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HOLOCENE EVOLUTION OF CANYONS AND IMPLICATIONS FOR CONTAMINANT TRANSPORT, PAJARITO PLATEAU

PAUL G. DRAKOS, JAY LAZARUS and CHRISTOPHER INOUÉ
Glorieta Geoscience, Inc., 1723 Second St., Santa Fe, NM 87505

Abstract—The preserved Holocene geologic record in canyons incised into the Pajarito Plateau indicates that sediment is cycled through canyons on time scales of tens to hundreds of years. Canyon stream systems draining the Sierra de los Valles and Pajarito Plateau exhibit episodic sediment transport and deposition during the Holocene, including multiple episodes of incision and aggradation during Holocene and recent (historic) time. Formation of a mid-Holocene fill terrace in Frijoles, Rendija, Los Alamos and Bayo canyons suggests that both the larger canyon systems draining the Sierra de los Valles (e.g., Frijoles and Los Alamos Canyons) and smaller canyons heading on the Pajarito Plateau (e.g., Rendija and Bayo Canyons) are responding synchronously to local or regional climatic changes. Although detailed correlations of the multiple late Holocene and historic surfaces between canyons has not been completed, the presence of Holocene valley floors indicates significant Holocene sediment storage in canyons on the Pajarito Plateau. Canyons examined contain between 3 and 6 ft of sediment less than 50 yrs old in some locations, and also contain one or more inset geomorphic surfaces of historic age. The late Holocene and historic record of multiple cut-and-fill events indicate that the potential exists for remobilization and transport of contaminants through canyon systems. Contaminants discharged into canyons discussed in this paper include (1) ^{90}Sr, natural and depleted uranium dispersed throughout a segment of Bayo Canyon during munitions testing; (2) plutonium discharged into Acid Canyon and transported into Pueblo Canyon; and (3) plutonium released into DP Canyon. Contaminants entrained as part of the sedimentary package have been transported through canyon systems; in Pueblo Canyon contaminants have been transported downstream through Los Alamos Canyon to the Rio Grande.

INTRODUCTION

Geomorphic mapping conducted in Bayo and Los Alamos Canyons provides a stratigraphic framework for comparison with the geomorphic and Holocene geologic record in DP, Frijoles, Pueblo, Rendija and Cabra canyons (Drakos and Inoué; 1993, 1994; Graf, 1995, unpubl. reports to Los Alamos National Laboratory; Reneau, 1993; Reneau and Gardner, 1993; Graf, in press; Fig. 1). These canyons were examined as part of the Environmental Restoration Project at Los Alamos National Laboratory (LANL). The purpose of the geomorphic mapping conducted in the vicinity of LANL was to: (1) define historic and prehistoric Quaternary geomorphic surfaces through surface mapping at 1:1200 scale; (2) identify discrete stratigraphic units within the alluvium and colluvium and associated geomorphic surfaces and to identify areas of historic erosion and deposition; (3) estimate sediment transport rates; (4) identify potential contaminants within a canyon system; and (5) identify specific geomorphic units and underlying sediments as sampling locations for potential contaminants. An additional outcome of these investigations was the development of the Quaternary geologic history of individual canyons.

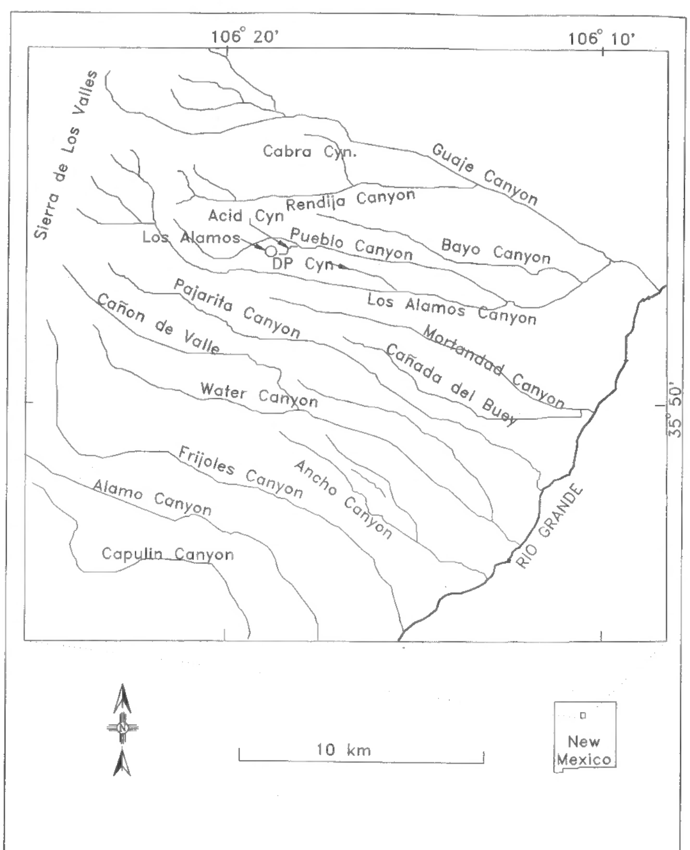

FIGURE 1. Map showing selected drainages on the Pajarito Plateau (adapted from Reneau et al., this volume).

The geomorphic characterization of canyon segments involved field mapping, air photo analysis, profiling using a hand level and stadia rod, field soil and stratigraphic descriptions, and analysis of topographic maps and drillers' logs. Geomorphic features examined include drainage channels, areas of historic sedimentation and terrace formation, older sedimentary deposits and geomorphic surfaces along the valley floor, and talus or colluvial slopes between the valley floor and adjacent cliffs. Geomorphic surfaces were differentiated based on height above local base level, radiometric dating, the presence or absence of historic materials in the underlying deposits, the degree of preservation of depositional or constructional morphology, and where possible, relative soil development. A series of 1:1200 scale geomorphic and Quaternary geologic maps of the areas of Bayo, Los Alamos and DP canyons are available from LANL Facility for Information Management, Analysis, and Display (FIMAD).

GEOLOGIC SETTING

Canyons on the Pajarito Plateau in the vicinity of Los Alamos are incised into a sequence of the Tshirege Member of the Bandelier Tuff, overlying the Cerro Toledo interval and Otowi Member of the Bandelier Tuff (Fig. 2). The Bandelier Tuff ranges in age from 1.2 to 1.6 Ma, based on ^{40}Ar - ^{39}Ar dates for the Tshirege Member (1.2 Ma) and the Otowi Member (1.6 Ma) (Izett and Obradovich, 1994). The Otowi Member of the Bandelier Tuff is underlain by alluvial fan deposits that comprise the Plio-Pleistocene Puye Formation, Pliocene basaltic rocks of the Cerros del Rio volcanic field, and Santa Fe Group (Tesuque Formation) sediments.

Canyon incision into the Pajarito Plateau commenced during the Pleistocene following deposition of the Bandelier Tuff (Tshirege Member) at 1.2 Ma. In several canyons (e.g., Cabra, Los Alamos, Mortandad and Ancho

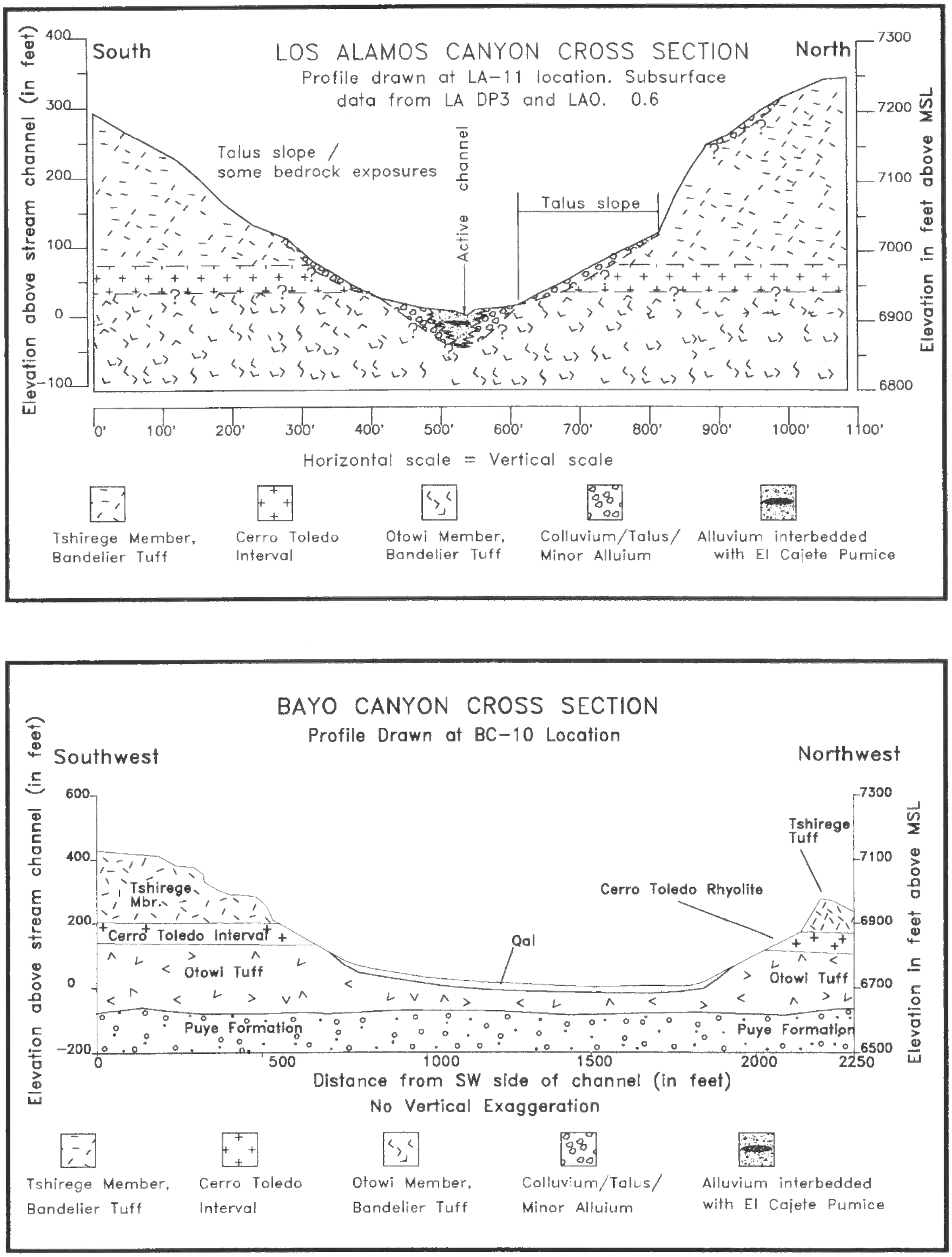

FIGURE 2. Los Alamos Canyon and Bayo Canyon cross sections.

Canyons) stream systems incised until the late Pleistocene, but have experienced aggradation during the past 50-60 ka (Reneau et al., this volume). Radiocarbon dating indicates that an episode of aggradation and terrace formation occurred at or near the Pleistocene-Holocene boundary in Frijoles, Rendija and Ancho canyons (Reneau et al., this volume), suggesting that a change in geomorphic processes and depositional patterns occurred at that time. Another period of apparently synchronous aggradation and terrace formation occurred in the mid-Holocene. The mid- to late Holocene geologic record in canyons on the Pajarito Plateau has generally been characterized by multiple episodes of alternating channel aggradation, incision, and relatively brief periods of stability.

STUDY AREAS

Bayo Canyon

Bayo Canyon was mapped in the area north of Kwage Mesa and south of Otowi Mesa, near the eastern terminous of each mesa (Fig. 3). This area of Bayo Canyon was selected for mapping because it was the location of LANL Technical Area 10 (TA-10). Potential sources of contamination pertinent to this study include shrapnel dispersed throughout the canyon as a result of firing site activities conducted from 1944 through 1963. Four firing pads apparently used for munitions testing were observed during mapping in Bayo Canyon. Approximately 1 to 2 % of this

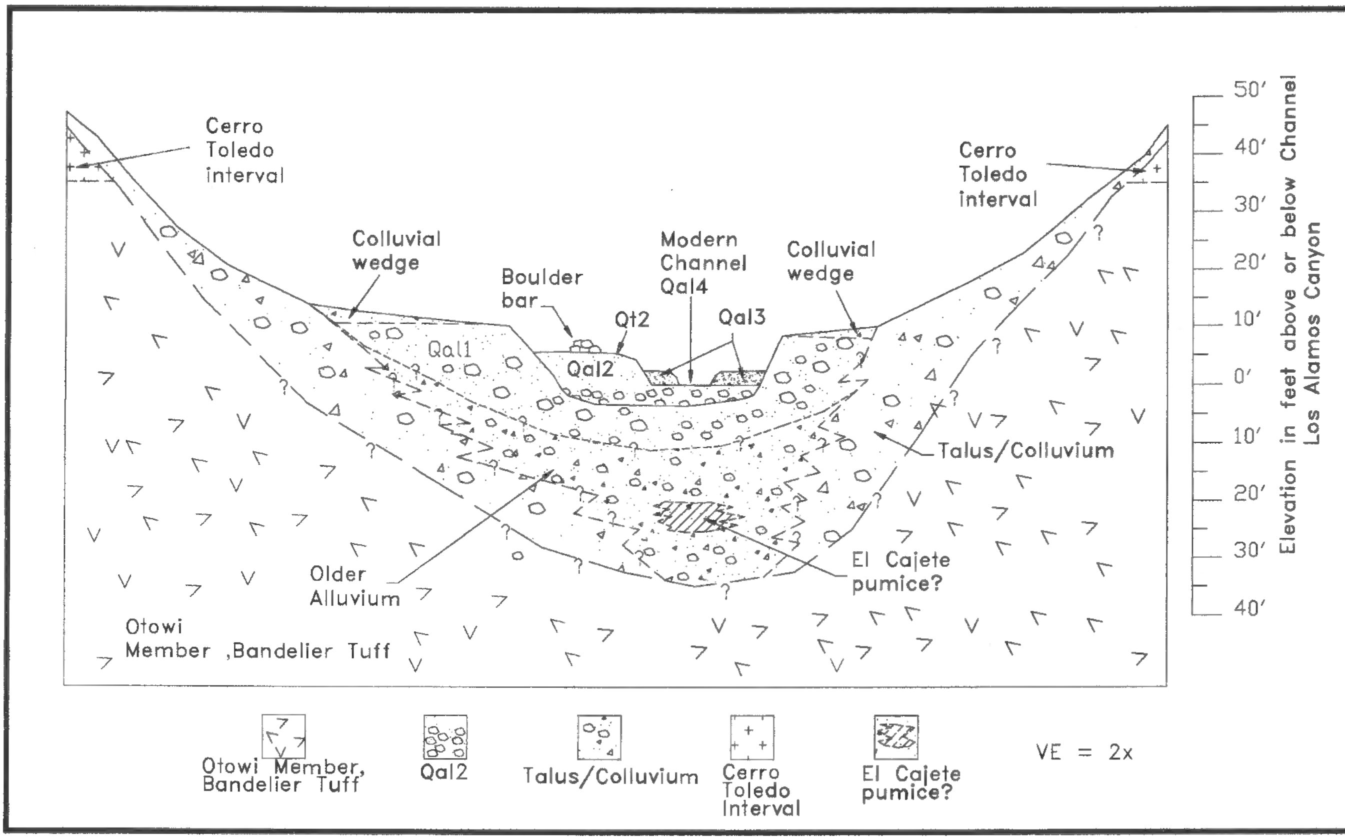

FIGURE 3. Diagram of inner canyon deposits and surfaces, Los Alamos Canyon. Subsurface data from Broxton et al. (1994).

shrapnel contains Strontium-90 (^{90}Sr) contamination or is composed of natural or depleted uranium. These contaminants are present because TA-10 was used to test conventional high explosives containing natural and depleted uranium and a radioactive tracer (Lanthanum-140 or ^{140}La) "source" with a half-life of 40.3 hrs. The ^{140}La was contaminated with a small amount of ^{90}Sr with a half-life of 28.8 yrs.

Bayo Canyon heads on the Pajarito Plateau, and therefore does not receive runoff from Sierra de los Valles. The primary landforms in the canyon are steep cliffs developed in the Tshirege Member of the Bandelier Tuff; slopes ranging from 10° to 30° mantled with talus derived primarily from the Tshirege Member and underlain by the Cerro Toledo interval and Otowi Member of the Bandelier Tuff; and a wide, relatively flat valley floor (Fig. 2). The valley floor can be subdivided into two sections consisting of broad, low-angle valley floor side slopes covered with 1–6 ft of colluvium, and a fairly narrow inner canyon consisting of the modern channel flanked by one to three stepped terrace surfaces.

Los Alamos Canyon

Los Alamos Canyon heads in the Sierra de los Valles and was mapped in the area south of and adjacent to the Los Alamos townsite. This area of Los Alamos Canyon was selected for mapping because it includes Technical Area 2 (TA-2) and Technical Area 41 (TA-41). TA-2 includes the facility for the Omega West Reactor, which is currently shut down and is planned for decommissioning. TA-41 is a weapons research facility. Los Alamos Canyon is bordered by the Los Alamos townsite to the north and South Mesa to the south and is incised approximately 350 ft into the Tshirege Member, Bandelier Tuff; Cerro Toledo interval; and Otowi Member, Bandelier Tuff (Fig. 2). Both the Rendija Canyon and Guaje Mountain fault zones have been projected through Los Alamos Canyon within the mapped area (Gardner and House, 1987; Vaniman and Wohletz, unpubl.). Both faults exhibit down-to-the-west displacement, although only the Rendija Canyon fault clearly offsets the Bandelier Tuff within Los Alamos Canyon.

The primary landforms in the canyon are steep cliffs developed in the Tshirege Member; slopes ranging from 10° to 35° mantled with talus derived primarily from the Tshirege tuff and underlain by the Cerro Toledo interval and Otowi Member; and a narrow, relatively flat valley floor (Fig. 2). The valley floor can be subdivided into two sections consisting of laterally-restricted areas of colluvial deposition at the base of talus slopes and low angle valley floor side slopes underlain by colluvium; and a fairly narrow inner canyon consisting of the modern channel incised into one to three stepped terrace surfaces (Fig. 3). Several small landslide blocks (Qls) were observed at the base of steep side slopes.

The reach of Los Alamos Canyon between DP Canyon and the Rio Grande was also mapped as part of a study addressing plutonium transport through the Los Alamos Canyon system (Graf, unpubl. report for LANL, 1995; Graf, in press). The sections of Los Alamos Canyon examined by Graf were located downstream from plutonium disposal areas in Acid and DP canyons. The area of Los Alamos Canyon investigated by Graf is incised through the Puye Formation, basalt flows of the Cerros del Rio volcanic field, and underlying Santa Fe Group (Tesuque Formation) sediments.

DP Canyon

DP Canyon is a tributary to Los Alamos Canyon (Fig. 1), which was mapped in detail by Reneau (1995) because of previously documented transport of low concentrations of plutonium into this canyon from adjacent Technical Area 21 (TA-21) on DP Mesa (Purtymun, 1971, 1974; Purtymun et al., 1990; Reneau, 1995). DP Canyon was also examined to determine cliff retreat rates and the stability of subsurface Material Disposal Areas (MDAs) located within TA-21 (Reneau, 1995). DP Canyon is incised 70 to 100 ft into the Tsherige Member of the Bandelier Tuff and enters Los Alamos Canyon downstream from Technical Areas 2 and 41 (the mapping area described above for Los Alamos Canyon).

Pueblo Canyon

Plutonium-contaminated material had been discharged into Acid Canyon, which is a tributary of Pueblo Canyon (Fig. 1). Contamination of Acid Canyon occurred primarily between 1945 and 1952, during which time a sewer system from LANL buildings discharged liquid waste containing plutonium to the edge of the canyon (Kingsley, 1947; Graf, unpubl. report to LANL, 1995. Upon reaching the canyon floor, the relatively high pH (8.0 or above) of canyon floor sediments caused the plutonium to precipitate onto sedimentary particles in the form of plutonium oxide (Graf, unpubl. report to LANL, 1995). Contaminated soil and rock from the canyon side and valley floor were removed and stored in burial sites during the 1960s. Because Acid Canyon is a very short tributary canyon to Pueblo Canyon, plutonium-contaminated sediments were transported into Pueblo Canyon. Historic sediments and areas of active deposition in Pueblo Canyon were therefore mapped by Graf to identify areas of plutonium storage in sedimentary deposits. Graf's data for plutonium concentrations in sediments are from previously published LANL environmental surveillance reports from a set of sample sites throughout the Pueblo/Los Alamos Canyon system that laboratory personnel have sampled on an annual basis for 15 yrs or more. Although Graf did not describe how measurements of plutonium concentrations from individual sites were obtained, these data are useful for making broad observations regarding plutonium concentrations in sediments in Pueblo and Los Alamos Canyons. We have no independent data substantiating or refuting plutonium concentrations reported by Graf in his 1995 report to LANL.

Pueblo Canyon is located between Los Alamos and Bayo Canyons and borders the Los Alamos townsite on the north side of the downtown area. Pueblo Canyon heads on the Pajarito Plateau approximately 3 mi west of the head of Bayo Canyon (Fig. 1). Because Pueblo Canyon has a drainage basin intermediate in size between the Bayo Canyon and Los Alamos Canyon drainage basins, Pueblo Canyon is incised to a depth greater than Bayo but less than Los Alamos Canyon.

Rendija, Frijoles and Cabra Canyons

Sections of Rendija, Frijoles and Cabra Canyons were mapped as part of a seismic hazards investigation for LANL (Gardner et al., 1990). Numerous radiocarbon dates were obtained from buried charcoal exposed in trench walls and natural exposures in these canyons. These data provide a good framework of age constraints for Quaternary sedimentary units in Pajarito Plateau canyons.

PLEISTOCENE/HOLOCENE STRATIGRAPHY

Los Alamos and Bayo Canyons

Quaternary sediments in Los Alamos (LA) and Bayo Canyons were subdivided into deposits underlying surfaces Q1 through Q4, from oldest to youngest (Table 1). Quaternary deposits include alluvium in channels, terrace deposits along the main drainage and tributary drainages, fan deposits originating from smaller tributary drainages, and colluvium and talus along valley side slopes (Table 1; Fig. 3). Based on soils data (see below), the presence or absence of cultural materials within a particular deposit, and height of surfaces above local base level, Bayo and Los Alamos Canyons have similar stratigraphic records and a sequence of surfaces that can apparently be correlated between canyons.

Sediments underlying Q1 surfaces are composed primarily of fluvial terrace deposits near the valley floor and colluvium underlying valley side slopes. Qc1 colluvium generally grades to partially buried Qt1 terrace surfaces (Figs. 3, 4). Qt1 terrace deposits are typically coarse-grained, weakly imbricated cobbly gravels. Q2 sediments (Qal2) consist of terrace and fan deposits at or near the valley floor (Fig. 3). Qal2 is greater than 2.5 ft thick and typically consists of sandy, massive to weakly imbricated medium to coarse pebble-size gravel, fining upwards at some locations to gravelly sand (Fig. 5). Qal3 sediments consist of terrace deposits along the main drainage and tributary streams, and colluvial deposits at the base of steep valley side slopes. Qal3 sediments are 1 to 3 ft thick and include buried pine needles, quartzite and granite pebbles, tires, metal and concrete fragments, and a variety of other cultural materials which postdate the initial development of Los Alamos townsite and laboratory facilities. Qal3 terrace deposits generally consist of cross-bedded gravelly sand (Fig. 6).

Gravel composition in Qal1, Qal2, and Qal3 deposits consist primarily of pumice, subrounded to rounded Tschicoma dacite, and subangular to subrounded tuff. Rounded quartzite and granite pebbles occur commonly in Qal3 but rarely in Qal2 and are absent in Qal1. Qa4 deposits in the main channel and in tributary drainages contain a relatively greater

TABLE 1. Summary of Los Alamos Canyon and Bayo Canyon Holocene stratigraphy.

UNIT	GEOMORPHIC SURFACES/ TYPE OF DEPOSIT	SURFACE HEIGHT*	AGE	BASIS FOR AGE ESTIMATE
Q4	Qa4 - Active channel (including main drainage and active point bar deposits), active alluvial fan and tributary drainage deposits. Qf4 - Active fan and side slope deposits	0	Modern	Evidence for active transport (flowing water in channel, pine needle mounds, fresh sedimentation or incision, etc.), deposits include numerous rounded quartzite and granite pebbles.
Q3	Qt3 - Historic terrace deposits and vegetated point bar deposits Qf3 - Historic fan deposits Qc3 - Historic colluvial deposition at the base of steep side slopes	1 to 3 feet[a] 0.5 to 2 feet[b]	Less than 50 years	Presence of rounded quartzite and granite pebbles in Qal3 deposits, presence of recent flood debris, burial of tires, concrete, culverts, and other historic artifacts; lack of soil development. Buried metal fragments from munitions testing.[b]
Q2	Qt2 - Young terrace deposits Qf2 - Probable Late Holocene fan deposits Qb2 - Boulder bar deposits on Q2 surfaces	2 to 6 feet[a] 3 to 6 feet[b]	Historic to 10^2's of years[a] 10^2's to 10^3's of years[b]	Few rounded quartzite pebbles present in isolated locations in Qal2 deposits.[a] Preservation of bar and swale topography, presence of large trees on some surfaces.[ab] Lack of soil development.[a] Incipient soil development.[b]
Q1	Qt1 - Older terrace deposits Qf1 - Older Holocene fan deposits Qc1 - Older alluvial terrace deposits overlain by colluvium grading into valley side slope colluvial deposits	6 to 14 feet[a] 5 to 9 feet[b]	Mid Holocene (?)	Incipient soil development; stratigraphic position relative to Qal2; deposits lack historic artifacts or buried soils.

Notes:
* Terrace or fan height above local base level
[a] Los Alamos Canyon
[b] Bayo Canyon

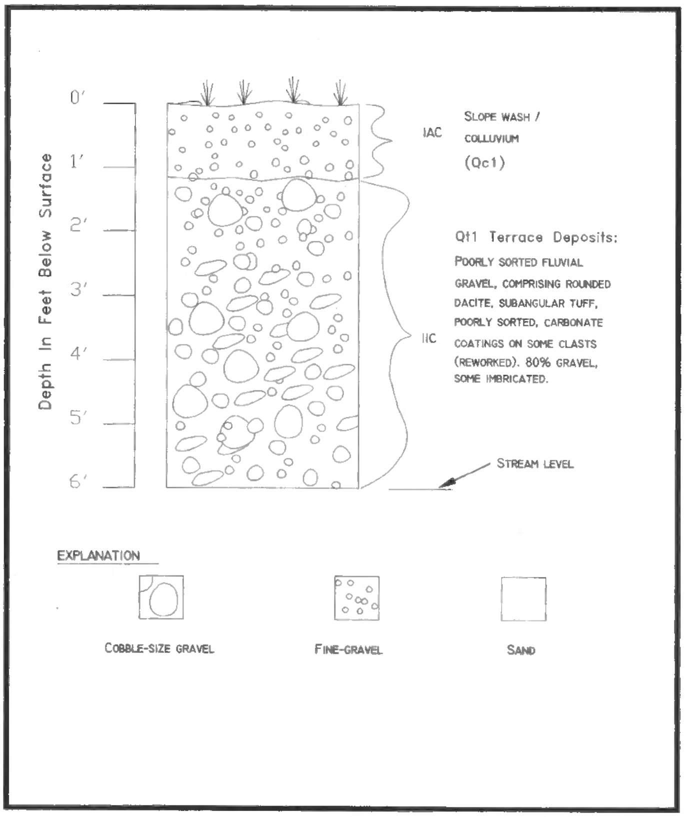

FIGURE 4. Soil/stratigraphic description from stream cut into Qt1 exposing Qal1 sediments in Los Alamos Canyon

proportion of rounded quartzite and granite pebbles reworked from the roadbed and firing pad materials or from the townsite above Los Alamos canyon.

DP Canyon

The Quaternary sedimentary record preserved in DP Canyon includes deposits of Pleistocene age through historic age (Reneau, 1995). According to Reneau, DP Canyon incision was likely caused by headward

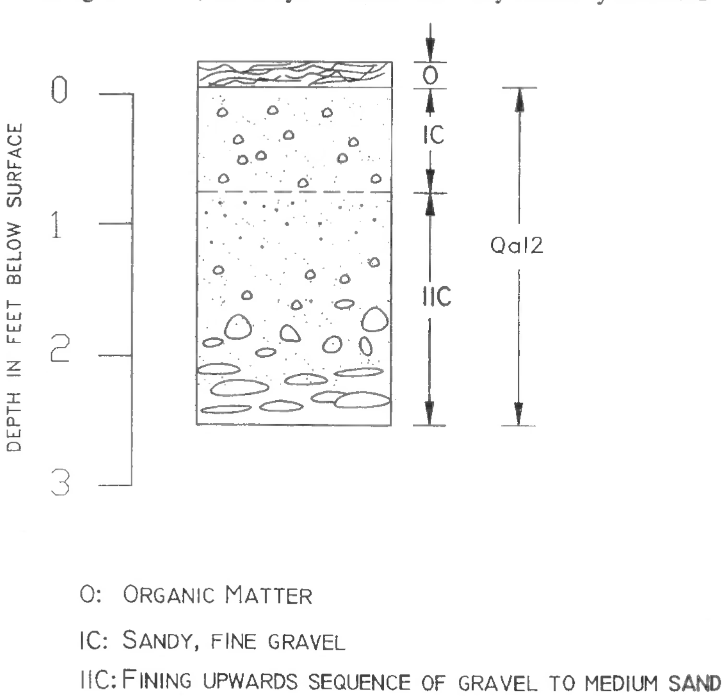

FIGURE 5. Stratigraphic and soil horizons of Qal2 in Los Alamos Canyon.

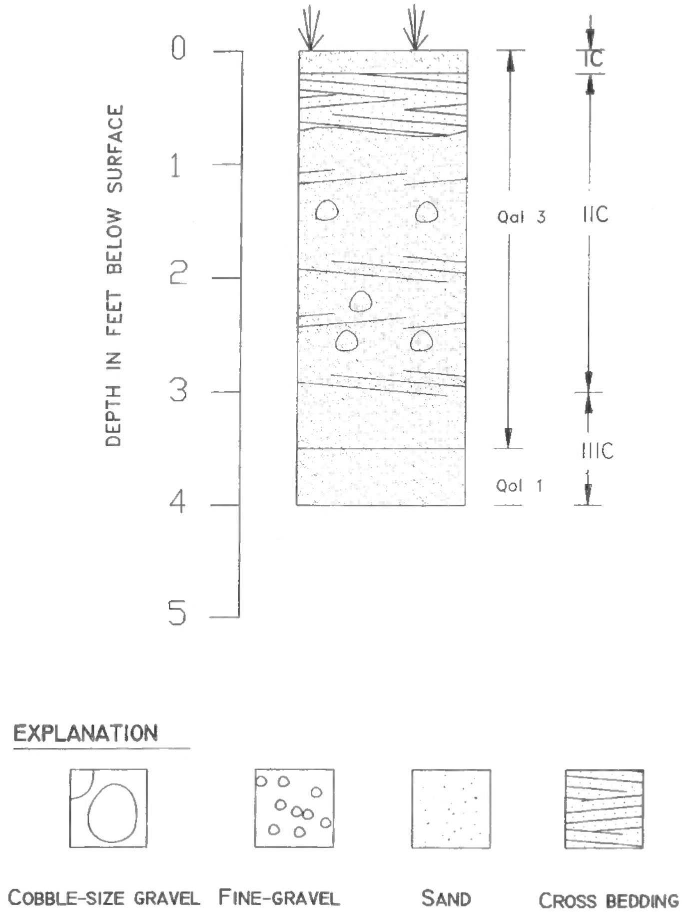

FIGURE 6. Stratigraphic and soil horizons of Qal3 in Bayo Canyon.

knickpoint migration from the Rio Grande some time after 1.2 Ma and prior to 37 ka, at which time the DP drainage system headed in the Sierra de los Valles. Although very little net incision has occurred in upper DP Canyon since the time of major drainage consolidation, multiple episodes of incision and aggradation have occurred from late Pleistocene through historic time. Late Pleistocene (approximately 37 ka) sediments underlie terrace remnants located approximately 20 ft above the modern channel. Holocene slopewash deposits were apparently deposited during a period of channel aggradation that extended from before 5.4 ka to after 2.0 ka. The DP Canyon Holocene slopewash deposits are likely intermediate in age between LA/Bayo Canyon Qal1 and Qal2 deposits.

Extensive deposits of alluvium of historic age that range from 3 to 7 ft in thickness are exposed in terrace deposits along the channel in upper DP Canyon (Reneau, 1995). As documented in Bayo and Los Alamos Canyons, the modern stream channel has incised into and has reworked historic sediments. The extensive sedimentation and subsequent incision in upper DP Canyon that occurred during historic time was likely caused by widespread building construction and paving over large areas of the drainage basin which began in the 1940s. This likely resulted in an initial increase in sediment supply during construction, and subsequent increase in runoff from paved-over areas of the drainage basin.

Frijoles, Rendija and Cabra Canyons

Radiocarbon dates from Frijoles and Rendija canyons document the presence of a mid- Holocene fill terrace with an age of approximately 6.2 ka (Reneau et al., 1993). This terrace represents the culmination of Holocene aggradation in both canyons and may correspond to the Q1 surfaces in Bayo and Los Alamos Canyons. Three lower strath terraces in Frijoles Canyon (radiocarbon ages of 4.6 ka, undated, and 1.6 ka) record temporary pauses in channel incision during the late Holocene. A single lower late Holocene terrace is documented in Rendija Canyon. Cabra Canyon has been aggrading since the mid-Holocene, but the oldest sediments exposed in a 13-ft deep trench yielded an age of 5.7 ka. Three overlying paleochannel-fill units have radiocarbon ages indicating the fill units may correlate with the strath terrace deposits in Frijoles canyon. In all three canyons, the modern flood plains are aggrading (Reneau et al., 1993).

Pueblo Canyon

The focus of Graf's Pueblo Canyon mapping was to identify areas of historic sediment deposition and areas of active sediment transport. A total of 108 areas of historic sediment deposition were identified within the Los Alamos and Pueblo Canyon system (Graf, unpubl. report to LANL, 1995). Graf determined the thickness of historic deposits by driving in a section of iron rebar until reaching rebar refusal. Using this method, he determined that historic deposits range in thickness from 1 to 10 ft. These deposits likely correlate to Los Alamos and Bayo Canyon Qal3 and Qal4 deposits.

SOILS

Soils developed in Qal1 through Qal4 in LA and Bayo Canyons exhibit little or no pedogenic alteration with a maximum profile thickness of 1.1 ft (Table 2). Qal3 and Qal4 may, however, be distinguished from Qal1 based on soil development. Qal3 and Qal4 sediments exhibited no pedogenic alteration; neither carbonate accumulation, soil structure development, nor soil horizonation were observed (Table 2; Fig. 6). By comparison, soils developed in Qal1 have a slightly darkened surface horizon (10YR4/2 dry color), which was designated as an AC horizon because soil structure and other soil characteristics are absent or so poorly developed that it is transitional between an A and a C horizon (Table 2; Fig. 4). The AC horizon is 0.6 to 1.2 ft thick and has weak subangular blocky or granular structure. Most Qal2 soils exhibited no pedogenic alteration and could not be distinguished from Qal3 soils; however, other Qal2 profiles exhibited an AC horizon similar to that observed in Qal1 deposits. Qal2 deposits therefore cannot be distinguished from other deposits in these canyons based on soil development. All soils described in Los Alamos and Bayo Canyons were non-calcic, with the exception of discontinuous coatings on some reworked clasts in Qal1 soils (Table 2). In some locations Qal1 and Qal2 soils exhibit O horizons 0.1 to 0.3 ft thick (Fig. 5). The O horizons observed in Bayo and LA Canyon soils consist primarily of pine needles, partially decayed wood and bark fragments. The lack of soil development observed in Bayo and LA Canyon deposits is consistent with the relatively young ages (mid-Holocene to historic/modern) estimated for these deposits.

CONTAMINANT TRANSPORT

Bayo Canyon

Shrapnel was distributed throughout Bayo Canyon during munitions testing conducted between 1944 and 1963, and in some cases was buried during decommissioning of the facilities within TA-10. While much of this material remains in place, some of the shrapnel has been remobilized and is buried up to 3 ft below the surface in Qal3 deposits (Fig. 7) or is present in active channel, colluvium, and point bar deposits (Qal4). Most metal fragments observed during mapping exhibited radiation levels equal to background levels, but a small percentage of discs and metal fragments exhibited 2 to 4 times background radiation levels. Preliminary mapping conducted southeast and downstream of TA-10 in Bayo Canyon indicates that Q1 through Q4 surfaces and underlying deposits can be traced down canyon from TA-10. The presence of Qal3 and Qal4 deposits in the area down canyon from TA-10 demonstrates that the potential exists for downstream transport of shrapnel from TA-10. The presence of Q3 terrace and fan surfaces throughout Bayo Canyon indicates that there is significant historic sediment storage, and possible contaminant storage, within Bayo Canyon. LANL initiated and carried out an extensive cleanup operation in 1993 and 1994 following identification of the presence of the metal fragments and lead discs in Bayo Canyon.

Los Alamos Canyon

In Los Alamos Canyon, Qal3 deposits partially bury trees and contain quartzite and granite pebbles, tires, concrete fragments, and a variety of other cultural materials buried below Q3 surfaces. These materials date from the early 1940s to the present, when TA-2 and TA-41 have been in use. Although no contaminated materials were identified during mapping of this segment of Los Alamos Canyon, the presence of cultural materials within Qal3, Qal4, and some Qal2 deposits demonstrates transport of cultural materials, and indicates that any potential contaminants released into Los Alamos Canyon would be found within these sedimentary units. In both Bayo and Los Alamos Canyons, Qal3 and Qal4 are appropriate sampling targets for potential contaminants associated with LANL activities. Radiation levels measured throughout the mapping area were within the range of background levels.

Pueblo Canyon

The majority of plutonium released into Acid Canyon is stored in historic sediments within lower Pueblo Canyon (Fig. 8; Graf, unpubl. report to LANL, 1995). Graf estimated that the Pueblo and Los Alamos

TABLE 2. Summary of soil characteristics for Los Alamos and Bayo Canyon deposits. Field methodology for soil descriptions from Soil Survey Staff (1975) and Birkeland (1984). See Table 1 for age estimates of deposits.

UNIT	PROFILE#	AC HORIZON THICKNESS	CARBONATE	CLAY FILMS	COLOR/MAXIMUM DARKENING (DRY)	STRUCTURE
Q4	---	---	---	---	---	---
Q3	IC IIC	0	none observed	none	10YR5/3	massive to weak subangular blocky
Q2	AC C or IC IIC	0 to 1.1 feet	none observed	none	10YR4/2	massive to weak subangular blocky
Q1	AC C	0.6 to 1.2 feet	none observed in matrix; some carbonate coatings on clasts (likely reworked)	none	10YR4/2	weak granular to weak medium subangular blocky

O horizon sometimes present in Qal1 and Qal2 deposits.

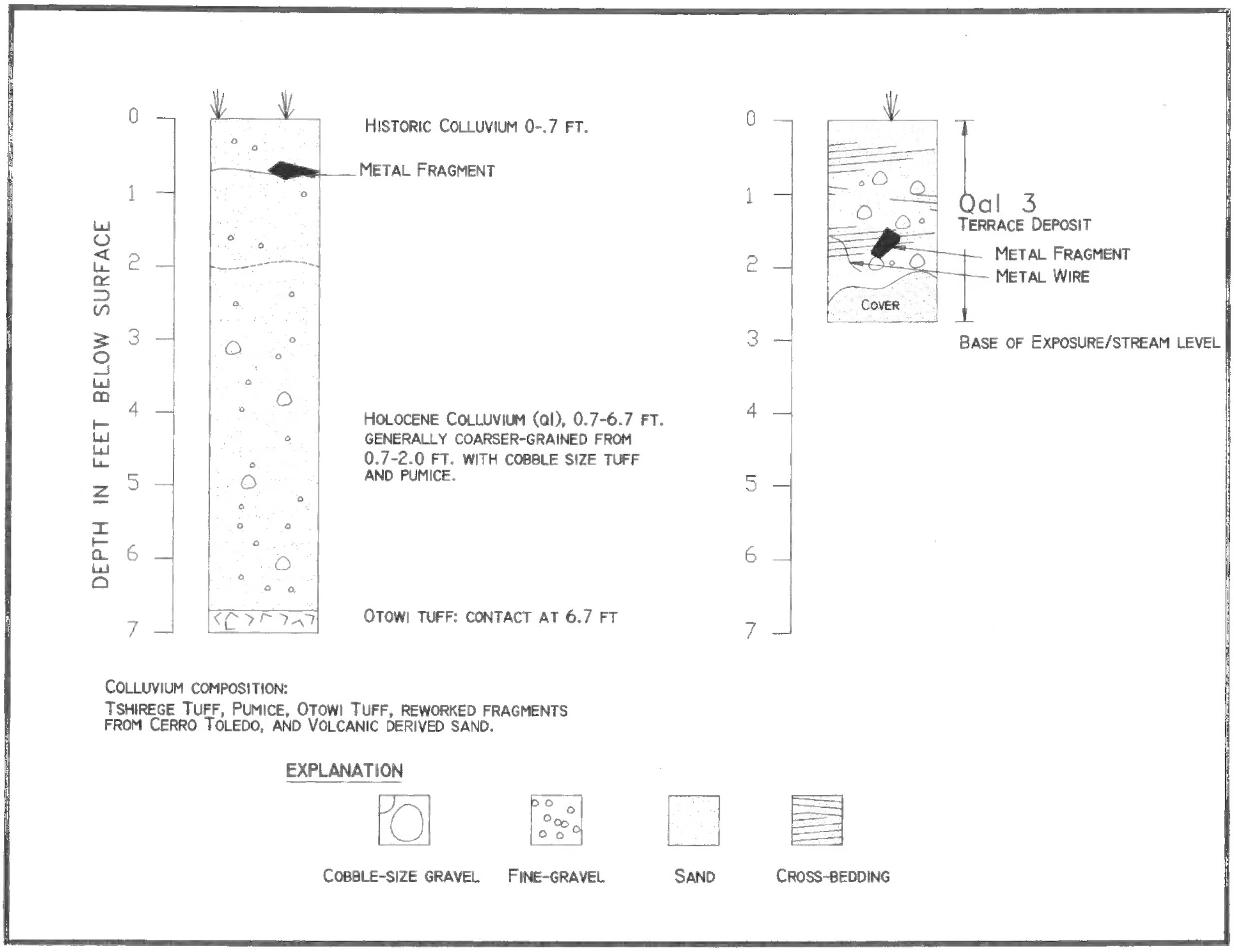

FIGURE 7. Sketch showing metal fragments (shrapnel) buried by Qal3 colluvium (left/top) and Qal3 terrace deposits (right/bottom).

Canyon system stores a total of approximately 1,000 mCi plutonium in bed load, channel bars, slack water deposits, and flood plain sediments. Graf identified 108 deposits throughout the canyon system that contain plutonium. When sediments containing plutonium are transported to the Rio Grande, dilution of channel sediments by tributary sediments reduces the concentrations from about 10,000 fCi/g to about 100 fCi/g (Graf, unpubl. report to LANL, 1995). Plutonium concentrations within a particular stream reach increase and decrease over a period of a few years due to episodic incision and aggradation that cycle contaminated sediment from flood plain, point bar, bed load, and slackwater deposits through the system. These data support the theory that during the late Holocene and historic time, sediments are transported through canyon

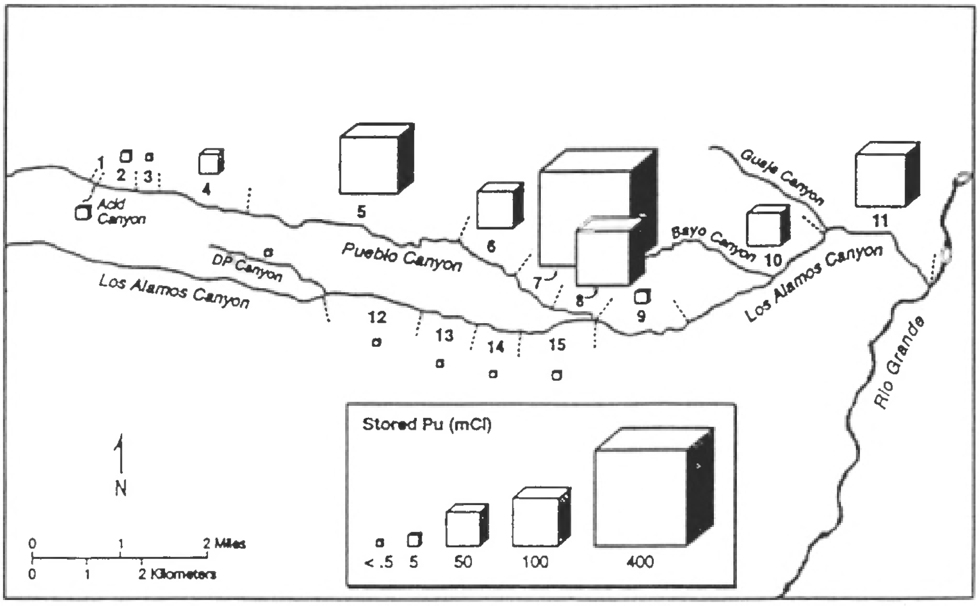

FIGURE 8. Map showing the general distribution of stored plutonium in sediments of the Pueblo Canyon/Los Alamos Canyon system (from Graf, unpubl. report to LANL, 1995; Graf, in press).

systems on the Pajarito Plateau on time scales of a few years to a few hundred years, and that entrained contaminants can be transported through canyon systems on similarly short time scales. These data also show significant contaminant storage in historic sediments within the Pueblo/Los Alamos Canyon system. Taken together, it is likely that sediment and contaminant transport is episodic. Contaminants stored in Qal3 and Qal4 deposits are likely remobilized only during high discharge flood events.

RECENT GEOLOGIC HISTORY AND SEDIMENT TRANSPORT IN PAJARITO PLATEAU CANYONS

The Holocene sedimentary record indicates that canyons incised into the Pajarito Plateau have experienced multiple episodes of incision and aggradation from the mid- Holocene to the present. Apparently these canyons are dynamic geomorphic systems, and sediment is cycled through the canyons on relatively short time scales of tens to hundreds of years. Any contaminants included in canyon sediments therefore have the potential to be transported down stream over periods of tens to hundreds of years.

Net aggradation during the early Holocene has been documented for Los Alamos, Bayo, Ancho, Mortandad and Frijoles canyons (Drakos and Inoué, unpubl. reports to LANL, 1993, 1994; Reneau et al., this volume). Formation of a mid-Holocene fill terrace in Frijoles, Rendija, Los Alamos and Bayo canyons suggests that both the larger canyon systems draining the Sierra de los Valles (e.g., Frijoles and Los Alamos Canyons) and smaller canyons heading on the Pajarito Plateau (e.g., Rendija and Bayo Canyons) are responding synchronously to local or regional climatic changes. Reneau et al. (1993) suggested that episodes of Holocene stream aggradation and floodplain development occur during relatively dry climatic periods, followed by channel incision during wetter periods.

The late Holocene sedimentary record indicates that multiple periods of erosion and deposition have occurred in many of the canyon systems on the Pajarito Plateau (e.g., Cabra, Bayo and Los Alamos Canyons) since the mid-Holocene whereas Frijoles and Rendija Canyons record a history of progressive incision during the same time period. In contrast to a history of erosion and deposition or of progressive incision, Ancho and Mortandad Canyons have been aggrading during the mid- and late Holocene, although the buried stratigraphic sequence suggests multiple cut-and-fill sequences comprising the sedimentary package (Reneau et al., this volume). These data indicate that factors such as drainage basin size, lithology, or very localized climatic factors are more important than regional climatic control on channel incision or aggradation for streams on the Pajarito Plateau during the late Holocene. The presence of two terraces deposited between the mid-Holocene and historic time in Bayo and Los Alamos Canyons (Q1 and Q2) demonstrates some longer term (hundreds to thousands of years) sediment storage in these canyons.

In several of the canyons investigated, multiple cycles of erosion and deposition have occurred during the past 50 yrs. The presence of Qt2 and Qt3 surfaces and underlying deposits along the main drainages in Los Alamos and Bayo Canyons, indicates that at least two cycles of incision and aggradation followed by a third period of incision have occurred during the past several hundred years, with the deposition of 0.5 to 3 ft of sediment since development started in these canyons. In areas where Qal2 is a historic deposit (Los Alamos Canyon) or where a lower fill terrace is inset into Qal3 (Bayo Canyon), at least three periods of incision and aggradation have occurred during the past 50 yrs. Similarly, in DP Canyon up to 6 to 9 ft of sediment were deposited and then incised (Reneau, 1995). Graf measured thicknesses of historic deposits in Pueblo and Los Alamos Canyons ranging from 1 to 10 ft (Graf, unpubl. report to LANL, 1995). The apparent abundance of historic deposition and multiple episodes of incision and aggradation in canyons during the past 50 yrs is likely related to land use changes associated with development of the Los Alamos townsite and adjacent laboratory facilities.

CONCLUSIONS

The preserved Holocene geologic record in canyons draining the Sierra de los Valles and Pajarito Plateau records multiple cut-and-fill events or progressive incision during the mid to late Holocene following early Holocene aggradation. Several canyons exhibit multiple cut-and-fill events during historic time. This implies that sediments are cycled through canyon systems on time scales of tens to hundreds of years, and that contaminants entrained in sediments may be transported relatively rapidly through canyons on the Pajarito Plateau. The preservation of two terraces of mid- to late Holocene age in Bayo and Los Alamos Canyons demonstrates sediment storage in the range of hundreds to thousands of years in canyons incised into the Pajarito Plateau. Sediment storage, episodic sediment transport and the cycling of sediment through canyon systems on time scales of tens of years or less is supported by the presence of surfaces (Qal3 and Qal4) and underlying deposits of historic age that can be traced throughout Bayo and Los Alamos Canyons. The presence of shrapnel in Bayo Canyon Qal3 and Qal4 deposits and the transport of plutonium from Acid Canyon through the Pueblo Canyon/ Los Alamos Canyon system indicates that contaminants are cycled through canyon systems on similar time scales. Unless contained or removed, contaminants released into other canyons on the Pajarito Plateau will also likely experience episodic downstream transport, with the potential of reaching the Rio Grande.

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