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EROSION AND DEPOSITION ON THE PAJARITO PLATEAU, NEW MEXICO, AND IMPLICATIONS FOR GEOMORPHIC RESPONSES TO LATE QUATERNARY CLIMATIC CHANGES

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Abstract--The gently-sloping mesa tops and adjoining canyons of the Pajarito Plateau contain a diverse record of late Quaternary landscape changes that was probably strongly affected by fluctuations in climate. The streams show considerable variability in their behavior during the Holocene, with some experiencing progressive incision into tuff that was interrupted by periods of lateral cutting and floodplain development, while others experienced progressive aggradation interrupted by episodes of channel cutting into alluvial fills. Available data indicate that many streams were incised below their present level in the late Pleistocene and have subsequently aggraded in the Holocene, and this aggradation was probably due to a major increase in sediment supply within the drainage basins accompanying the Pleistocene-Holocene transition. Although the processes producing such accelerated erosion are not fully understood, they may have been aided by an enhancement of intense summer rainfall in the early Holocene. Widespread erosion has continued into modern times, progressively stripping soils from mesa tops, including well-developed soils that are older than 50-60 ka, and exposing tuff bedrock in many areas. Additional effects of climatic change near the Pleistocene-Holocene transition may have included an increased

influx of eolian sediment onto mesas, accounting for local mesa-top aggradation despite the high erosion rates that have apparently characterized the Holocene.

INTRODUCTION

The Pajarito Plateau of northern New Mexico contains a rich and diverse record of late Quaternary landscape changes in a variety of geomorphic settings that include gently-sloping mesa tops, steep canyon walls, and canyon bottoms. A broad range of investigations during the past decade, motivated by environmental and seismic hazard concerns, have resulted in examination of the characteristics, stratigraphy, and age of sediments and soils at numerous locations throughout the Plateau. Geochronologic control is provided by >140 radiocarbon dates (mostly on disseminated charcoal fragments), supplemented by soil characterization and tephrochronology.

In this paper we first summarize some of the results of recent and ongoing work on late Quaternary deposits on the Pajarito Plateau, illustrating both the complexity of the geomorphic record and some common elements that have been observed in multiple locations. We then use these observations, in combination with other work in the Southwest, to make some inferences about the local geomorphic response to regional climatic changes. Because the geomorphic and paleoclimatic records are fragmentary, and because the relations between large scale climate changes and local variations in precipitation, vegetation, and geomorphic processes are not fully understood, many uncertainties exist concerning the response of the local landscape to past climatic fluctuations. In addition, variations in local landscape sensitivity related to prior erosional history and spatial variations in vegetation, and the localized nature of many storms, probably contribute to the complexity of the geomorphic record. Nevertheless, the work discussed in this paper suggests a strong relation between regional climatic changes and local geomorphic history, and provides a framework for considering relations between modern processes, the record of past landscape changes, and future erosion and deposition on the Plateau and in surrounding areas.

SETTING

The Pajarito Plateau is an area of gently-sloping mesas separated by numerous narrow canyons that are up to 180 m in depth. The Plateau is bordered on the west by the Sierra de los Valles (the eastern Jemez Mountains), and on the east by White Rock Canyon of the Rio Grande (Fig. 1). The part of the Plateau discussed in this paper is mainly between 1900 and 2300 m in elevation, although some contributing drainage basins in the Sierra de los Valles extend to over 3100 m. None of the drainage basins were glaciated. Vegetation is dominated by ponderosa pine forest to the west and piñon-juniper woodlands to the east (Allen, 1989). Modern climate is semiarid, with average annual precipitation that ranges from about 300 mm on the eastern Plateau to about 500 mm on the western Plateau (Bowen, 1990). Roughly 40% of the precipitation occurs during intense convective storms in July and August, and these storms have been responsible for the most extensive surface erosion (e.g., Wilcox, 1994; Wilcox et al., in press) and the highest flood peaks on record.

Bedrock immediately beneath the mesa tops consists of massive early Pleistocene ignimbrites of the Tshirege Member of the Bandelier Tuff (Griggs, 1964; Smith et al., 1970). The canyon walls are mainly cut into the Tshirege Member, but also expose early Pleistocene alluvium and pumice beds of the Cerro Toledo interval, early Pleistocene ignimbrites and pumice beds of the Otowi Member of the Bandelier Tuff, Plio-Pleistocene fanglomerates of the Puye Formation, Pliocene basaltic rocks of the Cerros del Rio volcanic field, and Miocene to Pliocene dacites of the Tschicoma Formation. In most of the canyons, channel incision is impeded by Cerros del Rio basalts (or, in part, Puye fanglomerates) to the east, imposing major local base level constraints such that the streams are not directly influenced by base level changes along the Rio Grande.

Surficial deposits vary substantially in thickness and characteristics across the Pajarito Plateau. Tuff on the mesa tops is typically overlain by 0-2 m of soils and sediments, although mesa-top deposits locally exceed 3-4 m in thickness. Canyon walls include extensive cliffs, particularly on south-facing exposures, and also extensive colluvial deposits that range from fine-textured slopewash to bouldery rockfall deposits. Alluvium in the canyon bottoms is typically dominated by sand derived from weathering of the Bandelier Tuff, although streams heading in the

Sierra de los Valles generally transport dacite gravels as bedload. The alluvium locally exceeds 10 m in thickness, although it thins to <1 m to the east near knickpoints in resistant bedrock units. A key late Quaternary stratigraphic marker on much of the Pajarito Plateau is the El Cajete pumice, erupted from the Jemez Mountains about 50-60 ka (Toyoda et al., 1995; Reneau et al., 1996), which provides precise correlation of horizons in diverse geomorphic settings.

MESA TOPS

Exposures of soils and sedimentary deposits on several mesas reveal a complex record of both erosion and deposition. The most complete mesa-top record examined so far is on Pajarito Mesa (site 2 of Fig. 1), where exceptional exposures were provided by 1300 m of trenches (Kolbe et al., 1994, and unpubl. report for Los Alamos National Laboratory, 1994; Reneau et al., in press). The El Cajete pumice was present in most of the trenches, overlying a soil with a well-developed argillic Bt horizon (unit 3 of Fig. 2). The degree of soil development in this buried unit indicates on the order of perhaps 50-100 ky of relative stability of the mesa top prior to 50-60 ka, based on a comparison with soils formed in late Pleistocene deposits at other locations on the Pajarito Plateau (McDonald et al., this volume). Similar or better developed pre-El Cajete soils are common (but not universal) on other Pajarito Plateau mesa tops (e.g., Longmire et al., in press).

Overlying the El Cajete pumice at Pajarito Mesa is a complex, in part discontinuous, sequence of units with radiocarbon ages extending back to 30 ka (units 1 and 2 of Fig. 2; Kolbe et al., unpubl. report for Los Alamos National Laboratory, 1994; Reneau et al., in press). The abundance of silt in the upper units (about 55-65% silt; P. Watt and E. McDonald, unpubl. 1995), deposited on top of the pumice bed, and the absence of an upslope source for fine sediment on this mesa, implies significant eolian contributions to the mesa-top soils (although such eolian sediment may be locally reworked). Shallow Paleo-Indian fire pits within and buried by fine-grained sediments at two locations, identified by the presence of oxidized tuff clasts and charcoal and dated at ca. 9.5 ^{14}C ka (Fig. 2a), and an additional date of 9.4 ^{14}C ka from a correlative fine-grained deposit, suggest an early Holocene period of mesa-top aggradation associated with high rates of eolian sediment influx. A more recent episode of enhanced eolian input is suggested by a fine-

grained deposit (unit 1), averaging 10-30 cm thick, that occurs throughout the trenches and that buries several Anasazi sites with radiocarbon ages of about 760-1020 yr B.P. (~1000-1300 cal A.D.) (Fig. 2b). Similar fine-grained deposits that probably record late Quaternary eolian influx are widespread on the Plateau (e.g., Longmire et al., in press), although no other sites have yet yielded age control, and the timing and duration of eolian events on the Plateau are probably incompletely defined.

Considerable variability exists in the soils and stratigraphic units on individual mesas of the Pajarito Plateau, indicating significant spatial variations in the magnitude and extent of late Quaternary erosion. For example, a series of mesa-top trenches 600 m in total length excavated along Pajarito Road (site PR of Fig. 1; Kolbe et al., unpubl. report for Los Alamos National Laboratory, 1995), only 0.8 km north of the Pajarito Mesa trenches, displayed units that were much different than on Pajarito Mesa, including generally thinner soils and the virtual absence of El Cajete pumice. Total post-El Cajete erosion at the Pajarito Road trench sites has apparently been much greater than that on Pajarito Mesa. Although the reasons for these local variations in erosion are not certain, the mesa along Pajarito Road has a much broader crest than Pajarito Mesa, perhaps resulting in a greater concentration of surface runoff (due to less divergence of runoff onto mesa shoulders) and consequently greater erosion.

Additional records of the erosional history of Pajarito Plateau mesa tops are provided by deposits occurring within shallow mesa-top drainages. At one site east of the Los Alamos townsite ("EG&G gully", Fig. 3), a 4-m section of Holocene fill is exposed in gully walls (Longmire et al., in press). Rapid deposition of the lower half of this section is indicated by two statistically indistinguishable radiocarbon dates of ca. 8 ka, separated by about 1 m of sediment (Fig. 3), presumably recording a period of accelerated erosion of the surrounding mesa-top soils. A period of subsequent stability or minimal aggradation after 8 ka is indicated by a buried soil within the section, which was followed by renewed deposition beginning at or before 4.0 ^{14}C ka (Fig. 3). As discussed in later sections, this mesa-top record is consistent with the stratigraphic record in several canyons that also indicate major valley bottom aggradation during the early Holocene,

providing evidence for a major change in erosional processes that coincided with the Pleistocene-Holocene climatic transition.

Field observations indicate that modern surface erosion is much higher on the drier, eastern Plateau than to the west, and large areas are currently being eroded on the eastern Plateau, stripping both the El Cajete pumice and underlying soils and exposing Bandelier Tuff bedrock in many areas (e.g., site SR4 of Fig. 1, discussed in Longmire et al., in press). A small monitored watershed on the eastern Plateau near Frijoles Canyon (Frijolito watershed, Fig. 1) is presently eroding at the rapid rate of several mm/yr, a rate that would strip all the soil within centuries (Wilcox et al., in press). The modern erosion rates at the Frijolito watershed and elsewhere on the eastern Plateau may be heavily influenced by land use changes since 1880, including the loss of ground cover due to grazing (Allen, 1989; Wilcox et al., in press), and the relation of the modern erosion to prehistoric periods of accelerated erosion is uncertain.

CANYON WALLS

Few chronologic data have been obtained from deposits along canyon walls on the Pajarito Plateau, although available data suggest erosion rates that are high enough so that the "residence times" of colluvium at many or most mid-slope sites are short. Radiocarbon data from two steep (~30°) sites in Cañon de Valle, on both north- and south-facing slopes, indicate ages of <1.0 ka for mid-slope colluvium (Fig. 4), consistent with the weakly-developed soils present on these slopes (A-R or A-Bw-R profiles; E. McDonald and S. Reneau, unpubl. 1995). Buried soils within colluvial aprons below these mid-slope sites record episodic transport of colluvium off the slopes for the last 4 ^{14}C ka (Fig. 4). Similar young ages of ≤3 ^{14}C ka have been obtained from buried soils within a colluvial apron at the base of a steep north-facing slope in upper Los Alamos Canyon (Longmire et al., in press). Abundant evidence of active erosion on canyon walls during summer thunderstorms (such as debris lobes below shallow canyon-wall channels), particularly on south-facing slopes, suggests that these slopes contribute a significant (though not quantified) amount of sediment to the stream channels.

Dissected remnants of older, Pleistocene colluvial deposits, both pre-dating and post-dating the El Cajete pumice, are widespread along the lower slopes in many canyons, preserving an older record of hillslope processes and suggesting episodic deposition and erosion of colluvium through the late Quaternary. One such lower-slope colluvial deposit in DP Canyon, overlying stream sediments dated at ca. 26.7 ^{14}C ka, has yielded an age of 21.6 ^{14}C ka (Reneau, 1995), and the upper parts of two toe-slope deposits along the north fork of Ancho Canyon yielded ages of 16.6 and 20.6 ^{14}C ka (S. Reneau, unpubl. 1994). Both of these dated Ancho Canyon deposits overlie the El Cajete pumice, and stratigraphic relations, the apparent absence of buried soils, and additional ^{14}C dates (32.8 and 44.4 ka) suggest that deposition of colluvium began at or before 50-60 ka and continued without major breaks until 17-21 ka, with minimal aggradation or net erosion occurring at these sites since then.

CANYON BOTTOMS

Canyon bottoms on the Pajarito Plateau show considerable diversity in their record of late Quaternary erosion and deposition, with some experiencing net aggradation while others experienced net incision, although all that have been studied indicate major geomorphic changes through the late Pleistocene and the Holocene.

At one extreme are canyons that have significantly incised into tuff, producing terraces that record temporary pauses in this incision or local aggradation. Both strath terraces, recording lateral stream erosion and concurrent development of floodplains, and fill terraces, recording significant channel aggradation, are present, although the distinction between strath and fill terraces is often not clear. In part of Frijoles Canyon, terrace remnants dated at ca. 5.3-6.2 ^{14}C ka are stranded up to 25 m above the modern channel (Fig. 5; Reneau et al., 1993), indicating average incision rates of up to 4 mm/yr since the mid Holocene. Along Rendija Canyon (Fig. 1), terraces dated at ca. 8.8-8.9 ^{14}C ka. occur 7 m above the modern channel, and a well-dated sequence of lower terraces document progressive incision during the Holocene at rates of ~1 mm/yr (see Gardner and Reneau, this volume, and McDonald et al., this volume).

In contrast to the record of incision present in some canyons, extensive late Quaternary aggradation is recorded in many others. A 4-m deep trench excavated in Cabra Canyon (Fig. 1), only 0.6 km from an incising part of Rendija Canyon, exposed deposits that document net aggradation since at least 4.0 ^{14}C ka, interrupted by several channel cutting events (Gardner and Reneau, this volume). A borehole in Los Alamos Canyon (LADP-3) penetrated the ca. 50-60 ka El Cajete pumice (largely or entirely reworked) as deep as ~7 m below the modern channel (Broxton et al., 1995), thus demonstrating net aggradation since that time. Sediment samples from core holes in both Ancho and Mortandad Canyons indicate the presence of a complex stratigraphy buried beneath the canyon floor, including pure layers of El Cajete pumice that, at least in part, represent primary fallout deposits (Fig. 6). The El Cajete pumice may have been deposited either on broad, generally unincised canyon bottoms, as are present today in these canyons, or on terraces, and was subsequently buried during a period of extensive aggradation. The magnitude of Holocene aggradation is indicated by radiocarbon dates on charcoal fragments from core holes in Ancho and Mortandad Canyons. A floodplain deposit 4 m below the modern channel along the north fork of Ancho Canyon yielded a date of 9.9 ^{14}C ka, and coarse channel sands 10-12 m deep in Mortandad Canyon yielded dates of 7.2-7.8 ^{14}C ka (Fig. 6). These data indicate average Holocene aggradation rates of 0.5->1.5 mm/yr in some canyons, although we expect that rates of sediment deposition have been highly variable; for example, part of Frijoles Canyon had aggraded at least 13 m before 6.2 ^{14}C ka, while subsequently experiencing net incision since 6.2 ka (Reneau et al., 1993).

Available data from Pajarito Plateau canyons suggest that a major change in fluvial systems occurred at or near the Pleistocene-Holocene climatic transition. The highest of the late-Quaternary flight of terraces in part of Frijoles Canyon yielded an age of 8.2 ^{14}C ka (S. Reneau, unpubl. 1994), and a prominent Rendija Canyon terrace has yielded ages of 8.8-8.9 ^{14}C ka. Notably, soil characteristics suggest that the next higher Rendija Canyon terrace is >50 ka in age (McDonald et al., this volume), and the apparent absence of terraces between about 10 and 20 ka provides supporting evidence that the latest Pleistocene fluvial systems on the Pajarito Plateau were significantly different from the Holocene streams. Along the north fork of Ancho Canyon, channel

aggradation near the upstream end of the modern valley floor had commenced by at least 8.8 ^{14}C ka (S. Reneau, unpubl. 1994), and subsurface data (Fig. 6A) suggest that aggradation downstream may have begun by 11.6 ^{14}C ka. Data from a 4-m thick section exposed at the east end of Mesita del Buey, at the head of a minor tributary to Cañada del Buey, indicates inception of aggradation close to 10 ^{14}C ka, with episodic deposition during the Holocene suggested by the apparent presence of buried soils in the section (Fig. 7). These records are similar to that at "EG&G gully" (Fig. 3), where aggradation in a shallow mesa-top drainage commenced around 8.0 ^{14}C ka.

Stratigraphic relations and radiocarbon dating indicate that the mid to late Holocene sediments in many canyons record repeated episodes of alternating channel aggradation or stability and channel incision (e.g., Cabra Canyon; Gardner and Reneau, this volume), as has also been observed in drainages throughout the Southwest (e.g., Miller and Wendorf, 1958; Hall, 1977; Love, 1983; Karlstrom, 1988; Balling and Wells, 1990). However, the available data are not sufficient to determine if such episodes were largely synchronous across the Pajarito Plateau (which would imply a control imposed by regional climatic variations), or if they instead vary significantly in timing between canyons.

Changes between aggradation and incision have continued into historic time along both low order and high order channels, although, in detail, the canyons are not displaying synchronous behavior in regard to the timing of recent geomorphic changes. For example, an examination of sequential airphotos showed that a presently unchanneled, aggrading part of Potrillo Canyon possessed a channel until at least 1965 (Becker, 1991). In contrast, exposures along DP and Pueblo Canyons show that since major development began at the Los Alamos townsite (ca. 1943 A.D.), up to 2-3 m of sediment were first deposited and then incised (Reneau, 1995; Graf, in press). Drakos and Inoue (unpubl. reports for Los Alamos National Laboratory, 1993, 1994) and Aldrich and Harrington (1995) also report observations of historic cut-and-fill along Bayo and Los Alamos Canyons, and along a small drainage near the Los Alamos townsite. It is not known to what extent land use changes have affected the historic erosion and deposition along Pajarito Plateau channels, although we suspect that, at least locally, increases in sediment supply

accompanying development has resulted in aggradation, and that increases in the extent of impermeable surfaces has increased flood peaks, resulting in incision.

EFFECTS OF REGIONAL CLIMATIC CHANGES

Many studies have demonstrated that major changes in both vegetation and the amount and seasonal distribution of precipitation accompanied climatic changes at the Pleistocene-Holocene transition across the American Southwest, as discussed below. These late Quaternary changes in climate likely resulted in significant changes in geomorphic processes on the Pajarito Plateau, although the sensitivity of the land surface to climatic change probably varied greatly across the landscape related to factors such as local vegetation, catchment area, and slope gradient.

Available paleoclimatic data indicate that the late Pleistocene climate of the Southwest was wetter than today, with precipitation probably dominated by winter frontal storms (shown schematically in Fig. 8A) (Spaulding et al., 1983; Hall, 1985; Van Devender et al., 1987; Allen, 1991; Phillips et al., 1992; Thompson et al., 1993). Late Pleistocene vegetation at the elevation of the Pajarito Plateau elsewhere in the Southwest included montane forests or parklands of spruce and fir (Wright et al., 1973; Betancourt, 1990; Anderson, 1993). Vegetation more closely resembling modern communities became established perhaps around 10 ^{14}C ka, associated with a warmer, drier climate than in the latest Pleistocene and greatly enhanced summer precipitation. A variety of paleoclimate records from the Rocky Mountains of Colorado, the Colorado Plateau, and the southwestern deserts imply that summer rainfall in the early Holocene was higher than today (Fig. 8A), indicating stronger monsoonal circulation at that time (e.g., Markgraf and Scott, 1981; Friedman et al., 1988; Betancourt, 1990; Davis and Shafer, 1992; Thompson et al., 1993).

The apparent concurrence of these changes in vegetation and storm characteristics with the inception of major aggradation or episodic terrace formation on the Pajarito Plateau (shown schematically in Fig. 8B), suggest that these climatic changes triggered a period of accelerated erosion and increased sediment supply within the drainage basins of the Plateau. Although there are relatively few published records elsewhere in the region pertaining to possible changes in fluvial systems at this time, other workers from diverse areas have reported the inception of

widespread aggradation near the Pleistocene-Holocene transition (e.g., Holliday and Gustavson, 1991; Wells, 1994), providing some support for the regional nature of significant changes in geomorphic processes associated with late Quaternary climatic changes.

Major episodes of aggradation at the Pleistocene-Holocene transition elsewhere in the Southwest have been attributed primarily to destabilization of slopes caused by major reductions in vegetation, such as from woodlands to desert scrub communities (e.g., Bull, 1991). However, field observations suggest that much of the cobble- to boulder-sized gravel associated with aggradation along many Pajarito Plateau streams was derived from north-facing slopes and the higher elevation, western parts of drainage basins that remained forested into the Holocene. For example, bouldery Holocene debris fans are common below steep north-facing slopes in Frijoles Canyon, and coarse gravelly late Quaternary fans occur along many streams on the western Plateau where they exit the Sierra de los Valles. Although the age of these fans is not well constrained at present, soils developed in the Cañon de Valle fan suggest an early Holocene age (E. McDonald, unpubl. 1995). The coarse texture of these deposits suggest original mobilization of the sediment from hillslopes as debris flows, which are typically triggered during high intensity storms (e.g., Neary and Swift, 1987; Wieczorek, 1987). Recent observations of a debris flow on a north-facing slope in the Frijoles Canyon watershed, triggered by a summer thunderstorm (S. Reneau, unpubl. 1991), demonstrate that this is an active process under modern climate, although the relative importance of debris flows in providing coarse sediment to Pajarito Plateau channels is not quantified. Based on these observations, we infer that the enhancement of intense summer rainfall in the early Holocene may have been significant in accelerating erosion and increasing the supply of sediment in local watersheds, and that, at least on the forested slopes, the effects of vegetation changes may have been of lesser importance.

The accelerated erosion of mesa-top soils in the early Holocene requires a different process than that occurring on forested slopes, and mesa-top erosion has probably been dominated by surface runoff. Under modern climate, this erosion is greatest during intense summer thunderstorms, and is most effective on bare ground in "intercanopy" areas (Wilcox, 1994; Wilcox et al., in press). These relations suggest that changes in ground cover may have been critical in

controlling long-term variations in mesa-top erosion, although temporal variability in ground cover cannot be estimated at present. The local abundance of charcoal in some deposits (e.g., "EG&G gully", Fig. 3) suggests that erosion following fires (cf. White and Wells, 1984) may also have contributed to some of the mesa-top erosion, although the importance of fires in influencing Holocene erosion rates is unknown.

An additional geomorphic response to late Quaternary climatic change, as indicated by the stratigraphic record at Pajarito Mesa (Fig. 2), may have been a significant increase in the rate of eolian deposition on the Pajarito Plateau, including the period 9.4-9.5 ^{14}C ka (Fig. 8B). This eolian sediment may have partly had a source along aggrading stream channels, either within Pajarito Plateau canyons or farther to the south, and an increase in eolian sediment transport could thus been a secondary effect of an early Holocene increase in fluvial sediment transport. However, the eolian record on the Pajarito Plateau is poorly understood, with only Pajarito Mesa yielding age control, and determining the timing and duration of eolian events, and the actual source for the sediment, will require additional work.

Late Pleistocene geomorphic processes on the Pajarito Plateau are poorly understood due to the scarcity of deposits dated to between 10 and 20 ka. The apparent rarity of stream deposits from this period suggests that minimal aggradation occurred within the canyons, and it is possible that many streams had incised to bedrock along presently alluvial reaches. An absence of major late Pleistocene stream deposits suggests lower basin-wide erosion rates associated with lesser amounts of summer rainfall, and possibly higher sediment transport capacity associated with snowmelt floods that were larger and of longer duration than today. Kelson and Wells (1987) used similar reasoning to explain why a largely nonglaciated basin near Taos apparently experienced incision during glacial periods and floodplain formation during interglacial periods. In contrast to the inferred low erosion rates on the Pajarito Plateau in the latest Pleistocene, available data indicate that adjacent areas in White Rock Canyon experienced an enhancement of large-scale landsliding at that time (Fig. 8; see Reneau and Dethier, this volume), illustrating how local variations in landscape sensitivity may result in much different responses to the same climate changes.

The role of Holocene climatic fluctuations in producing the alternation of channel cutting and filling seen in some Pajarito Plateau canyons (i.e., Cabra Canyon), or the alternation of lateral cutting and incision into bedrock seen in others (i.e., Frijoles and Rendija Canyons), is not clear. The available data have not yet revealed mid to late Holocene geomorphic events that are synchronous across the Plateau, although the data set is still relatively small. Although workers elsewhere in the Southwest have proposed that Holocene erosional and depositional episodes along streams display strong synchroneity and are controlled by regional climatic fluctuations (e.g., Karlstrom, 1988), other processes involving complex responses along the channels related to internal drainage basin parameters (Schumm, 1977; Bull, 1991) or rare high-magnitude storms may also contribute to the record of erosion and deposition within Pajarito Plateau canyons. In addition, we expect that progressive reductions in sediment yield and progressive increases in surface runoff during the Holocene may have resulted from the stripping of soils and consequent increase in exposure of tuff bedrock, which could have locally caused incision of early to mid Holocene fills without changes in storm characteristics; such process-response models have been proposed for other arid or semiarid areas (Bull, 1991).

CONCLUSIONS

Sediments and soils on the Pajarito Plateau contain a diverse record of late Quaternary erosion and deposition that is probably strongly affected by regional climatic changes. Available data indicate that at least some of the streams were incised below their present level in the late Pleistocene and have subsequently aggraded in the Holocene, and this aggradation was probably due to a major increase in basin-wide erosion rates and sediment supply accompanying the Pleistocene-Holocene transition. Although the processes producing such accelerated erosion are not certain, they may have been aided by an enhancement of intense summer rainfall in the early Holocene. Erosion has continued into modern times, progressively stripping soils from mesa tops, including well-developed soils that are older than 50-60 ka, and exposing tuff bedrock in many areas. Additional effects of climatic change near the Pleistocene-Holocene transition

probably include an increased influx of eolian sediment onto mesas, accounting for local mesa-top aggradation despite the high erosion rates that have apparently characterized the Holocene.

The canyons of the Pajarito Plateau show considerable variability in their behavior in the Holocene, with some experiencing progressive incision into tuff that was interrupted by periods of lateral cutting and floodplain development, while others experienced progressive aggradation that was interrupted by episodes of channel cutting into the alluvial fills. We believe that variations in drainage area, channel gradient, and bed material size between canyons probably contribute to the varied late Quaternary geomorphic history seen on the Pajarito Plateau, although these variables have not yet been examined in detail. The effects of regional climatic changes during the Holocene on erosion and deposition on the Plateau are also not certain, and available data have not yet revealed mid to late Holocene changes in geomorphic processes that are synchronous across the Plateau. Determining the relative importance of regional climatic changes in comparison with more local controls on Holocene episodes of erosion and deposition on the Pajarito Plateau thus requires further work.

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FIGURE CAPTIONS

FIGURE 1. Map showing selected drainages on the Pajarito Plateau and location of sites discussed in text. Filled circles indicate sites with radiocarbon age control mentioned in this paper, and open circles indicate other sites mentioned in text. Numbers indicate sites of Figures 2-7. DPC: DP Canyon; FW: Frijolito watershed; LA: Los Alamos; PM: Pajarito Mesa; PR: Pajarito Road trench sites; SR4: State Road 4 site.

FIGURE 2. Soil-stratigraphic units in Pajarito Mesa trenches and buried archaeological sites. (A) Log of part of trench E1, showing Paleo-Indian fire pit (~8530 cal B.C.) in fine-grained early Holocene eolian (?) deposit. (B) Log of part of trench E8, showing Anasazi site (~1280 cal A.D.) excavated into late Pleistocene and Holocene units, and buried by fine-grained late Holocene (eolian?) deposits (unit 1b, with typical ages of 540-710 ^{14}C yr B.P.; 1290-1410 cal A.D.). A distinctive buried soil (unit 3) underlies the ca. 50-60 ka El Cajete pumice and is present throughout the trenches; unit 2b is bioturbated El Cajete pumice, and unit 2a includes soils and deposits above the pumice which have yielded ages of 2-30 ^{14}C ka. Horizontal axis indicates trench distance. No vertical exaggeration. (From Kolbe et al., unpubl. report for Los Alamos National Laboratory, 1994, and Reneau et al., in press.)

FIGURE 3. Cross section showing stratigraphy and radiocarbon dates at "EG&G gully" (informal name), in a shallow mesa-top drainage east of the Los Alamos townsite (from Longmire et al., in press). The deposit is generally an unstratified loam or silt loam, except for sand and granule layers that occur in the ca. 8 ka unit and which may record relatively high energy surface runoff.

FIGURE 4. Schematic cross section across Cañon de Valle (stream elevation ~2240 m), showing relations of colluvial soils on canyon walls, colluvial aprons at slope base, and Holocene alluvial fill. Canyon is about 70 m deep and 190 m wide here. (Thicknesses of surficial units are not to scale).

FIGURE 5. Schematic cross section across bottom of Frijoles Canyon about 8 km upstream of the Rio Grande (stream elevation ~1945 m) showing mid Holocene terrace remnant and location of ^{14}C date in basal part of overlying colluvium. Stream-cut alcoves are formed in this canyon during periods of local base level stability and floodplain development (including about 5.3 ^{14}C ka and today), and become stranded on cliff walls following renewed incision, recording former stream levels.

FIGURE 6. Cross sections across (A) north fork of Ancho Canyon and (B) Mortandad Canyon, showing radiocarbon dates and inferred stratigraphic context of units exposed in core holes. Stratigraphy modified from unpublished core logs (K. Shisler et al., unpubl. 1994; S. McLin et al., unpubl. 1994). Bedrock in (A) includes the Tshirege and Otowi Members of the Bandelier Tuff and alluvium of the intervening Cerro Toledo interval.

FIGURE 7. Sketch showing stratigraphy and radiocarbon dates at the head of a minor tributary to Cañada del Buey, at the east end of Mesita del Buey. This early to mid Holocene fill has been extensively dissected and eroded, and the modern channel is close to tuff bedrock.

FIGURE 8. Schematic representations of possible gross variations in (A) precipitation and (B) geomorphic processes on the Pajarito Plateau and in surrounding areas for the last 20,000 years, illustrating inferred temporal relations between climatic changes and the geomorphic record. Geomorphic processes presented here include: the supply of sediment to channels derived from erosion throughout the basins, and associated aggradation of channels; local mesa-top aggradation that probably records increased eolian influx; and large-scale landsliding. Vertical scales are intended to show relative differences between the late Pleistocene and the Holocene, as inferred from regional paleoclimatic records and from local geomorphic evidence, and not absolute values. Because available records are incomplete, the plotted curves are of necessity partly speculative. See text for discussion.

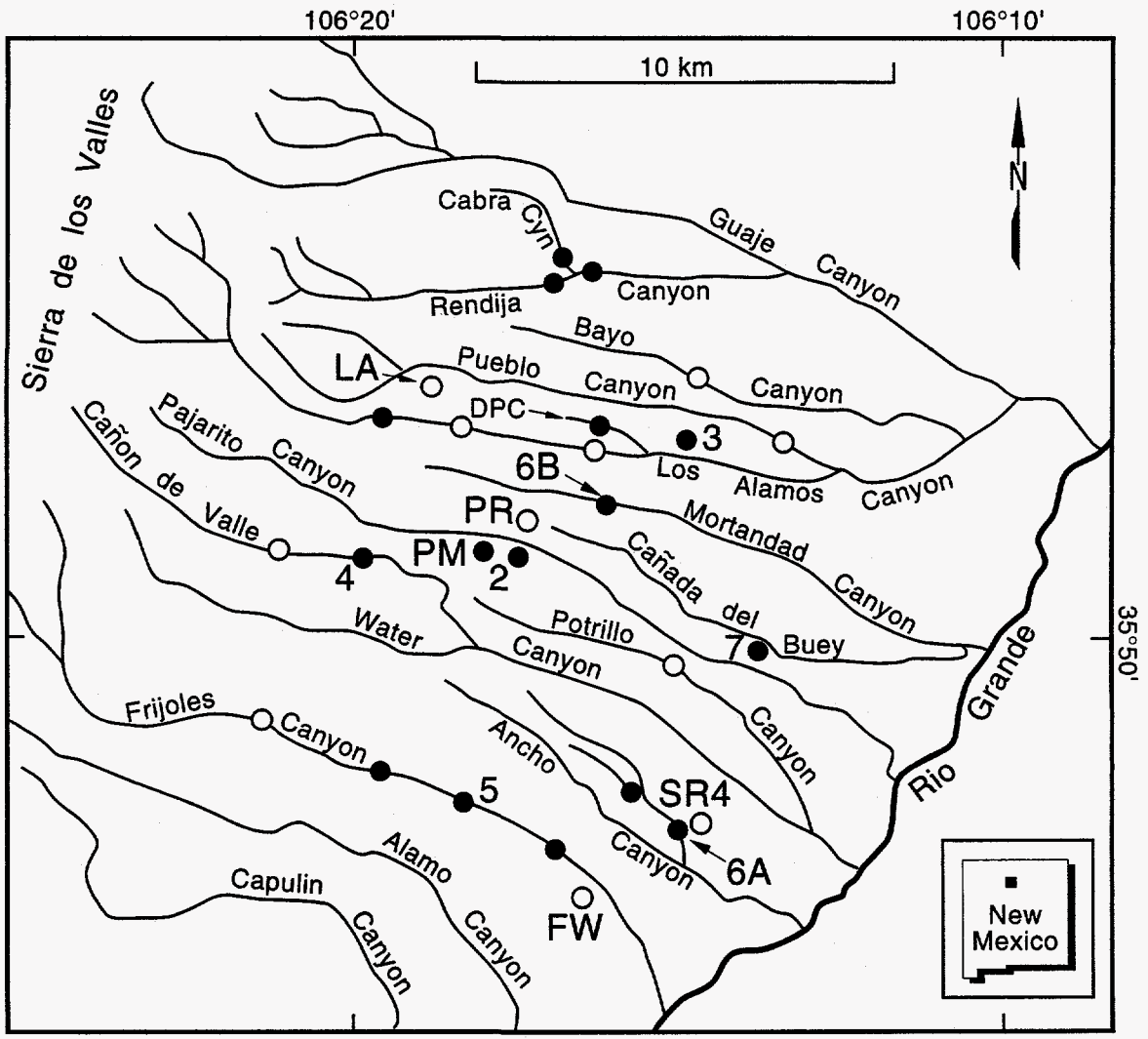
106°20'
106°10'
10 km
N
Sierra de los Valles
Cabra Cyn
Guaje Canyon
Rendija Canyon
Bayo Canyon
LA
Pueblo Canyon
DPC
3
Los Alamos Canyon
Cañon de Valle
Pajarito Canyon
6B
PRO
Mortandad Canyon
PM
2
4
Cañada del Buey
7
Water Canyon
Potrillo Canyon
Frijoles Canyon
Ancho Canyon
SR4
6A
5
Alamo Canyon
Capulin Canyon
FW
Rio Grande
New Mexico
35°50'

Fig. 1

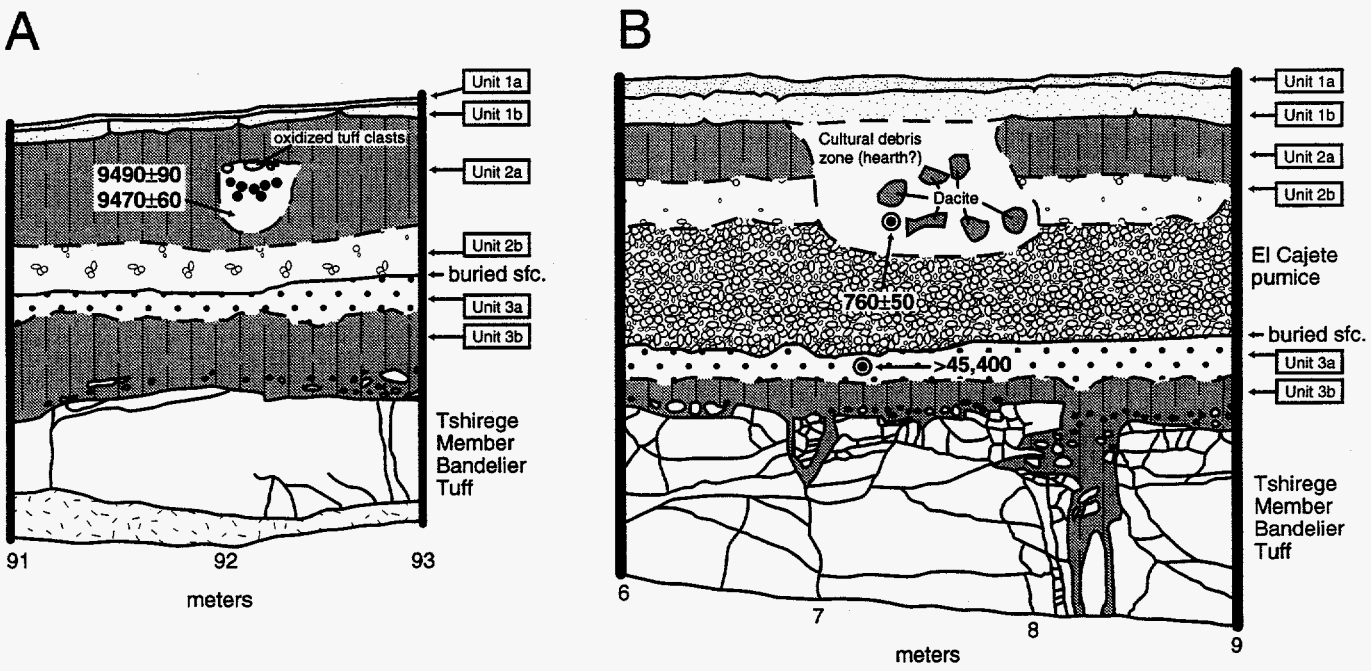
A
Unit 1a
Unit 1b
oxidized tuff clasts
9490±90
9470±60
Unit 2a
Unit 2b
buried sfc.
Unit 3a
Unit 3b
Tshirege
Member
Bandelier
Tuff
91
92
93
meters
B
Unit 1a
Unit 1b
Unit 2a
Unit 2b
Cultural debris
zone (hearth?)
Dacite
760±50
El Cajete
pumice
buried sfc.
>45,400
Unit 3a
Unit 3b
Tshirege
Member
Bandelier
Tuff
6
7
8
9
meters

Fig. 2

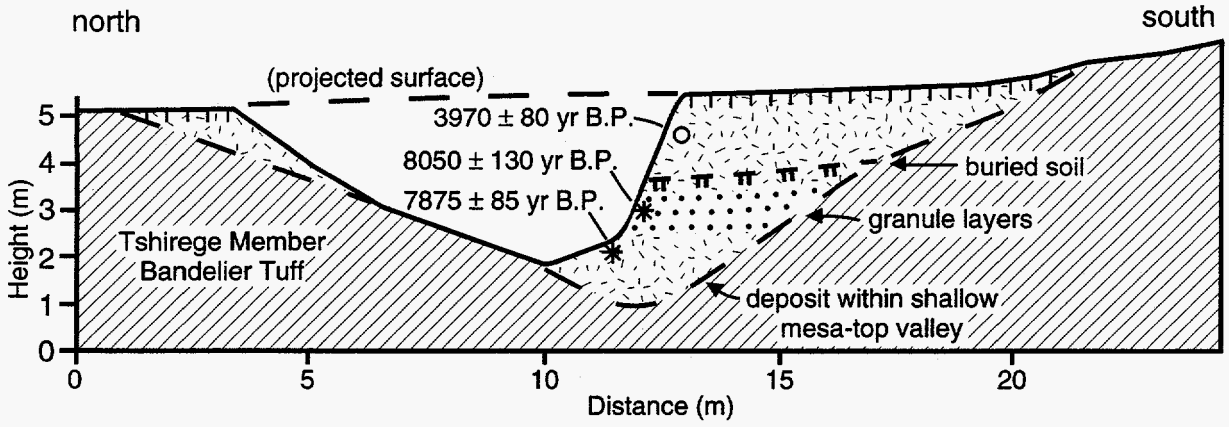
north
south
(projected surface)
3970 ± 80 yr B.P.
8050 ± 130 yr B.P.
7875 ± 85 yr B.P.
buried soil
granule layers
Tshirege Member
Bandelier Tuff
deposit within shallow
mesa-top valley
Height (m)
0
1
2
3
4
5
0
5
10
15
20
Distance (m)

Fig. 3

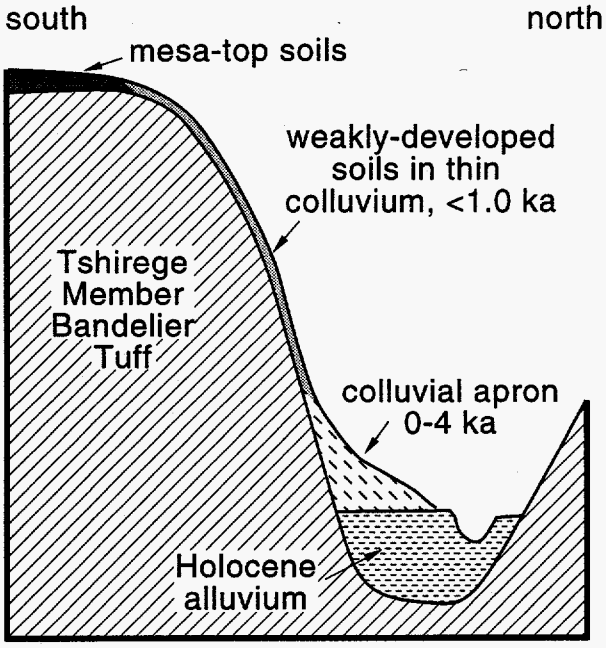
south
north
mesa-top soils
weakly-developed soils in thin colluvium, <1.0 ka
Tshirege Member Bandelier Tuff
colluvial apron 0-4 ka
Holocene alluvium

Fig. 4

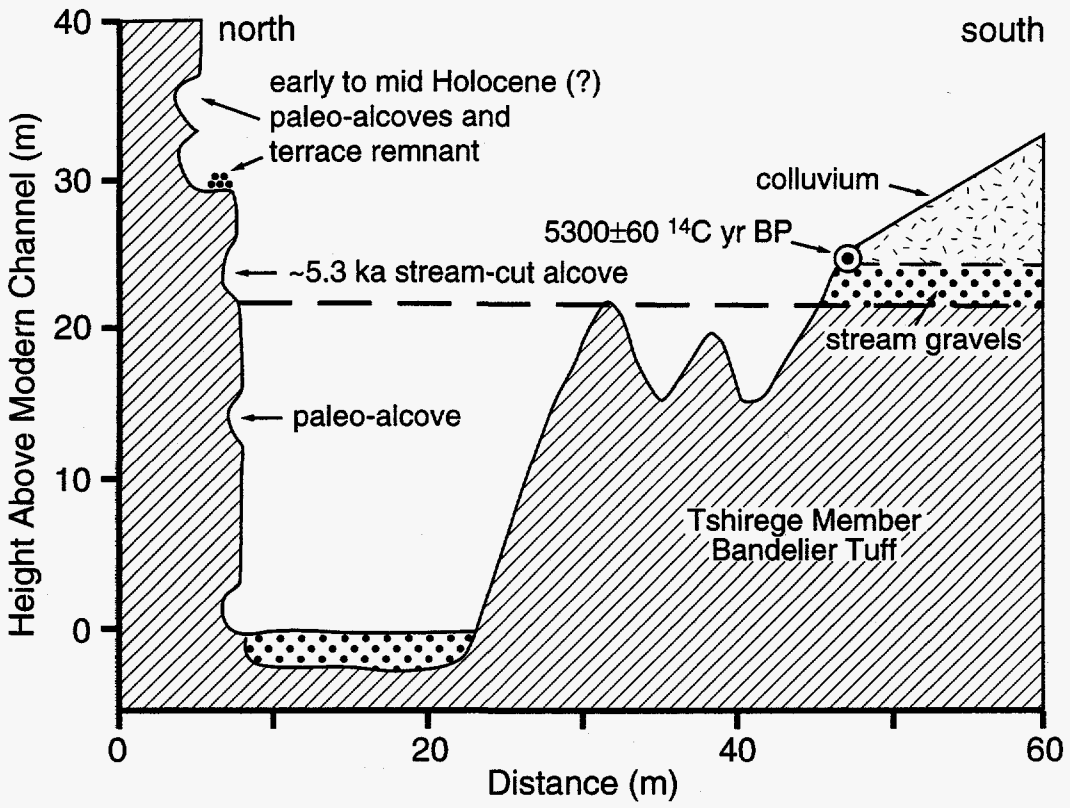
north
south
early to mid Holocene (?)
paleo-alcoves and
terrace remnant
colluvium
5300±60 14C yr BP
~5.3 ka stream-cut alcove
stream gravels
paleo-alcove
Tshirege Member
Bandelier Tuff
Height Above Modern Channel (m)
40
30
20
10
0
0
20
40
60
Distance (m)

Fig 5

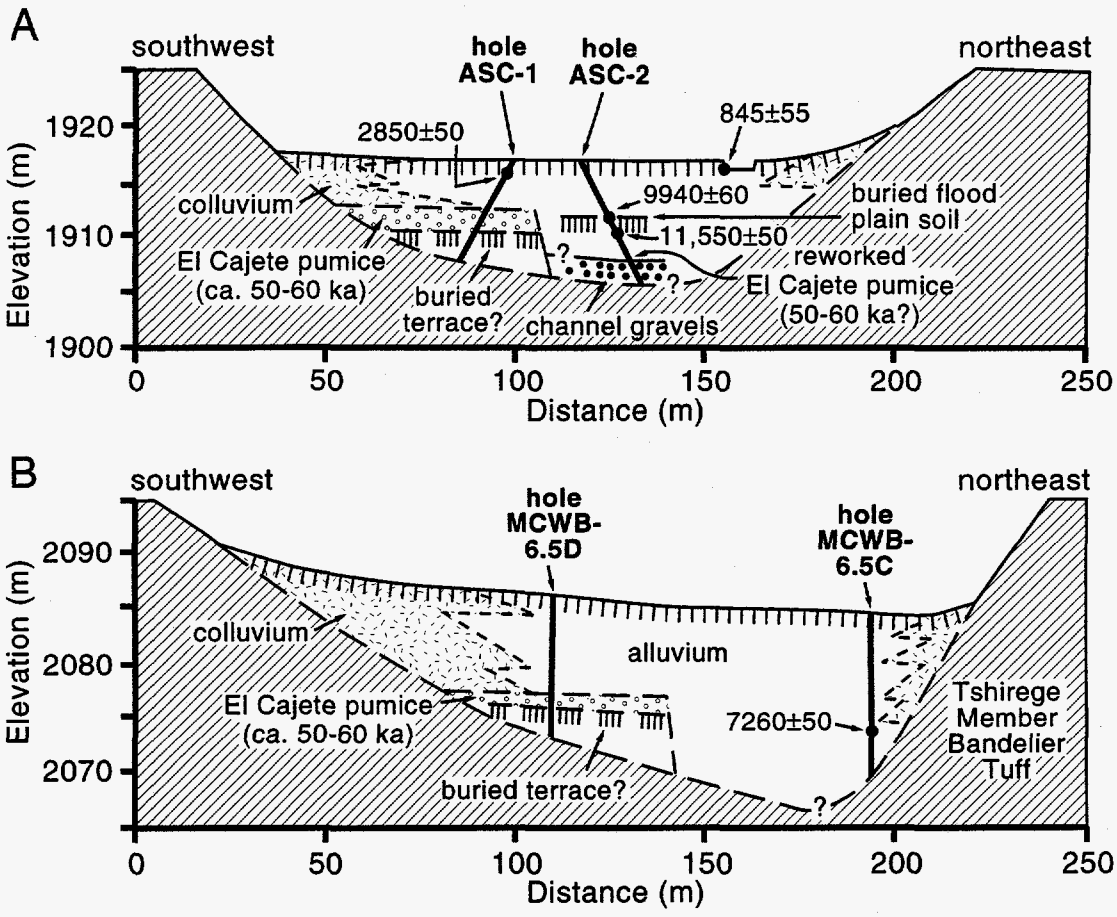
A
southwest
northeast
hole ASC-1
hole ASC-2
2850±50
845±55
9940±60
11,550±50
buried flood plain soil
reworked El Cajete pumice (50-60 ka?)
colluvium
El Cajete pumice (ca. 50-60 ka)
buried terrace?
channel gravels
Elevation (m)
1920
1910
1900
0
50
100
150
200
250
Distance (m)
B
southwest
northeast
hole MCWB-6.5D
hole MCWB-6.5C
colluvium
alluvium
El Cajete pumice (ca. 50-60 ka)
7260±50
Tshirege Member Bandelier Tuff
buried terrace?
Elevation (m)
2090
2080
2070
0
50
100
150
200
250
Distance (m)

Fig. 6

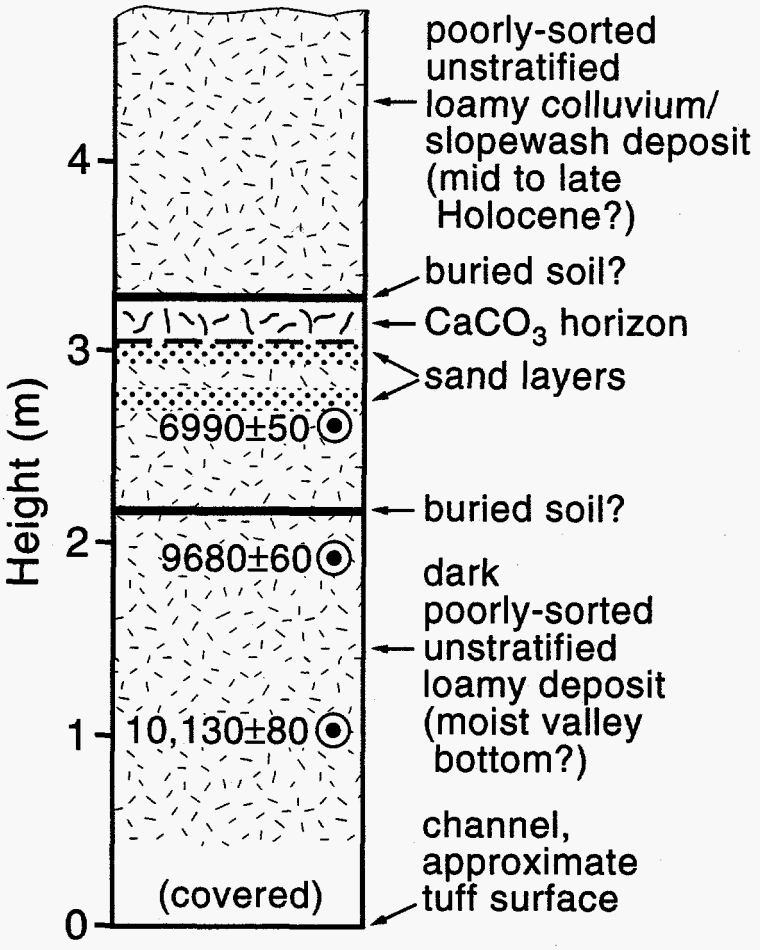
poorly-sorted
unstratified
loamy colluvium/
slopewash deposit
(mid to late
Holocene?)
buried soil?
$CaCO_3$ horizon
sand layers
6990±50
buried soil?
9680±60
dark
poorly-sorted
unstratified
loamy deposit
(moist valley
bottom?)
10,130±80
channel,
approximate
tuff surface
(covered)
Height (m)
4
3
2
1
0

Fig. 7

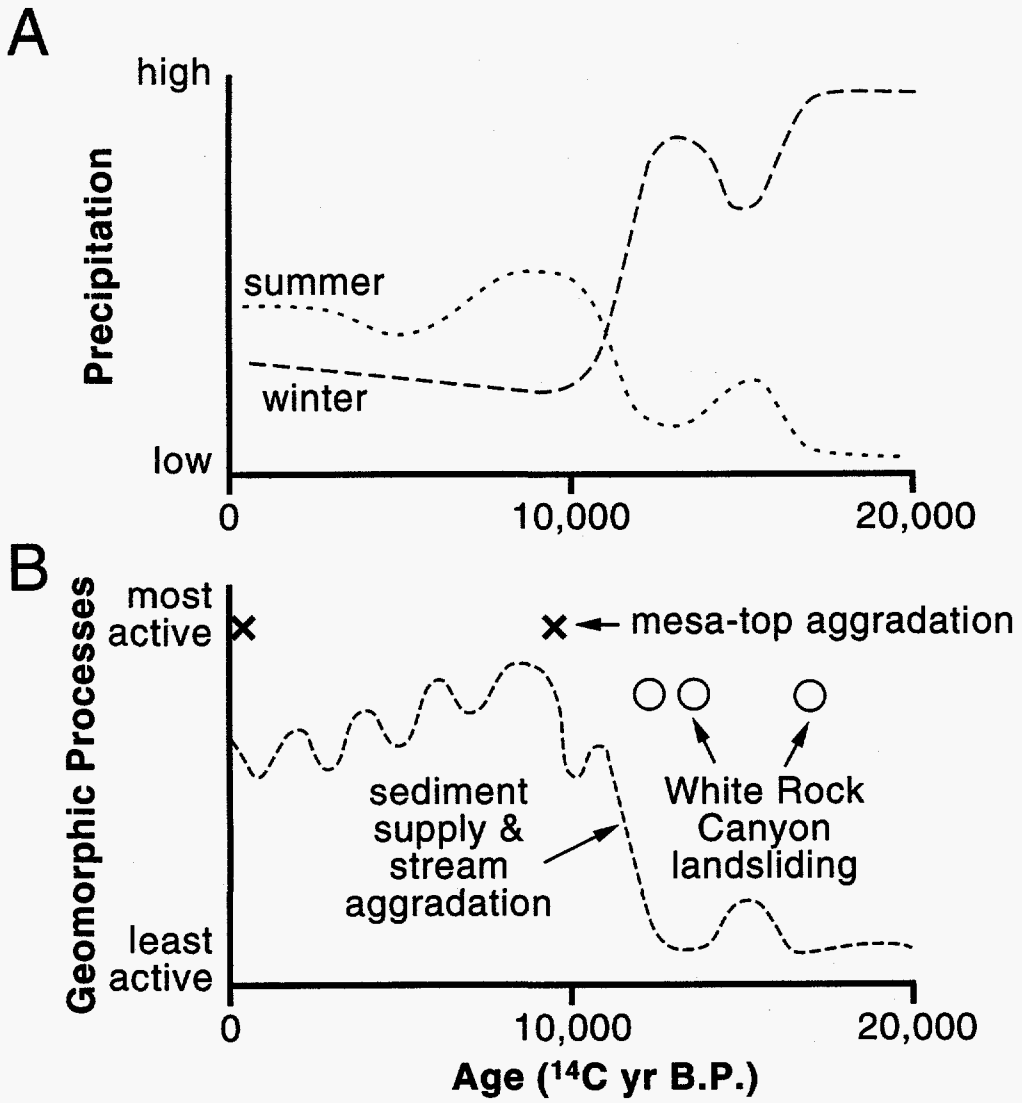

Fig-8

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