includes blocks of lower Bandelier Tuff as large as 5 m (G. A. Smith, written

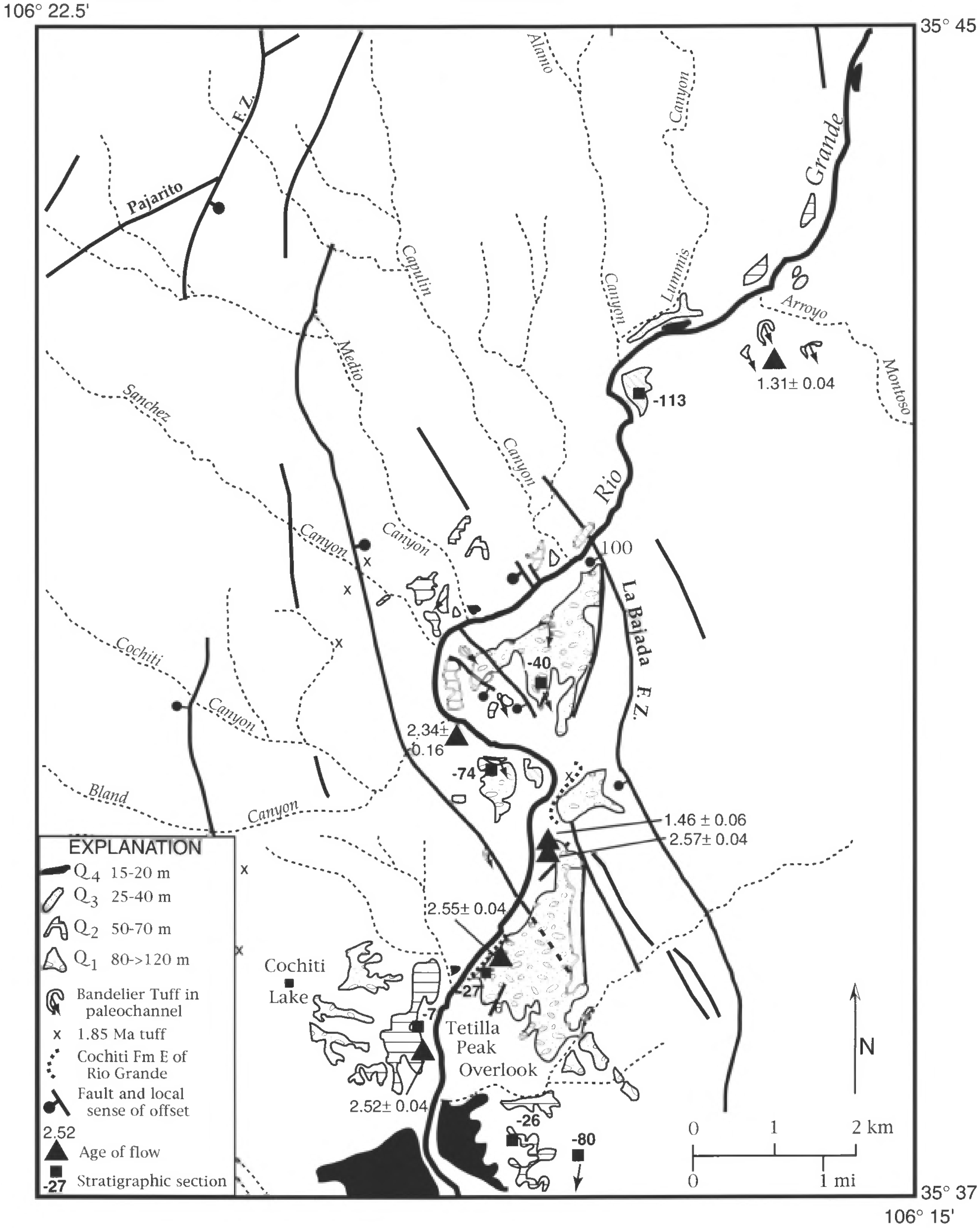

FIGURE 2. Sketch map of the Cochiti Dam 7.5-minute quadrangle showing Quaternary terrace deposits, selected geologic features, locations of stratigraphic sections and Ar/Ar ages of volcanic rocks (W. C. McIntosh, personal commun., 1997).

commun., 1998). Other Q_1 fills contain large fragments or boulders of upper Bandelier Tuff and pumiceous sand that might be derived from either unit. Surface soils on Q_1 terraces contain stage III+ and local stage IV soil-carbonate morphology (Birkeland, 1984) and abundant eolian fine material; buried soils in Q_1 alluvial fills contain well-developed Bt (argillic) horizons and local stage III soil-carbonate morphology.

Q_2 terrace and underlying deposits

Remnants of Q_2 are preserved from north of Arroyo Montoso to the

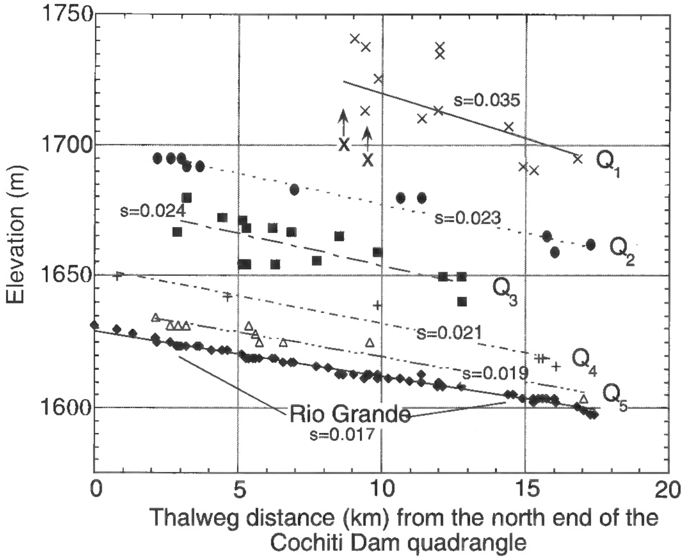

FIGURE 3. Gradients of Quaternary terraces and Rio Grande, Cochiti Dam quadrangle. Bold Q_1 points have been lowered by faulting; unfaulted elevations are not known with certainty. Gradients are linear fits to the data.

southern margin of the Cochiti Dam quadrangle, defining a south-sloping paleosurface about 60 m above the present channel of the Rio Grande. Terrace remnants upstream from Arroyo Montoso (Fig. 2) are underlain by >10 m of poorly exposed boulder gravel containing subangular blocks of basalt as large as 5 m and <15% axial lithologies. Surfaces of both remnants are mantled with colluvium and slope toward the Rio Grande. Two principal Q_2 terraces downstream overlie apparently dissimilar fill sequences. The extensive terrace east of the town of Cochiti Lake overlies a fill >15 m thick that includes a basal layer of rounded boulder gravel rich in intermediate volcanic rocks and contains sparse clasts of Bandelier Tuff (Fig. 5; section 96-7). Basal deposits resemble those at the base of the Q_1 fill. Reworked pumice in a channel filled with piedmont facies deposits gave an $^{40}Ar/^{39}Ar$ age of 0.55 Ma (Smith and Kuhle, 1998b), but the sedimentary context does not suggest if this is a close limiting date for this zone of the Q_2 fill. Well-developed buried soils in the upper part of the fill at 96-7 record pauses in aggradation that lasted at least tens of thousands of years. South of the Tetilla Peak Overlook, Q_2 deposits exposed at sections 96-26 and -80 (Fig. 5) are composed of >15 m of axial gravel. The upper 5–15 m of the axial deposits contain clasts of Bandelier Tuff and thus are demonstrably Pleistocene. Gravel lower in the section could be late Pliocene or Pleistocene. The upper part of the axial gravel interfingers with and is capped with 6–8 m of gravel-rich to silty piedmont deposits derived from the northeast. Gastropod AARs from these deposits suggest an age of 250–300 ka (Table 1), considerably younger than the <0.55-Ma age of the middle of the Q_2 fill exposed at site 96-7. Available age control thus suggests that Q_2 aggradation could have lasted as long as 300 ka in the northern Santo Domingo basin.

Q_3 terrace and underlying deposits

The Q_3 terrace, which is most extensive north of the La Bajada fault zone, is preserved as remnants near the Rio Grande south of Arroyo Montoso (Fig. 2). Near Alamo and Lummis Canyons, the terrace is present on both sides of the river and consists of two surfaces separated by a riser about 8 m high. Two closely spaced Q_3 surfaces are also suggested by topographic relationships on pre-lake maps and air-photo views of remnants now mainly submerged near the mouth of Sanchez Canyon (Fig. 2). Near Lummis Canyon, the higher of the two surfaces is underlain by 10–15 m of boulder gravel composed mainly of subangular blocks of basalt and minor axial lithologies (Fig. 6). Fill beneath the lower surface on both sides of the Rio Grande fines upward above a layer of rounded, locally imbricated 2-m-diameter boulders consisting mainly of intermediate volcanic rocks. Both fill deposits overlie strath surfaces on Pliocene hydromagmatic rocks. A south-sloping channel 3–8 m deep is cut into underlying bouldery deposits along the eastern margin of the terrace. I did not observe well-preserved soils in Q_3 deposits, but the El Cajete tephra overlies the terraces, demonstrating that they are older than 50–60 ka (Reneau et al., 1996a).

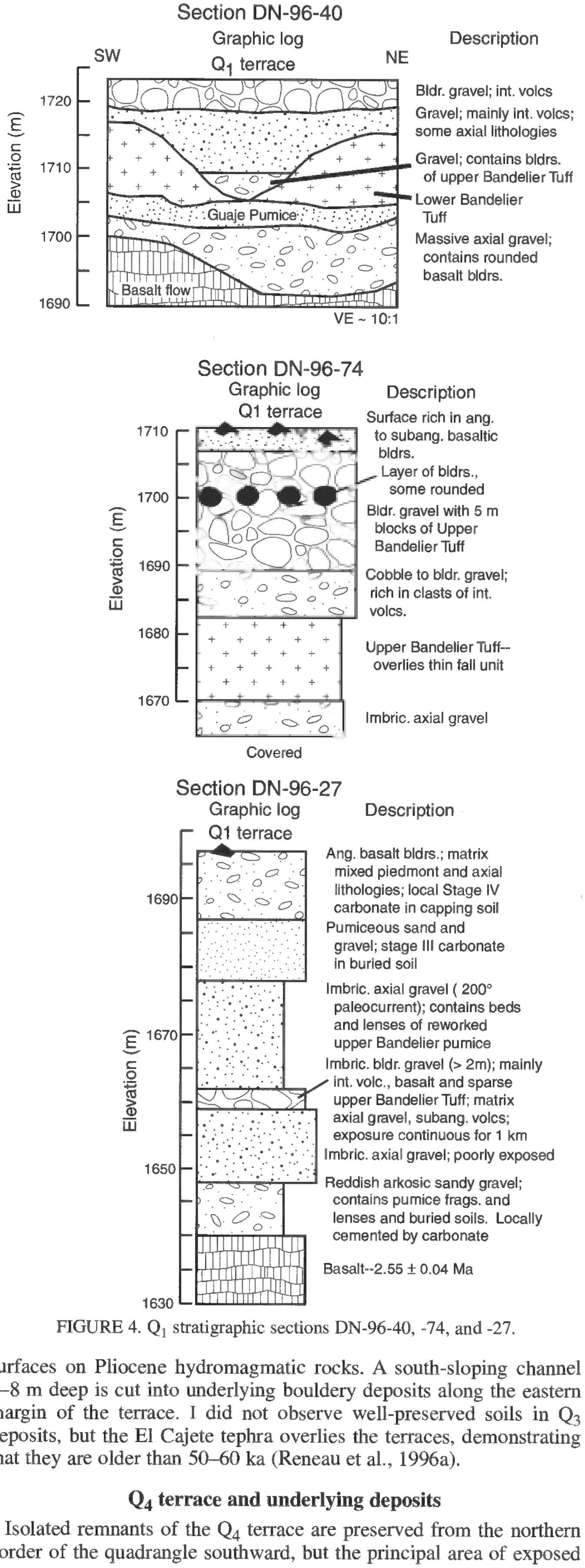

FIGURE 4. Q_1 stratigraphic sections DN-96-40, -74, and -27.

Q_4 terrace and underlying deposits

Isolated remnants of the Q_4 terrace are preserved from the northern border of the quadrangle southward, but the principal area of exposed

TABLE 1. Height and estimated age of late Pliocene and Quaternary deposits and landforms related to the ancestral and modern Rio Grande, northern Santo Domingo basin and vicinity, New Mexico.

Surficial or bedrock unit	Height[1] above Rio Grande (m)	Estimated age, in ka	Method[2]	Location and stratigraphic context
Basalt flow	30	2550	Ar/Ar	On axial gravel above Cochiti Lake
Pumiceous alluvium in Cochiti Fm	45–55	1850	Ar/Ar	Pumice from San Diego Canyon ignimbrite
Axial gravel	95–100	1610	Ar/Ar	Beneath I.Bandelier Tuff near La Bajada scarp
Basaltic flow	75–85	1460	Ar/Ar	Rests on Guaje pumice, pumiceous alluvium
Dacite flow	210	1370	Ar/Ar	Rests on I. Bandelier Tuff, n. of La Bajada fault
U. Bandelier Tuff	90–100	1220	Ar/Ar	In paleochannel at Rio Grande
Q1 fill, base	60	≤1220		Tetilla Pk. Recreation area exposure
Q1 fill, base	95–100	<1220		Northern exposure, near La Bajada scarp
Q1 terrace	120	≤1220		Northern exposure, near La Bajada scarp
Q1 terrace	95	≤1220		Tetilla Pk. Recreation area exposure
Q1 (?) fill	75[3]	620	Ar/Ar	Axial Rio Grande seds. with Lava Creek B tephra, beneath Q1, w. o f Santo Domingo Pueblo area
Q2 fill, base	45–50	≥250–300[4]		Lithologic similarity to Q1 base in area
Q2 fill	58	550	Ar/Ar	Valles Rhyolite pumice (reworked) in Q2 fill
Q2 terrace	60–70	250–300[4]		AARs from gastropods at two sites
Q3 terrace	38–48	60–300[4]		Near Alamo Canyon mouth; two local terraces
Axial gravel	33	≤100[4, 5]		Near Otowi Bridge north end White Rock Canyon
El Cajete pumice	15(?)	50 to 60		Near level of Q4 terrace (see Aby, 1997)
Q4 terrace	15-18	>38[6]	^{14}C	Sediment on Q4 terrace; AARs suggest 30–70 ka
Axial gravel	15	≥43.5	^{14}C	Base of overlying lacustrine sediment n. White Rock Canyon
Axial gravel	5–12	14–12	^{14}C	Interbedded with lacustrine sediment,White Rock Canyon
Q5 surface	3–8			
Axial gravel	5	9	^{14}C	Central White Rock Canyon
Holocene sediment	2	3	^{14}C	Central White Rock Canyon archeological site
Floodplain deposits	0	0[4]		Rio Grande, Española basin

[1] Measured from the active channel (former active channel where inundated) to the top of gravel or base of volcanic flow.

[2] Argon/argon ages from W. C. McIntosh (personal commun., 1977); Izett and Obradovich, 1994 (Guaje pumice) and Sama-Wojcicki et al., 1987 (Lava Creek B ash); El Cajete age from Reneau et al., 1996a; ^{14}C ages from Reneau and Dethier, 1996a.

[3] In Española basin north of White Rock Canyon, Lava Creek "B" ash is ~110 m above Rio Grande (Dethier et al., 1990); in l. Jemez R. drainage, ash is ~95 m above grade (Rogers and Smartt, 1996).

[4] Based on hydrolysate alle/Ile ratios (AARs) from Succinea or Vallonia from sections 96-26 and 96-80 (Dethier and McCoy, 1993, and unpublished).

[5] Maxium limiting age estimate because of shallow (<3 m) burial.

[6] Shell dates at two sites assumed to be minimum limiting ages.

deposits is near Cochiti Dam and as far as 10 km downstream from the Dam, primarily east of the Rio Grande (Fig. 1; Smith and Kuhle, 1998b). The fill consists of >5 m of axial gravel, locally overlying a layer of large basalt boulders. Piedmont sand and gravel derived from eastern and western sources, and local eolian deposits, interfinger with and cover the axial gravels. The terrace ranges from ~14–20 m above the modern Rio Grande; exposures at several locations south of Cochiti Dam, however, suggest that the Q_4 may include two closely spaced terraces (see also Aby, 1997). Gastropods from finer deposits overlying the axial gravel in two locations gave ^{14}C ages of about 38 ka, which I consider to be infinite for shell material and thus a minimum limiting age for the aggradational event. AARs from nearby sites beneath the same surface indicate an age of 30–70 ka (Table 1). Near the western margin of Cochiti Dam, alluvium rich in El Cajete pumice overlies the axial gravel, suggesting that the deposit is older than 50–60 ka. After reviewing geologic reports for the foundation of Cochiti Dam, Smith and Kuhle (1998b) concluded that the Q_4 fill is older than the El Cajete pumice and could be much older than the overlying fine material. I believe that the overlying deposits are only slightly younger than the gravel, and that AARs from gastropods in the fine sediment provide close limiting estimates for the period of gravel deposition. It is possible, however, that eolian portions of these piedmont deposits are considerably younger than the gravel. An early Wisconsinan age thus seems most likely for the upper surface of the gravel.

Q_5 terrace

When lake levels are low, terraces are exposed 5–8-m above the Rio Grande at several locations north of the La Bajada fault zone; they apparently correlate with low surfaces shown on pre-dam maps and with areas slightly higher than the floodplain downstream of Cochiti Dam. In addition, low terraces flank most of the major arroyos that drain into the Rio Grande. These terraces are likely of latest Pleistocene and/or Holocene age (Table 1).

DISCUSSION

Buried late Pliocene and early Pleistocene surfaces and Pleistocene terraces in the northern Santo Domingo basin record aggradation, then net downcutting of >120 m since 1.2 Ma, punctuated by periods of aggradation that produced fills as thick as 40 m. Stratigraphic relationships suggest that the Rio Grande, which eroded a shallow(?) canyon though sediment of the Santa Fe Group in early or middle Pliocene time, began to aggrade after ~2.7 Ma in the Cochiti Dam area. Aggradation in the northern Santo Domingo basin continued until after ~2.3 Ma, and the ancestral river cut a shallow paleocanyon east of White Rock Canyon before eruption of the lower Bandelier Tuff at 1.61 Ma (Reneau and Dethier, 1996b). Regional relationships and local stratigraphic relationships suggest that rapid excavation of southern White Rock Canyon occurred after the 1.6- and 1.2-Ma Bandelier Tuff eruptions. Deepening and headward extension of the Canyon followed in the middle Pleistocene, a time of regional climate change, drainage evolution, net incision and episodic aggradation (Dethier et al., 1988; Formento-Trigilio and Pazzaglia, 1998). Approximate terrace heights and age ranges in the northern Santo Domingo basin are similar to those of the Q_1–Q_4 sequence of erosion surfaces in the Española basin (Dethier et al., 1988; Dethier and McCoy, 1993), suggesting a close relationship between geomorphic events in the two basins. Formation and drainage of landslide-dammed lakes became a significant geomorphic process in White Rock Canyon in middle Pleistocene time

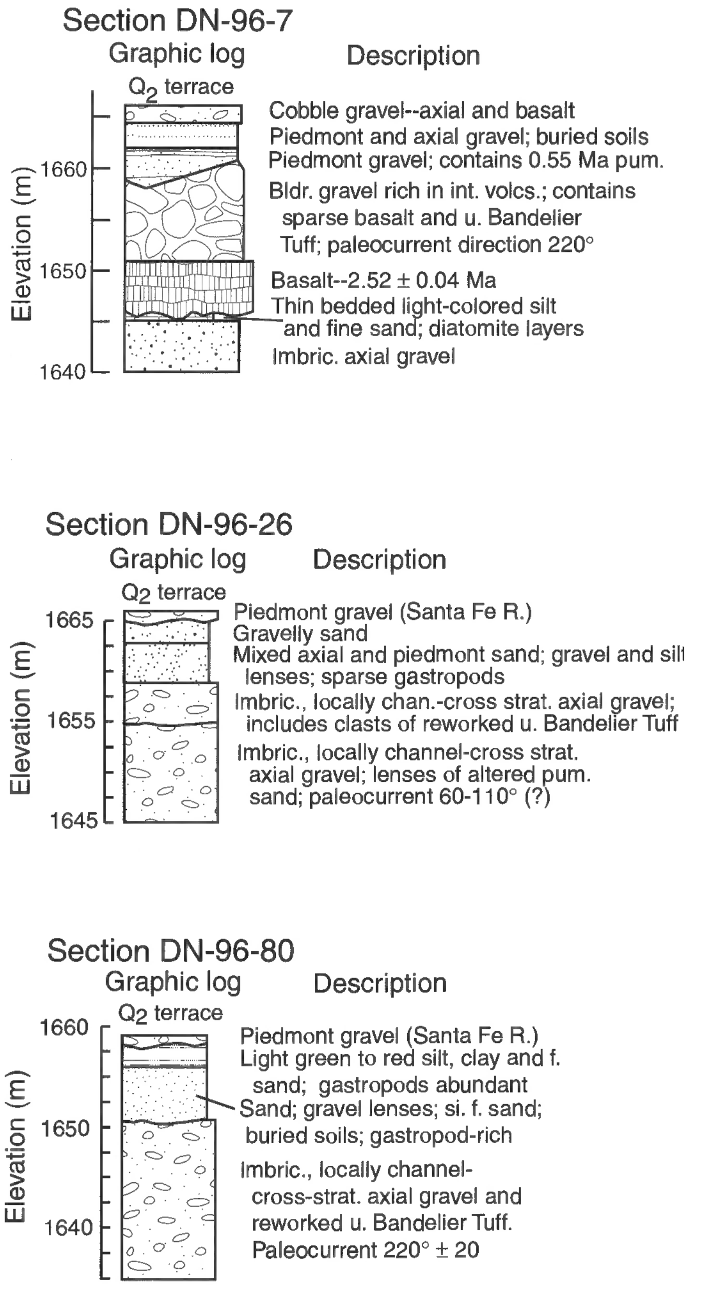

FIGURE 5. Q_2 stratigraphic sections DN-96-7, -26, and -80.

(Reneau and Dethier, 1996a). Elevation and distribution of the Q_1 and Q_2 fills suggest that early and middle Pleistocene aggradation in the northern Santo Domingo basin represented regionally significant volumes of sediment and occurred in a broad zone centered near a shallow canyon cut by the ancestral Rio Grande (Fig. 7). Fills beneath terraces Q_3, Q_4, and Q_5 comprise smaller volumes of sediment and are mainly confined within the modern canyon in the Cochiti Dam area. Boulder-rich sediment underlying the Q_1 and Q_3 terraces appears to be associated with geologically rapid or catastrophic deposition events, whereas the Q_2 terrace truncates a deposit with a more complex history.

Pleistocene incision follows late Pliocene aggradation

Stratigraphic and temporal relationships allow me to use the local position of the ancestral Rio Grande to sketch the geomorphic evolution of the Cochiti Lake area during a period of faulting, volcanism and drainage rearrangement that occurred between about 2.5 and 1.2 Ma (Fig. 7). Where the La Bajada fault zone crosses the Rio Grande, lower Bandelier Tuff is offset ~100 m; to the southeast, offset of Pliocene units is greater (Smith and Kuhle, 1998a). Formation of fault scarps and contemporaneous tilting of tectonic blocks likely influenced the position of the axial drainage and provided potential sources of sediment. Radiometric ages from basalt flows that cap axial gravel along Cochiti Lake (Fig. 2) demonstrate that at ~2.5 Ma, the Rio Grande flowed near and about 30 m above its modern position. Alluvium that covers the basalt is rich in pumice erupted with the ~1.85-Ma San Diego Canyon ignimbrites. Paleocurrent directions show that by that time, arroyos transporting the pumiceous debris drained southeast toward a now-buried valley axis located >1 km east of the modern Rio Grande. Eruption of andesitic flows from centers near the mouth of Cochiti Canyon at 2.34 Ma (Fig. 2) helped to force the Rio Grande east, but tilting of the hanging wall of the La Bajada fault zone may also have played a role.

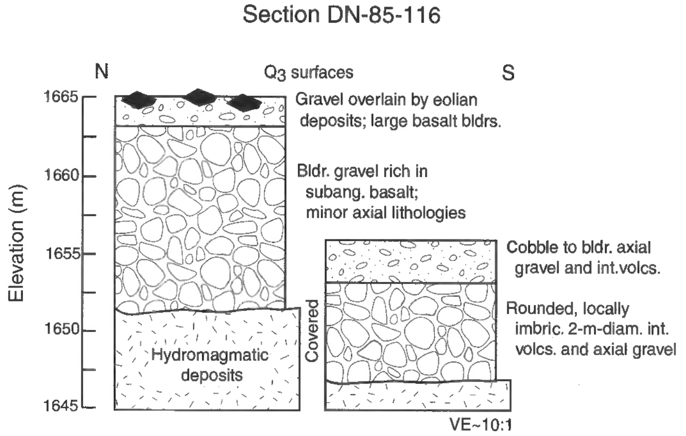

FIGURE 6. Q_3 stratigraphic section DN-85-116.

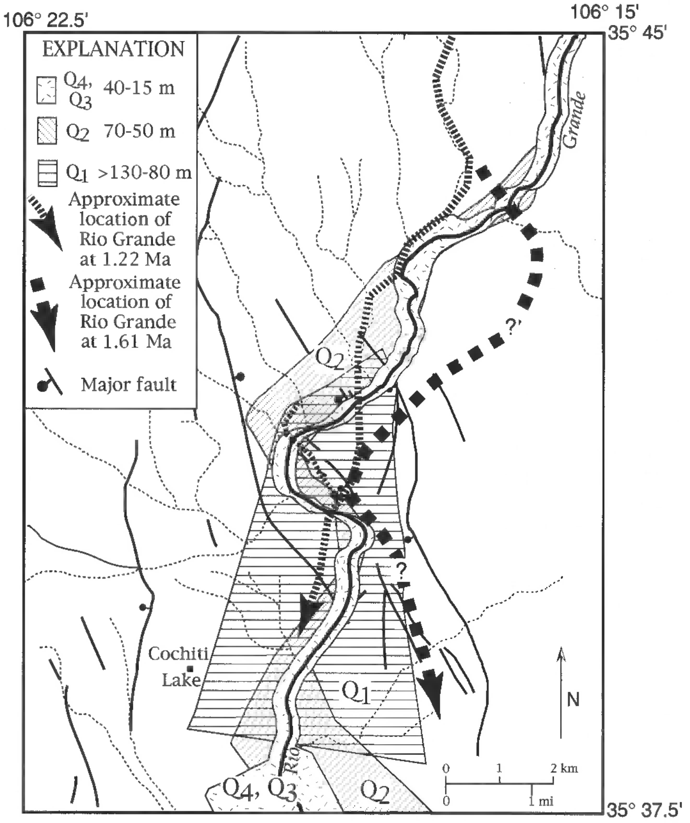

FIGURE 7. Cartoon showing the approximate location of the axial channel at 1.61 and 1.22 Ma in the Cochiti Dam 7.5' quadrangle and inferred original distribution of alluvial fills Q_1, Q_2, and Q_3+Q_4. Height ranges in explanation are m above the former active Rio Grande channel.

Eruption of the lower and upper Bandelier Tuff and andesitic and dacitic volcanism, which began east of the Rio Grande at about 1.5 Ma, dominated early Pleistocene base-level change at the southern end of White Rock Canyon. Isolated outcrops of lower Bandelier Tuff (Figs. 2, 7) fill a southeast-trending paleochannel ~100 m above present grade, suggesting that net aggradation continued south of the La Bajada escarpment, at least locally, until 1.6 Ma. North of the escarpment, near Arroyo Montoso, an extensive outcrop of lower Bandelier Tuff fills a shallow paleovalley. Underlying deposits are poorly exposed, but the tuff outcrop shows that axial drainage was >1.5 km to the east of the present Rio Grande and suggests that local base level was ~200 m higher than at present. North of Arroyo Montoso, the axis of the paleochannel apparently was west of the modern Rio Grande (Reneau and Dethier, 1996b). The ~100-m difference between the elevations of these lower Bandelier outcrops approximates offset on the main strand of the La Bajada fault zone since 1.6 Ma.

The fall deposits and ignimbrite that comprise lower Bandelier Tuff have little strength and probably were eroded soon after emplacement or were buried by andesitic flows. In White Rock Canyon north of the study area, canyons as deep as 150 m were cut into the lower Bandelier Tuff or were re-excavated before eruption of the upper Bandelier Tuff (Reneau and Dethier, 1996b). Evidence in the western Cochiti Dam quadrangle does not indicate downcutting of this magnitude. Preserved thicknesses of the lower Bandelier Tuff vary locally by tens of meters, suggesting a minimum depth of erosion. Evidence of the axial drainage system that must have conveyed this sediment, however, is mainly buried or eroded. Near the La Bajada scarp, the Rio Grande paleocanyon is only 25–35 m deep; other outcrops of upper Bandelier Tuff are too poorly exposed to infer canyon depths. Eruption at volcanic centers in the western Cerros del Rio covered much of the area west of the La Bajada escarpment with tens of meters of basaltic andesite and more evolved rocks between about 1.5 and 1.2 Ma (Table 1). Lava flows forced the axial channel westward, but I can map its location with confidence only where it was filled with the upper Bandelier Tuff.

Aggradation of 25–40 m in a zone ~2 km wide extending south toward Cochiti Dam from the La Bajada escarpment followed eruption of the upper Bandelier Tuff. The original distribution of this fill has been disrupted by erosion and by faulting along splays of the La Bajada zone. Blocks of Bandelier Tuff as large as 3 x 5 m, and 3–4-m clasts of angular basalt within and capping the fill, indicate that sediment transport must have occurred by catastrophic processes during at least some of this period. In contrast, the lower 10–20 m of each of the Q_1 fill sequences that I have examined are rich in rounded boulders of intermediate volcanic rocks, contain limited amounts of axial lithologies and few boulders of vesicular basalt. This observation suggests that boulders were derived from the southern Jemez Mountains, perhaps transported in Capulin or Alamo Canyon, and that only limited sources of basalt were exposed upstream in White Rock Canyon. The scarcity of rounded basalt boulders is consistent with the hypothesis of Reneau and Dethier (1996b) that the early Pleistocene canyon was not sufficiently deep to generate the landslides that deliver large quantities of basalt boulders to the Rio Grande. My data do not suggest when Q_1 aggradation ceased. Some 20 km downstream, the Rio Grande was ~75 m above its modern level when the Lava Creek B tephra was deposited at about 0.62 Ma (G. A. Smith, written commun., 1998). Angular basalt boulders in the upper part of the fill beneath the Q_1 terrace suggest delivery by mass-flow processes after failure of an upstream landslide dam or after scarp formation and erosion along the La Bajada Fault zone. If the boulders were derived from nearby slopes, they could have continued to accumulate on eastern Q_1 surfaces after local base level had dropped. Stage III+ or stage IV carbonate is common in soils developed on Q_1, suggesting relative stability of the terrace and nearby slopes during late Pleistocene time.

The elevation and distribution of Q_2 fill remnants requires >40 m of base-level fall and narrowing and extension of the depositional axis northward along the Rio Grande between the end of Q_1 filling and the beginning of Q_2 aggradation. Rapid incision implies a period of increased stream power and/or decreased sediment supply as the Rio Grande cut down closer to its modern position. Subsequent aggradation recorded by the Q_2 fill is rich in axial lithologies, and capping piedmont gravels do not contain the angular boulders abundant on Q_1 surfaces. The boulder layer at the base of section 96-7 (Fig. 5) may be a truncated remnant dating from Q_1 aggradation, but the middle of the section is ≤550 ka, and AARs from gastropods at two locations east of the Rio Grande indicate that the upper part of the Q_2 fill cannot be older than 300 ka. What controlled this extended period of middle Pleistocene aggradation in the northern Santo Domingo basin? The most northerly Q_2 remnants are poorly exposed but appear to be flood deposits that record collapse of a basalt-rich dam upstream in White Rock Canyon. Assuming the coarse boulder layer beneath Q_2 downstream correlates with the northern remnants, deposition of alluvium rich in axial lithologies began after a catastrophic flood, probably after 550 ka. The timing and sedimentary record of this event is consistent with the initiation of massive slumping in northern White Rock Canyon during middle Pleistocene time (Reneau and Dethier, 1996b). Rapid removal of landslide dams would have enhanced upstream incision, extension of the drainage network and downstream delivery of sediment. In the upstream Española basin, rapid incision and denudation typical of middle Pleistocene time (Dethier et al, 1988) sent large volumes of sediment downstream through White Rock Canyon. Probable causes of incision include: (1) a change to wetter climates in the middle Pleistocene (Dethier et al., 1988); (2) drainage capture (Wells et al., 1987); and (3) long-term, upstream response to removal of the basalt knickpoint in White Rock Canyon in early(?) Pleistocene time. Evidence presently available does not allow me to choose among these interrelated sources of sediment for the northern Santo Domingo basin. Aggradation near Cochiti Dam, broken by periods of at least local surface stability and soil formation, apparently continued for 100–300 ka until about 300 or 250 ka.

Punctuated incision in the middle and late Pleistocene

During the past 250–300 ka, the Rio Grande cut down ≥60 m near Cochiti Dam, punctuated by episodes of backfilling, entrenching a narrow canyon in Pliocene rock. The locus of aggradation shifted south and extensive younger terraces and underlying fills are preserved only near and south of Cochiti Dam. Fills beneath Q_3 and Q_4 surfaces record both similar and disparate evidence of processes that produced these fill-cut terraces. Boulder-rich deposits beneath the two Q_3 remnants near the mouth of Alamo Canyon, for instance, indicate that a fill 10–15 m thick accumulated during a brief period between ~300 and 60 ka. Downstream convergence of Q_3 remnants and the modern Rio Grande (Fig. 3) suggests an upstream source of sediment. Climate change accompanied by landslides and catastrophic lake drainage in White Rock Canyon (Dethier and Reneau, 1996a) may have produced the boulder-rich Q_3 fills downstream. Several landslide complexes, including a debris avalanche <8 km upstream (Reneau and Dethier, 1996a) are likely candidates for a dam older than 60 ka. Failure of a dam and scour of talus slopes composed of basalt boulders downstream from the dam provides a likely source for the angular boulders in the higher of two fill terraces exposed near Alamo Canyon.

It is also plausible that rapid Q_3 aggradation reflects regional climate change accompanied by extensive hillslope erosion and debris flow generation that sent a wave of coarse sediment downstream. There is no local record of middle Pleistocene climate nor direct dating of geomorphic response in the vicinity of White Rock Canyon. Upstream in the Española basin, boulder-rich alluvial fans deposited by aggrading arroyos forced the Rio Chama and Rio Grande to the east at about 150 and ~70 ka, during or after transitions from pluvial to interpluvial climates (Dethier and McCoy, 1993). Major periods of aggradation that ended ~140 and ~65 ka on Pajarito Plateau drainages (Reneau et al., 1996b; Phillips et al., 1998) and along the Jemez River (Rogers and Smartt, 1996) may correlate with the periods of fan growth in the Española basin and with Q_3 aggradation downstream. Fills rich in bouldery intermediate volcanic rocks derived from the Jemez Mountains suggest a local source for at least some of the coarse debris beneath the lower Q_3 terrace. Boulder-covered surfaces in the lower reaches of arroyos downstream from Alamo Canyon thus could record widespread aggradation or backfilling of arroyo mouths by floods along the Rio Grande.

Large basalt boulders that form the base of the Q_4 fill near the west abutment of Cochiti Dam may be a flood deposit, a channel lag, or may indicate high stream power at the beginning of Q_4 aggradation. Most of the fill, which crops out extensively in the Santo Domingo quadrangle, is composed of axial lithologies, mixed locally with piedmont alluvium. At the north end of White Rock Canyon, Reneau and Dethier (1996a) obtained a ^{14}C age of ~43 ka from charcoal in lake deposits overlying a 15-m terrace, but were not certain if the date should be considered "finite." Rapid erosion of the extensive sedimentary fill and redeposition of the coarse fraction downstream after draining of this lake could have contributed to the Q_4 aggradation. The broad extent of the Q_4 fill downstream from Cochiti Dam, however, suggests that deposition was more likely the result of a regional episode of sediment transport sometime between ~80 and 40 ka.

Evidence of latest Pleistocene incision and backfilling mainly is submerged beneath Cochiti Lake and buried by the dam; low terraces considered to be Q_5 may not be coeval. In White Rock Canyon, Reneau and Dethier (1996a) demonstrated that base level defined by the Rio Grande was within 10 m of present level before about 18 ka and that episodes of late Pleistocene incision might have cut as much as 10 m below present values. In the Española basin north of White Rock Canyon, Holocene aggradation has been <10 m, whereas contemporaneous aggradation in the Albuquerque basin may have been as much as 30 m (Lozinsky et al., 1991). Regional evidence thus suggests that a late Pleistocene erosion surface may be buried by Holocene deposits in the northern Santo Domingo basin. However, late Pleistocene incision upstream may have produced aggradation at the southern end of White Rock Canyon, or little change in base level.

Net incision in the northern Santo Domingo basin since ~1.2 Ma has averaged about 7.5 cmka^{-1}, composed of rates ≤ 3.5 cmka^{-1} between ~1.2 Ma and ~300 ka and rates >20 cmka^{-1} since 300 ka (Table 1). Local incision of ≥ 40 m also took place between the end of Q_1 deposition and the initiation of Q_2 aggradation in a time period of ≤ 500 ka. Axial river gradients recorded by terraces (Fig. 3) decreased during this period of increasing incision rates. If incision was related to increased stream power, peak discharges on the Rio Grande must have increased. Alternatively, fluctuations in sediment loads derived from regional and Jemez Mountain sources may have strongly influenced the balance between Pleistocene aggradation and incision in the northern Santo Domingo basin.

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