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QUATERNARY HISTORY OF THE WESTERN ESPAÑOLA BASIN, NEW MEXICO

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Abstract—Quaternary deposits and landforms are exposed widely in the Española Basin, where base level has fallen >150 m since early Pleistocene time and drainages have eroded weak Cenozoic rocks, stranding ancestral piedmont and axial channel deposits beneath terraces that flank the Rio Grande valley. Extended periods of high flow on drainages that carried pluvial and glacial runoff probably produced middle and late Quaternary incision. The Bandelier Tuff (1.6 and 1.2 Ma), Lava Creek B ash (0.62 Ma) and the El Cajete pumice (50-60 ka) provide local age control, supplemented by ages estimated from amino-acid ratios in gastropods and by ^{14}C ages. The Pajarito, Rendija Canyon and Guaje Mountain faults displace Pleistocene deposits; the latter faults were probably active in the Holocene. The NE-trending Embudo fault zone has been the northern structural margin of the Española Basin since middle Miocene time, but it is difficult to demonstrate Quaternary slip along the zone. Quaternary fluvial deposits consist of axial-channel gravels and thin overbank deposits covered by coarse sand and gravel delivered by ancestral alluvial fans. Sequences of lithologically similar deposits are preserved at heights from more than 170 m to 15 m above the modern floodplain between Abiquiu and Otowi Bridge. These sequences suggest that alluvial fans expand across the Rio Grande floodplain during transitions from pluvial to interpluvial climate and that deposits are preserved when the river cuts down during the next pluvial period. Holocene cut-and-fill sequences are preserved along some tributaries to the Rio Grande, but their climatic significance is uncertain. Incision along the Rio Grande in upper White Rock Canyon generated massive slumps beginning in middle Pleistocene time as the river cut through weak rocks of the Santa Fe Group, the Puye Formation and Pliocene lacustrine deposits. Reactivation of toe areas of some slumps dammed the Rio Grande at >43 ka and at least four times between 18 and 12 ka, producing lakes as deep as 60 m. Landslide motion and lake age in White Rock Canyon coincide with the glacial maximum and final pluvial pulses of the latest Pleistocene, suggesting that climate change destabilized older slumps through toe incision or by greater pore pressures from increased groundwater recharge. The Rio Grande flowed at its modern grade before about 12 ka.

INTRODUCTION

The Española Basin is the most deeply dissected of the basins that form the Rio Grande rift and exposes extensive Quaternary deposits and prominent landforms, particularly west of the Rio Grande and in the vicinity of White Rock Canyon. Kelley (1979) reviewed the geomorphology of the basin in a speculative paper that focused on the classic late(?) Pliocene Ortiz erosion surface (Bryan, 1938) and its dissection coincident with Quaternary canyon cutting and regrading. In this paper we acknowledge the important influence of pre-Quaternary bedrock geology and structures and the Pliocene landscape, but focus primarily on the record of Pleistocene and Holocene processes and events, relying on the results of two decades of isotopic and relative dating. We report published and unpublished data mainly from the western Española Basin between Abiquiu and Española and along White Rock Canyon.

We define the Española Basin as that area northeast and east of the volcanic Jemez Mountains drained by the Rio Chama and Rio Grande, bounded on the south by the La Bajada escarpment and the Cerros del Rio, on the east by the Sangre de Cristo Mountains and to the north by the Colorado Plateau, Brazos-Tusas ranges, and the Taos Plateau. Perennial drainages and arroyos have been cutting down into the relatively weak upper Tertiary sediment of the Santa Fe Group since early Pliocene time, forming a badland landscape north of Española and a deeply dissected plateau to the south (Fig. 1). Baldridge et al. (1994) demonstrated that the NW Española Basin (Abiquiu embayment of Kelley, 1978) lies within the Rio Grande rift and Gonzalez and Dethier (1991) showed that the embayment and main basin are geomorphically continuous.

The Rio Grande, joined by the Rio Chama north of Española, flows through the middle of the Española Basin at elevations ranging from 1845 m to about 1600 m. Local relief is substantial: the Sangre de Cristo Mountains reach nearly 4,000 m to the east. Arroyos with relatively wide sandy beds flow at gradients of about 2% through the highly dissected landscape that flanks the alluvial valley. The Rio Chama runs through gravelly alluvium at a gradient of 0.20% from Abiquiu to its confluence with the Rio Grande. The floodplain of the Rio Grande is relatively broad near Española, river gradient drops to 0.07%, and sediment is richer in sand. The floodplain disappears as the river steepens to 0.20% where it plunges into White Rock Canyon below Otowi Bridge. Perennial tributaries from north to south include Canones Creek, El Rito, Rio del Oso, Rio Ojo Caliente, Santa Cruz River, Santa Clara Creek, Pojoaque River and Frijoles Creek.

BEDROCK GEOLOGY AND FAULTS

The central Española Basin (Fig. 1) exposes poorly consolidated bedrock consisting of silty sandstone of the Santa Fe Group, capped to the south by a Pliocene fanglomerate (Puye Formation), Pliocene basalt and Pleistocene(?) andesite of the Cerros del Rio, and the early Pleistocene Bandelier Tuff (Spiegel and Baldwin, 1963; Griggs, 1964; Kelley, 1979). To the east, the Sangre de Cristo Mountains comprise mainly crystalline rocks of Precambrian age. The basin was drained internally until early(?) Pliocene time, when the ancestral Rio Grande-Rio Chama system began to flow through the area (Manley, 1979). Quaternary rocks and unconsolidated deposits are exposed most extensively in the western part of the Española Basin between Abiquiu and Española and along the margin of the Pajarito Plateau.

Structures that bound the Española Basin, such as the Canones fault zone (Gonzalez and Dethier, 1991; Baldridge et al., 1994), and many intrabasin faults were active during middle to late Miocene time, but it is difficult to demonstrate Quaternary activity along most fault zones. Geophysical evidence suggests that the Tertiary fill is 2 to 3 km thick in the Velarde graben south of the Embudo fault zone and along the Pajarito fault zone (Biehler et al, 1991) and <1 km thick in the northwest and east parts of the basin (Baldridge et al., 1994). These asymmetries suggest that the Española Basin is a half graben with the western side down and that the NW basin area (Abiquiu embayment) is structurally distinct. Field evidence and stratigraphic relations indicate that the Pajarito fault zone has been active at least since Pliocene time, with < ca 150 m of mainly dip-slip motion since 1.2 Ma. The Rendija Canyon and Guaje Mountain faults, which comprise the Pajarito fault zone north of Los Alamos, have been active in Pleistocene and probably in Holocene time (Wong et al., 1993). Careful mapping of the Pajarito Plateau and the presence of the Bandelier Tuff as a clear marker unit have contributed to identification of numerous additional fault splays. There may have been some late Cenozoic motion on faults that form the eastern border of the Española Basin (Vernon and Riecker, 1989), but the faults display little surface expression. Motion younger than Pliocene has not been unequivocally demonstrated along the La Bajada escarpment, on the south edge of the basin, the Canones fault zone to the northwest (Gonzalez and Dethier, 1991; Baldridge et al., 1994) or the intrabasin Velarde graben (Manley, 1979). Baldridge et al. (1994), for example, concluded that apparent offset of middle Pliocene basalt flows along the Garcia fault zone (Gonzalez and Dethier, 1991) is probably a result of local topo-

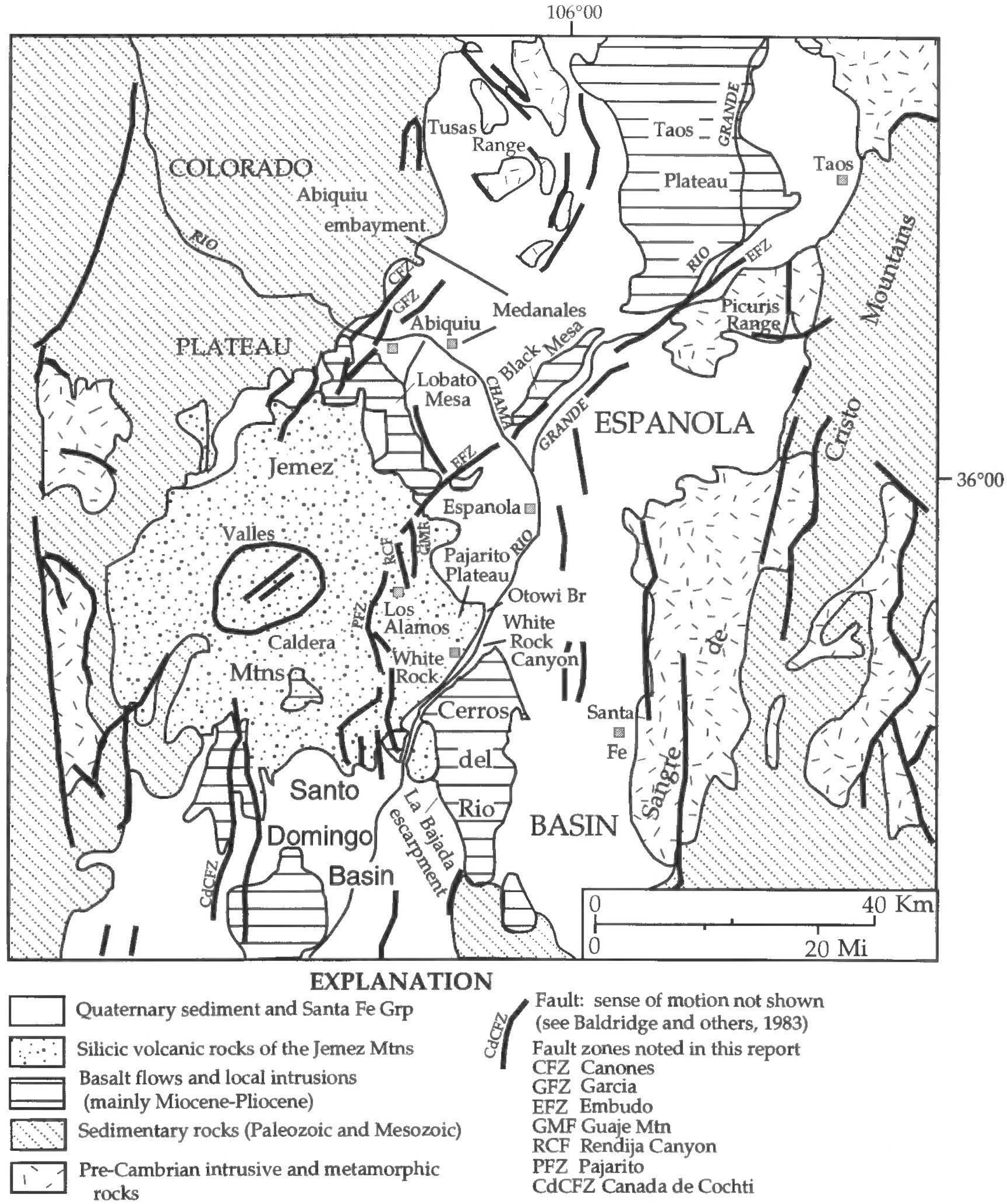

FIGURE 1. Map showing geology of Española basin and surrounding area (modified from Gonzalez and Dethier, 1991).

graphic variation and that the fault is of middle Miocene age. One fault in this zone (Madera Canon fault zone of Gonzalez and Dethier, 1991), however, does appear to offset middle Pleistocene erosion surfaces.

The NE-trending Embudo fault zone is the most problematic structure in the Española Basin (Muehlberger, 1979; Dungan et al., 1984). Manley (1979) and Aldrich and Dethier (1990) suggested that middle Miocene rocks are faulted hundreds of meters down to the southeast, but that dip-slip motion reoriented to mainly strike-slip after about 10 Ma. Muehlberger (1979) documented Quaternary deformation along the zone near Embudo, and Harrington and Aldrich (1984) suggested that Pliocene and possibly Quaternary sediment and erosion surfaces are deformed and drainage diverted west of Black Mesa. The height above grade of the 0.62 Ma Lava Creek B ash changes <10 m across the fault zone, but evidence does not rule out Pleistocene strike-slip motion along the Embudo fault west of the Rio Chama. We believe, however, that most deformation along the SW Embudo fault zone probably predates the Pleistocene.

QUATERNARY CLIMATE

The present geomorphology of the Española Basin reflects long-term changes in Pleistocene climate, including the profound changes of the past 25,000 years, and local rock resistance. Both pluvial and glacial climates influence the basin because of its substantial local relief and the mountainous sources of the Rio Grande. Present climate is semi-arid to arid at lower elevations near the Rio Grande, and semiarid at elevations above about 1800 m (Bowen, 1990). Peak discharge in the Rio Grande tends to occur during the sustained spring snowmelt season and in the summer storm season, which is characterized by peak flows of short duration (Graf, 1994).

During much of the Pleistocene, climate in the southwestern United States was cooler and probably wetter than that of the late Holocene, including pluvial climates that lasted approximately 0.1 Ma and interpluvial climates that lasted about 20 ka (Winograd et al., 1992). The duration, timing, and fine structure of these climatic regimes, however, show considerable variation over the past 0.5 Ma and suggest that climatic variation was different before and after about 0.5 Ma. Evidence for Quaternary paleoclimate in the Española Basin is largely inferential, but geologic and palynologic data suggest the magnitude of climate change during latest Pleistocene and Holocene time. Glaciers formed in cirques above an elevation of 3260 m, moraines were constructed as low as 2880 m (Wesling, 1987) during at least two late Pleistocene advances, and the Sangre de Cristo Mountains supported small glaciers and rock glaciers in Holocene time. The best dated evidence for climate change comes from the pluvial lakes that filled nearby areas, such as the Estancia basin (Allen and Anderson, 1993) and the San Agustin Plains (Markgraf et al., 1984). Pleistocene Lake Estancia, nourished primarily by groundwater flow, had high stands between 25 and 21 ka, at about 17 ka, and between about 14 and 12 ka (Bachhuber, 1989; Allen and Anderson, 1993). The two earlier ages correspond approximately with the latest Pleistocene glacial maximum in the Rocky Mountains and the period of rapid ice retreat, respectively (Porter et al., 1983; Elias et al., 1991). The later age probably represents a pluvial event not reflected in the glacial record. Phillips et al. (1992) demonstrated that large, but variable volumes of surface water flowed into Glacial Lake San Agustin between 27 and 14 ka, a time when bedrock aquifers in the San Juan Basin (Phillips et al, 1986) and shallow aquifers and lakes elsewhere in the Southwest (Phillips et al, 1994) received far more recharge than they have in Holocene time. Both lakes shrank after about 12 ka, but Lake Estancia expanded slightly at about 10 ka; the pluvial lakes disappeared in Holocene time.

Glacial and lacustrine evidence suggests that temperatures during the latest Pleistocene were colder and that more moisture was available for groundwater recharge and for surface runoff. Local and regional palynologic records suggest sharp spatial and temporal contrasts (Spaulding et al., 1983; Spaulding and Graumlich, 1986; COHMAP Project Members, 1988; Thompson et al., 1993), consistent with fluctuations in the position of the jet stream axis. As the statistical position of the jet moved north, winter precipitation probably decreased and the summer monsoon pattern became reestablished over northern New Mexico sometime after about 15 ka. Regional evidence suggests that the mid-Holocene was drier and possibly warmer than the present climate and that the late Holocene is cooler (Spaulding, 1992, unpubl.).

QUATERNARY DEPOSITION, EROSION AND LANDSCAPE EVOLUTION ALONG THE RIO GRANDE VALLEY

Sequences of terraces and underlying sediment near the axial drainage in the Española Basin preserve a long record of Quaternary geomorphic change due to coincidence of (1) an actively downcutting perennial drainage; (2) a flanking piedmont composed of easily eroded material; and (3) sources of resistant materials such as boulder gravel or volcanic flows to preserve some geomorphic surfaces. Pliocene basalt flows from Lobato Mesa and the Taos volcanic field protect underlying materials from erosion and provide time control, as does the Lava Creek B ash (Dethier et al., 1990), erupted from the Yellowstone caldera at 0.62 Ma, and the Bandelier Tuff. Channel gravel and finer sediment from the ancestral axial-river and piedmont deposits, mainly coarse sand and eolian deposits, are preserved beneath the coarse sediment.

Age control

The age of many deposits and landforms are closely constrained in the Española Basin by radiometric dating of upper Tertiary and Quaternary volcanic rocks, and by ^{14}C dating of latest Pleistocene deposits (Table 1). Volcanic activity in the Cerros del Rio, Jemez Mountains and other nearby complexes shed debris into the Española basin in Plio/Pleistocene time, episodically damming the Rio Grande near modern White Rock Canyon, and producing a series of invaluable time-stratigraphic units. Late Pliocene and early (?) Pleistocene flows of andesite and basaltic andesite comprise much of the surface of the Cerros del Rio volcanic field (Smith et al., 1970; Aubele, 1978; Baldridge et al., 1980). For example, a basaltic andesite overlying silicic tuff (Bandelier?) along the east edge of the Rio Grande in the Cochiti Dam quadrangle gave a K-Ar age of 1.69±0.06 Ma (Dethier, unpubl.), andesitic flows exposed along southern White Rock Canyon lie above Bandelier-like pyroclastic deposits at many locations and Manley (1976) dated an andesitic flow capping the Ancha Formation along the northern Cerros del Rio as 1.96 Ma.

The Bandelier Tuff is a complex sequence of pyroclastic flow and fall deposits erupted from the Valles and Toledo calderas in early Pleistocene time. Ignimbrites flowed into the Rio Grande along White Rock Canyon and extended to within 10 km of the Rio Chama in the northwestern Española Basin. The Otowi Member, exposed in many of the deep canyons west of the Rio Grande, erupted at about 1.6 Ma (Izett and Obradovich, 1994). The basal Guaje Pumice Bed of the Otowi Member is widely preserved as far east as White Rock Canyon, where it lies unconformably on surfaces cut into Pliocene basalt of the Cerros del Rio or on Pliocene alluvium. The Tshirege Member consists of pyroclastic flows and a thin basal pumiceous fall unit, the Tsankawi Pumice Bed (Bailey et al., 1969), erupted about 1.22 Ma (Izett and Obradovich, 1994). These units have not been recognized in the central or eastern parts of the basin.

Volcanic activity continued in the vicinity of the Valles caldera after its collapse at about 1.22 Ma. Rhyolite domes, pyroclastic rocks and flows erupted at about 1.1, 0.95, 0.8, 0.55 Ma, and after about 0.15 Ma (Spell and Harrison, 1993). Only the El Cajete pumice constitutes an important stratigraphic marker in the southwestern Española Basin. The rhyolitic pumice, erupted from the El Cajete crater in the southern Valles caldera, is present as deposits tens of cm thick as distant as 10 km east of the Rio Grande (Dethier, in press). Conflicting ages have been obtained for the pumice and related units. Fission-track and $^{40}Ar/^{39}Ar$ analyses indicate ages of 130 to 180 ka and > 200 ka, respectively (Self et al., 1988, 1991). Recent electron spin resonance analyses (Toyoda et al., in press), a thermoluminescence estimate for a soil buried beneath the pumice (S. L. Forman,

TABLE 1. Height and estimated age of Quaternary deposits, western Española basin, New Mexico.

Height[1] above Rio Chama or Rio Grande (mm)	Amino-acid ratio[2]	Estimated age, in ka (method)[3]	Material and Location
260	nd	3650 (Ar/Ar)	Basal basalt flow, Black Mesa
172	nd	—	Ancestral Rio Chama seds.
150	nd	1600 (Ar/Ar)	Gravel beneath Guaje pumice E. of Lobato Mesa (4 sites)
125	0.68	650	Ancestral Rio Chama seds.
110	0.70	620 (Ar/Ar)	Ancestral Rio Chama seds. beneath Lava Creek B ash
91	0.53	350	Ancestral Rio Chama seds.
84	0.47	280	Ancestral Rio Chama seds.
75	0.45	250	Ancestral Rio Chama seds.
63	0.34	150	Ancestral Rio Chama seds.
54	0.32	130	Ancestral Rio Chama seds.
45	0.32	130	Ancestral Rio Chama seds.
38	0.24	70	Ancestral Rio Grande seds
33	<0.29[4]	<100[4]	Ancestral Rio Grande seds nr Otowi Bridge
27	0.16	40	Ancestral Rio Grande seds
15	0.17(?)	>26[5] (^{14}C)	Ancestral Rio Chama seds
15	—	43.5[6] (^{14}C)	Lacustrine, White Rock C.
—	0.10	19 (^{14}C)	Eolian sands E. of Española
12–5	—	14–12 (^{14}C)	Lacustrine, White Rock C.
5		9 (^{14}C)	Fluvial, White Rock C.
2	—	3 (^{14}C)	Archeological, White Rock C.
0	0.0	0	Floodplain

1. Measured from the active channel to the top of paleogravel.
2. Hydrolysate aIle/Ile ratios from *Succinea* or *Vallonia* (Dethier and McCoy, 1993, and unpublished).
3. Argon/argon ages from Laughlin et al., 1993 (Black Mesa); Izett and Obradovich, 1994 (Guaje pumice) and Sarna-Wojcicki et al., 1987 (Lava Creek B ash); ^{14}C ages from Reneau et al. (in press).
4. Maximum limiting amino-acid ratio and age estimate because of shallow burial.
5. Shell date: assumed to be minimum limiting age.
6. AMS date: assumed to be minimum limiting age.

unpubl., 1994), and radiocarbon analyses from charcoal entrained within the pumice beds (S. L. Reneau and J. N. Gardner, unpubl., 1993) suggest a much younger age of about 50–60 ka for the El Cajete.

Height above the axial river is an excellent primary indicator of age along the Rio Grande within the Rio Grande rift. Age control is provided by the Bandelier Tuff, the Lava Creek B ash bed, amino-acid ratios in fossil gastropods from fluvial deposits (Dethier and McCoy, 1993), and by ^{14}C ages of charcoal and gastropods from a number of settings. An extensive series of radiocarbon ages (Table 1) helps to define episodes of late Pleistocene lake formation in White Rock Canyon (Reneau et al., in press). These data and deposit elevations demonstrate that rates of incision have not been constant (Fig. 2). The net rate of base-level lowering in the western Española basin was <0.05 m/ka from middle Pliocene to middle Pleistocene time, when it increased dramatically to a rate of >0.20 m/ka. Details of early and middle Quaternary geomorphic history are poorly defined before about 0.62 Ma because stratigraphic markers of known age are scarce.

Preservation of the Quaternary record along the Rio Grande and Rio Chama

Ancestral Rio Chama and Rio Grande deposits and associated piedmont sediment are preserved in sequences of lithologically similar deposits at heights from more than 170 m to 15 m above the modern floodplain between Abiquiu and Otowi Bridge. To help explain this sequence of deposits, we suggest that the response of the Rio Grande and alluvial fans to late Pleistocene and Holocene changes of climate provides a model for the response to pluvial/interpluvial transitions earlier in the Pleistocene. In the Española area, surface mapping and subsurface evidence shows that during the most recent climatic transition, west-flowing arroyos built a fan complex several kilometers wide, burying the margins of a broad late Pleistocene braid plain (Love et al., 1987). Since early Holocene (?) time, the extent of fans and width and elevation of the Rio Grande have remained relatively constant. Subsurface investigations of latest Pleistocene and Holocene deposits south along the Rio Grande suggest that comparable geomorphic changes occurred in the Albuquerque Basin and near Socorro. In the Albuquerque Basin (Lozinsky et al, 1991) and to the south (McGrath and Hawley, 1987), middle to late Pleistocene incision, interrupted by episodes of tens of meters of alluvial-fan and valley-floor aggradation, produced a stepped sequence of terraces that flank the modern flood plain. Geologic evidence thus suggests that alluvial fans expand across the edge of the broad braid plain of the Rio Grande, probably during the transition to interpluvial climate, restricting its width and inducing some aggradation. Broadening and entrenchment of the floodplain, probably in the succeeding pluvial period, erodes the fluvial deposits, but channel migration helps to preserve some older deposits. During the next interpluvial period, fans again expand over the floodplain, followed by pluvial incision. If the river continues to cut down and is free to migrate laterally, older deposits will be preserved if they acquire a protective cover.

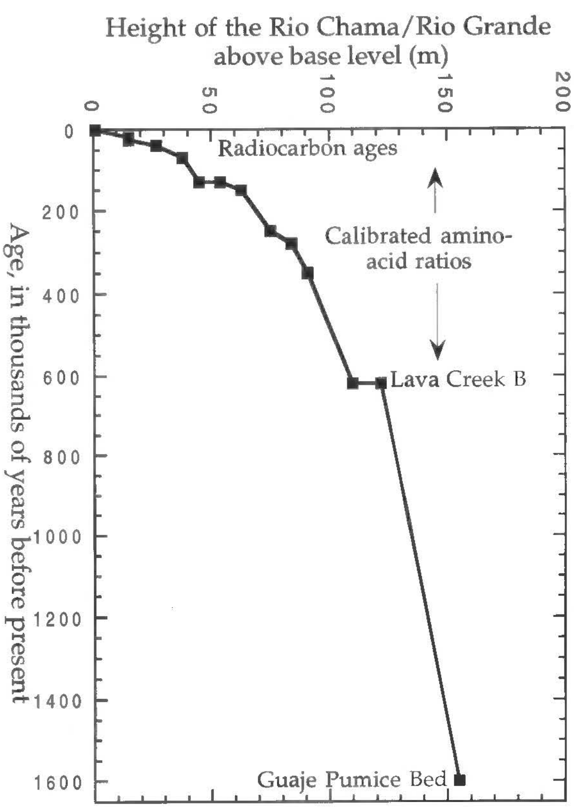

FIGURE 2. Relationship between age and height above base level, western Española Basin, New Mexico (see also Table 1.).

Quaternary deposits

Sedimentary sequences and volcanic rocks that rest on gravel deposited by the ancestral axial drainage provide critical evidence about depositional processes and base level, and inferences about paleoclimate. Middle to late Pleistocene alluvial fan and axial river deposits are best exposed northwest of Medanales, New Mexico. Similar sequences have been mapped in detail from Abiquiu south to Española and near the Rio Grande upstream from San Jose (Dethier, unpubl.; Gonzalez and Dethier, 1991) and in reconaissance south to Otowi Bridge (Fig. 3). Descriptions below are derived mainly from detailed mapping along the Rio Chama valley northwest of Española.

The Pleistocene Rio Chama deposited both medium to coarse gravel in channels eroded into Miocene bedrock and fine sand and silt, probably as overbank deposits (Fig. 4). Massive to channel cross-stratified, imbricated cobble gravel, in a layer 2 to 8 m thick, is the most common preserved deposit and can be traced laterally as much as 1000 m. At a few locations, a second channel gravel lies 5 to 10 m above the top of the basal gravel, separated by overbank or alluvial fan deposits, suggesting a period of local aggradation in the axial channel. Overbank deposits are thin-bedded to massive silty sand, medium-grained sand and local clay-rich silt 1 to 3 m thick. Fossil gastropods, burrows, and calcareous root traces suggest abundant organic activity. Buried soils, mainly B_w or weakly developed B_k horizons, are present locally. The Lava Creek B ash is interbedded with overbank deposits in more than 25 locations at an elevation of ~110 m above the active flood plain (Dethier et al., 1990). Alluvial-fan deposits, mainly medium-grained sand, generally lie above the axial-channel deposits. Relatively coarse alluvial-fan deposits extend laterally as much as 1000 m across ancestral river deposits, forming wedge-shaped units with preserved thicknesses as great as 40 m. Thin-bedded coarse sand, boulder-rich gravel, boulder-rich diamicts and discontinuous beds of cross-stratified sand are the predominant sediment types. Geologic evidence suggests that some of the alluvial fans represented by these remnants accumulated rapidly, perhaps during a single climatic regime, whereas other deposits appear to record longer periods of time. The thickest sections deposited at about 0.62 Ma, for example, contain neither buried soils nor other evidence for breaks in sedimentation. Other thick exposures contain weakly developed calcic soils, but little evidence of hiatuses longer than about 10 ka. Several exposures, most notably near San Jose, may have developed over tens of thousands of years and contain buried soils with moderately well-developed B_k horizons. The upper part of the alluvial fan deposits are truncated by erosion and generally consist of bouldery gravel or lag deposits that contain large subangular boulders of basalt. Strongly developed soils, including thick B_t horizons and Stage III or IV caliche (Machette, 1985) are present locally, but are most frequent south of the Rio del Oso. Erosion surfaces generally truncate alluvial fan sequences, suggesting that surface boulders may be derived from erosion of debris flows that form a significant component of some piedmont deposits.

Holocene deposits

Holocene alluvial deposits are widespread along intermittent and perennial streams in the Española Basin and contain a complex record of aggradation and channel incision similar to that documented in other

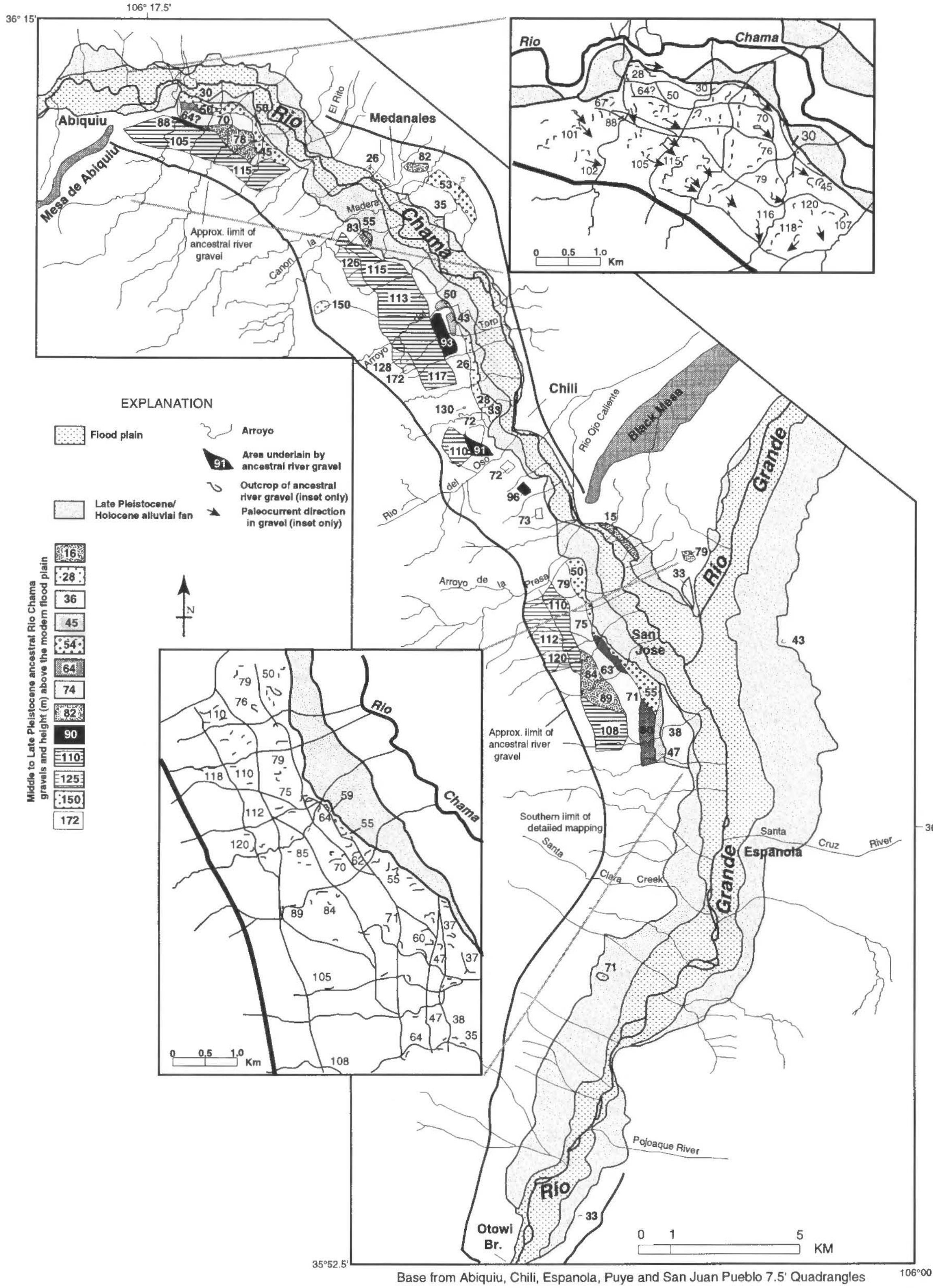

FIGURE 3. Map showing preserved ancestral Rio Chama and Rio Grande deposits and their height (from top of gravel) above the modern channel, the extent of latest Pleistocene/Holocene alluvial fans and the modern floodplain. Insets show areas near Abiquiu and San Jose in greater detail, emphasizing the location and height of ancestral channel deposits.

parts of the Southwest. The best age control has been obtained from sediment within canyons on the Pajarito Plateau (Reneau et al., 1993; Reneau, unpubl.) and near archeological sites (Miller and Wendorf, 1958; Anschuetz, K.F., 1993, unpubl.). Extensive Holocene fills contrast with apparently rare late Pleistocene deposits, and suggest a major change in geomorphic processes at perhaps 10 to 8 ka or earlier. The Holocene deposits may record initiation of a period of accelerated erosion following the change to Holocene aridity and the enhancement of monsoonal precipitation. These deposits may also provide an analog for earlier interpluvial climates in the Española Basin, when fans prograded over axial

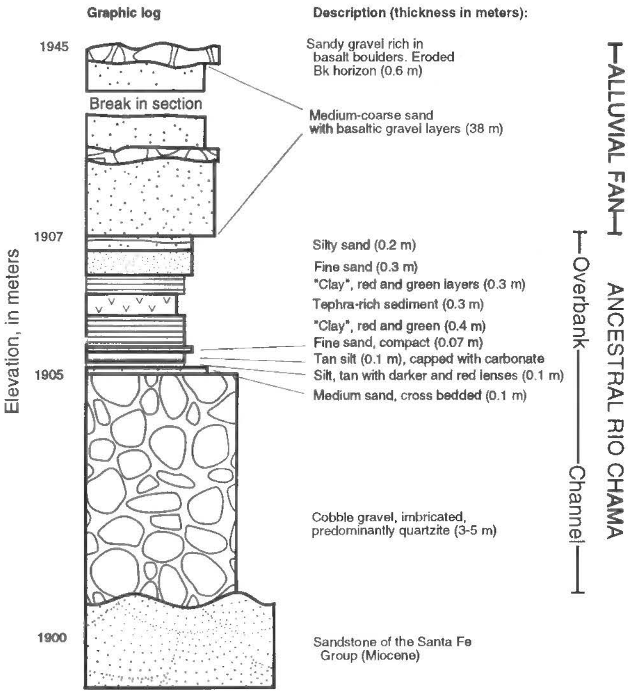

FIGURE 4. Typical stratigraphic section showing ancestral Rio Chama and alluvial fan deposits southeast of Abiquiu.

river terraces, recording upland erosion following regional climate changes.

Middle and late Holocene alluvial deposits in the Española Basin display multiple cut-and-fill cycles, indicating alternating aggradation and degradation of the channels. Three canyons draining the Pajarito Plateau, for instance, show a major period of aggradation before about 6.0 ka, and aggradation or slowing of incision between 3 and 4 ka, at about 1.6 ka, and between 0 and 0.4 ka (Reneau et al., 1993), when channels generally were near their present level. The Rio Tesuque sequence (Miller and Wendorf, 1958) records a major aggradation event at about 2.2± 0.25 ka and a smaller one before about A.D. 1200. Arroyos in arid and semiarid portions of the basin also cut down into existing floodplains between 1880 and 1920, much as they did elsewhere in the Southwest (Leopold, 1994). Holocene changes generally represent fluctuations of ± 6 m in local channel elevation over periods of hundreds of years to a few millenia, at most. The scale of such changes suggests variations in sediment supply or flood characteristics produced by climate change. However, much variability exists in the ages of sedimentary packages, and the relative importance of regional climate changes versus more local controls (Miller and Wendorf, 1958) is not known.

Plio/Pleistocene incision and topographic inversion

The Rio Chama/Rio Grande and most tributary arroyos cut down >300 m into weak rocks of the Santa Fe Group after early Pliocene time, but boulder gravel, volcanic flows and other materials locally resisted erosion, preserving paleosurfaces and producing significant topographic inversion in the western Española basin. The oldest surfaces are capped by basalt flows, whereas most of the early Pleistocene surfaces are protected by cemented boulder gravel rich in volcanic clasts, or by indurated Bandelier Tuff. Elongate mesas underlain by Pliocene basalt, such as Black Mesa (3.65 Ma, Laughlin et al., unpubl., 1994), Mesa de Abiquiu and Canones Mesa (near Abiquiu), indicate the position of base level and the approximate local gradient of axial channels during the middle and late Pliocene (Gonzalez and Dethier, 1991). Preservation of early Pleistocene deposits is more complete, particularly along the eastern margin of the Jemez Mountains. Isolated outcrops containing the lower Bandelier Tuff allow us to estimate early Pleistocene base level. Field evidence in the central part of White Rock Canyon demonstrates that the Rio Grande cut down >140 m to within ~130 m of present base level between about 2.3 and 1.6 Ma. To the north, between Arroyo del Toro and Rio del Oso (Fig. 4), boulder-rich alluvium caps small mesas that expose ancestral Rio Chama gravel about 170 m above present base level. South of Canon la Madera, an isolated butte and several ridges near Lobato Mesa are underlain by the Guaje Pumice Bed. The pumiceous deposits at these sites rest on mainly basaltic piedmont gravels some 150 m above present base level. If gradients of these ancestral arroyos were similar to present gradients, the Rio Chama at 1.6 Ma was, at most, about 150 m above present grade (Fig. 2). Pyroclastic flows and fall deposits of the upper Bandelier Tuff overlie and locally fill canyons cut in the lower Bandelier Tuff, particularly south of Española, and field evidence in White Rock Canyon demonstrates that the Rio Grande was about 120 m above present base level at 1.2 Ma (Reneau et al., in press).

Sections of alluvial fans truncated by erosion surfaces, ridges formed of paleochannel gravels (inverted paleochannels of Fig. 5), and strongly cemented remnants of colluvial deposits record the degree of landscape inversion along the eastern flank of Lobato Mesa since early Pleistocene time. Erosion surfaces labeled Q_2 through Q_5 stand 150 to 28 m above present base level, are protected by boulder-rich gravel deposits and strong soils locally, and are covered by 1 to >5 m of dune sand. The southern margins of some Q_2 and Q_3 surfaces overlie 30 to 45 m of piedmont alluvium and probably represent a slightly eroded aggradational surface of the middle Pleistocene alluvial apron. The broad extent of Q_2 and the apparent pinching out to the northwest of underlying deposits suggests that the surface represents most of the original width of the alluvial apron, which was broader than the modern belt. Much of the surface area, however, probably was active until erosion exposed coarse deposits within the alluvial wedge. In two areas the Q_2 surface fringes slopes rich in angular boulders that are interpreted as talus slopes active before eruption of the Lava Creek B tephra. South of the zone of extensive erosion surfaces (Fig. 5), narrow ridges as long as 1.5 km and mantled with angular basaltic boulders delimit the position of early Pleistocene arroyos that drained the Lobato Mesa area southeast of Mesa de Abiquiu. The longest of these inverted, composite paleochannels ranges from 200 m to about 120 m above nearby arroyos, showing that segments were active in early Pleistocene time.

GEOMORPHIC EVOLUTION OF WHITE ROCK CANYON

The Rio Grande has flowed in the vicinity of White Rock Canyon (Fig. 6) since before early Pliocene time, but a deep canyon did not develop until after basaltic volcanism in the Cerros del Rio and growth of the Puye fan ceased in late Pliocene time (Waresback and Turbeville, 1990). The Tshirege Member of the Bandelier Tuff fills a paleocanyon about 150 m deep, cut by the Rio Grande before 1.2 Ma, and exposed mainly west of the modern Rio Grande (Reneau et al., in press) in the 10 km south of Water Canyon. The paleocanyon records the early Pleistocene position of the river about 115 to 125 m above modern base level. The present geomorphology of White Rock Canyon evolved during middle Pleistocene time as the Rio Grande eroded below the level of the early Pleistocene paleocanyon, exposing mechanically weak Pliocene and Miocene rocks that failed in massive slumps. We suggest that the timing of slumping and canyon widening was related to the height of base level (compared to the modern Rio Grande), allowing us to link cutting of the canyon with the upstream alluvial sequences described above.

Mass movements

Massive bedrock slumps and other landslides that flank the Rio Grande in the 20 km south of Otowi Bridge mainly formed during middle (?) Pleistocene deepening of White Rock Canyon, but have been active episodically at least as recently as the latest Pleistocene (Reneau et al., in press). Most failure surfaces sole in the Santa Fe Group, in the volcaniclastic portion of the Puye Formation, or in clay-rich fluvial and lacustrine interbeds that separate upper Pliocene basalt flows. Between Otowi Bridge and Chaquehui Canyon, a distance of about 16 km, landslides cover some 20 km^2 and the average distance between canyon rims is about 1.8 km. South of Chaquehui Canyon, the distance between rims averages less than 1 km and landslides cover less than 20% of this area.

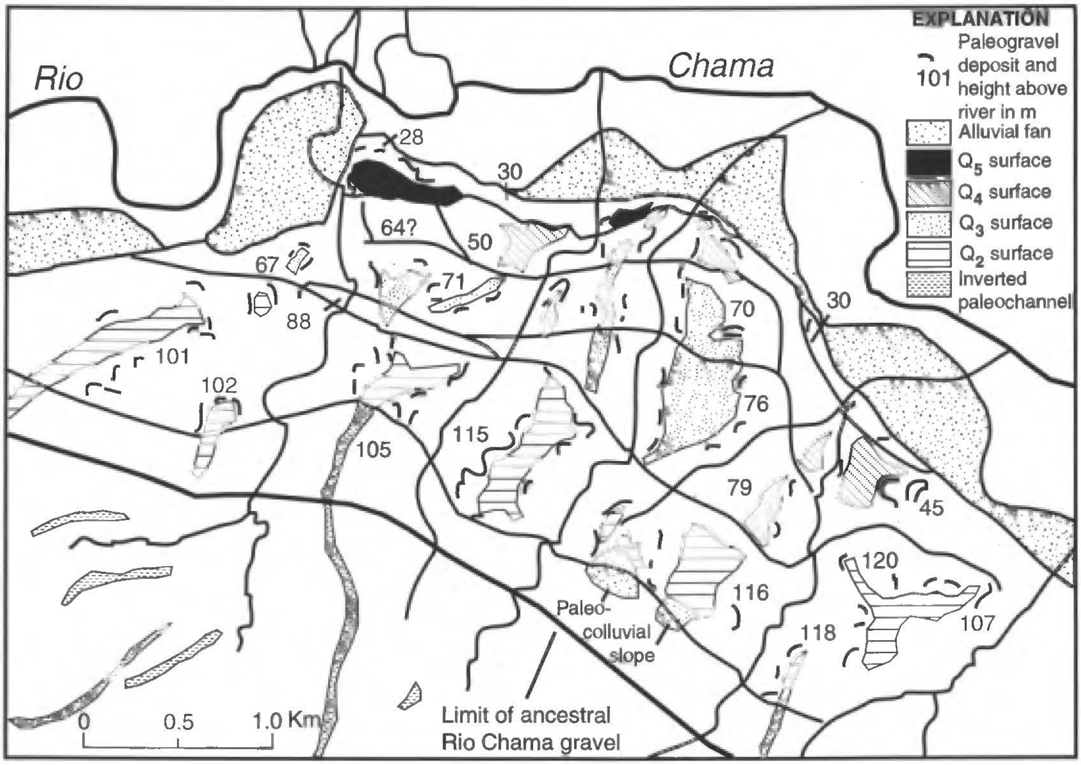

FIGURE 5. Map showing the relationship of modern drainages to erosion surfaces, inverted paleochannels and ancestral channel gravels southeast of Abiquiu.

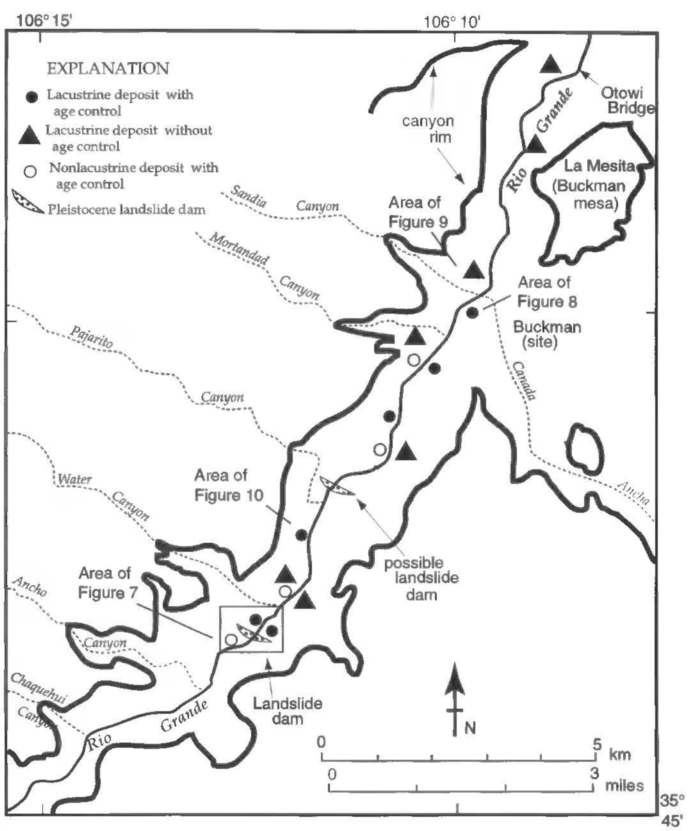

FIGURE 6. Map of northern White Rock Canyon showing location of late Pleistocene lacustrine outcrops and the approximate location of landslide dams (modified from Reneau et al., in press).

We propose that canyon widening by mass wasting was initially slow through basalts and related rocks, and increased significantly with the exposure of weaker underlying sedimentary rocks and the initiation of large slumps. We do not know when major slides moved first, but slumping probably occurred when the downcutting river exposed a sufficient thickness of sedimentary rocks (estimated as ~70 m from field relations) beneath the basalts. Elevation of the lowermost basalts exposed along the canyon walls generally decreases downstream from Otowi Bridge (Dethier, in press). Landslides would thus be initiated earlier up-canyon, assuming that the gradient of the Rio Grande has been roughly constant since about 1.2 Ma.

Upstream data (Fig. 2) and possibly correlative alluvial surfaces downriver in the Cochiti Dam area (Dethier et al., 1988) indicate that the Rio Grande has cut down 120 ± 30 m in White Rock Canyon since 0.62 Ma, at an average long-term rate of 0.19 ± 0.05 m/ka. This rate and elevations of the lower basalts along the canyon walls suggests that downcutting exposed 70 m of sediments at most sites after about 0.5 Ma, in middle Pleistocene time. This method of estimating the time of slump initiation greatly oversimplifies factors that control slope stability, but allows us to suggest that slumps have been occurring in White Rock Canyon for hundreds of thousands of years. These time scales are consistent with soil development and the presence of the ca. 50–60 ka El Cajete tephra on almost all of the slump blocks (Reneau et al., in press).

Landslide reactivation, damming, and lakes

During the late Pleistocene and probably during earlier periods, downcutting by the Rio Grande reactivated toe areas of older slumps along narrow parts of White Rock Canyon (Fig. 6), producing landslides that dammed lakes as deep as 60 m (Reneau et al., in press). Detailed mapping and extensive ^{14}C dating of lacustrine deposits in the 14 km south of Otowi Bridge shows that the most recent sequence of lakes coincide with deglaciation of the Rocky Mountains and with highstands of pluvial Lake Estancia (Allen and Anderson, 1993). This temporal correlation clearly links landslide movement and the pluvial maximum with downcutting by the Rio Grande.

Geomorphic evidence shows that one or more slumps near Water Canyon (Fig. 7) have been active in late Pleistocene time, repeatedly dam-

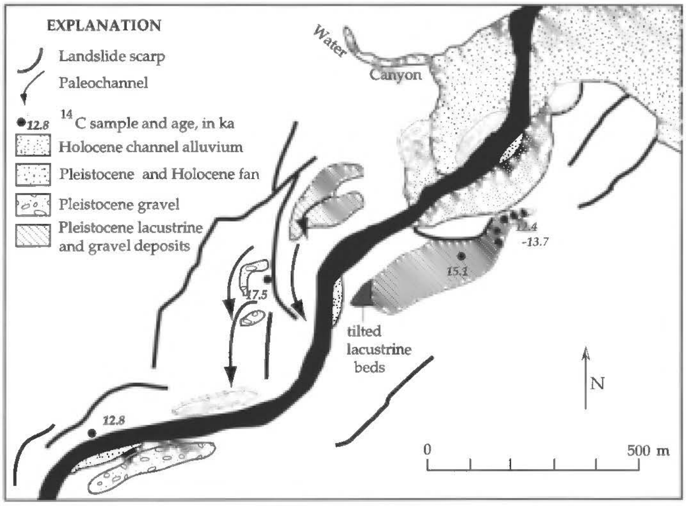

FIGURE 7. Map showing location of landslide dams, lacustrine and fluvial deposits, and ^{14}C ages along northern White Rock Canyon, southwest of Water Canyon (modified from Reneau et al., in press).

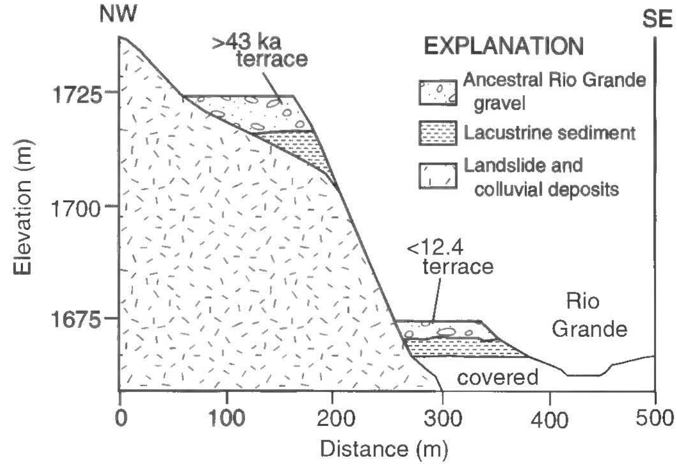

FIGURE 9. Sketch cross-section showing relationships of lacustrine sediment, ancestral Rio Grande gravel, and landslides near the mouth of Sandia Canyon. Vertical exaggeration about 4:1 (modified from Reneau et al., in press).

ming the Rio Grande. The most prominent exposure of lacustrine deposits upstream from the dam area, near the mouth of Canada Ancha (Fig. 8) consists of nearly 30 m of silt, clay and fine sand that overlie gravels of the ancestral Rio Grande. Charcoal fragments at the base of the Canada Ancha lacustrine sequence, about 15 m above the modern Rio Grande, gave an apparently finite ^{14}C age of about 43 ka. The height of the ancestral Rio Grande gravel is typical of deposits that formed between about 40 and 70 ka (Fig. 2; Dethier and McCoy, 1993) and we regard the age of the lake as 43 ka because of the possibility of sample contamination. Additional evidence for the lake is provided by a high terrace that overlies lacustrine deposits near the mouth of Sandia Canyon (Fig. 9) and at other sites in northern White Rock Canyon.

Radiocarbon ages and stratigraphic relations from several lower sequences of lacustrine sediment and Rio Grande gravel show that at least four lakes formed between 18 and 12 ka, including three separate lakes between 13.7 and 12.4 ka (Reneau et al., in press). Lacustrine deposits and contact relations with gravels are similar in each of these lake sequences (Fig. 10), but are thinner and lower than those at Canada Ancha. Rio Grande gravels overlie some of the lacustrine sequences, demonstrating that some landslide dams were sufficiently stable that the lakes filled with sediment and the Rio Grande prograded over them. Extremely coarse, boulder-rich alluvium beneath terraces downstream from the sites of landslide dams (Fig. 7) suggests that other episodes of damming ended with catastrophic failure and sudden draining of lakes. Radiocarbon and elevation evidence (Fig. 11) suggest that (1) lakes must have extended upstream from White Rock Canyon; (2) none of the late Wisconsinan

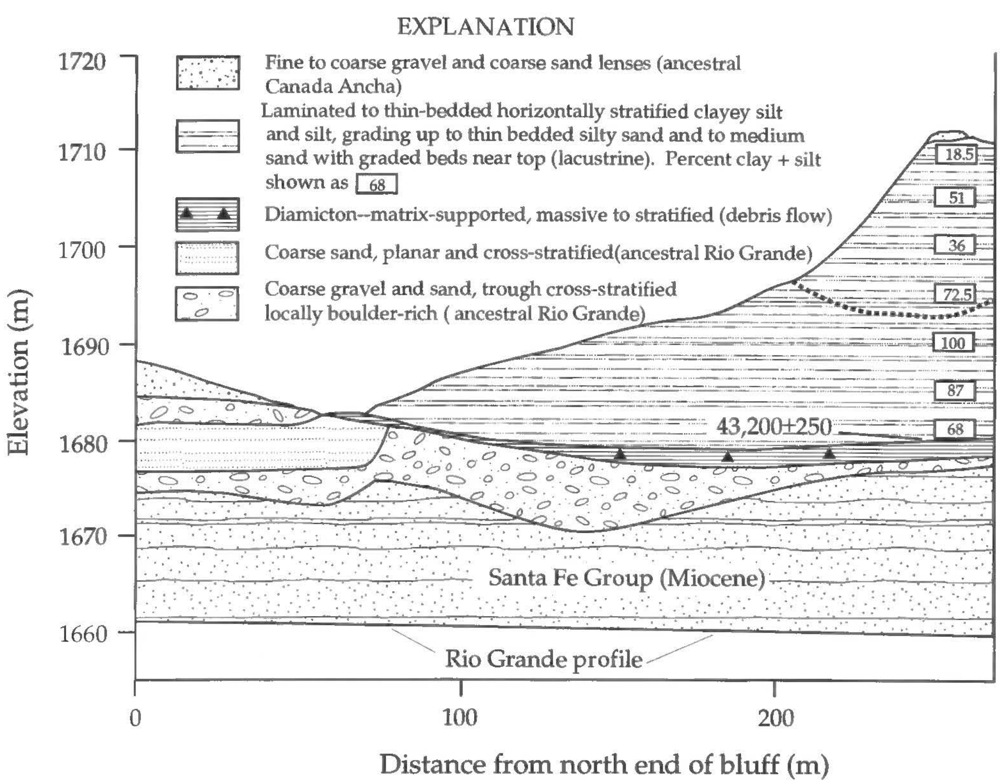

FIGURE 8. Stratigraphy of Quaternary deposits exposed near the mouth of Canada Ancha, White Rock Canyon (see Fig.7; modified from Reneau et al., in press).

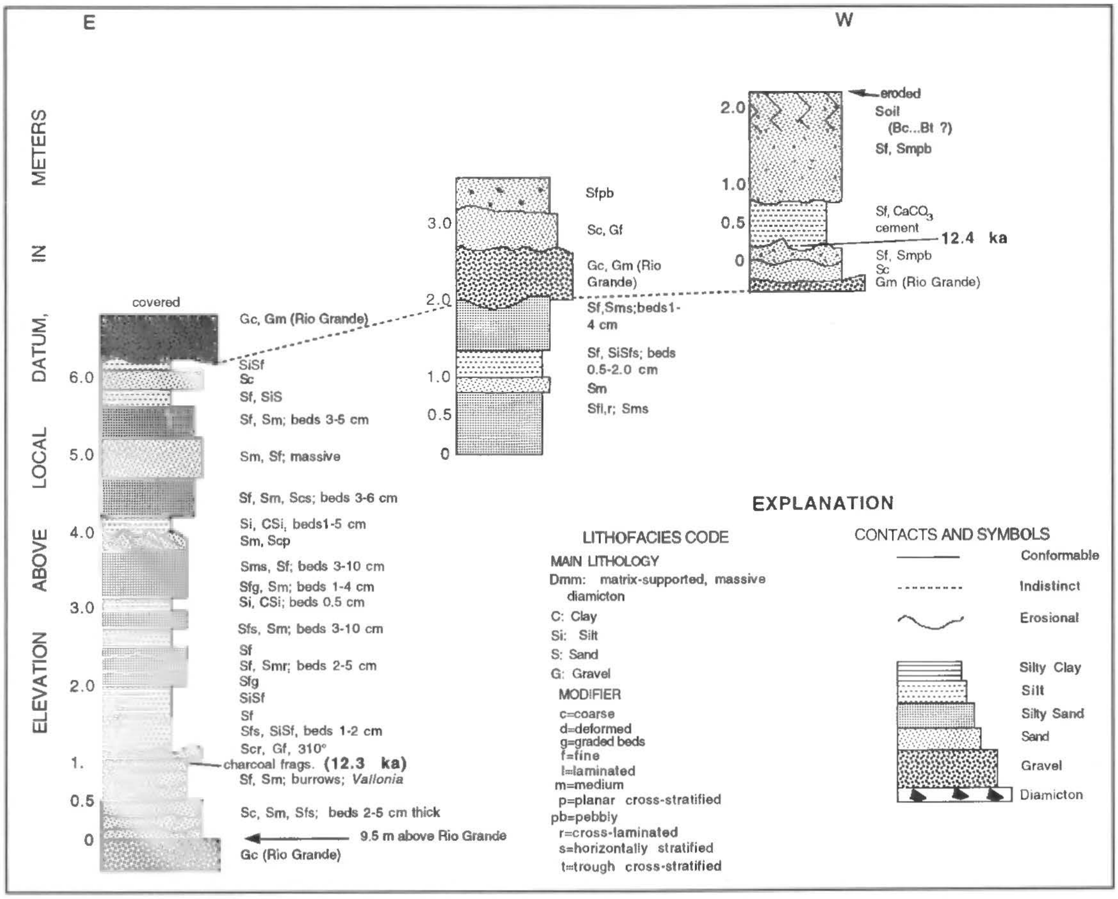

FIGURE 10. Typical measured sections showing lacustrine lithofacies and ancestral Rio Grande gravel, northern White Rock Canyon.

lakes persisted for more than a few hundred years; and (3) downcutting through these dams was essentially complete by about 10 ka or earlier.

Repeated damming of the Rio Grande in White Rock Canyon between 18 and 12 ka suggests that slide activity was related to the final pluvial episode of the late Pleistocene and to rapid melting of glaciers in the upper Rio Grande drainage. Increased recharge of aquifers during this period (Phillips et al., 1986) probably resulted in higher water table elevations and decreases in slope stability. Peak discharge and the duration of high flows on the Rio Grande increased from higher regional precipitation and melting of glaciers and extensive snowpacks. Downcutting and scour during such episodes of high stream power also would have helped to destabilize toe areas of slump complexes along constrictions in White Rock Canyon. Our evidence cannot distinguish between these processes, and slumping may have been related both to extra water in the channel and within the slides. We have not mapped any evidence of extensive slumping or lacustrine deposits after about 12.4 ka. Regional evidence suggests that alpine glaciers had disappeared before this time, the change to interpluvial climate had taken place in central and northern New Mexico, and that the northern Rio Grande and Rio Chama flowed at modern levels.

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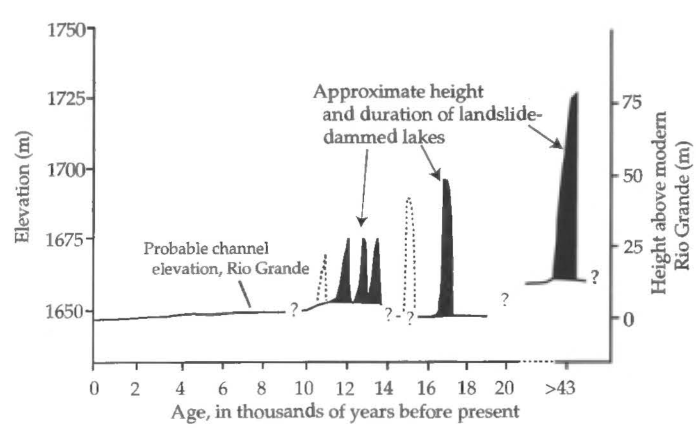

FIGURE 11. Sketch showing radiocarbon age, minimum depth, and approximate duration of late Pleistocene lakes, White Rock Canyon (modified from Reneau et al., in press).

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