

Stream incision and terrace development in Frijoles Canyon, Bandelier National Monument, New Mexico, and the influence of lithology and climate

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Abstract

The record of stream incision and terrace development in Frijoles Canyon, NM, was investigated to examine the controls on channel evolution in this region. Frijoles Canyon developed after deposition of the voluminous ignimbrites of the Tshirege Member of the Bandelier Tuff at ca. 1.22 Ma, which provides excellent temporal constraints on canyon evolution. Base level fall along the Rio Grande, the master drainage in the region, contributed to initial incision of the stream. Development of a major knickpoint in basalt near the Rio Grande, however, has effectively isolated most of the stream channel from direct effects of this base level change since the Early or Middle Pleistocene. Late Quaternary evolution of the channel has included development of strath and fill terraces that record the effects of climatic variations and local lithologic variations within the tuff on channel processes. A fill terrace, underlain by up to 13 m of coarse gravelly alluvium, records significant aggradation in the Early to Middle Holocene following a major regional climate change. Aggradation probably resulted from large increases in sediment supply in the Holocene relative to the Late Pleistocene, which was perhaps related to variations in intense summer rains. Rapid incision in the Middle to Late Holocene has stranded the underlying strath up to 21 m above the modern channel, and local rates of incision of up to 4 m/ka are more than 10 times the average rates since 1.22 Ma. Holocene incision displays great spatial variability associated with local lithologic variations, and results in a stream profile that has evolved rapidly in the last 10,000 years. The high rates of incision occur where easily eroded nonwelded tuff is exposed in the canyon bottom, whereas a more resistant vapor-phase altered tuff unit upstream has impeded incision. Incision may also have been affected by migration of knickpoints within the tuff. Paired strath terraces record periods of local base level stability and lateral erosion that were terminated by episodes of downcutting. The downcutting was probably controlled by rare high magnitude floods capable of stripping the pervasive gravel armor and exposing nonwelded tuff beneath the stream-bed. No tectonic influence on Late Quaternary terrace development or stream incision has been recognized despite Frijoles Canyon being crossed by the Pajarito fault zone, a major bounding structure of the Rio Grande Rift. Instead, climatic influences on sediment supply and flood characteristics, mediated by lithologic variations in the canyon bottom, have controlled Late Quaternary stream profile evolution. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Stream incision and development of stream profiles are fundamental aspects of landscape evolution that can be examined over a wide range of spatial and temporal scales. On a watershed scale, long-term stream incision commonly occurs in response to the downstream lowering of base level, and is often influenced by regional or local tectonic processes. On a local or reach scale, incision occurs in response to interactions between individual floods and the channel bed, which are in turn influenced by flood hydrology, sediment transport, channel gradient, and substrate resistance. Lithologic variations within a watershed, by providing variable resistance to erosion, can affect incision and development of the stream profile on temporal scales ranging from individual floods to millennia to millions of years. The amount and nature of sediment flux can also affect stream incision on a variety of time scales. Coarse sediment can armor stream-beds and prevent substrate erosion in all but rare floods, and inputs of sediment in excess of transport capacity can cause

channel bed aggradation, also preventing incision into underlying substrates.

In this paper, I present data on the age and characteristics of stream terraces in Frijoles Canyon, northern New Mexico, that provide insights into the evolution of stream channels in this region. Frijoles Canyon formed after deposition of the Tshirege Member of the Bandelier Tuff at ca. 1.22 Ma, providing excellent constraints on the time frame and initial conditions associated with evolution of the canyon. Development of the canyon and surrounding topography have been influenced by base level fall at its mouth, because of incision of the Rio Grande, and by faulting along the Pajarito fault zone, a major bounding structure of the Rio Grande Rift. Evidence from terraces in Frijoles Canyon indicates that development of the stream profile has been strongly influenced both by climatic changes and by lithologic variations within the watershed, and the effects of tectonics have been subordinate. Rates of climatically induced aggradation and lithologically influenced stream incision in parts of the canyon have both been more than an order of magnitude higher

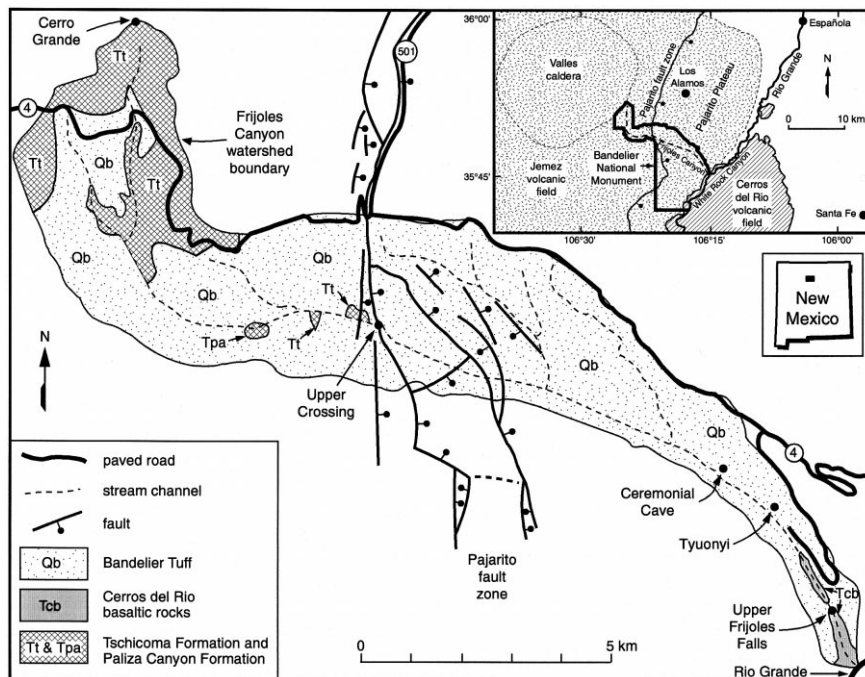


Fig. 1. Map of Frijoles Canyon watershed showing geologic units, fault traces, and selected geographic features. Geology from Smith et al. (1970), Gardner and House (1987), Goff et al. (1990), and S. Reneau (unpublished). Inset map shows regional setting of study area.

than long-term rates of faulting and downcutting. Rates of incision have also varied spatially, resulting in a dynamic and complex stream system that has evolved rapidly in the Holocene.

2. Setting

Frijoles Canyon, located on the Pajarito Plateau of northern New Mexico, is bordered on the west by the Jemez Mountains and on the east by White Rock

Canyon of the Rio Grande (Fig. 1). Frijoles Canyon, one of the deepest of a series of canyons that incise the plateau (Fig. 2a), has a drainage area of about 51.5 km². The canyon is located entirely within Bandelier National Monument, which was established to protect ancestral Puebloan (Anasazi) ruins on the plateau, including Tyuonyi in Frijoles Canyon which was mostly constructed between about 1350 and 1450 AD (Fig. 2b; Stuart, 1989).

The Pajarito Plateau is a landscape of alternating mesas and canyons underlain primarily by Early

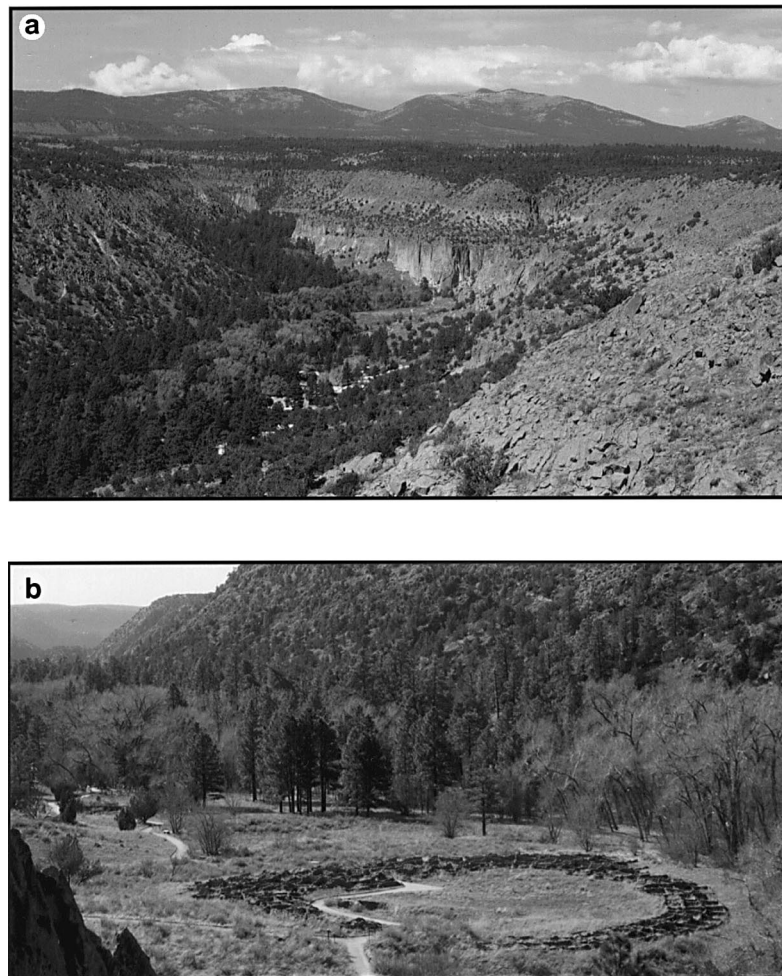


Fig. 2. (a) Photograph of Frijoles Canyon, looking upstream past Tyuonyi ruins. Cliffs are composed of multiple cooling units within the Early Pleistocene Tshirege Member of the Bandelier Tuff, and nonwelded tuff intervals form sloping benches on the canyon walls. A relatively wide and flat valley floor has developed in nonwelded tuff upstream of a knickpoint in basalt. The Sierra de los Valles, the eastern part of the Jemez Mountains and the eastern topographic rim of the Valles caldera, is on the skyline. (b) Photograph of ruins of Tyuonyi, constructed on a Middle or Late Holocene stream terrace.

Pleistocene ignimbrites of the Bandelier Tuff (Smith et al., 1970). The Bandelier Tuff was erupted from the Jemez volcanic field in two voluminous eruptions ($\sim 300 \text{ km}^3$ each) at about 1.61 and 1.22 Ma (ages are from Izett and Obradovich, 1994 and Spell et al., 1996), producing the Otowi and Tshirege Members and creating the Toledo and Valles calderas (Smith and Bailey, 1966; Bailey et al., 1969). The younger Tshirege eruptions blanketed the landscape with up to 260 m of ignimbrite, burying much of the former topography and erasing the former drainage network (Broxton and Reneau, 1996). The modern Frijoles Canyon is a Quaternary feature which has developed since 1.22 Ma, oblique to the pre-Tshirege drainages.

2.1. Bedrock and structure

Bedrock units exposed within Frijoles Canyon include the Tshirege and Otowi Members of the Bandelier Tuff, the Early Pleistocene Cerro Toledo Rhyolite, Pliocene basalts and associated phreatomagmatic deposits of the Cerros del Rio volcanic field, Miocene and Pliocene dacites of the Tschicoma Formation, and Miocene andesites of the Paliza

Canyon Formation (Figs. 1 and 3; Smith et al., 1970; Goff et al., 1990). The Tertiary lavas are the most resistant units within the watershed, and have generated prominent knickpoints along the channel (Fig. 4a).

The Tshirege Member dominates most of the watershed and varies significantly both vertically and laterally in welding, alteration, and resistance to erosion. Welded parts of some tuff units form prominent cliffs along the entire length of the canyon, separated by slopes or benches that form in non-welded intervals (Fig. 2a). The degree of welding also increases to the west, towards the source of the eruptions (Smith and Bailey, 1966). The least resistant part of the Tshirege Member is a basal unit of glassy, nonwelded tuff that is $> 45 \text{ m}$ thick along most of Frijoles Canyon (unit Qbt 1g of Broxton and Reneau, 1995). Locally, thin zeolitized zones that form resistant ledges occur within the glassy tuff (Fig. 4b), and may influence stream incision (Bailey and Smith, 1978, p. 193 and Goff et al., 1996, pp. 71–73 discuss similar zeolitized zones in Ancho Canyon).

The middle reaches of Frijoles Canyon are cut by a series of traces of the 41-km long Pajarito fault

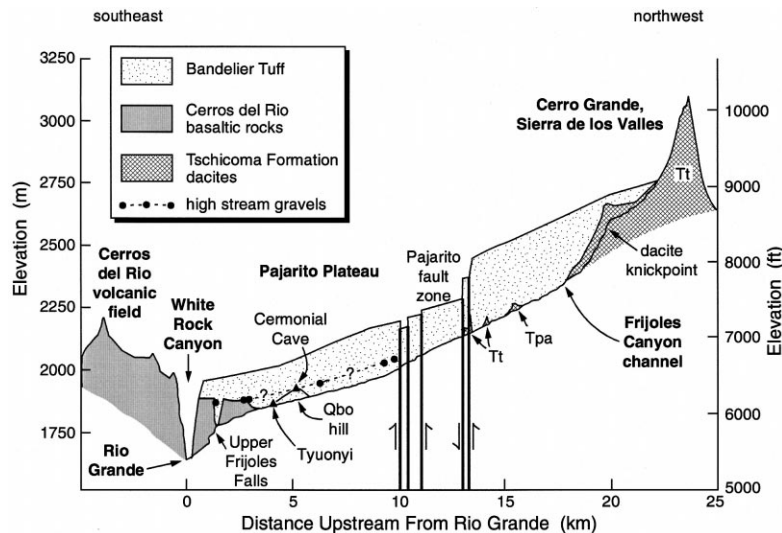


Fig. 3. Longitudinal cross-section of Frijoles Canyon and adjacent areas showing stream channel profile, bedrock units, and faults. The original upper surface of the Bandelier Tuff is estimated from an envelope connecting high points on adjacent mesas. Qbo: Otowi Member Bandelier Tuff; Tt: Tschicoma Formation dacites; Tpa: Paliza Canyon Formation andesites. The 1.22-Ma Rio Grande paleocanyon through the Cerros del Rio volcanic field, filled with the Tshirege Member of the Bandelier Tuff, is immediately northwest of Upper Frijoles Falls. Stream profile constructed from Frijoles and Bland 7.5' quadrangles (1:24,000, 20-ft contours). Vertical exaggeration = $11.7 \times$.

zone, a major bounding structure of the Rio Grande Rift that is dominated by normal faulting (Fig. 1) (Manley, 1979; Golombek, 1983; Gardner and House, 1987; Olig et al., 1996). The Tshirege Member in Frijoles Canyon has been displaced ~ 145 m down to the east along the main fault zone, which provides an average displacement rate of about 0.12 m/ka since 1.22 Ma. Offsets along subsidiary faults to the

east that cross Frijoles Canyon are up to 35 m, mainly down to the east but also including a west-facing fault bounding a graben (Figs. 1 and 3). The most recent surface rupture along the Pajarito fault zone is believed to have occurred ca. 1.5 ka (McCalpin, 1998). Earthquake magnitude and recurrence intervals along the Pajarito fault zone are poorly constrained, but available data suggest that earth-

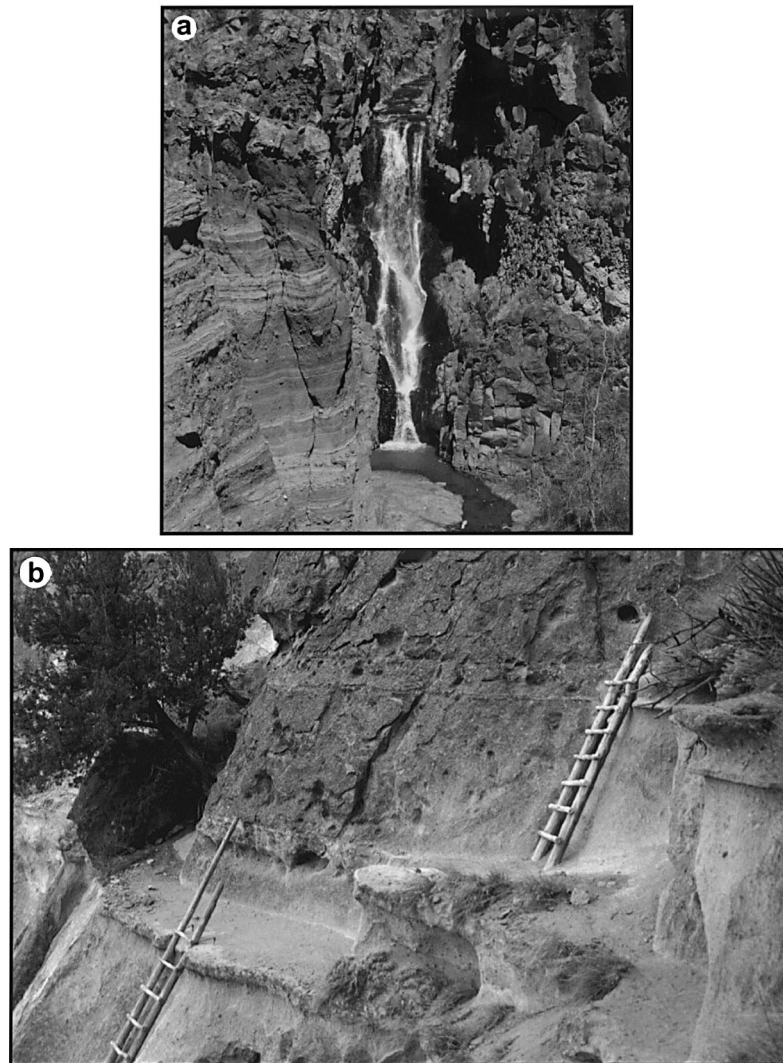


Fig. 4. Photographs of resistant rock units within Frijoles Canyon. (a) Upper Frijoles Falls, 1.35 km upstream from and 130 m higher than the Rio Grande, where Pliocene basalt of the Cerros del Rio volcanic field impedes the stream and controls local base level. Pliocene phreatomagmatic deposits are exposed in the cliffs below the falls. (b) Zeolitized zones within lower nonwelded tuff of the Tshirege Member, below Ceremonial Cave.

quakes of magnitude 6.5 to 7 may occur at intervals of perhaps 10 to 60 ka (Wong et al., 1995).

2.2. Modern stream profile

Along most of Frijoles Canyon the modern stream is incised entirely into tuff, although older rock units are associated with two major knickpoints along the channel (Fig. 3). To the east, the lowest knickpoint includes Upper and Lower Frijoles Falls, and occurs where the stream has eroded through the Bandelier Tuff into the underlying Cerros del Rio basalts (Fig. 4a). The basalt forms a local base-level control, isolating the upstream part of the canyon from the direct effects of incision along the Rio Grande. The minimum channel gradient (about 2%) occurs in the reach from Tyuonyi to west of Ceremonial Cave, upstream of basalt outcrops and 4 to 7 km from the Rio Grande (Fig. 3). Downstream from Lower Frijoles Falls, the stream has deposited a steep bouldery fan that is graded to the Rio Grande. The boulders on the fan are dominated by basalt, indicating a local source. The uppermost knickpoint occurs where the stream has incised through the Bandelier Tuff and into the underlying Tschicoma Formation dacites. Limited outcrops of Tertiary dacites and andesites adjacent to the channel upstream of the Pajarito fault zone are associated with local increases in channel gradient, and apparently influence stream incision in the upstream reaches.

Between the major lithologically controlled knickpoints one reach within the Bandelier Tuff, about 10 to 11 km upstream from the Rio Grande, has a gradient that is anomalously high. In this area the stream gradient reaches 5% to 6%, contrasting with a gradient of about 3% to 3.5% 2 km upstream. This reach coincides with eastern strands of the Pajarito fault zone and with a lithologic change within the tuff, and the character of stream terraces indicates that the knickpoint in tuff is related to the lithologic change and not related to young faulting, as discussed later. No prominent knickpoints in the longitudinal profile of the stream can be linked to the main trace of the Pajarito fault zone farther west. The steepest upstream reaches are associated with outcrops of Tertiary volcanic rocks, and indicate lithologic and not tectonic influences on the modern stream profile.

2.3. Modern climate, vegetation, and hydrology

Frijoles Canyon has a semiarid climate, with roughly 40% of the annual precipitation occurring during thunderstorms in July and August (Bowen, 1992). Summer moisture is derived primarily from the Gulf of Mexico. Winter precipitation generally consists of snow provided by frontal storms originating over the Pacific Ocean, and intermediate amounts of precipitation from mixed sources occur in the spring and fall. Total precipitation on the Pajarito Plateau shows a strong elevational gradient, ranging from about 30 cm to the east near White Rock Canyon to 50 cm on the western Plateau (Bowen, 1992). Precipitation data are not available for the upper and lower basins, but regional relations presented by Rogers (1994) (see also Reneau and McDonald, 1996, p. 5) suggest a range in annual precipitation from about 25 cm at the elevation of the Rio Grande (1635 m) to about 75 cm at the summit of Cerro Grande (3109 m elevation). Vegetation in the watershed includes montane forests with spruce, fir, and aspen in the upper elevations, ponderosa pine forests on the western mesas, piñon–juniper woodlands on the eastern mesas, and juniper grasslands in the lowest elevations near the Rio Grande (Allen, 1989).

Frijoles Canyon has a perennial stream that is fed by springs issuing from the Tschicoma Formation. The largest floods in the period of historic record have been produced by summer thunderstorms, with peak discharges from spring snowmelt being much less; frontal storm systems in the fall also occasionally produce floods. The largest flood this century, with an estimated peak discharge of 77 to 86 m³/s (U.S. Geological Survey, 1979; McCord, 1996), occurred in July 1978 and followed the 1977 La Mesa Fire, an unusually intense fire that burned much of the watershed. Discharge in this event was similar to the estimated 100-year design flood for Frijoles Canyon of McLin (1992). In comparison, the largest flood in a 6-year gauged period before the fire was 0.5 m³/s (Purtymun and Adams, 1980; Veenhuis, 1999).

2.4. Paleoenvironments

Direct evidence for local paleoclimates and paleovegetation have not been obtained from the Pajarito

Plateau or the Jemez Mountains, although studies in surrounding areas provide insight into likely conditions in the Frijoles Canyon watershed. Available data indicate that the jet stream in the Late Pleistocene was located far south of its present position, resulting in greater regional precipitation that was probably dominated by winter storms (Spaulding et al., 1983; Hall, 1985; Van Devender et al., 1987; Allen, 1991; Phillips et al., 1992; Thompson et al., 1993). At the elevation of Frijoles Canyon, this precipitation would have fallen largely as snow. Late Pleistocene vegetation at the elevation of the Pajarito Plateau elsewhere in the American southwest included montane forests or parklands of spruce (*Picea*) and fir (*Abies*) (Wright et al., 1973; Betancourt, 1990; Anderson, 1993), and similar vegetation communities presumably occurred on the plateau. No evidence for glaciation has been reported in the Jemez Mountains, although boulder fields are present that suggest flowage under periglacial conditions (Reneau and McDonald, 1996, pp. 97–98), and the higher elevations may have supported alpine vegetation in the Late Pleistocene.

Major climatic changes occurred in the region during the Pleistocene–Holocene transition, and are inferred to be associated with a northward migration of the jet stream and an increase in solar insolation that peaked about 9 ^{14}C ka (e.g., Thompson et al., 1993). Available data indicate that winter precipitation declined and many coniferous forest species became largely restricted to higher elevations. A variety of paleoenvironmental records from the Rocky Mountains of Colorado, the Colorado Plateau, and the southwestern deserts suggests that summer rainfall was higher in the Early Holocene than either today or in the Late Pleistocene, in turn suggesting enhanced monsoonal circulation at that time (Markgraf and Scott, 1981; Friedman et al., 1988; Betancourt, 1990; Davis and Shafer, 1992; Thompson et al., 1993; Fall, 1997), although other records suggest that summer rainfall in the Late Pleistocene was similar to at present (Pendall et al., 1999).

3. Methods

Geologic units and fault traces were mapped in most of the Frijoles Canyon watershed at a scale of

1:12,000, revising earlier geologic maps and incorporating stratigraphic variations within the Tshirege Member of the Bandelier Tuff. Stream terraces were plotted on a longitudinal profile of the channel constructed from a 1:24,000 topographic map with 20-ft contours. Channel sinuosity as depicted on the map is low (< 1.1), and the channel profile is similar to the valley bottom profile. Because most terrace remnants are of limited areal extent, occurring within the narrow canyon bottom, it was not feasible to map them to scale. For most terrace exposures a hand level was used to measure the height of the bedrock surface (strath) underlying the stream deposit and/or the top of the rounded channel gravel, depending on exposure. The longitudinal position of terraces was determined by measurements to geographic features recognizable on the topographic map. For a few terraces in the more open eastern part of the canyon, terrace heights were obtained directly from the topographic map.

The top of the channel gravel instead of the actual terrace tread (representing the upper limit of overbank deposition) was focused on because the former was relatively well defined in the field. In contrast, the elevation of the original terrace tread was usually indeterminate because of either erosion of fine-grained overbank deposits or burial by colluvium.

Correlations of terrace remnants were made in areas where exposures were sufficiently continuous or measurement density was high enough to permit physical correlation. A distinctive fill terrace and its underlying strath could be directly traced along 3 km of channel, and downstream a flight of four strath terraces could be traced along 2 km of channel. Elsewhere exposures were not sufficient to allow reliable correlations except over short distances. These correlative terrace remnants may or may not represent approximate time lines, and age control was insufficient to evaluate possible time-transgressive terrace formation in detail.

Age control for Late Quaternary deposits was provided by radiocarbon dating of charcoal, wood, or cones. All analyses were calibrated to the dendrochronologic time scale using the CALIB 3.03 program of Stuiver and Reimer (1993), allowing better comparison with the local archaeological record and more accurate calculation of incision rates. One of the samples had a high ^{14}C content that

indicated an age postdating the beginning of atmospheric testing of atomic weapons, and the calendar age of the sample was estimated by comparison to the post-bomb ^{14}C curve of Baker et al. (1985). Direct age control was not available for older terraces, but age constraints are provided by comparison with the incision history of the Rio Grande.

4. Early to Middle Pleistocene stream terraces

Stream gravel that predate the Late Quaternary terraces are sparsely preserved within Frijoles Canyon. The highest stream gravel occur 1.3 km upstream from the Rio Grande on basalt about 105 m above the lip of Upper Frijoles Falls and about 100 m below the estimated top of the Bandelier Tuff (Fig. 3). Remnants of possibly correlative terrace gravel on top of basalt and on nonwelded tuff occur for 2 km upstream, and appear to define an old canyon bottom that was graded to either a basalt knickpoint in lower Frijoles Canyon or to the Rio Grande. The associations of these high gravel with the top of the basalt suggest that they record a temporary base level that was established after the stream first encountered basalt. Several additional terrace remnants have been located 6 to 10 km upstream from the Rio Grande at heights of 40 to 50 m above the modern channel (Fig. 3) and may be correlative with the downstream gravel, although this is not certain because of the lack of age control and the discontinuous exposures of the gravel.

The high stream gravel are probably Early to Middle Pleistocene in age, based on available data on the incision history of the Rio Grande in White Rock Canyon and vicinity. These gravel project to a height of about 200 m above the mouth of Frijoles Canyon, indicating that the Rio Grande had incised to at least this level before formation of the upstream terrace or terraces. The Quaternary history of the Rio Grande is not tightly constrained, but downcutting

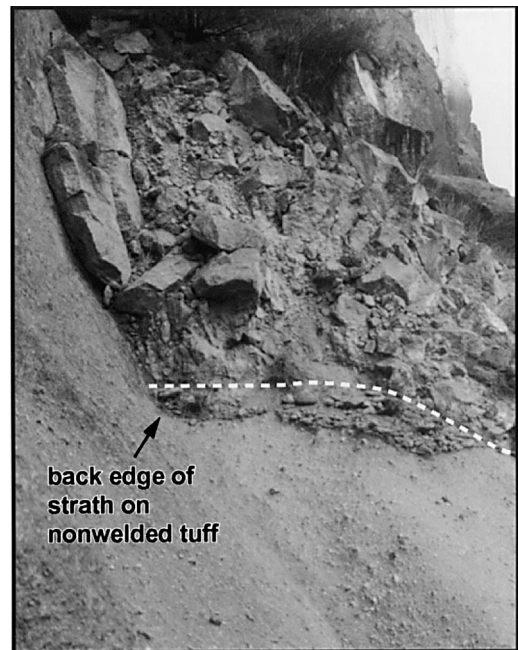


Fig. 5. Photograph of Early or Middle Holocene terrace remnant cut into nonwelded tuff, about 7.0 km upstream from the Rio Grande. Strath is about 22 m above the modern channel, and 0.3 to 0.8 m of fluvial sediment is buried beneath bouldery colluvium. Dashed line indicates base of colluvium.

may have been relatively rapid after 1.22 Ma as the Rio Grande eroded through an upriver knickpoint that postdated damming of the river by the Tshirege Member ignimbrites (Reneau and Dethier, 1996). The pre-1.22-Ma Rio Grande channel was about 100 m above modern grade in this area (at the site of a buried paleocanyon northwest of Upper Frijoles Falls; Fig. 3), and a knickpoint in basalt may have formed in Frijoles Canyon before the Rio Grande had reattained its pre-Tshirege grade. Upriver, the Rio Grande was about 110 m above modern grade at 0.6 Ma (Dethier and McCoy, 1993; Dethier et al., 1990; Lava Creek B tephra age revised by Gansecki et al., 1998), suggesting that the basalt knickpoint in lower

Notes to Table 1:

^aCalibrated ages from CALIB 3.03 (Stuiver and Reimer, 1993) except sample F-11 (which used Baker et al., 1985, curve). Ages in () are 2σ range and use error multiplier of 2.0. For samples that were not corrected for $\delta^{13}\text{C}$, the $\delta^{13}\text{C}$ value was assumed to be $-23.8 \pm 1.2\text{‰}$ based on $\delta^{13}\text{C}$ values of 107 samples collected from the Pajarito Plateau.

^bDate possibly influenced by bomb ^{14}C .

^cRadiocarbon date was not corrected for $\delta^{13}\text{C}$.

Table 1
Radiocarbon dates from Frijoles Canyon

Field sample number	Laboratory sample number	¹⁴ C date (years BP)	Calibrated age ^a	Approximate stream elevation (ft)	Height above channel (m)	Materials	Notes
<i>Latest Holocene alluvium</i>							
F-11	Beta-54872	143% modern	1962–1963 or 1973–1974 AD (2σ)	6365	1.75	cones	0.75 m deep; litter layer beneath sooty silt
F-15	Beta-68801	510 ± 70	520 cal BP (0 ^b –700); 1430 cal AD (1250–1952 ^b)	6365	1.6	charcoal	0.9 m deep; fine sand layer
F-14	Beta-54873	420 ± 70 ^c	500 cal BP (0 ^b –660); 1450 cal AD (1290–1954 ^b)	6365	1.1	charcoal	1.4 m deep; fine sand layer interstratified with coarse sand and gravel
F-24	Beta-68849	550 ± 70	540 cal BP (300–730); 1410 cal AD (1230–1650)	6220	0.65	charcoal	1.65 m deep; lowermost fine sand layer, above coarse sand and gravel
<i>Latest Holocene rockfalls</i>							
F-9	Beta-68800	40 ± 40	0 ^b cal BP (0 ^b –280); 1955 ^b cal AD (1670–1955 ^b)	6480	0	wood	exhumed stump behind rockfall
F-6	A-6824	195 ± 80	0 ^b –280 cal BP (0 ^b –530); 1670–1953 ^b cal AD (1420–1955 ^b)	6420	0	wood	stump buried by silt-rich lake sediments
F-25	Beta-68802	290 ± 50 ^c	310 cal BP (0 ^b –530); 1640 cal AD (1420–1954 ^b)	6400	3.0	charcoal	2.5 m deep below post-rockfall fill surface; silt-rich layer interstratified with coarse sands
<i>Late Holocene terraces</i>							
F-23	Beta-68848	1290 ± 60	1200–1240 cal BP (950–1400); 710–760 cal AD (550–1010)	6190	1.05	charcoal	1.95 m deep; lower part of fan, 0.3 m above coarse channel sands
F-8	AA-9421	1545 ± 60 ^c	1410 cal BP (1270–1720); 540 cal AD (240–680)	6695	4.6	charcoal	1.5 m deep; fine sands at top of fluvial section
F-17	AA-9422	1605 ± 55 ^c	1520 cal BP (1300–1800); 430 cal AD (150–650)	6695	4.3	charcoal	1.8 m deep; base of fine sand layer, above medium sand layer
<i>Early to Middle Holocene terraces</i>							
F-29	Beta-93926	3940 ± 40	4410 cal BP (4260–4510); 2460 cal BC (2310–2560)	6380	20	charcoal	1.3 m deep; slope wash fill above strath surface, in paleoalcove (minimum-limiting age)
F-4	AA-7582	4505 ± 110 ^c	5080–5280 cal BP (4540–5710); 3130–3330 cal BC (2590–3760)	6290	13.5	charcoal	2.5 m deep; basal slope wash colluvium above fluvial deposit
F-5	AA-7583	4590 ± 65 ^c	5310 cal BP (4870–5600); 3360 cal BC (2920–3650)	6290	12.5	charcoal	3.5 m deep; fine sand bed in upper fluvial deposit
F-27	Beta-68850	5300 ± 60	6040–6170 cal BP (5760–6310); 4090–4220 cal BC (3810–4360)	6375	20	charcoal	2 m deep; top of 3.5 m thick fluvial deposit; below colluvium
F-7	AA-9420	6195 ± 85 ^c	7090–7160 cal BP (6720–7390); 5140–5210 cal BC (4770–5440)	6615	16	charcoal	1 m deep; basal slopewash colluvium above fluvial deposit
F-22	Beta-68847	8200 ± 60	9050–9200 cal BP (8720–9440); 7100–7250 cal BC (6770–7490)	6180	7.5	charcoal	2 m deep; upper fluvial gravel

Frijoles Canyon had formed prior to this time. The length of time that the stream channel persisted at or near the height of the high stream gravel is unknown, and the isolated terrace remnants could span a considerable period of time.

5. Late Quaternary stream terraces

Late Quaternary stream terraces have been studied along a 10-km reach of Frijoles Canyon extending upstream from Upper Frijoles Falls. The terrace deposits typically consist of coarse gravel in a coarse sandy matrix. Fine-grained overbank deposits are only locally present. Lithologically, the gravel are approximately 40% dacite and related lavas and 60% tuff. Many of the terrace remnants do not have relatively flat terrace treads preserved. The rounded gravel is instead buried beneath colluvium derived from the adjacent canyon walls (Fig. 5).

Sixteen radiocarbon analyses have been obtained from samples of charcoal, wood, and cones collected from Holocene deposits within Frijoles Canyon (Table 1), and provide constraints on the timing of aggradation, strath formation, and incision along the canyon. Sample locations are shown in Fig. 6. Detrital charcoal is relatively rare and has only been found in a few terrace deposits in Frijoles Canyon, although charcoal and wood are fairly common in the youngest fluvial sediments associated with the modern floodplain. Samples collected from different stratigraphic layers within several sections are internally consistent and suggest that reworking of detrital material much older than the flood event of interest is not a significant problem in these deposits.

The morphology of the inner canyon changes significantly in the vicinity of the tuff knickpoint about 10 to 11 km upstream from the Rio Grande. The canyon floor is relatively flat upstream of this knickpoint, and consists of floodplains and low (1 to

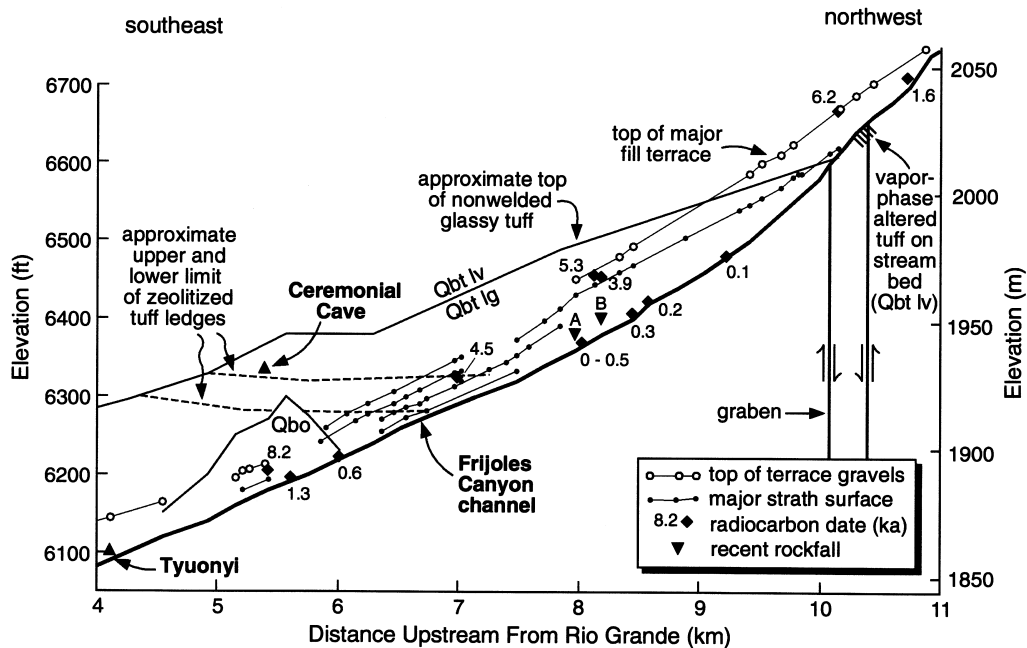


Fig. 6. Longitudinal profile of part of Frijoles Canyon, showing strath surfaces, terrace surfaces, locations of radiocarbon dates, and key stratigraphic contacts within the Banderier Tuff. Tops of terrace gravel are shown only for the major Early to Middle Holocene fill terrace and for the highest terraces between Tyuonyi and Ceremonial Cave. Straths are typically overlain by 0.5 to 2 m of stream gravel, and are shown only for the most continuous, correlative surfaces; additional isolated straths are also present. Sites labeled "A" and "B" indicate rockfalls that occurred in 1989 and 1994 and produced rockfall dams. "Qbt Iv" and "Qbt Ig" indicate glassy and vapor-phase altered parts of the Tshirege Member of the Banderier Tuff, respectively. "Qbo" indicates nonwelded Otowi Member of the Banderier Tuff. Stream profile constructed from Frijoles 7.5' quadrangle (1:24,000, 20-ft contours). Vertical exaggeration = 21.2 ×.

2 m high) terraces that are overlain by colluvium and fans derived from the canyon walls. In contrast, the stream is incised up to 28 m below stream terraces downstream of the knickpoint, with an inner gorge that is as narrow as 15 m at its base in nonwelded tuff (Fig. 7). Narrow floodplains occur within this inner gorge and the stream is commonly cutting laterally into tuff, producing prominent stream side alcoves (Fig. 8a). Remnants of paleoalcoves occur on the canyon walls at the same heights as stream terraces, and record former stream levels (Fig. 8b). Streamside rockfalls that represent the collapse of undercut cliffs are relatively frequent, and local damming of the stream by such rockfalls occurred in 1989 and 1994. At least three larger rockfalls dammed the stream in the last 100 to 500 years, as discussed later. Flights of strath surfaces cut into nonwelded tuff are common downstream of the tuff knickpoint, and are typically overlain by 0.5 to 2 m of stream gravel. Farther downstream, in the vicinity of Tyuonyi, the valley floor broadens (Fig. 2) and consists of stream terraces up to 14 m above the

modern channel that are overlain by colluvium and inset by the modern floodplain.

Terrace remnants have not been located upstream from the Pajarito fault zone at Upper Crossing or for approximately 2 km downstream; thus, terraces cannot be used to constrain the displacement history of the main fault. In the reach of canyon upstream and downstream of Upper Crossing, much of the valley bottom is composed of fans derived from small drainages on the canyon walls. Apparent truncation of some of these fans immediately east of Upper Crossing suggest the possibility of fault offset, but these topographic breaks could also reflect either erosion along the main stream or the toe of debris flow lobes. Confidently determining the presence or absence of fault offset is not possible at this time.

5.1. Early to Middle Holocene terraces

The most significant aspect of the Late Quaternary terraces in Frijoles Canyon is the presence of a distinct fill terrace that is underlain by up to 13 m or



Fig. 7. Photographs of part of Frijoles Canyon about 8.5 km upstream from the Rio Grande, where the stream has cut a narrow inner canyon > 20 m deep into nonwelded tuff below a Holocene terrace. (a) View from edge of inner canyon. Large rockfall in foreground has boulders 5 to 9 m in size, and produced a temporary rockfall dam. (b) View from stream channel, upstream from rockfall. Inner canyon is 15 m wide here.

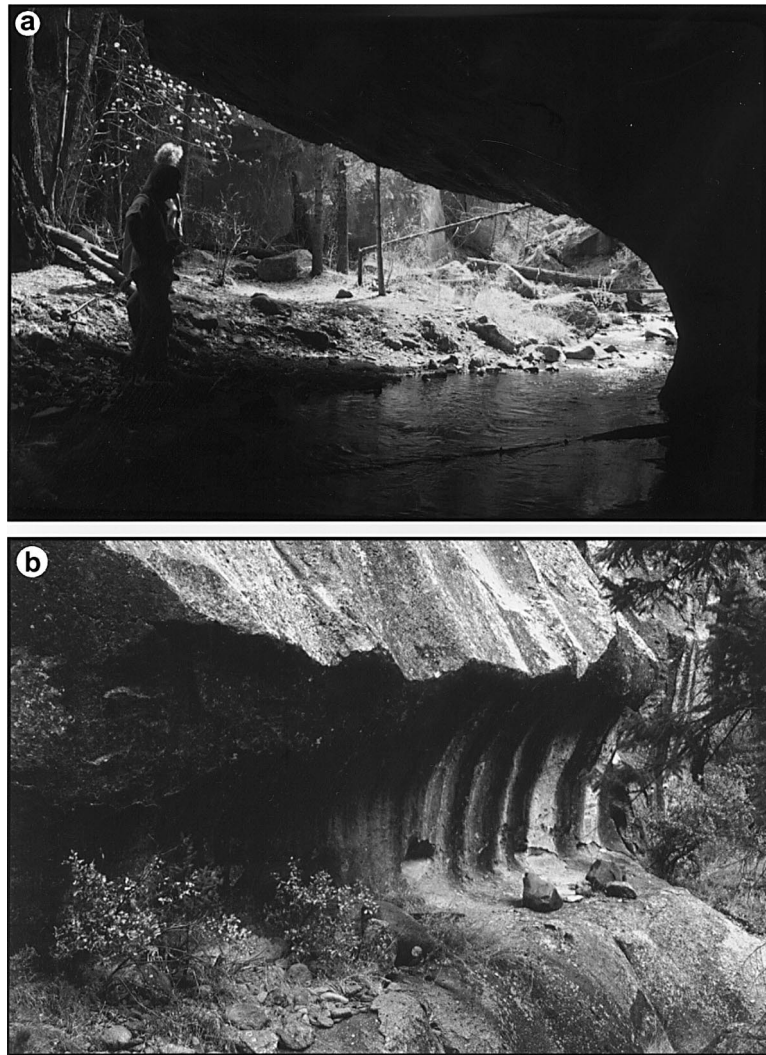


Fig. 8. (a) Photograph of modern stream-cut alcove, about 9.5 km upstream from the Rio Grande. (b) Photograph of paleoalcove preserved on canyon wall about 21 m above modern channel and 8.4 km upstream from the Rio Grande. Lag of stream gravel in foreground is at eroded edge of a terrace remnant.

more of rounded stream gravel with a sandy matrix (Figs. 6 and 9). No buried soils or other evidence of significant depositional breaks have been found in the fill, and this terrace records a major aggradational event in Frijoles Canyon. In contrast to the fill terrace, other terrace exposures typically display < 2 m of rounded gravel resting on a relatively planar surface cut onto tuff, and constitute strath terraces.

Field relations indicate that deposition of the fill terrace is, at least locally, temporally related to deposition of fans derived from side drainages off the

canyon walls (Fig. 10). In the area where the terrace gravel are thickest, one lobe of a fan was truncated by the terrace, whereas an adjacent fan lobe is graded onto the top of the terrace. The remainder of the fan is truncated by an inset terrace several meters below the top of the fill terrace, which indicates that fan-deposition had ceased before development of the inset terrace.

The fill terrace can be confidently traced along a 3-km reach where the top of the terrace gravel and the underlying strath both have a gentler gradient

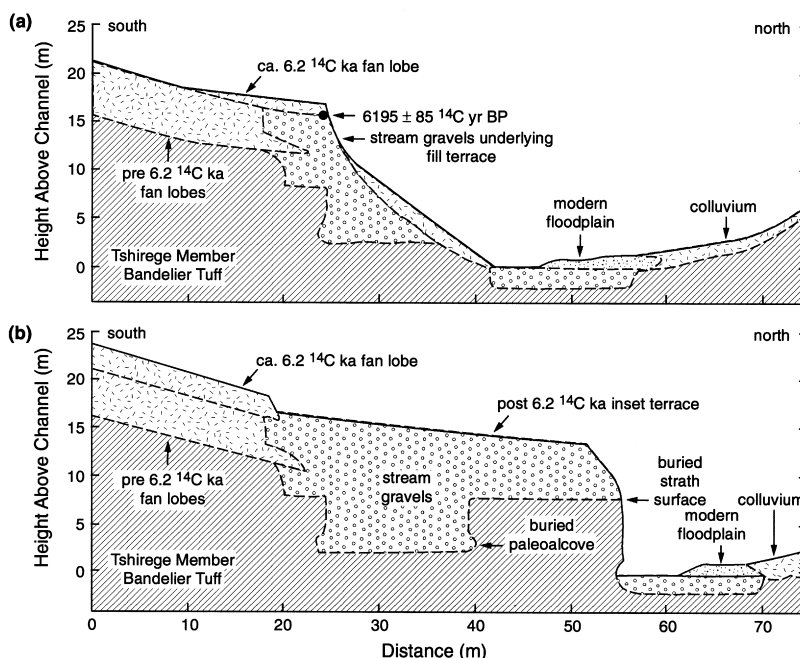


Fig. 9. Cross-sections through major fill terrace in area where the underlying terrace deposit is thickest, about 10.2 km upstream from the Rio Grande, showing location of radiocarbon date and inferred relations of terraces to adjacent fans. The buried stream-cut alcove is exposed in a stream bank here (Fig. 10). (a) Section through highest level of the fill terrace, where stream gravel is overlain by distal fan sediments dated at ca. 6.2 ^{14}C ka. (b) Section 25 m to east through inset terrace which truncates ca. 6.2 ^{14}C ka fan lobe. No vertical exaggeration.

than the modern stream channel, which causes the terrace to diverge from the channel downstream (Fig. 6). Whereas at the upstream exposure of this terrace the upper surface is only a few meters above the channel, downstream the basal strath and the upper gravel are up to 21 m and 28 m above the channel, respectively. This divergence is in the reach of channel with anomalously steep gradients and heads near the contact between nonwelded tuff (unit Qbt 1g) and vapor-phase altered tuff (Qbt 1v) 10 km from the Rio Grande (Fig. 6), consistent with a lithologic influence on stream incision. In contrast, the fill terrace crosses the easternmost strands of the Pajarito fault zone without recognizable offset and the change in stream gradient cannot be explained by young faulting, although at the resolution of available data it is not possible to identify offsets of less than 1 to 2 m.

At the farthest downstream exposure of the fill terrace, the deposit thins and the underlying strath surface apparently steepens (Fig. 6). From these

observations it is inferred that a knickpoint existed about 8 km upstream from the Rio Grande at the time of aggradation, indicated by the steepening of the strath surface, and that major deposition of gravel did not occur in this steeper reach. Correlative terrace remnants probably exist farther downstream, although such correlation is not well established because of longitudinal gaps in the terrace sequence and the scarcity of age control.

No dateable material has been found in the lower part of the major alluvial fill, and the timing of initial aggradation is not known. The timing of abandonment of the terrace level, however, is constrained by several internally consistent radiocarbon analyses from the fill terrace and high inset terraces. A date of ca. 6.2 ^{14}C ka from basal fan sediments immediately above stream channel gravel in the area where the fill terrace is thickest provides the best age constraint for the end of aggradation (sample F-7, Table 1) (Figs. 9 and 10). Downstream, a date of ca. 5.2 ^{14}C ka from the uppermost fluvial sediments in one high

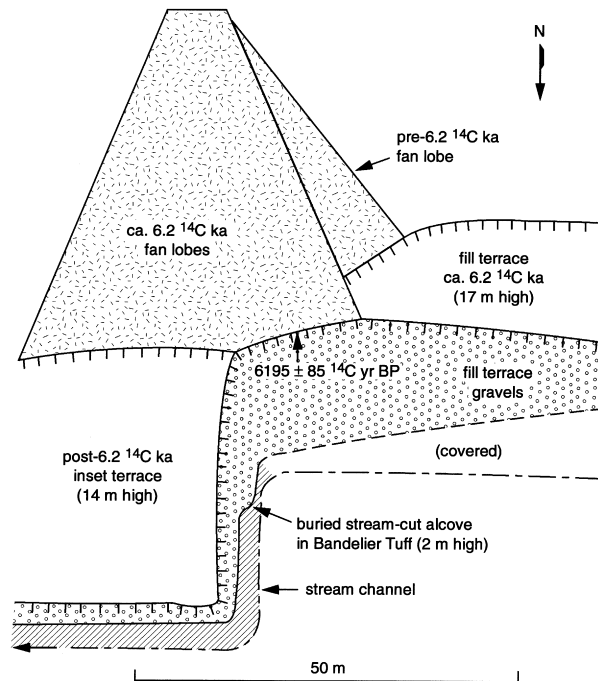


Fig. 10. Sketch map of area of Fig. 9 showing location of radiocarbon date and relation of fans to terraces. Cross-cutting relations indicate that fan-deposition was contemporaneous with deposition of the fill terrace, but had largely stopped before abandonment of the high inset terrace.

terrace remnant (sample F-27) is either related to the main aggradation event or to a high inset terrace level; the latter possibility is suggested by the relatively thin gravel deposit at this site (3 m, as compared with 6 to 7 m upstream and downstream) (Fig. 11b). Farther downstream, the highest inset strath terrace yielded paired analyses of ca. 4.5 to 4.6 ^{14}C ka (samples F-4 and F-5) (Fig. 11c), which demonstrates abandonment of the fill terrace before this time. A less definitive minimum-limiting age for abandonment of the fill terrace is provided by a date of ca. 3.9 ^{14}C ka from slopewash sediments that backfilled an exhumed paleoalcove (sample F-29).

The oldest radiocarbon analysis obtained in Frijoles Canyon was from the highest of a set of terraces near Ceremonial Cave, ca. 8.2 ^{14}C ka from the upper part of a 3- to 5-m thick gravel deposit overlying a 4 to 5 m high strath surface (sample F-22, Table 1). This analysis indicates that Holocene aggradation had begun by ca. 8.2 ^{14}C ka in at least part of the canyon. Exposures are poor in this reach and the upstream and downstream extent of this

terrace are not certain, but it appears to be correlative with some terrace remnants and paleoalcoves upstream that occur above the level of the ca. 5.3 to 6.2 ^{14}C ka terrace (e.g., high terrace remnants in Fig. 11b and c).

Terrace remnants older and higher than the major fill terrace have been identified at several locations, but too few remnants exist to reliably reconstruct older terrace levels. Many more remnants of younger terraces exist. In the reach where the fill terrace pinches out, at least two lower terrace levels have been identified, characterized by strath surfaces overlain by 0.5 to 2 m of gravel and recording pauses in downcutting.

5.2. Late Holocene fluvial history

Insight into the Late Holocene fluvial history in Frijoles Canyon is provided by radiocarbon analyses from low terraces and floodplains, and from deposits associated with streamside rockfalls. In particular, these data indicate that the timing of incision can be

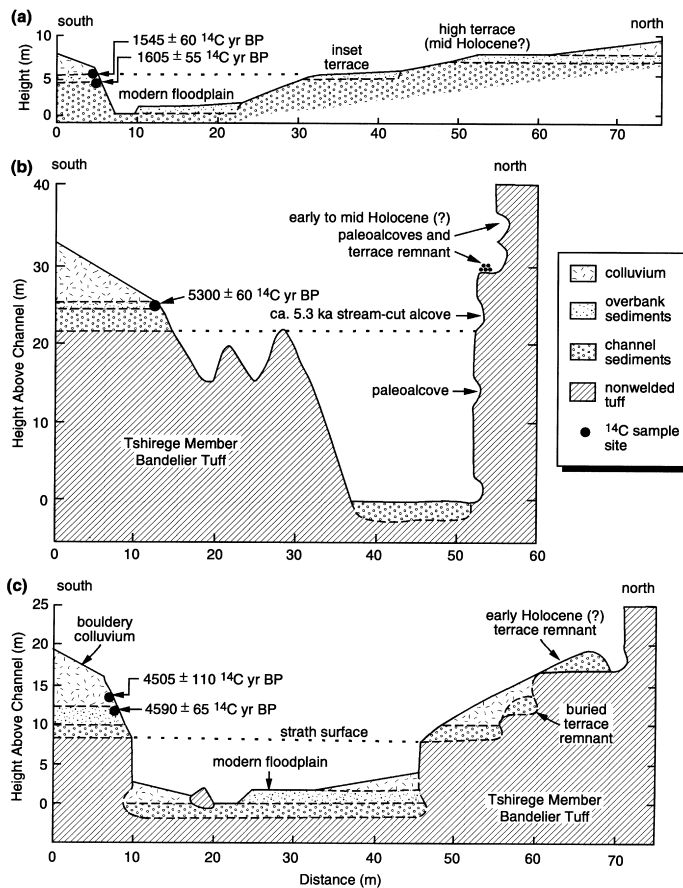


Fig. 11. Cross-sections at radiocarbon sample sites. (a) 1.6 ¹⁴C ka sample site, about 10.7 km upstream from the Rio Grande. (b) 5.3 ¹⁴C ka sample site, about 8.1 km upstream from the Rio Grande. (c) 4.5 ¹⁴C ka sample site, about 7.0 km upstream from the Rio Grande. No vertical exaggeration.

spatially variable, and constrain the time scale of periods of local base-level stability.

Intermediate age, Late Holocene terraces were sampled at two locations. At a downstream sample site, a short distance west of Ceremonial Cave, an age of ca. 1.3 ¹⁴C ka was obtained from basal fan sediments overlying a stream channel deposit (sample F-23, Table 1), and indicated relatively little stream incision in this area since ca. 700 cal AD. In contrast, analyses of ca. 1.5 to 1.6 ¹⁴C ka from a 4- to 5-m high terrace 5 km upstream indicated significant Late Holocene incision there since ca. 500 cal AD (samples F-8 and F-17, Table 1) (Fig. 11a).

Analyses from low floodplain exposures at two locations have yielded dates of 420 to 550 ¹⁴C years

BP from relatively fine-grained overbank sediments, calibrated to ca. 510 to 540 cal years BP or ca. 1410 to 1440 cal AD (samples F-14, F-15, and F-24, Table 1). These sites are close enough to the modern channel to be overtopped during large floods. Cones of *Pseudotsuga menziesii* from a litter layer buried beneath sooty silt at one of the exposures yielded an estimated post-bomb age of either 1962 to 1963 or 1973 to 1974 AD (sample F-11, Table 1). This sample probably records deposition from floods in 1977 or 1978 that post-dated the 1977 La Mesa Fire and included the largest floods in Frijoles Canyon this century (McCord, 1996). The analyses from these two exposures indicate that the elevation of the stream channel has been relatively stable since at

least ca. 1400 AD, overlapping with the peak Puebloan occupation at Tyuonyi.

Radiocarbon analyses from sites immediately upstream from three streamside rockfalls that locally dammed the channel provide additional data on the recent fluvial history of Frijoles Canyon (samples F-6, F-9, and F-25, Table 1). Dates of 50 to 290 ^{14}C years BP from stumps that likely record burial by post-rockfall sediments or from detrital charcoal within such sediments indicate that failure of the inner canyon walls has been common during the last several hundred years, a conclusion supported by observations of two separate rockfalls in 1989 and 1994 that also produced small lakes. All of these rockfalls represent collapse of cliffs adjacent to the channel and were probably caused by lateral erosion and undercutting (e.g., Fig. 8a) processes which should be most effective during times of local base level stability. Notably, alluvial deposits upstream from the rockfalls are sedimentologically distinct from the gravelly alluvium associated with other terraces, being much finer grained. No evidence exists that rockfalls have played a significant role in development of the major strath and fill terraces in Frijoles Canyon.

6. Discussion

6.1. Rates and controls of stream incision

Data from Frijoles Canyon provides evidence for the rates and controls of stream incision over a range of time scales. Stream incision has not been constant either spatially or temporally, and the incision history of Frijoles Canyon has probably been influenced by variations in lithology and flood characteristics.

The upper surface of the 1.22-Ma Tshirege Member of the Bandelier Tuff constitutes an approximate Early Pleistocene datum that allows examination of long-term patterns of incision. Between the knickpoints in basalt and dacite, where Frijoles Canyon is cut largely into tuff, canyon depth ranges from 150 to 300 m (Fig. 3) and total incision since 1.22 Ma has thus varied by a factor of two. Notably, despite the increasing welding of the Tshirege Member to the west, closer to its source, total incision has been greatest through the most welded section west of the

Pajarito fault zone. Thus, stream power has been generally sufficient to allow incision to keep pace with fault uplift despite the increase in rock resistance.

Average rates of Quaternary incision can be estimated by making assumptions about the time when downcutting began through the Bandelier Tuff. The character and stratigraphy of alluvial deposits and associated paleochannels on mesa tops to the north, in the vicinity of the shallower Los Alamos and Pajarito canyons (Reneau, 1995; Reneau et al., 1995), indicate that stream incision there did not begin immediately following tuff emplacement but could have been delayed for tens of thousands of years or more. This delay in incision probably resulted in part from the formation of a knickpoint along the Rio Grande after deposition of the Tshirege Member, which imposed a high local base level and would have hindered incision along tributary drainages (Reneau and Dethier, 1996). Assuming that initial incision of Frijoles Canyon was delayed for up to 200 ka provides maximum average rates of incision of 0.25 to 0.29 m/ka to the west, and lower average rates of 0.12 to 0.15 m/ka to the east. Because incision of the stream channel is impeded by basalt near the Rio Grande, potential rates of incision through tuff (in the absence of this base level constraint) can be assumed to be higher.

Exceptionally high rates of incision have characterized the middle reaches of Frijoles Canyon during the Holocene. As discussed earlier, the stream has incised up to 28 m below the top of the fill terrace, which provides average rates of incision of up to 4 m/ka since the Middle Holocene as calculated from the top of terrace gravel (Fig. 12). Average net rates of incision into tuff over this time period are somewhat less, but still approach 4 m/ka (Fig. 12). These rates are an order of magnitude higher than longer term (10^5 – 10^6 years) averages on the Pajarito Plateau and along larger axial drainages in northern New Mexico (e.g., Dethier and McCoy, 1993; Formento-Trigilio and Pazzaglia, 1998). The Holocene rates of incision are comparable to those found in some tectonically active mountain ranges experiencing exceptionally rapid uplift and erosion (e.g., Burbank et al., 1996) and in some areas of relatively erodible bedrock (e.g., Stock et al., 1996; Tinkler and Parish, 1998).

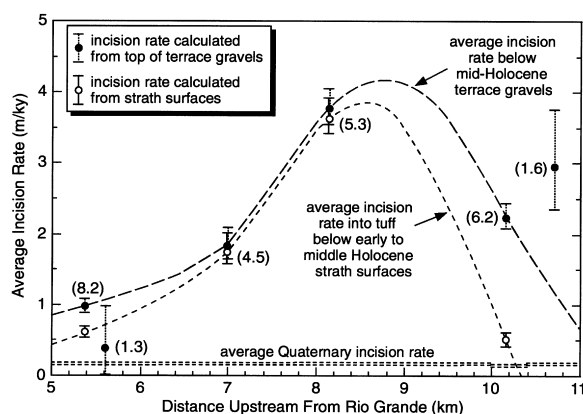


Fig. 12. Plot showing longitudinal variations in the rate of incision along Frijoles Canyon. Data points indicate net rates of incision at sites with radiocarbon age control (numbers indicate ^{14}C age, in ka). Rates of incision into tuff assume that 1.25 m of gravel underlies the modern channel. Error bars incorporate conservative estimates of uncertainty in age from Table 1, and ± 0.5 m uncertainty in the thickness of gravel below the channel and in the height of gravel above the channel. Upper dashed lines indicate inferred variations in incision rate since the Middle Holocene, based on the distribution of terraces and available age control. Lower dashed lines indicates the average incision rate in this part of the canyon since deposition of the Tshirege Member of the Bandelier Tuff, assuming that incision began within 200 ka of tuff emplacement.

Available data indicate that the rates of incision in Frijoles Canyon during the Holocene are partly dependent on the chosen time frame. Calculated Late Holocene rates of incision at two upstream and downstream sites with radiocarbon control are much higher or lower than average rates since the Middle Holocene at these locations, although more uncertainty occurs in rates calculated over the shorter time periods (Fig. 12). This apparent variability in Holocene rates of incision limits the reliability of using the calculated rates to estimate the age of undated terraces.

Lithologic variations within the Tshirege Member have strongly influenced the spatial variations in incision during the Holocene. The upstream limit of the area of rapid incision corresponds to the change from the lower nonwelded glassy ignimbrite to overlying vapor-phase altered ignimbrite (Fig. 6), and such variability within the Bandelier Tuff has, therefore, affected rates of incision over time scales of thousands of years. This clear lithologic control in-

validates earlier assumptions that, in the context of stream incision, the Bandelier Tuff acts as a uniform rock unit despite substantial vertical variations in welding and alteration (Wachs et al., 1988).

Additional lithologic influences on Holocene stream incision in Frijoles Canyon may have been imparted by the resistant zeolitized zones that occur upstream from Ceremonial Cave (Figs. 4b and 6). At present, a zeolitized zone in Ancho Canyon, 1 km north of Frijoles Canyon, produces a local knickpoint along the channel with a step in the stream-bed. Areas of locally steeper tuff surfaces below the Frijoles Canyon terraces 6 to 8 km upstream from the Rio Grande may be associated with the migration of such knickpoints. Although terrace development may have been partly affected by knickpoint migration (cf., Seidl and Dietrich, 1992), the major knickpoint in tuff about 10 to 11 km from the Rio Grande is associated with a more resistant rock unit and no evidence has been found that it has migrated upstream.

Incision in Frijoles Canyon has been episodic during the Late Quaternary. Periods of local stability in the elevation of the stream-bed are recorded by paired strath surfaces and associated abandoned stream-cut alcoves perched on canyon walls. The morphology of the canyon bottom indicates similar stability today (Fig. 8a). Radiocarbon analyses indicate that the present period of relative channel stability has lasted longer than 500 years.

Recent observations elsewhere on the Pajarito Plateau indicate that much of the stream incision in Frijoles Canyon may have occurred during very short periods of time. Following the intense Dome Fire in April 1996, Capulin Canyon, 4 km south of Frijoles Canyon, experienced repeated major floods caused by high rates of runoff from burned slopes during summer thunderstorms (Cannon, 1997; Veenhuis, 1999). These floods stripped the gravel from the stream-bed, exposed friable sandstone that was quickly incised in several areas, and stranded the pre-fire channel up to 2 m above the new channel by Fall 1996. Holocene incision in Frijoles Canyon may have been similarly influenced by rare, high magnitude floods capable of removing the pervasive gravel bed and exposing nonwelded tuff below the channel. However, the floods that followed the 1977 La Mesa Fire, the largest floods in Frijoles Canyon this cen-

ture (McCord, 1996), did not remove the gravel armor (White and Wells, 1984). Therefore, significantly larger floods appear to be required to strip the stream-bed gravel and allow incision in Frijoles Canyon. The likely causes of such large floods are not certain, but could involve a variety of processes including unusually intense basin-wide monsoonal rainfall, rain in combination with melting snow-packs, fire-related runoff, or rare extra-tropical storms. The latter have been shown to be the cause of many geomorphically effective floods in Arizona (e.g., Smith, 1986; Kresan, 1988), although they are much less common in northern New Mexico.

The inference that episodes of Holocene incision in Frijoles Canyon have been brief, occurring during periods of unusually high flood discharges, is similar to interpretations made by other workers in diverse regions (e.g., Macklin et al., 1992; Meyer et al., 1995). Similarly, the interpretation that removal and reestablishment of a gravel armor plays a key role in a cycle of alternating incision and lateral erosion in Frijoles Canyon is consistent with that inferred for the development of Holocene fill-cut and strath terraces by Bull (1990, 1991) and Meyer et al. (1995).

6.2. Early to Middle Holocene aggradation and relation to climate

The fill terrace in the mid-reaches of Frijoles Canyon records a period of significant aggradation during the Early to Middle Holocene that contrasts with the stream history during the Latest Pleistocene and during the Middle to Late Holocene. During this period the channel was locally buried by ≥ 13 m of coarse gravelly alluvium, whereas other Late Quaternary terraces are characterized by straths overlain by ≤ 2 m of sandy gravel. Aggradation during the Early Holocene is also documented by a fill terrace in a downstream reach.

Available age control indicates that aggradation began prior to 8.2 ^{14}C ka in the lower part of Frijoles Canyon and continued until at least 6.2 ^{14}C ka upstream. Although the duration of aggradation has not been documented in either area and the fill terraces cannot be directly correlated, the similar age and character of the terraces suggest a common geomorphic control. Similar dates of about 5 to 9 ^{14}C

ka have also been obtained from alluvium in several canyons farther north on the Pajarito Plateau (McDonald et al., 1996; Reneau and McDonald, 1996; Reneau et al., 1996), and suggests that aggradation occurred throughout the plateau at this time. In particular, the most extensive Holocene terrace in Rendija Canyon north of Los Alamos, the well-dated Qt6 terrace, overlaps in age with the Frijoles Canyon fill terrace at about 5 to 7 ^{14}C ka (McDonald et al., 1996; Reneau and McDonald, 1996).

Stratigraphic and chronologic evidence elsewhere in the region also indicates extensive sediment deposition away from the major axial rivers during the Holocene. Widespread Holocene sedimentation on piedmont slopes in the Basin and Range province was noted by Hawley et al. (1976) and attributed to erosion caused by decreased vegetation cover in the more arid interglacial period. Aggradation of fans in the Española Basin, derived from the northeastern Jemez Mountains, has similarly been proposed to occur during interglacial periods, such as the Holocene (Dethier and McCoy, 1993; Dethier et al., 1988). Early to Middle Holocene aggradational units that may correlate with the Frijoles Canyon fill terrace include sediments in Chaco Canyon, 170 km west on the Colorado Plateau (lower Gallo unit of Hall, 1977; see also Wells et al., 1983), and 430 km south in the Rio Grande valley near Las Cruces (Fillmore and Organ alluvium of Gile et al., 1981). The inception of widespread aggradation near the Pleistocene–Holocene transition has also been reported on the Southern High Plains by Holliday and Gustavson (1991) and on the southeastern Colorado Plateau by Wells (1994).

The occurrence of this aggradation following a major regional climate change indicates a direct relation between local geomorphic processes and climatic variations, although the exact linkage between surface processes and climate in the Early to Middle Holocene is uncertain. Stratigraphic relations between the major fill terrace in Frijoles Canyon and fans derived from canyon wall drainages (Figs. 9 and 10) suggest that aggradation was associated with a period of high sediment supply, reflecting accelerated erosion in the watershed. Two lines of evidence suggest the hypothesis that such accelerated erosion and related aggradation was directly linked to an increase in intense summer rains (Reneau and Mc-

Donald, 1996; Reneau et al., 1996). First, most of the modern surface erosion on the Pajarito Plateau occurs during summer thunderstorms (e.g., Wilcox et al., 1996). Second, paleoenvironmental data from surrounding regions suggest increased summer precipitation in the Early Holocene relative to the Latest Pleistocene (Markgraf and Scott, 1981; Friedman et al., 1988; Betancourt, 1990; Davis and Shafer, 1992; Thompson et al., 1993; Fall, 1997). Erosion may also have been aided by either major regional vegetation changes that could affect surface stability (e.g., Bull, 1991), or short-term reorganization of plant communities and associated changes in ground cover during periods of climatic change (cf., Allen and Breshears, 1998). Flood magnitude–frequency relations may also have changed significantly following the Pleistocene–Holocene climatic transition, in turn affecting sediment transport in Frijoles Canyon, although possible changes in floods have not been quantified.

6.3. Holocene profile development

Spatial variations in Late Quaternary aggradation and incision within Frijoles Canyon have resulted in geologically rapid changes in the stream profile and

consequently in stream power exerted during floods in each reach. Profile changes associated with aggradation were temporary, but changes imposed by incision may have a longer-lasting effect on fluvial processes and subsequent evolution of the stream profile.

The estimated Early Holocene stream channel in the middle reaches of Frijoles Canyon possessed relatively little longitudinal variations in gradient relative to the modern profile. The most prominent feature was apparently a downstream decrease in gradient where the channel passed from the more resistant vapor-phase altered tuff into glassy non-welded tuff, approximately 10 km upstream from the Rio Grande (Fig. 13). Other variations in gradient may have been associated with incision through the zones of zeolitized tuff 3 to 4 km downstream, although these are not well defined.

Aggradation in the Early to Middle Holocene resulted in an estimated 25% to 30% steepening of the channel 8 to 10 km from the Rio Grande, downstream from the Early Holocene break in slope (Fig. 13). This increased gradient would have allowed more effective transport of the gravel that was being supplied from the upper watershed. The downstream extent of aggradation apparently corresponded with a local increase in the gradient of the tuff surface

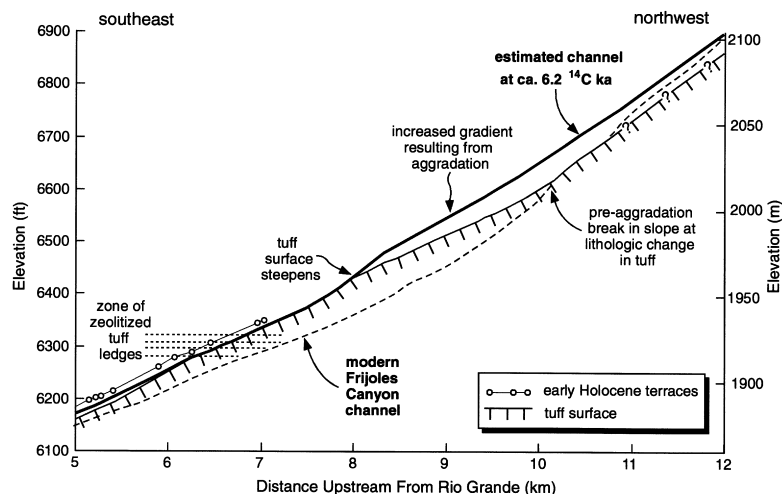


Fig. 13. Estimated longitudinal profile in Frijoles Canyon at ca. 6.2 ^{14}C ka (7.1 cal ka), showing effect of Holocene aggradation and incision on development of the stream profile. Approximate positions of the Early Holocene channel are represented by the buried tuff surface beneath the fill terrace to the northwest, and by strath and fill terraces to the southeast. Vertical exaggeration = $18.6\times$.

about 8 km from the Rio Grande. The steeper tuff surface here may record a perturbation generated by incision through the zeolitized tuff farther downstream or by other resistant material on the channel bed such as large boulders. Downstream of this change in gradient the channel continued to incise episodically into tuff through the reach containing the zeolitized tuff, and also to aggrade its bed farther downstream.

Aggradation ceased in the middle reaches of Frijoles Canyon near or sometime after ca. 6.2 ^{14}C ka, perhaps because the sediment supply from upstream reaches decreased. The rapid, spatially variable incision since that time (Fig. 12) has resulted in major increases in channel gradient upstream and downstream from the lithologic change in tuff, and reductions in channel gradient farther downstream (Fig. 13). Relative to the Early Holocene, before aggradation, the channel gradient is an estimated 30% higher in the reach 8 to 10 km from the Rio Grande, and an estimated 20% lower 5 to 8 km from the river. Floods during this period have had sufficient stream power to continue incision into tuff in the downstream reaches despite a reduced gradient, yet have been largely ineffective at incising the vapor-phase altered tuff in the much steeper upstream reach. What was a relatively minor lithologic effect on the stream profile at the beginning of the Holocene has been greatly enhanced, and has created a significant and possibly long-lived perturbation in profile evolution.

7. Conclusions

The evolution of the stream profile in Frijoles Canyon has been strongly affected by lithologic variations within the watershed, over longer ($> 10^5$ years) and shorter ($< 10^4$ years) time frames. In the Early or Middle Pleistocene, the incising stream encountered resistant basalt that has subsequently provided local base level constraints and isolated most of the watershed from base level changes along the Rio Grande. Incision during the Holocene has been influenced by lithologic variations within the Bandelier Tuff, with a relatively resistant vapor-phase altered unit providing a major impediment to inci-

sion and producing a knickpoint along the channel. Thin zeolitized zones in the tuff may also have affected incision during the Holocene by producing temporary knickpoints, and some strath terraces may have formed in response to the migration of such knickpoints (cf., Seidl and Dietrich, 1992), although no evidence has been found that the prominent tuff knickpoint has migrated.

Variations in Late Quaternary climate may have affected development of the stream profile in Frijoles Canyon in at least two ways. First, the occurrence of aggradation following a major regional climate change indicates a direct link between sediment transport and climate. One hypothesis to explain this linkage is that intense summer rainfall was more significant in the Early to Middle Holocene relative to the Late Pleistocene, causing accelerated erosion in the watershed and contributing to extensive aggradation along the channel. Vegetation changes during this period may also have contributed to increased erosion. Second, the exceptional rates of Holocene incision are inferred to have resulted from unusually high magnitude floods that were capable of stripping gravel from the stream-bed and exposing the erodible underlying tuff. Similar high rates of incision in the Holocene relative to the Late Pleistocene have also been documented in Rendija Canyon, farther north on the Pajarito Plateau (Reneau and McDonald, 1996, p. 140), which suggests a regional increase in flood magnitude in the Holocene, although the specific processes producing such floods are not certain.

In contrast to the large effects on the evolution of the stream profile imposed by lithologic and climatic variations in Frijoles Canyon, the only apparent effect of faulting along the Pajarito fault zone is the long-term increase in relief of the upper watershed. This is consistent with results from other studies in the region that have shown the effects of tectonics to be subordinate to climatically driven erosion in affecting stream evolution in northern New Mexico (e.g., Formento-Trigilio and Pazzaglia, 1998).

The evidence provided by stream terraces in Frijoles Canyon demonstrates that stream incision in this region can display great spatial and temporal variation, which imposes major constraints on the resultant evolution of stream profiles. The interplay between lithology and climate has had a major role

in stream profile evolution over various time scales, whereas the effects of tectonics have been minor.

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