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PLIOCENE AND QUATERNARY HISTORY OF THE RIO GRANDE, WHITE ROCK CANYON AND VICINITY, NEW MEXICO

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Abstract—Surface and subsurface evidence shows that the elevation of the Rio Grande in the vicinity of White Rock Canyon fluctuated greatly during the Pliocene and the Quaternary, influenced by volcanism, tectonism, and climatic changes. After the first appearance of distinctive quartzite-rich fluvial deposits at ca. 4-5 Ma, the Rio Grande incised 250 m or more into rift-filling sediments of the Santa Fe Group. The Rio Grande then aggraded 300 m by about 2.4 Ma, coinciding with eruption of and repeated damming of the river by basaltic lavas of the Cerros del Rio volcanic field. Simultaneous deposition of thick Puye Formation fanglomerates to the north may have been aided by blockage of the valley by the lavas and the resultant rise in local base level. By early Pleistocene the Rio Grande had incised a narrow canyon up to 180 m deep through the western Cerros del Rio field, which was filled first by the Otowi Member of the Bandelier Tuff at 1.61 Ma and then by the Tshirege Member at 1.22 Ma. Both deposits undoubtedly dammed the river, and erosion of the spillways may have generated catastrophic outburst flooding. Notably, the low spot on the 1.22 Ma dam was east of the paleocanyon, forcing the Rio Grande to cut a new channel through 200 m of basaltic rocks to reach its former grade. The resistant basalt probably produced a persistent knickpoint and a local control for base level upriver. Extensive slumps developed in northern White Rock Canyon after the river had incised into mechanically weak sediments beneath basalts, probably beginning in mid-Pleistocene time. Reactivation of slumps in wetter periods in the late Pleistocene repeatedly dammed the river, producing lakes up to 60 m deep and 25 km long. By the early Holocene the Rio Grande was within 5 m of its present grade, and the river has remained near its modern level through the Holocene.

INTRODUCTION

White Rock Canyon (Fig. 1) forms one of two major constrictions along the Rio Grande in northern New Mexico, the other being the Rio Grande Gorge through the Taos Plateau. The elevation of the Rio Grande has fluctuated greatly in the vicinity of White Rock Canyon, including major local base level rises in both the Pliocene and the Pleistocene, separated by extensive incision. During this period, the river was dammed repeatedly by mafic lava flows, silicic tuff, and landslides, probably resulting in a late Cenozoic history that is different in many respects from areas to the north and south.

In this paper we revise and expand upon the history of the Rio Grande in White Rock Canyon and vicinity, synthesizing earlier mapping of the White Rock quadrangle (Dethier, in press), recent work in White Rock Canyon (Reneau et al., 1995a, and unpubl.), new $^{40}Ar/^{39}Ar$ ages of Pliocene lavas (WoldeGabriel et al., 1995, and this volume), subsurface data from beneath the Pajarito Plateau (Purtymun, 1995), and other work in the region.

GEOLOGIC SETTING

White Rock Canyon is located at the southern margin of the Española basin of the Rio Grande rift, bordered on the east by the Cerros del Rio volcanic field and on the west by the Pajarito Plateau (Fig. 2). The Española basin is an asymmetric half-graben tilted westward towards the Pajarito fault zone. It is bounded to the north by the Embudo fault and to the south by the La Bajada fault, which are interpreted as accommodation zones that transfer displacement between the Española basin, the San Luis basin and the Abiquiu embayment to the north, and the Santo Domingo basin to the south (Kelley, 1979; Muehlberger, 1979; Aldrich, 1986; Baldridge et al., 1994; Chapin and Cather, 1994; Gonzalez, 1995). The La Bajada fault zone (Fig. 3), as mapped by Smith et al. (1970), displays perhaps 50-100 m of down-to-the-southwest offset of an early Quaternary basaltic andesite near the southern end of White Rock Canyon; faulting here may have had a major influence on the incision history of the Rio Grande (Kelley, 1952, 1978), although the fault history is not yet characterized in detail. The Pliocene and Quaternary displacement history of the Embudo fault zone is even less well understood. The net sense

FIGURE 1. White Rock Canyon, looking upriver. Canyon is ~300 m deep. Late Holocene fan of Frijoles Canyon is in center of view. Cliffs on left expose Tshirege Member of Bandelier Tuff (40-90 m thick) overlying basaltic andesite and basalts of the Cerros del Rio volcanic field. Phreatomagmatic deposits are exposed on lower slopes.

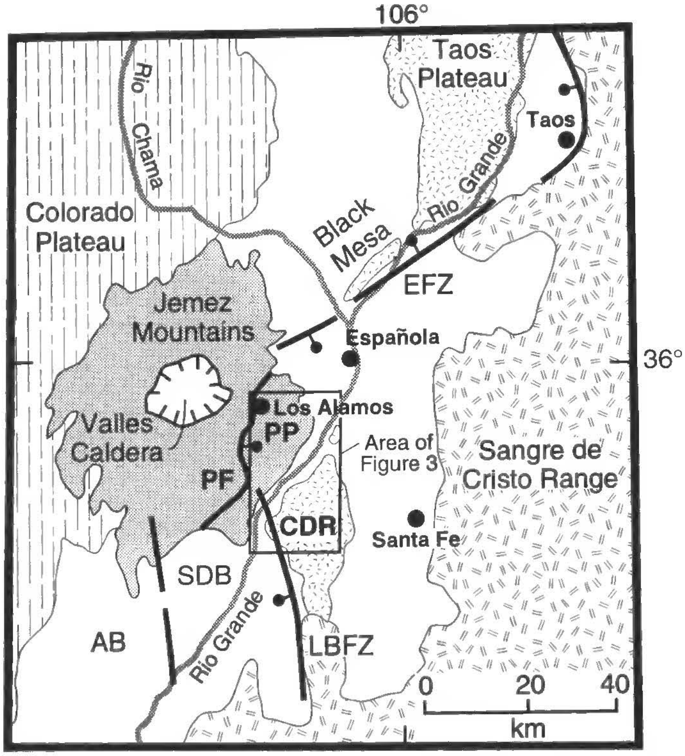

FIGURE 2. Map showing location of White Rock Canyon and major physiographic features in region. AB, Albuquerque basin; EFZ, Embudo fault zone; LBFZ, La Bajada fault zone; PF, Pajarito fault zone; PP, Pajarito Plateau; SDB, Santo Domingo basin.

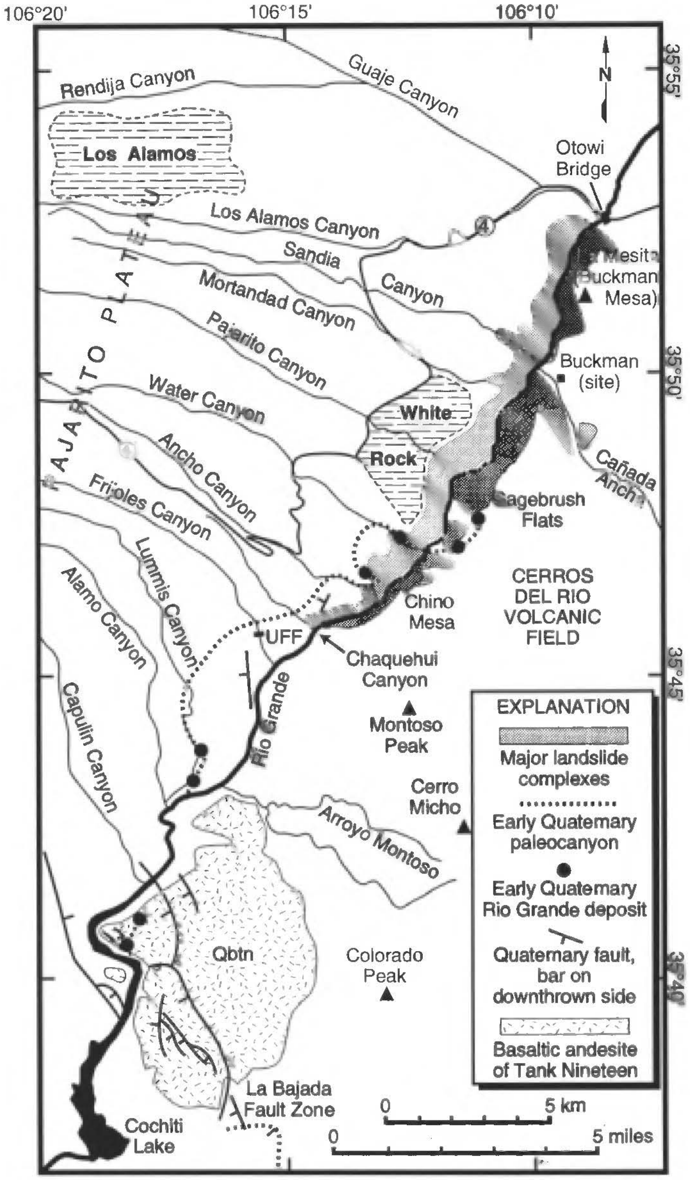

FIGURE 3. Map showing selected geographic and geologic features along White Rock Canyon. Basaltic andesite of Tank Nineteen (Qbtn) and La Bajada fault zone from Smith et al. (1970). Approximate course of early Quaternary Rio Grande and faults between Alamo and Ancho Canyons from Reneau et al. (1995). UFF, Upper Frijoles Falls.

of offset changes in the vicinity of the confluence of the Rio Chama and the Rio Grande from down-to-the-north to the east to down-to-the-south to the west (Fig. 2; Kelley, 1978, 1979), and the influence of the Embudo on the history of the Rio Grande is uncertain.

The oldest rock units exposed along White Rock Canyon are Miocene rift-filling sediments of the Santa Fe Group (Chamita and/or Tesuque Formations of Galusha and Blick, 1971). Pliocene and Quaternary units in White Rock Canyon include basalts, andesites, and phreatomagmatic deposits of the Cerros del Rio volcanic field, volcanic fanglomerates and ancestral Rio Grande alluvium of the Puye Formation, the Otowi and Tshirege Members of the Bandelier Tuff (1.61 and 1.22 Ma; ages from Izett and Obradovich, 1994), and Quaternary alluvium, lacustrine deposits, and landslide deposits (Griggs, 1964; Smith et al., 1970; Dethier, in press). The Pliocene Rio Grande deposits are variously referred to as the Totavi Lentil of the Puye Formation by Griggs (1964) and Purtymun (1995), as the Totavi Formation by Waresback and Turbeville (1990) (along with related lacustrine deposits), and as an axial facies of the Puye Formation by Manley (1976) and Dethier (in press).

EARLY TO MID-PLIOCENE INCISION

The Rio Grande has probably been present in the region since at least 4-5 Ma, recorded by the first appearance of distinctive quartzite-rich fluvial deposits similar to those carried by the modern river (Manley, 1976, 1979; Bachman and Mehnert, 1978; Chapin, 1988). Subsequently, the Rio Grande in the vicinity of White Rock Canyon and the Pajarito Plateau incised deeply into rift-filling sediments of the Santa Fe Group (Fig. 4), as is also documented upriver along the Rio Chama (e.g., Gonzalez and Dethier, 1991).

The initial elevation of the Rio Grande is poorly constrained, but exposures of the Santa Fe Group near northern White Rock Canyon suggest that Miocene aggradation had reached an elevation at least 185 m above the modern river (Dethier, in press). Quartzite-rich gravels similar to those deposited by the modern Rio Grande (Totavi Lentil of Griggs, 1964), overlying Miocene sediments and assumed to be Pliocene in age, have been reported in water supply wells beneath the northern Pajarito Plateau as high as 225 m above the modern river (well G-6; Purtymun, 1995), providing a minimum limiting estimate of the initial height of the Rio Grande. Similar river gravels have been reported in wells as low as 30 m below the modern river (well PM-2; Purtymun, 1995), suggesting a minimum of 255 m of Pliocene incision into the Santa Fe Group. Although the elevation of these gravels may be affected by faulting along structures buried in the subsurface beneath the Plateau, inferred faults have primarily down-to-the-west offset (Dransfield and Gardner, 1985), whereas elevations of the river gravels in a well field typically increase to the west (e.g., Fig. 5; Griggs, 1964; Purtymun, 1995); faulting would thus tend to lead to an underestimation of total Pliocene incision. The age of deepest incision is unknown, but is estimated to be between 3.65 and 2.5 Ma based on $^{40}Ar/^{39}Ar$ ages of basalts upriver at Black Mesa and in White Rock Canyon (Table 1, Fig. 4).

The general eastward decrease in elevation of the Rio Grande gravels in the subsurface, and their common position at the base of Puye Formation fanglomerates (Griggs, 1964; Purtymun, 1995), suggest that they in part record buried terraces of the Pliocene Rio Grande produced during

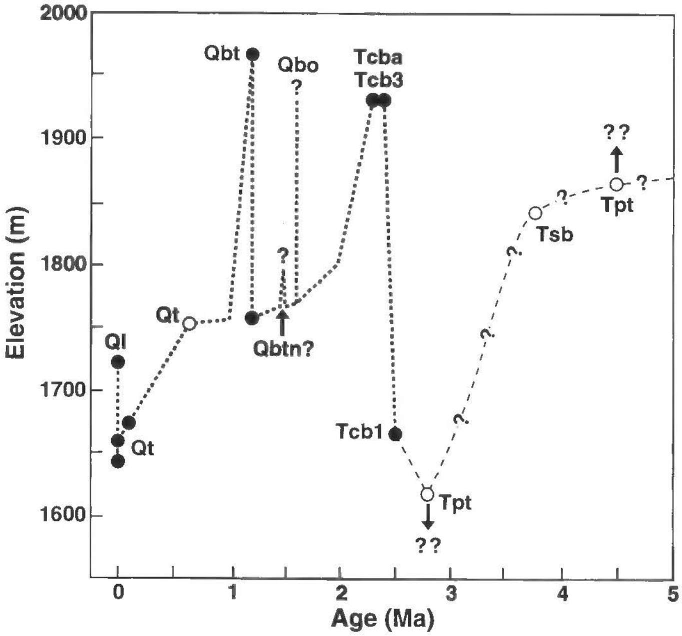

FIGURE 4. Estimated variations in Pliocene and Quaternary elevation of Rio Grande in vicinity of White Rock Canyon, shown for the reach from Water Canyon to Chaquehui Canyon (elevation relative to modern sea level; see text and Table 1 for discussion and explanation of units and age control). Filled circles indicate age and/or elevation control in White Rock Canyon, and open circles indicate data from elsewhere in the vicinity. Height of Rio Grande gravels below Servilleta basalt upriver at Black Mesa decreased to adjust for inferred reduction in river gradient since the Pliocene (i.e., less net incision since 3.65 Ma at White Rock Canyon than at Black Mesa).

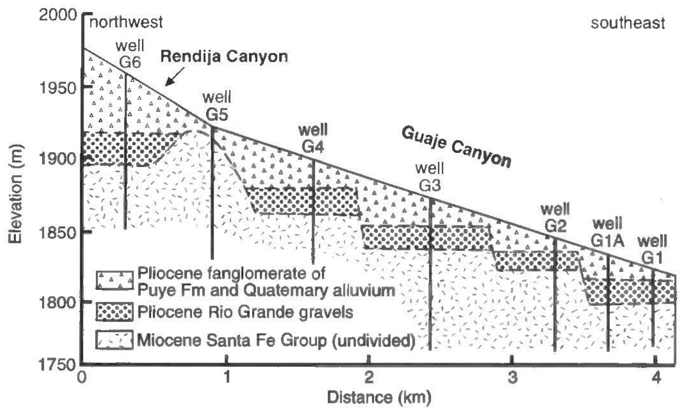

FIGURE 5. Schematic cross section through the Guaje well field, Guaje and Rendija Canyons, northern Pajarito Plateau, showing possible context of axial Rio Grande gravels ("Totavi Lentil") at base of Puye Formation as buried Pliocene terraces. Well logs from Purtymun (1995; see also Griggs, 1964).

incision into the Santa Fe Group as the river migrated eastward (Fig. 5). Such Pliocene terraces would be analogous to the Quaternary terraces upriver in the Española basin, which are similarly buried beneath fans composed of volcanic debris derived from the west (Dethier et al., 1988).

The extensive early to mid-Pliocene incision in the vicinity of White Rock Canyon (Fig. 4) contrasts with inferred aggradation during this period downriver in the Albuquerque basin (e.g., Lozinsky et al., 1991). This incision may record the breaching and erosion of a topographic high that separated the Española and Albuquerque basins following inception of the Rio Grande as a through-going drainage. Incision may also have been aided by down-to-the-southwest faulting along the La Bajada fault zone (Kelley, 1952, 1978), although the timing and amount of Pliocene faulting there are not determined.

LATE PLIOCENE VOLCANISM AND AGGRADATION

Extensive late Pliocene aggradation occurred in the vicinity of White Rock Canyon; most rock units exposed in the canyon (Fig. 1) and along adjacent tributaries were deposited during this period. This aggradational sequence includes lavas and phreatomagmatic deposits of the Cerros del Rio volcanic field, axial Rio Grande gravels, lacustrine deposits, fanglomerates of the Puye Formation derived from the Jemez Mountains to the west, and alluvium derived from the Sangre de Cristo Range to the north and east (Dethier, in press). Basaltic volcanism in the Cerros del Rio field has had a significant influence on the late Pliocene history of the Rio Grande, and shallow groundwater near the river has in addition affected the style of volcanism. Widespread interaction between magma and groundwater near the Pliocene Rio Grande generated phreatomagmatic eruptions associated with many separate maar volcanoes that are discussed in more detail by Aubele (1978, 1979), Dethier (in press), and Heiken et al. (in press).

Ages of the Cerros del Rio lavas provide constraints on the timing and duration of the period of late Pliocene aggradation. K-Ar dates from lavas at seven sites, summarized in Dethier (in press), range from 1.8 to 2.7 Ma, which are generally similar to more recent $^{40}Ar/^{39}Ar$ analyses of 2.3 to 3.2 Ma from a variety of sites near White Rock Canyon (WoldeGabriel et al., 1995, and this volume). In particular, $^{40}Ar/^{39}Ar$ ages of about 2.4-2.5 Ma have been obtained from basaltic lavas exposed near the ancestral Rio Grande between White Rock and Chaquehui Canyon that span an elevation range of 225 m, suggesting extremely rapid valley aggradation during a relatively brief period of intense volcanism (Fig. 4; Table 1; Tcb1 and Tcb3 of Dethier, in press; Reneau et al., 1995). A $^{40}Ar/^{39}Ar$ analysis of 2.47 ± 0.03 Ma from unit Tcb1 in Water Canyon (Table 1), whose base is within 15-20 m of the modern river, indicates that the Rio Grande was at an elevation of <1665 m at that time. Fairly continuous eruptions were also suggested by Aubele (1978, p. 16), on the basis of the lack of soils between overlapping flows.

The late Pliocene lava flows repeatedly dammed the ancestral Rio Grande, recorded by lacustrine deposits that crop out from Mortandad Canyon to Los Alamos Canyon and also farther north (Culebra lake clay of Kelley, 1952; see also Griggs, 1964; Manley, 1976, 1979; Waresback and Turbeville, 1990; Dethier, in press). Manley (1976, 1979) noted that the distribution of Pliocene lacustrine deposits suggests that the largest lake covered much of the Española basin. Our mapping suggests that the highest basalt dam was located at Water Canyon near its confluence with Potrillo Canyon, where basalts reach the highest elevation along the early Quaternary Rio Grande paleocanyon at about 1920-1945 m. This is consistent with the highest elevations of Pliocene lake deposits noted by Manley (1976) of about 1945 m. Contacts between topset and foreset layers in pillowed basalt between Water Canyon and Los Alamos Canyon record a lower late Pliocene lake level at about 1890 ± 10 m (Dethier, in press). At Water Canyon, the latest Pliocene Rio Grande flowed between a basaltic andesite to the southeast (Tcba of Dethier, in press; Table 1), and an extensive tholeiitic basalt to the northwest (Tcb3 of Dethier, in press; Table 1); field relations suggest that the tholeiitic flows likely created the highest dam.

Deposition of the extensive Puye Formation fan upriver from White Rock Canyon has been previously attributed primarily to Pliocene subsidence of the Española basin south of the Embudo fault zone, with volcanic events in the Jemez Mountains and a semiarid late Pliocene climate also influencing fan deposition (Waresback and Turbeville, 1990; Gonzalez and Dethier, 1991; Gonzalez, 1995). The evidence in White Rock Canyon for a concurrent local rise in river level of at least 300 m (Fig. 4) suggests that construction of the Cerros del Rio volcanic field may have significantly influenced Puye fan aggradation by effectively blocking the Rio Grande valley and imposing a major base level rise at the toe of the fan.

EARLY QUATERNARY PALEOCANYON

Early Quaternary Rio Grande deposits are locally exposed beneath the Tshirege Member of the Bandelier Tuff between White Rock and Alamo Canyon (Fig. 6), within a paleocanyon that can be traced for 12

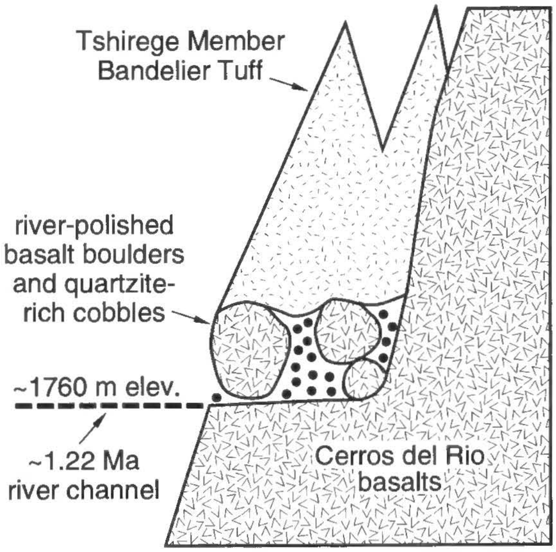

FIGURE 6. Sketch of stratigraphic relations along north side of Water Canyon, showing Tshirege Member of Bandelier Tuff overlying early Quaternary Rio Grande deposit.

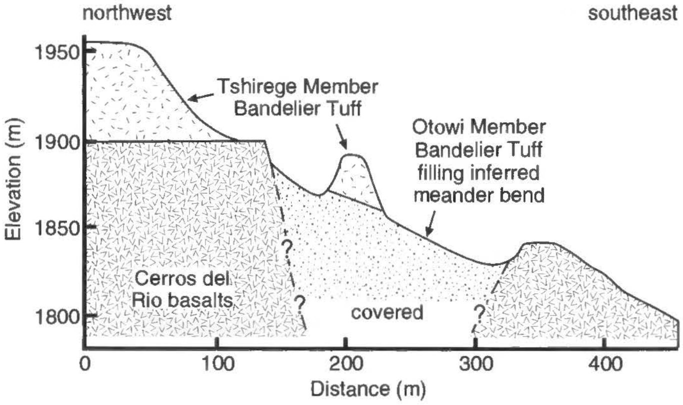

FIGURE 7. Cross section showing stratigraphic relations along north side of Ancho Canyon. The 1.61 Ma Otowi Member of the Bandelier Tuff fills an inferred meander bend within the early Pleistocene Rio Grande paleocanyon adjacent to the 1.22 Ma river course, and indicates that the pre-Otowi canyon was similar in form and depth to the pre-Tshirege canyon.

km through the eastern Pajarito Plateau, and indicate that at 1.22 Ma the Rio Grande was located as much as 2 km west of the modern river (Fig. 3; Reneau et al., 1995). Prominent exposures of the Tshirege Member that fill a paleocanyon on the east side of the river (Aubele, 1978, 1979) are also underlain by these deposits. The early Quaternary alluvial deposits are composed largely of quartzite-rich gravels and river-polished basalt boulders, the latter distinguishing them from Pliocene Rio Grande deposits that occur in the same area. At 1.22 Ma, the Rio Grande was at an elevation of about 1715 to 1770 m along this reach (Fig. 4), incised 80 to 180 m into basaltic rocks of the Cerros del Rio field.

Field relations in Ancho Canyon (Fig. 7) indicate that at 1.61 Ma, when the Otowi Member of the Bandelier Tuff was erupted, the paleocanyon was similar in location, form, and depth to the canyon at 1.22 Ma, although evidence is sparse. The Otowi Member presumably filled the paleocanyon and temporarily dammed the Rio Grande, and overtopping and breaching of the dam may have generated a catastrophic outburst flood that left Otowi-rich deposits 220 km downriver near Socorro (Cather and McIntosh, 1990) and 400 km downriver near Las Cruces (G. Mack, unpubl. 1995). Notably, the relations in Ancho Canyon (Fig. 7) and elsewhere suggest that the post-Otowi Rio Grande generally re-excavated the pre-Otowi paleocanyon, in contrast to the post-Tshirege river (as discussed below), and rapid incision of a channel through the nonwelded tuff may have resulted in a larger dam-burst flood at 1.61 Ma than at 1.22 Ma.

In the southern part of White Rock Canyon, early Quaternary basaltic andesites overlie the Otowi Member near the present river (Fig. 3; basaltic andesite of Tank Nineteen of Smith et al., 1970), suggesting that these

TABLE 1. Height and ages of Pliocene and Quaternary units in White Rock Canyon and vicinity, New Mexico.

Unit	Description	Height (m) [a]	Age (Ma)	Refs [b]	Notes
Tpt	axial facies, Puye Fm ("Totavi Lentil")	≥ 225	~4-5	1	highest elevation below Pajarito Plateau
Tsb	Rio Grande deposit at Black Mesa	260	3.65 ± 0.09	2	Ar-Ar age of overlying Servilleta basalt
Tpt	axial facies, Puye Fm ("Totavi Lentil")	≤ -30	?	1	lowest elevation below Pajarito Plateau
Tcb1	basaltic trachyandesite, lower Water Cyn	20	2.47 ± 0.03	3, 4	Ar-Ar analysis
Tcb3	tholeiitic basalts of Pajarito Plateau	285	2.44-2.49 [c]	3, 4	Ar-Ar analyses
Tcba	basaltic andesite near Water Canyon	285	2.33 ± 0.27	3, 4	Ar-Ar analyses
Qbo	Otowi Member, Bandelier Tuff	?	1.61 ± 0.01	5	Ar-Ar analysis
Qbtn	basaltic andesite of Tank Nineteen	?	1.69 ± 0.06 [d]	6	K-Ar analysis
Qbt	Tshirege Member, Bandelier Tuff	120	1.22 ± 0.02	5, 7	Ar-Ar age; base of paleocanyon
		325		7	highest point above axis of paleocanyon
Qt	Rio Chama terraces	110	0.62	8	age of overlying Lava Creek B tephra
Qt	Rio Grande terrace near Otowi Bridge	33	< 0.1	6	amino acid analyses of gastropods
Qt	Rio Grande deposit near Cañada Ancha	15	0.04-0.07	4, 6	14C analysis and correlation with upriver deposits
Ql	landslide-dammed lake	75	0.04-0.07	4, 6	age estimate of oldest and largest lake
Ql	landslide-dammed lake	45	0.015-0.018	4	14C age of intermediate lake
Ql	landslide-dammed lake	30	0.012	4	14C age of youngest lake
Qt	Rio Grande terrace near Mortandad Cyn	5	0.009	7	14C age of post-lake terrace
Qt	Rio Grande deposit near Soda Springs	2	0.003	4	14C age of floodplain deposits over bar

[a] Approximate height above modern Rio Grande. Heights for lavas are for outcrops adjacent to rim of late Pliocene canyon for Tcba and Tcb3 and for base of flow for Tcb1. Heights for Qbt show position immediately before and immediately after eruption. Heights for Ql are maximum lake height above modern Rio Grande.

[b] Sources of data: 1: Purtymun, 1995; 2: A. W. Laughlin et al., unpubl. report for Los Alamos National Laboratory, 1993; 3: WoldeGabriel et al., 1995, and this volume; 4: Reneau et al. 1995; 5: Izett and Obradovich, 1994; 6: Dethier and Reneau, 1995; 7: this paper; 8: Dethier et al., 1990.

[c] Ages for Tcb3 are from four samples near ancestral Rio Grande at White Rock overlook, Ancho Canyon, and near Chaquehui Canyon, and are believed to provide the best age estimate of the highest late Pliocene elevation of the Rio Grande. Uncertainties on these samples are ± 0.01-0.06 Ma.

[d] K-Ar age appears to be too old, because flow mapped as overlying 1.61 Ma tuff.

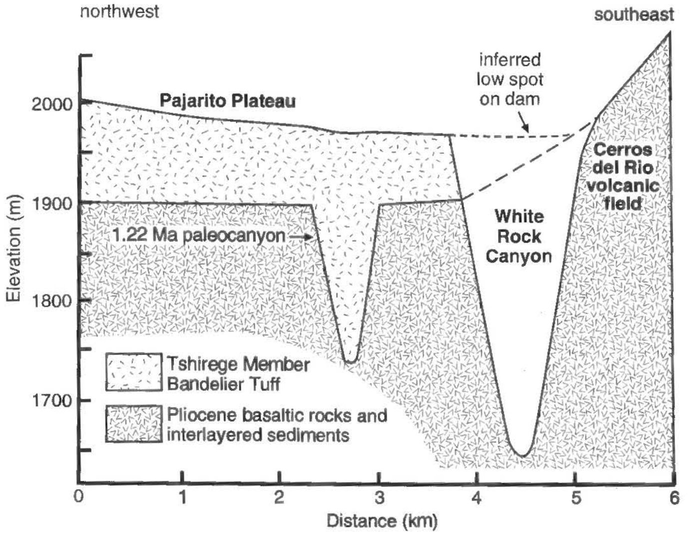

FIGURE 8. Schematic cross section through area of 1.22 Ma tuff dam near Chaquehui Canyon. Low point on dam was near eastern margin of ignimbrite about 2 km east of the buried paleocanyon.

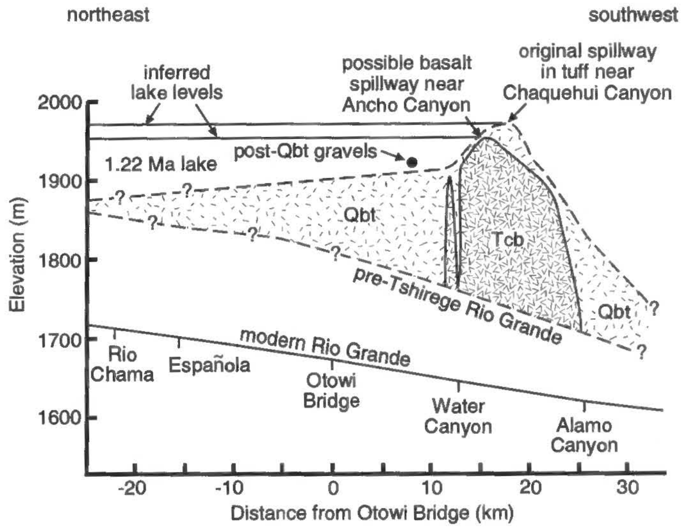

FIGURE 9. Profile of Rio Grande at White Rock Canyon and adjacent parts of the Española basin at ca. 1.22 Ma, showing pre-Tshirege Member river level, approximate topography immediately after eruption of the tuff and geologic units beneath the post-tuff channel, location of spillways, approximate lake elevations, and location of post-tuff Rio Grande gravels at White Rock. Estimated top of Tshirege Member in the vicinity of the post-Bandelier Rio Grande channel is based on projections from outcrops on the Pajarito Plateau, and are probably too low due to erosion of the uppermost tuff on the Plateau. The estimated upper profile of basaltic rocks is based on elevations on the opposite rims of White Rock Canyon. Qbt, Tshirege Member Bandelier Tuff; Tcb, Cerros del Rio basaltic rocks.

lavas entered the southern end of the paleocanyon and possibly dammed the river. A narrow paleocanyon, about 100 m wide and 45 m deep, was subsequently cut through these flows and is exposed on the east side of the Rio Grande, downriver from Capulin Canyon (Fig. 3).

The early Quaternary Rio Grande paleocanyon was much narrower than the modern canyon, with a maximum width of about 600 m, and was apparently unmodified by extensive slumps such as those along the modern canyon (Reneau et al., 1995). Between Water Canyon and Lummis Canyon the 1.22 Ma paleochannel had an apparent gradient of about 0.0031 to 0.0036 m/m (assuming that the paleocanyon had the sinuosity shown in Figure 3), which is significantly steeper than the modern Rio Grande gradient of about 0.002 but less than the late Pliocene gradient of about 0.005 inferred by Dethier (in press). A steeper early Quaternary gradient is consistent with a river discharge that was possibly much less than today, as discussed below, although we cannot evaluate possible effects of tectonic tilting on this apparent paleogradient.

1.22 MA DAM

Eruption of the Tshirege Member of the Bandelier Tuff at 1.22 Ma buried the early Quaternary Rio Grande channel with 230 m of pyroclastic deposits in the vicinity of Chaquehui and Frijoles Canyons (Fig. 8), effectively damming the river. At present, the highest elevation of the tuff above the paleocanyon is about 1965 m, east of Upper Frijoles Falls, recording the approximate location of the tuff dam. This is in the area where the river was closest to the rim of the Valles caldera, at a distance of 17 to 18 km. The original low point on the dam was apparently east of the early Quaternary paleocanyon in the vicinity of Chaquehui Canyon (Fig. 8), also at an elevation close to 1965 m, providing the best estimate of the upper elevation of a tuff-dammed lake. Deposits associated with this lake have not yet been recognized, and they may have been largely or entirely removed by erosion.

Based on an estimated position of the early Quaternary Rio Grande and Rio Chama upriver at about 140 m above modern grade (Dethier and Reneau, 1995), the tuff-dammed lake would have had a maximum length of about 75 km, stretching north up the Rio Grande to Pilar. The top of the Tshirege Member above the ancestral Rio Grande probably decreased in elevation to the north (Fig. 9), and the maximum lake depth may have been close to 100 m in the vicinity of San Juan Pueblo or Alcade.

The duration of the post-Bandelier lake is unknown, but it was probably controlled by both the resistance of the spillway to erosion and rates of sediment input. Initial erosion through tuff may have been very rapid once the dam was overtopped, although the degrading channel would have encountered basalt by an elevation of about 1950 m in the vicinity of Ancho Canyon (Fig. 9). Subsequently, the river had to excavate a new channel through about 200 m of basaltic rocks to reach its former grade. We expect that incision slowed significantly through the basalt, producing a persistent knickpoint that would have influenced base level far upriver, although we cannot estimate how long this knickpoint lasted. The duration of the lake itself may have been controlled by rates of sediment influx from surrounding drainages, with the lake filling with sediment before the river was able to cut a significant channel through the Cerros del Rio volcanic rocks.

POST-BANDELIER TUFF INCISION

The pattern of down-cutting by the Rio Grande following damming by the Bandelier Tuff would have varied along the length of White Rock Canyon, in turn affecting incision of tributaries to the east and west. Downriver of the dam, incision of the Rio Grande through tuff may have been rapid, dropping local base level and in turn allowing incision of tributary drainages south of the dam soon after emplacement of the tuff. However, incision of tributaries adjacent to and upriver of the dam would have been delayed until substantial erosion of the basalt spillway had occurred. The widespread occurrence of gravelly, dacite-rich alluvium derived from the Jemez Mountains on mesas of the northern Pajarito Plateau provides supporting evidence that incision of many drainages west of White Rock Canyon did not begin immediately following eruption of the tuff (Reneau, 1995; Reneau et al., in press). Incision of drainages such as Los Alamos and Pajarito Canyons may instead have been delayed until the Rio Grande had first cut through at least 30 to 60 m of basaltic rocks, dropping local base level sufficiently to allow the upstream propagation of knickpoints. Rio Grande gravels occurring on top of the Tshirege Member at White Rock (Fig. 9; Qoal of Gonzalez and Dethier, 1991) were probably deposited during this period when base level was controlled by a downriver knickpoint.

Details of the post-1.22 Ma incision history of the Rio Grande in White Rock Canyon are poorly defined due the scarcity of datable deposits and extensive modification by landslides. Upriver, the lower Rio Chama was about 110 m above modern grade at 0.62 Ma when the Lava Creek B tephra was erupted (Dethier et al., 1990; Gonzales and Dethier, 1991; Dethier and McCoy, 1993). Possibly correlative Rio Grande terraces downriver near Cochiti Dam are about 90 to 150 m above the river (Dethier et al., 1988), suggesting a similar amount of incision in White Rock Canyon since 0.62 Ma. Both upriver in the Española basin (Dethier et al., 1988; Dethier and Reneau, 1995) and downriver in the Albuquerque basin (Lozinsky et al., 1991), incision apparently accelerated sometime after 1.0-0.6 Ma, and a related increase in incision rates in White Rock Canyon is thus reasonable (Fig. 4).

Increases in river discharge associated with drainage capture during the Quaternary may have influenced the incision history in White Rock Canyon. The San Luis Valley of southern Colorado was internally drained in the early Quaternary, and complete integration of the present Rio Grande basin did not occur until between 0.3 and 0.7 Ma (Wells et al., 1987; Rogers et al., 1992). This capture would have increased the drainage area above White Rock Canyon from about 15,000 km^2 to its current 37,000 km^2, probably resulting in significant increases in flood discharge that in turn may have increased incision rates.

Net late Quaternary incision of the Rio Grande in northern White Rock Canyon has apparently been similar to that occurring upriver along the Rio Chama. Amino acid analyses of fossil gastropods collected from a 33-m-high Rio Grande terrace 1.7 km east of Otowi Bridge provided an age estimate of < 0.1 Ma (Table 1; Dethier and Reneau, 1995), which is consistent with the age of deposits at this height upriver (Dethier and McCoy, 1993). Similarly, a possibly finite ^{14}C age of 43.2 ka for sediments burying a 15 to 20 m high Rio Grande deposit near Cañada Ancha (Dethier and Reneau, 1995; Reneau et al., 1995) is consistent with the age of deposits at similar heights along the Rio Chama.

Maximum incision of the Rio Grande in White Rock Canyon may have occurred in the latest Pleistocene during a period of higher discharges than today when glaciers developed in the San Juan and Sangre de Cristo mountains. Data from both the Española and Albuquerque basins indicate that the Rio Grande had incised 10-40 m below its present level in the late Pleistocene and has subsequently aggraded (Love et al., 1987; Lozinsky et al., 1991); by inference, much of the incision in White Rock Canyon may have occurred during wetter parts of the Pleistocene that corresponded with glacial times. Although the timing of the late Pleistocene incision is not certain, the reactivation of the toes of landslides along the Rio Grande in White Rock Canyon between 18 and 12 ^{14}C ka, discussed in the next section, may record the time of maximum river discharge and deepest incision.

LANDSLIDES AND LANDSLIDE-DAMMED LAKES

The Rio Grande is flanked almost continuously by large landslide complexes for 16 km downriver of Otowi Bridge (Fig. 3; Smith et al., 1970; Reneau et al., 1995; Dethier, in press). Most of these landslides are slumps, with individual failures causing up to at least 0.5 km of retreat of the rim of White Rock Canyon (Fig. 10). Failure planes are usually covered by landslide debris or colluvium, but they appear to occur primarily in the sedimentary rocks interlayered with or underlying the basaltic rocks. Slump blocks are back-tilted from 8° to 70°. Several large rock avalanches composed of basaltic boulders are also present, including one north of Ancho Canyon that is 1.5 km in length (Reneau et al., 1995).

The landslides in White Rock Canyon record a long history of slope failure that was probably largely driven by progressive incision which exposed relatively weak sediments beneath the basaltic rocks, although climatic fluctuations and possibly seismic shaking may have provided the actual triggers. Slumps are relatively rare south of Chaquehui Canyon, where basaltic rocks dominate the exposed section. Based on a spatial relation between slumping and the thickness of exposed sediment, the distribution of bedrock units, and the incision history of the Rio Grande, we infer that slumping began near Otowi Bridge by ca. 0.5 Ma (where a thick section of sediments was first exposed below the basalts), and that it has progressed downriver as incision has continued through the middle and late Quaternary (Reneau et al., 1995). Most of the large landslide complexes are overlain by the El Cajete pumice, which indicates that they were emplaced prior to 50-60 ka (age from Toyoda et al., 1995; Reneau et al., 1996).

Late Quaternary lacustrine deposits are widespread in northern White Rock Canyon (Fig. 11), and indicate that the Rio Grande was repeatedly dammed by landslides (Dethier and Reneau, 1995; Reneau et al., 1995). The largest lake we have recognized has an estimated age of 40-70 ka

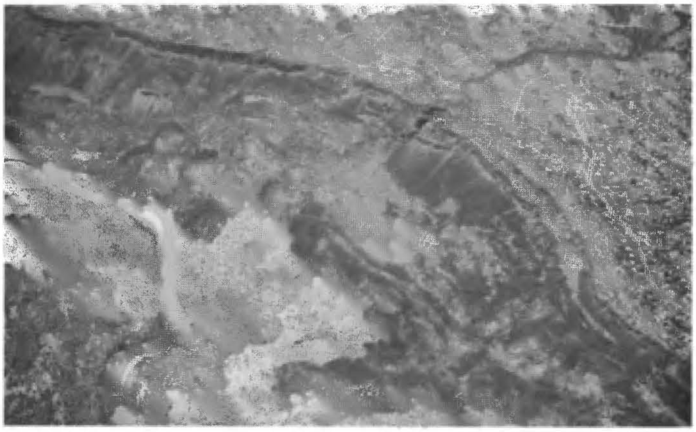

FIGURE 10. Oblique aerial photograph of Pajarito Canyon slump complex, below White Rock.

(Table 1), and had an estimated maximum depth of 60 m and a length of 25 km, extending upriver to Española. At least four additional lakes were formed between about 18 and 12 ^{14}C ka, caused by the failure of the toe of a large slump complex southwest of Water Canyon. The youngest lake, about 12.4 ^{14}C ka in age, had an estimated maximum depth of 25 m and a length of 12 km, extending upriver to Otowi Bridge.

Comparison of the ages of these landslide-dammed lakes and regional records of climate change indicates a strong climatic influence on the triggering of the youngest large slope failures in White Rock Canyon, with landsliding occurring during periods of enhanced precipitation at

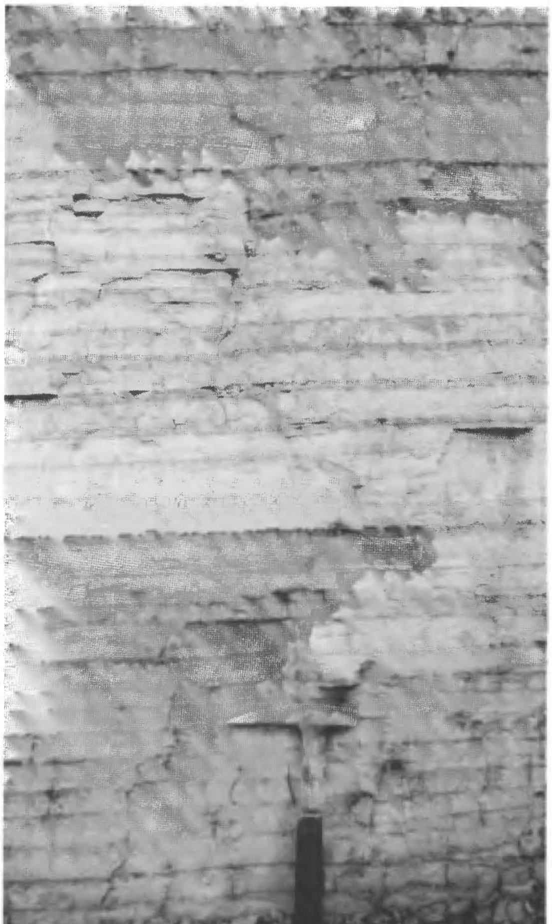

FIGURE 11. Well-laminated silt and clay rich lacustrine sediments exposed in bluffs south of Cañada Ancha. Charcoal collected from basal sediments provided a possibly finite radiocarbon age of 43.2 ka.

the end of the Pleistocene (Dethier and Reneau, 1995; Reneau et al., 1995). We propose that the failures were triggered by a combination of incision and toe erosion by the Rio Grande during periods of significantly higher flood discharges than today, enhanced infiltration directly onto the slump complexes, higher water tables, and increased groundwater discharge from the deep aquifer beneath the Pajarito Plateau.

Boulder-rich deposits extending downriver from the Water Canyon dam to Chaquehui Canyon probably record the catastrophic draining of one of the landslide-dammed lakes (Reneau et al., 1995). The use of relations between lake size and flood peak (Costa, 1988) indicates that discharges of perhaps 2000 to 9000 m^3/s were possible, up to an order of magnitude higher than the largest recorded flood of about 700 m^3/s. Additional boulder-rich deposits that occur between Frijoles and Alamo Canyons, older than 50-60 ka, probably record an additional, larger outburst flood, although we can not relate these deposits to a specific landslide dam.

The youngest landslide dam was apparently stable, and the lake completely filled with lacustrine deposits and overlying bedload sediments of the Rio Grande. Subsequent incision has left a series of river terraces upriver of the landslide dam which are primarily late Pleistocene in age. By 9 ^{14}C ka the Rio Grande was within about 5 m of its present grade, and by 3 ^{14}C ka it was within about 2 m of its present level (Table 1); during this period of relative base level stability in the Holocene, fans have aggraded at the mouths of tributary canyons (e.g., Frijoles Canyon fan, Fig. 1).

CONCLUSIONS

The record of fluctuations in the elevation of the Rio Grande at White Rock Canyon and vicinity during the Pliocene and Quaternary should aid in understanding controls on late Cenozoic fluvial history in the region. Base level rises imposed by local volcanism probably helped promote aggradation upriver (e.g., Puye Formation fan), producing local records that may differ from areas to the south. Temporal variations in climate, rates of faulting, regional uplift, and drainage integration in both the Pliocene and the Quaternary have also likely influenced the history of the Rio Grande and other drainages in White Rock Canyon and elsewhere in the Southwest, although the relative importance of these factors is not well understood and may vary spatially. For example, late Quaternary climatic fluctuations apparently had a major effect on the Rio Grande in White Rock Canyon due to the susceptibility of canyon walls to landsliding, but likely had different effects in areas of more resistant rock and in alluvial valleys. Resolution of many aspects of local vs. regional controls on late Cenozoic fluvial history thus awaits further work.

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