GEOMORPHIC STUDIES AT DP MESA AND VICINITY

by

S. L. Reneau

A geomorphic characterization of TA-21 was undertaken primarily to provide site-specific data on surficial processes that pertain to the potential erosion and deposition of contaminants. An additional objective was to define the geomorphic setting of the DP Spring, a perennial spring that contains contaminants probably originating from TA-21. These studies support RCRA RFI work at OU 1106 for the ER Program.

Sediment deposition areas downslope of MDAs at TA-21 include the narrow grassy floor of BV Canyon south of MDAs B and V and a broader grassy flat within DP Canyon north of MDAs A, T, and U. The floor of DP Canyon includes alluvium and slopewash of widely varying age, and these sediments record alternating cycles of sediment deposition and erosion extending back at least 27,000 years. The most recent cycle occurred in historic time, and up to 6 ft of sediment was deposited and subsequently partially eroded since major development began in the drainage basin. These historic sediments constitute a significant potential storage area for contaminants within DP Canyon, including plutonium, which has been documented previously in DP Canyon sediments.

Cliff retreat processes and rates apparently vary dramatically between cliffs bordering Los Alamos Canyon and those bordering the shallow tributary canyons at TA-21 (including DP Canyon). Partially detached landslide blocks along Los Alamos Canyon demonstrate that individual mass-wasting events can extend 75 ft or more from the mesa edge, and the unweathered appearance of many cliff faces also suggests relatively frequent failures. In contrast, retreat of cliffs bordering the tributary canyons probably involves failure of smaller fracture-bounded blocks; extensive erosional pitting of these cliffs suggests long periods between failures. The occurrence and composition of old alluvial deposits in one shallow tributary canyon at DP Mesa further suggests that these tributaries were largely eroded by streams originating in the Sierra de los Valles before incision of Los Alamos Canyon and that minimal cliff retreat has occurred in these canyons since then. The MDAs at TA-21 are all located along the shallow tributary canyons, and exposure of most of the MDAs through cliff retreat is improbable over periods exceeding 10,000 years. The exception, MDA V, is within 20 to 25 ft of the mesa edge, which is composed of artificial fill that buries a shallow embayment. Failure of this fill and the buried rock slope should be considered possible; such a failure could potentially expose Absorption Bed 3.

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DP Spring emerges from an extensive old valley fill in lower DP Canyon (dated at about 37,000 years old) that is perched ~20 ft above the modern valley bottom. This valley fill is confined to areas eroded into nonwelded units of the Bandelier Tuff and probably extends less than 300 ft upcanyon. Because the spring is perennial and surface runoff within DP Canyon is intermittent, the most likely flow path for the springwater may include fractures in units 2 and 1v, with the groundwater emerging from fractures into the upper part of the valley fill and then flowing through the fill to DP Spring.

INTRODUCTION

A geomorphic characterization of TA-21 was undertaken primarily to provide site-specific data on surficial processes that pertain to the potential erosion and deposition of contaminants. An additional objective was to define the geomorphic setting of DP Spring, a perennial spring containing contaminants that probably originated from TA-21.

The developed area at TA-21 is located on DP Mesa; it is bordered by Los Alamos Canyon to the south (350 to 400 ft deep) and DP Canyon to the north (generally 70 to 100 ft deep). Potential sources of contaminants include deep releases (such as from seepage pits and absorption beds), near-surface liquid releases from septic systems, subsurface solid-waste disposal areas, and surface contamination from stack-release fallout and spills. The two primary surficial processes of concern are sediment transport by surface runoff from the site into the adjacent canyons and cliff retreat that could potentially expose MDAs located near the mesa edge. Discharge of waters containing plutonium and other contaminants into DP Canyon occurred in the past, and transport of low concentrations of plutonium in this canyon has been documented previously (Purtymun, 1971, 1974; Purtymun *et al.*, 1990). Because of this known contamination, the geomorphic characteristics of DP Canyon were examined in particular detail.

METHODS

The geomorphic characterization of TA-21 involved a combination of airphoto analysis, field mapping, field investigations of selected sites, and analyses of topographic maps. The entire area was examined on 1:7200-scale, 1991 color airphotos, and features observed on these photos were either plotted directly onto 1:1200-scale Facility for Information Management Analysis and Display (FIMAD) 2-ft contour maps or first plotted on 1:1200-scale orthophotos and then transferred to the 1:1200-scale maps. Much of the area was also examined on the ground—particularly the canyon rims, canyon bottoms, and areas downslope of the MDAs—to field-check features identified on the photos and to examine features not visible on the photos. Geomorphic features examined include drainage channels, recent sediment-storage areas, older sedimentary deposits, cliff faces, partially detached landslide blocks, and areas of artificial fill. Geomorphic maps of parts of TA-21, at a scale of 1:1200, are presented on Plates 5, 6, and 7; additional surficial units are shown on Plate 1 at a scale of 1:4200.

Natural streambank exposures of valley-bottom sediments were examined in DP Canyon and Los Alamos Canyon, and radiocarbon dates were obtained for charcoal samples collected from the sediments in DP Canyon to constrain their age. After drainage channels downslope

of the MDAs were examined and located on the topographic maps, sites for topographically based sediment sampling were identified.

To provide additional data on the process of cliff retreat, two cliff areas immediately south of MDA B were chosen for more detailed investigation. Fracture-bounded blocks were measured and samples of cliff faces were collected for analyses of cosmogenically produced isotopes (see, for example, Poths and Goff, 1990; Lal, 1991; Nishiizumi *et al.*, 1991) to provide constraints on cliff retreat rates.

The analysis of topographic maps was undertaken primarily to provide additional data on canyon widths and, by inference, variations in cliff retreat. Measurements of the distance from the center-line of the modern valley floor to the north and south canyon rims were made using 1:1200-scale FIMAD 2-ft contour maps. These measurements were at frequent enough intervals to include the irregularities of canyon rims, particularly the promontories and the center of embayments.

TA-21 CANYONS

Los Alamos Canyon

Los Alamos Canyon forms the southern boundary of TA-21. This canyon was examined in only a preliminary manner during this study because it will be studied in more detail as part of the Canyons RFI work. DP Canyon, a major tributary to Los Alamos Canyon on the northern side of TA-21, was studied in greater detail. The main sources of contaminants in Los Alamos Canyon adjacent to TA-21 are probably at TA-2 and TA-41, which are located on the canyon bottom upstream of TA-21.

Los Alamos Canyon is one of the deepest canyons within the boundaries of LANL, and is >400 ft deep adjacent to TA-21. The primary landforms in the canyon are (1) steep cliffs of Bandelier Tuff (see mapping units described in Goff, Sec. II, this report), (2) extensive slopes mantled with colluvium derived from the tuff, and (3) a wide, fairly flat valley floor. The cliffs are developed in units 3, 2, and 1v of the Tshirege Member of the Bandelier Tuff; unit 2 exhibits the steepest, most continuous cliffs. Colluvium mantles nonwelded tuff in the lower part of the Tshirege Member (unit 1g), the Otowi Member of the Bandelier Tuff, and the intervening Cerro Toledo interval (see Goff, Sec. II, this report and Broxton *et al.*, Sec. IV, this report for description of bedrock units). The age of the colluvium is unknown, but probably ranges in age from historic (modern rockfall) to at least tens of thousands of years. The latter inference is drawn from observations that the colluvium locally buries older alluvial terrace deposits of Los Alamos Canyon, whose age probably exceeds 10,000 years, without the presence of an intervening buried soil to provide evidence for a significant gap in time. One buried alluvial deposit below TA-21 occurs ~23 ft above the stream channel (stream elevation ~6654 ft); its elevation above the channel is similar to that of a deposit in lower DP Canyon dated at ~37,000 years old. The sediments underlying the wide valley floor are inferred to be Holocene in age, deposited within the last 10,000 years. This inference is based on their similarity to sediments <6500 years old studied in other valley bottoms on the Pajarito Plateau (Gardner *et al.*, 1990; Reneau *et al.*, 1993).

BV Canyon

An unnamed, shallow, hanging valley on the south margin of TA-21 is incised within Tshirege unit 3 and the underlying nonwelded unit. This valley is herein informally called "BV Canyon" because it is located below MDAs B and V. The floor of the canyon is perched above the cliff-forming welded tuff of Tshirege unit 2. Relatively little sediment is stored in this canyon, and the sediment is largely confined to a narrow (6- to 33-ft-wide) grassy strip along the canyon bottom.The channel itself is discontinuous, and the flow often spreads out over the grassy valley

bottom. These areas of unchannelized flow are likely spots for modern sediment deposition. At the lip of the hanging valley, south of MDA V, the flow drops over a waterfall into Los Alamos Canyon and generally infiltrates an extensive bouldery colluvial deposit without reaching the main channel.

DP Canyon

The geomorphic characteristics of DP Canyon, on the north margin of TA-21, are strongly influenced by lithologic variations within the Bandelier Tuff (Fig. 1), and the canyon can be divided into four segments that reflect these bedrock variations.

The uppermost segment of DP Canyon, cut into the resistant part of Tshirege unit 3, is relatively steep and narrow, and the canyon bottom is generally choked with boulders derived from the adjacent canyon walls.

The next segment of DP Canyon, cut through the weaker, lower part of Tshirege unit 3 and the underlying Tshirege nonwelded unit, is relatively flat and wide. It contains extensive deposits of sediment derived from both the upper part of DP Canyon and the adjacent canyon walls. The low gradient of this segment is related to a base-level control immediately downstream, where the resistant Tshirege unit 2 is located. Historic outfalls from TA-21 discharged into this part of the canyon, and runoff from three of the five MDAs at TA-21 also flows into this segment.

The third segment of DP Canyon is incised into the resistant Tshirege unit 2 to form a steeper, narrow, rock-bound inner canyon. Little sediment is stored in this segment; instead, sediment is generally carried by runoff downstream past this segment.

The fourth segment, the steepest part of DP Canyon, is cut into Tshirege units 1v and 1g, the Cerro Toledo deposits, and the Otowi Member. The canyon bottom is generally choked with boulders and includes numerous small sediment-deposition areas. DP Spring, a perennial spring, emerges in the upper part of this segment and runoff is generally present for some distance downstream. This runoff does not usually reach the main Los Alamos Canyon stream channel; instead, it infiltrates the alluvium of lower DP Canyon.

Deposits of sediment within DP Canyon provide valuable data on both the episodic nature of sediment transport within the canyon and the canyon's development since deposition of the Tshirege Member of the Bandelier Tuff at 1.22 Ma (million years ago; age from Izett and Obradovich, 1994). The following report sections discuss the older alluvium of DP Canyon, the valley fill of lower DP Canyon, the late Pleistocene and Holocene sediments of upper DP Canyon, and historic alluvium in upper DP Canyon.

Older Alluvium of DP Canyon

Deposits of stream-rounded cobbles and boulders occur on the south side of lower D P Canyon, both on a bench developed within the Tshirege nonwelded unit (above the resistant cliff-forming unit 2) and within a short tributary to DP Canyon off the eastern end of DP Mesa (Plate 3). At the western exposure of the older alluvium, the deposits include consolidated, stratified sand and gravels that were deposited against a vertical, stream-polished wall of Tshirege unit 3. Clasts in the older alluvium are as large as 3 ft in diameter and include a mixture of ~20% Tschicoma Formation dacite derived from the Sierra de los Valles and 80% welded Bandelier Tuff eroded from a stratigraphically higher cooling unit not present at TA-21. Similar gravels are now being deposited only in the major canyons that originate in the Sierra de los Valles (such as Los Alamos Canyon), although the high percentage of welded Bandelier Tuff is unusual.

The nature and location of these older alluvial deposits indicate that incision of the main canyons on this part of the Pajarito Plateau did not occur immediately after deposition of

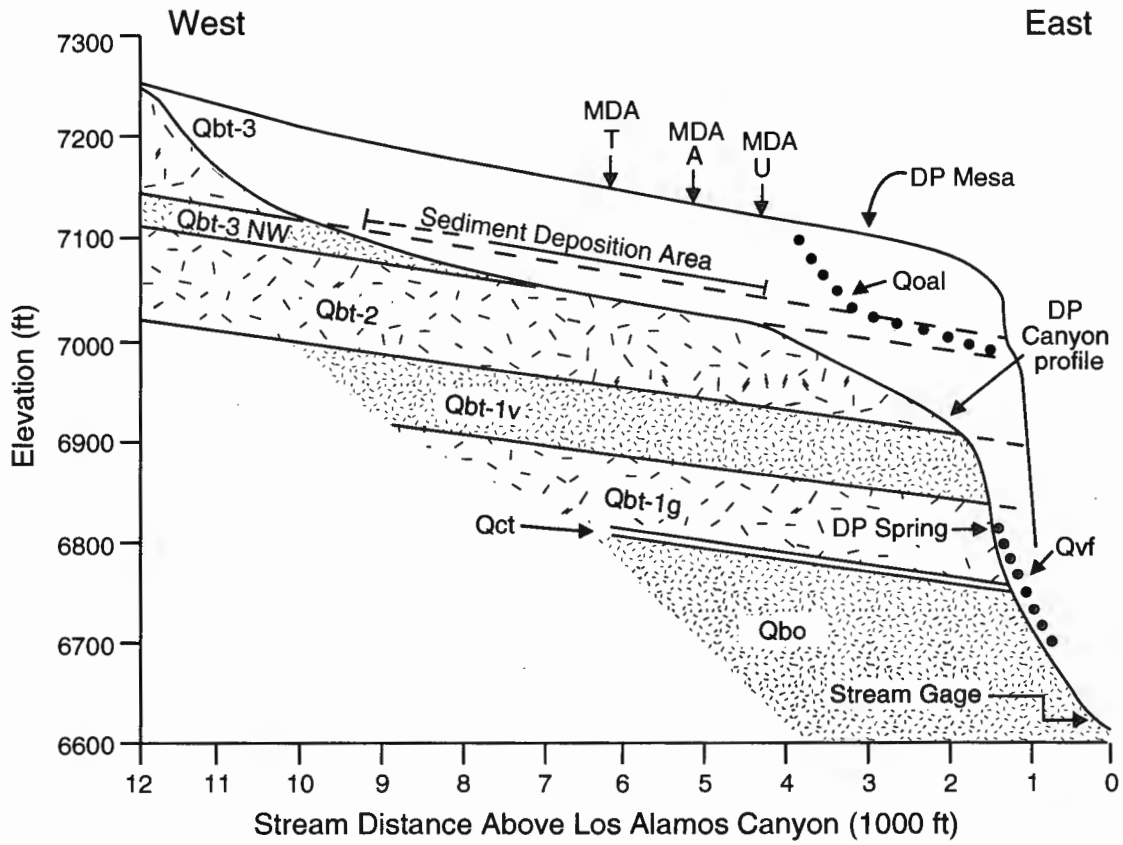

Fig. 1. Longitudinal profile of DP Canyon, showing relation of stream profile to lithologic variations and location of post-Bandelier Tuff sediment deposits. See Plates 1 and 5 for explanation of geologic unit symbols.

the Tshirege Member of the Bandelier Tuff at 1.22 Ma. Following Tshirege deposition, the streams originating in the Sierra de los Valles may have had a braided pattern as they traversed parts of the Plateau (such as DP Mesa) that now only receive local runoff (Fig. 2). Eventual incision of the main canyons was probably driven by headward erosion from the Rio Grande. The steep profile of the older alluvium in the DP Canyon tributary (Fig. 1) probably reflects deposition during this period of headward erosion of the canyons and consolidation of the drainages. It is possible that other shallow canyons on this part of the Pajarito Plateau (such as upper DP Canyon and BV Canyon) were similarly occupied by streams draining the Sierra de los Valles (Fig. 2); however, no deposits from such streams were found in this study.

An additional implication of these older alluvial deposits is that very little modification of some small tributary canyons has occurred since the time of major drainage consolidation. The upper part of the DP Canyon tributary is plugged with older alluvium, and no net incision of the head of this canyon or headward erosion has occurred since its deposition—implying incision of this canyon was largely the result of runoff from the Sierra de los Valles. However, local runoff has been sufficient to incise the lower part of this tributary canyon 10 to 20 ft below the gravels. The modern canyon walls are also very close to the older alluvial deposits; the tops of steep Tshirege unit 3 slopes to the south are only 50 to 130 ft from the alluvium (average ~100 ft). If the alluvium was originally deposited

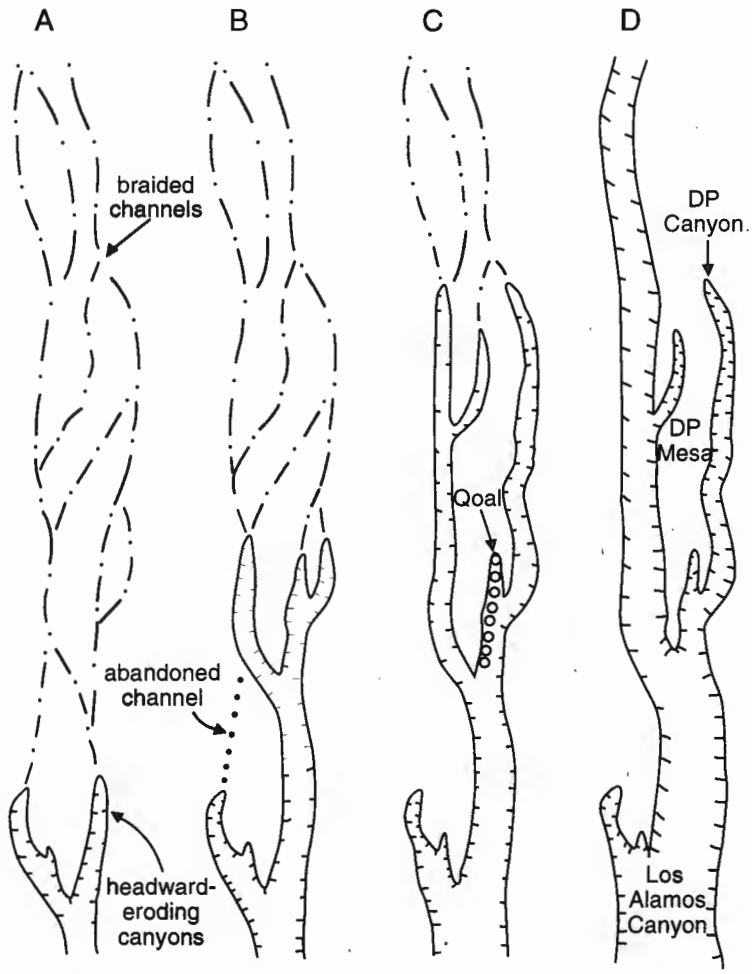

Fig. 2. Hypothetical evolution of Los Alamos Canyon drainage system. (A) Drainage channels are braided and not incised over western Pajarito Plateau. Headward erosion of canyons progresses westward from Rio Grande along braided channels. (B) Some channels are abandoned as headward erosion proceeds. (C) Older alluvium of DP Canyon (Qoal) is left along abandoned channel as incised canyons erode farther west. (D) Modern Los Alamos Canyon has widened significantly through cliff retreat, but the shallow tributary canyons have widened little.

against vertical cliffs of Tshirege unit 3, a maximum of 50 to 130 ft of retreat could have occurred since that time.

The age of the older alluvial deposits is not known, so measurements of maximum wall retreat can not be used to make precise estimates of long-term retreat rates. If this stream course was abandoned close to 1.22 Ma (the age of the Tshirege Member of the Bandelier Tuff), the average maximum retreat rate would have been 0.11 ft/ky (ky = 1000 years), and if the course was abandoned at 0.5 Ma, the average maximum retreat rate would have been 0.26 ft/ky.

Valley Fill of Lower DP Canyon

Remnants of a formerly extensive valley fill occur on both sides of lower DP Canyon (Plate 3 and Fig. 3). The base of the fill is ~20 ft above the modern channel. This valley fill consists of lenses of stratified sand and rounded stream gravels interbedded with and buried by coarse colluvium that contains

angular boulders of Bandelier Tuff from the adjacent canyon walls. DP Spring emerges from a layer of rounded stream gravels resting on a bevelled tuff surface of Tshirege unit 1g (Fig. 4). Downstream, a radiocarbon date of ~37 ka (thousand years before present) was obtained from charcoal contained within a sandy lens in the valley fill (Fig. 3, Table I) and provides an estimated average stream incision rate of 0.56 ft/ky.

The width of the valley fill suggests a period of relative stability for the stream channel, during which the channel was able to cut laterally. Since that time, the channel has incised the former valley floor, and at present the valley floor is less than one-fourth as wide as it was (Fig. 3). Many of the tuff boulders that choke the bottom of lower DP Canyon today may be derived from the older valley fill.

Occurrence of the valley fill is coincident with the presence of easily eroded, nonwelded units of the Bandelier Tuff and the Cerro Toledo interval (Fig. 1); thus it appears that the stream cuts laterally only where there is nonwelded tuff. Nonwelded units are not exposed in the valley walls upstream of DP Spring, and it is unlikely that the valley fill extends very far upstream past the limit of Tshirege unit 1g exposures. Similarly, the perched groundwater that emerges at DP Spring probably discharges into the fill from the tuff a short distance upstream (within <300 ft).

Late Pleistocene and Holocene Sediments of Upper DP Canyon

Extensive deposits of alluvium and colluvium (including slopewash) occur in the upper part of DP Canyon above the area where the

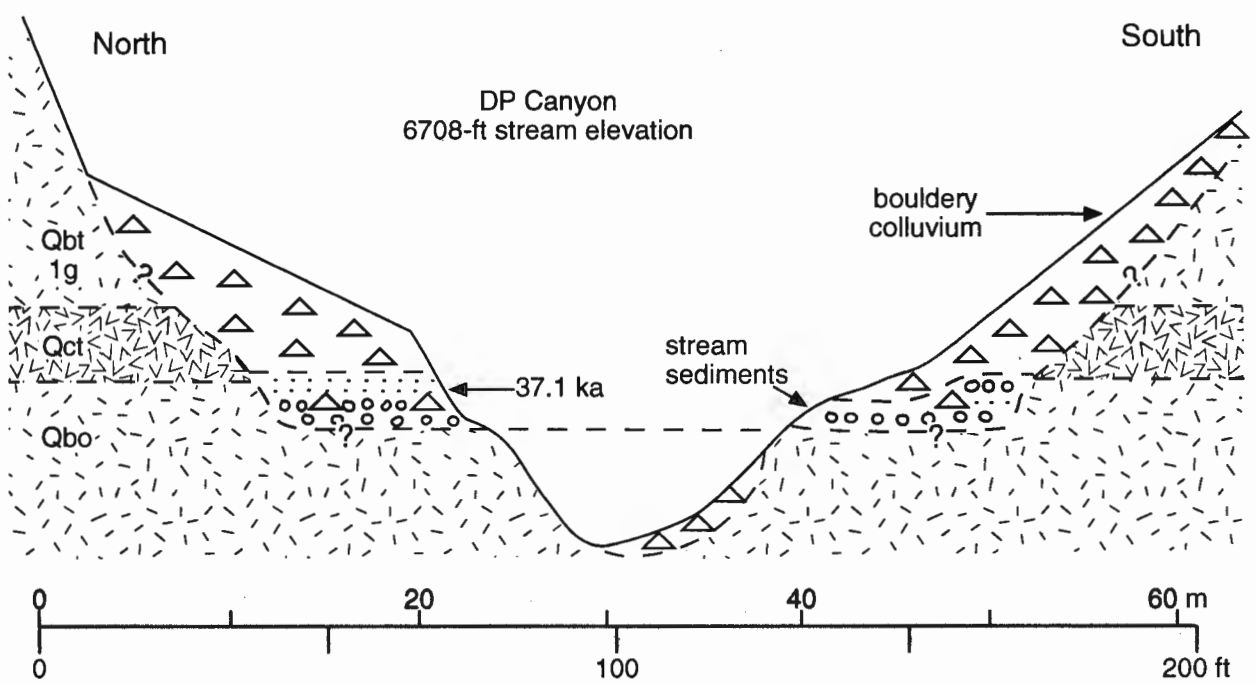

Fig. 3. Schematic cross section of radiocarbon sample site within valley-fill deposits of lower DP Canyon. Radiocarbon age in thousands of years before present (ka); there is no vertical exaggeration. See Plate 1 for explanation of geologic unit symbols.

canyon incises resistant Tshirege unit 2 (see Plate 4). Examination of these deposits along the stream channel indicates that deposits of multiple ages are present and that the canyon bottom has undergone many cycles of aggradation (raising of the stream bed through sediment deposition), subsequent incision, and partial erosion of these sediments. To provide some constraint on age of deposition and on the timing of former periods of aggradation in the canyon, five radiocarbon dates were obtained on charcoal fragments contained within the deposits at three sites. However, this limited number of dates is probably insufficient to fully document the cycles of sediment erosion and deposition of the deposits.

The radiocarbon dates confirm a long history of erosion and deposition cycles in upper DP Canyon. The oldest dated deposit is a stratified, clay-rich alluvium exposed near the modern stream bed; the deposit yielded a radiocarbon age of 26.7 ka (Figs. 5 and 6, Table I). This alluvium is texturally similar to that exposed at many other sites in the canyon. A fine-textured slopewash deposit that overlies the alluvium at this site provided a radiocarbon age of 21.6 ka, which is stratigraphically consistent with the older date. Upstream, a deposit of sandy and gravelly alluvium yielded a date of 16.0 ka (Fig. 6 and Table I). At this site, the stream channel has incised ~1.8 ft into the Tshirege nonwelded unit since deposition of the alluvium at an average rate

TABLE I
RADIOCARBON DATES FROM DP CANYON

Sample Number [a]	^{14}C Date (yr bp) [b]	Calibrated Age [c]	Stream Elevation (ft)	Height Above Channel (m)	Depth Below Surface (m)	Notes
Beta-58056 CAMS-4574	21,630±110	too old for calibration	7046	1.2	1.05	slopewash
Beta-58057 CAMS-4575	26,680±80	too old for calibration	7046	0.2	1.9	old alluvium
Beta-58058 CAMS-4576	15,980±80	18860 cal BP (18512-19259 cal bp) 16910 cal BC (16562-17309 cal bp)	7067	1.5	1.0	old alluvium
Beta-58059 CAMS-4577	5450±70	6280 cal BP (5923-6496 cal bp) 4330 cal BC (3973-4546 cal bc)	7035	0.8	1.4	slopewash; 0.2 m above old alluvium
Beta-58060 CAMS-4578	2010±80	1940 cal BP (1560-2343 cal bp) 10 cal AD (390 cal AD-393 cal bc)	7035	1.35	0.45	slopewash
Beta-58061 CAMS-4579	37,070±630	too old for calibration	6708	8.75	0.55 [d]	terrace; 6.4-m-high strath

[a] Samples prepared at radiocarbon laboratory of Beta Analytic, Inc., Miami, Florida (Beta sample number); analyses run at the Lawrence Livermore National Laboratory accelerator mass spectrometry facility (CAMS sample number).

[b] Calibrated ages obtained using computer program CALIB 3.0 (Stuiver and Reimer, 1993). Ages in parentheses are in the 2σ range using an error multiplier of 2.0.

[c] Analyses are radiocarbon years "before present" (before 1950 AD), uncorrected for atmospheric variations in $^{14}C/^{12}C$ ratios.

[d] Depth below top of alluvium, buried beneath bouldery colluvium.

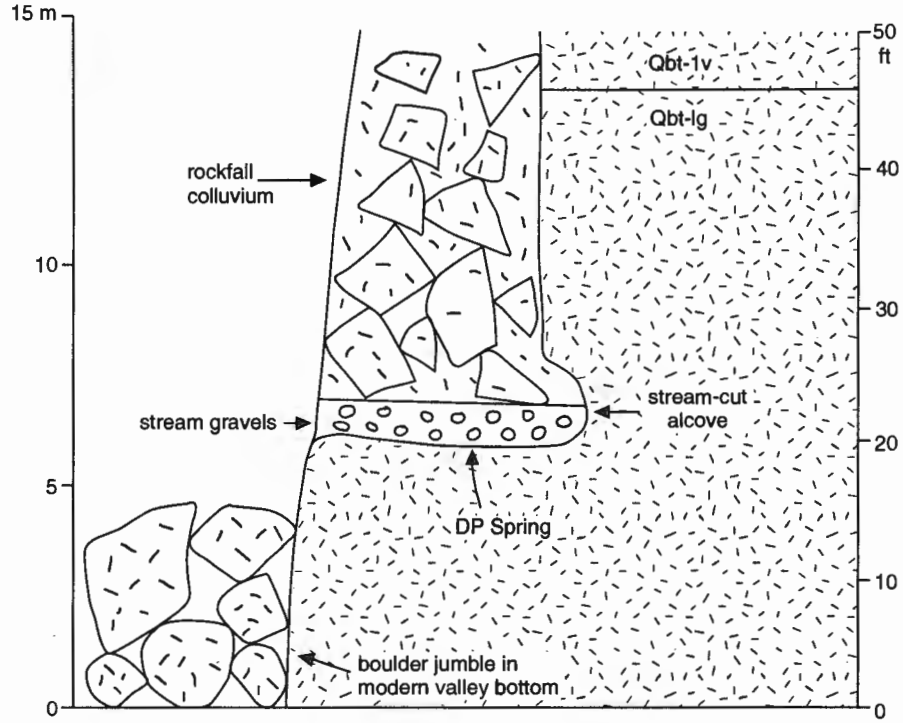

Fig. 4. Sketch of DP Spring looking northwest, showing stream-channel deposits in the valley-fill deposits of lower DP Canyon. See Plate 1 for explanation of geologic unit symbols.

of ~0.10 ft/ky. Downstream, two stratigraphically consistent dates of 2.0 and 5.4 ka were obtained from an extensive slopewash deposit that overlies an older alluvial deposit (Figs. 5 and 6, Table I). This slopewash deposit was graded to a level above the modern floodplain and may have been deposited during a period of channel aggradation that extended from before 5.4 ka to after 2.0 ka.

The long-term cycles of stream aggradation and degradation may be driven partly by climatically induced changes in runoff and/or sediment yield. Streams commonly aggrade their beds during periods of increased sediment supply, (derived from accelerated erosion of the surrounding basin) or during periods of decreased stream flow. Similarly, streams may degrade their beds during periods of increased flooding or when the sediment supply is reduced significantly.

In addition to providing data on the periods of stream aggradation and degradation, the radiocarbon dates confirm that the stream bed in upper DP Canyon has been near its present elevation for at least 26,000 years and possibly considerably longer. In many places, the modern channel rests on tuff bedrock that was exhumed after the overlying deposits were stripped, and in other locations the bedrock surface is buried. Only in the upper reaches, where the channel gradient steepens, has the stream been able to incise significantly into tuff (that is, the 16.0-ka site; Fig. 6), and the calculated incision rate of 0.10 ft/ky is considerably lower than the 0.56 ft/ky-rate estimated in lower DP Canyon.

Historic Alluvium of Upper DP Canyon

Extensive deposits of alluvium that post-date significant historic development in the basin (post-1943 AD) are exposed along the channel

in upper DP Canyon. The historic age of these deposits is shown by the presence of various man-made materials as well as exotic, rounded quartzite gravels that are commonly imported for road construction. The historic deposits are often ~3 ft thick in stream-bank exposures, but deposits up to 7 ft thick were observed. They commonly underlie a well-developed terrace surface that borders the modern channel (Figs. 5, 6, and 7). Since this terrace surface was abandoned, lowering of the channel has led to incision of gullies along several tributary channels (Figs. 5 and 7).

The extensive sedimentation that occurred in upper DP Canyon in historic time and the subsequent incision of the channel through these deposits may have been caused by land-use changes in the basin since widespread development began in the 1940s. Specifically, the historic deposits suggest the erosion of large volumes of material from developed areas adjacent to the canyon; their subsequent incision may have been caused by a reduction in sediment supply and/or an increase in runoff in the basin. At present, ~50% of the upper basin is covered by impermeable surfaces such as roads, parking lots, and buildings, and major increases in runoff associated with such widespread development is well documented in many areas (Dunne and Leopold, 1978).

The presence of the thick historic deposits complicates the identification and quantification of contaminants in DP Canyon. If significant amounts of contaminants were transported from TA-21 into upper DP Canyon during the period of channel aggradation, they may be locally buried under several feet of sediment or eroded from the modern stream banks. Alternatively, contaminants transported into upper DP Canyon before or after the period of channel aggradation may have been largely flushed downstream into lower DP Canyon or Los Alamos Canyon.

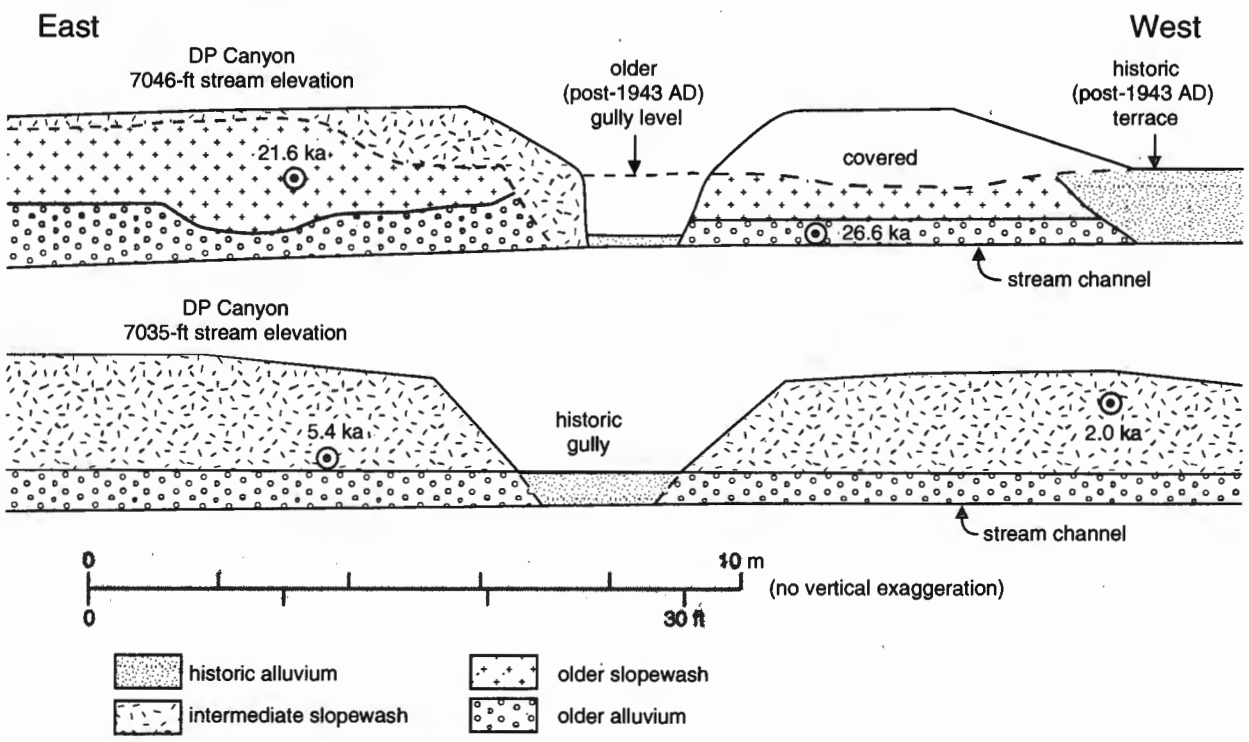

Fig. 5. Sketches of radiocarbon sample sites in upper DP Canyon.

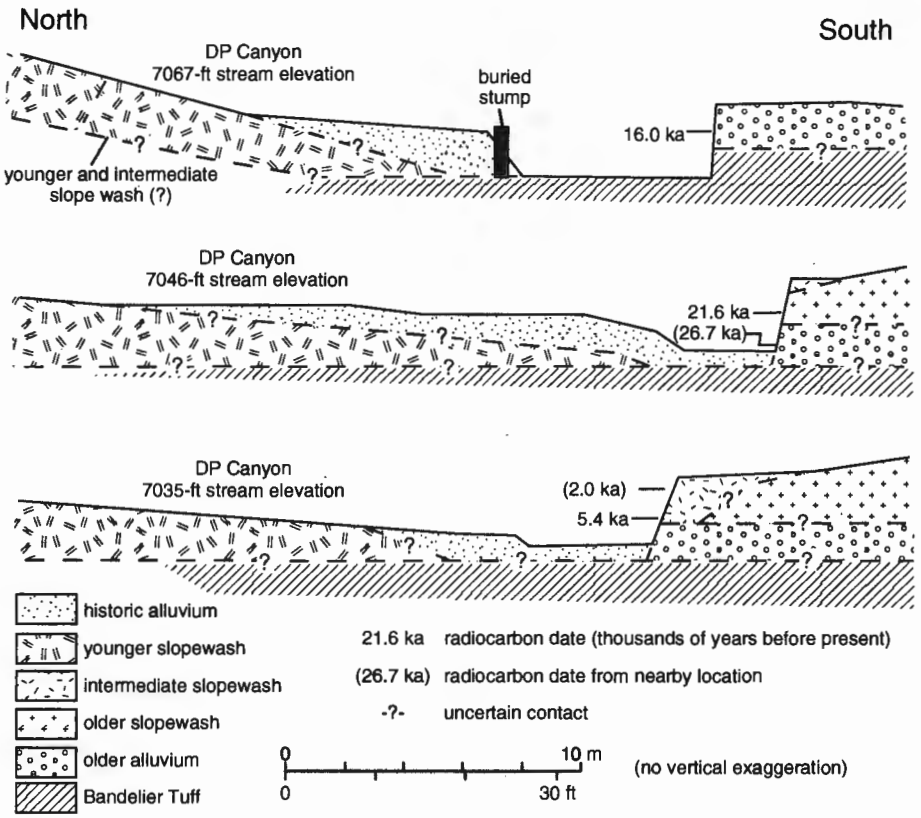

Fig. 6. Simplified cross sections across upper DP Canyon floor show generalized stratigraphy and location of radiocarbon dates.

CLIFF RETREAT

Knowledge of cliff-retreat rates at TA-21 would make it possible to estimate the length of time that MDAs near cliff edges will be stable. However, cliff-retreat rates are difficult to acquire, which limits the confidence of such stability estimates. At TA-21, several different approaches have provided insight into the processes and rates of cliff retreat, including (1) field mapping of landslides and field observations of cliff-retreat processes at TA-21, (2) analysis of cosmogenically produced ^{21}Ne in cliffs, (3) analysis of variations in canyon width, as measured from topographic maps, and (4) interpretation of long-term (post-1.22 Ma) canyon evolution.

Field Observations of Landslides and Rockfall

The retreat of the mesa edges at TA-21 occurs by a combination of small rockfalls from cliffs, detachment of rocks from slopes, and larger, deep-seated landslides. The character of the mesa edges differs significantly between north- and south-facing slopes and between slopes bordering Los Alamos Canyon and those bordering the shallower tributary canyons (DP and BV Canyons). These variations provide evidence for significant spatial differences in mass-wasting processes.

Fig. 7. Photograph of DP Canyon looking upstream at a radiocarbon sample site (7046-ft stream elevation). Surface to the right is an historic terrace ~3.3 ft above the channel. Radiocarbon dates of 21.6 and 26.7 ka were obtained from older deposits in stream banks to the left. An historic gully is visible to the left.

The most common type of mass wasting from the cliffs bordering DP Mesa is rockfall consisting of single- or multiple-fracture-bounded blocks of tuff. The youngest of these observed at TA-21 occurs within Tshirege unit 3, along the north rim of Los Alamos Canyon west of BV Canyon. For a distance of ~17 ft along the rim, the cliff face failed on steeply dipping fractures, resulting in ~10 ft of cliff retreat at this location. Both the cliff face behind the rockfall and the associated tuff boulders downslope expose unweathered, grey tuff, indicating a very young age. Rockfalls can also occur on the forested north-facing canyon walls. For example, an ~10-ft-diameter boulder dislodged from Tshirege unit 2 on the south wall of Los Alamos Canyon near TA-21 in the summer of 1992 and rolled and bounced down the slope to the valley bottom.

Rockfalls are frequent enough along the north rim of Los Alamos Canyon that Tshirege unit 3 is characterized by almost continuous cliffs where fracture-bounded blocks of tuff have dislodged (Fig. 8). In contrast, the north rims of DP and BV Canyons, formed in the same rock unit, possess discontinuous cliffs that typically have been exposed long enough that the original fracture-bounded rock surfaces have been deeply pitted and modified by secondary spalling (Figs. 9 and 10). In addition, the top of Tshirege unit 3 has been rounded extensively by erosion of the mesa edge along the side canyons, sharply contrasting with the abrupt cliff top that characterizes this unit along Los Alamos Canyon. These contrasting characteristics provide evidence for much slower cliff-retreat rates along the north walls of DP and BV Canyons than along the north wall of Los Alamos Canyon.

Measurements of the thickness of fracture-bounded blocks in the Tshirege unit 3 cliffs along BV Canyon suggest that individual rockfalls are typically small (an average thickness of 4 ft and median thickness of 3 ft, as shown in Fig. 11). These blocks are much smaller than the average spacing of primary fractures in the Bandelier Tuff, as measured by Vaniman and Wohletz (1990) and Wohletz (Sec. III, this report) because of the development of secondary fractures parallel to the cliff faces. The closest that the cliff embayments along BV Canyon approach MDA B is 60 ft, which would require the failure of 15 average-size blocks before waste pits could be exposed. Even if failure occurred by the largest block measured (16 ft), four failures would be required before exposure of the waste.

Along the rim of Los Alamos Canyon, several large, partially detached landslide blocks provide evidence for mass-wasting on a scale much larger than is seen along DP and BV Canyons. One landslide near the eastern end of DP Mesa (Plate 3 and Fig. 12) extends 330 to 500 ft along the mesa edge and reaches a width of 35 to 50 ft. The main block of the landslide has dropped ~3 ft below the mesa, and a 120-ft-long, 13- to 23-ft-wide, 3-ft-deep graben separates part of the landslide from the mesa. The outer edge of this landslide is broken into many smaller blocks that have dropped farther below the mesa, suggesting that the landslide was originally wider. One of these blocks clearly involves the Tshirege unit 2 cliff as well as the Tshirege unit 3 cliff. This evidence demonstrates that the failure involves multiple units of the Bandelier Tuff, including both the more-resistant cliff-forming units and intervening nonwelded units. The lower extent of this landslide is not known because it is covered by colluvium below the Tshirege unit 2 cliff, but Tshirege unit 1v and possibly underlying nonwelded units are likely to have been involved.

A second, partially detached landslide block, ~230 ft long and 75 ft wide, occurs at TA-21 northwest of Building 21-155. It has dropped the Tshirege unit 3 cliff 7 to 16 ft below the mesa. An additional, ~130-ft-long, 55-ft-wide landslide involving Tshirege unit 3 is present along the north rim of Los Alamos Canyon east of TA-21 and the Main Gate, dropping the Tshirege unit 3 cliff 3 to 8 ft. A failure ~265 ft long and 50 to 60 ft wide involving Tshirege unit 2 on the north wall of Los Alamos Canyon above TA-2 was mapped previously by Vaniman and Wohletz (1990). This failure dropped an intact block of tuff ~13 ft. Evidence for complete failure of a large section of Tshirege unit 2 cliff is provided by a large deposit of angular tuff boulders that clogs the drainage below the BV canyon hanging valley south of MDA V (Plate 5). The fact that the cliff above this location appears exceptionally fresh and uniform provides additional evidence for a large-scale cliff failure (Fig. 13).

The presence of the partially detached landslides demonstrates that the north wall of Los Alamos Canyon can fail in blocks much larger than those seen along either DP or BV Canyons, causing the mesa edge to retreat up to 75 ft; failures of at least this size can be expected in the future. Triggering of landslides by earthquakes is well documented (Keefer, 1984; Keefer and Wilson, 1989), and seismic shaking may thus be an important triggering mechanism for large-scale landslides along Los Alamos Canyon.

The reason for the large landslides along the margin of Los Alamos Canyon—in contrast to the small rockfalls within DP and BV Canyons—is probably related to the greater relief in Los Alamos Canyon. Observations of the cliff faces in embayments in Los Alamos Canyon and lower DP Canyon indicate that curved fracture surfaces can develop adjacent to the cliffs within the nonwelded parts of the Bandelier Tuff, much like the curved failure surfaces commonly developed in landslides (Fig. 14). These curved surfaces allow cliff failures to involve the predominantly unfractured, nonwelded tuff as well as the fractured cliff-forming units and allow a larger section of cliff to be involved in individual failures.

Fig. 8. Photograph of Tshirege unit 3 cliff along Los Alamos Canyon west of BV Canyon. Nearly continuous, near-vertical cliffs have been produced by repeated rockfalls.

Cosmogenic ^{21}Ne Analyses

When exposed rock surfaces are bombarded by cosmic rays, various stable and radioactive isotopes are produced in the rock. The concentrations of these isotopes progressively increase over time, making it possible to estimate exposure ages and/or erosion rates of the rock surfaces (see for example, Poths and Goff, 1990; Lal, 1991; Nishiizumi *et al.*, 1991). Samples collected from cliff faces along BV Canyon below MDA B were analyzed for concentrations of cosmogenically produced ^{21}Ne to provide constraints on the exposure history of these cliffs and to allow additional insights into cliff-retreat rates.

Preliminary estimates of the apparent exposure ages of three BV Canyon samples, provided by J. Poths (personal communication, 1994), are presented in Table II. Several simplifying assumptions (see below) were made to convert the measured ^{21}Ne concentrations into apparent exposure ages, and future modifications of these estimates will be necessary.

(1) A ^{21}Ne production rate one-half of that on a horizontal rock surface, which is appropriate for a vertical cliff. Because the sampled cliffs were less than vertical, actual production rates would be somewhat higher and the apparent exposure age somewhat lower.

Fig. 9. Photograph of Tshirege unit 3 cliffs along BV Canyon south of MDA B. Cliffs are discontinuous and the original rockfall surfaces have been highly modified.

Fig. 10. Photograph of Tshirege unit 3 cliff along BV Canyon south of MDA B; deep pits have been eroded into the cliff face (rock hammer provides scale).

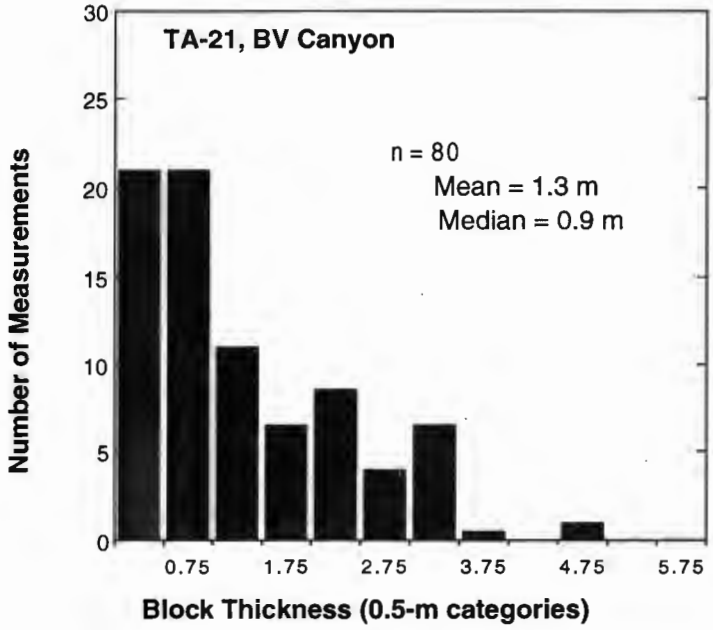

Fig. 11. Histogram of thickness of blocks along cliff faces south of MDA B, measured perpendicular to the cliffs. Measurements of the distance from the cliff face back to next fracture, made every 3.3 ft in two embayments along the edge of the canyon, represent the approximate thickness of individual rockfall blocks. Measurements include both blocks bounded by primary cooling fractures and those bounded by secondary fractures produced by spalling.

Fig. 12. Photograph of partially detached landslide block near east end of DP Mesa, along north rim of Los Alamos Canyon. Graben at head of landslide in foreground is about 3.3 ft deep and 16.4 ft wide. Landslide has moved to right, towards Los Alamos Canyon.

Fig. 13. Photograph of Tshirege unit 2 cliff south of MDA V at a site of relatively young cliff failure. Cliff appears to be exceptionally unweathered and angular rockfall boulders are present at cliff base.

(2) ^{21}Ne is produced only from cosmic rays bombarding the cliff face, not from cosmic rays penetrating the upper subhorizontal rock surface. Because the BV Canyon cliffs are relatively short (typically 6 to 8 ft high) and the tuff has a relatively low density that allows the cosmic rays to penetrate deeply, this assumption is probably not completely valid, and actual exposure ages would be less than estimated.

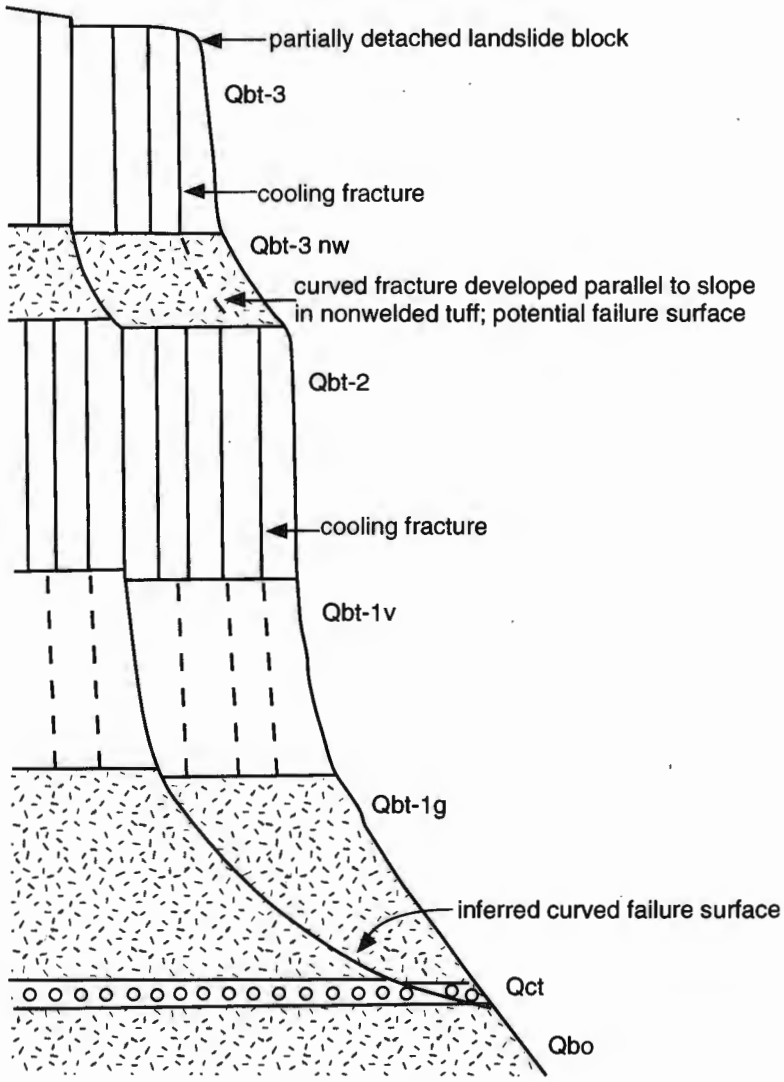

Fig. 14. Sketch showing inferred characteristics of large failures along the south edge of DP Mesa that borders Los Alamos Canyon. Landslides involving both welded and nonwelded units link primary cooling fractures in welded units. See Plate 1 for explanation of geologic unit symbols.

(3) The rockfall that exposed the sampled cliff was large enough to remove all tuff that previously contained ^{21}Ne—thus completely "resetting the clock." Because of the small size of the typical block along BV Canyon (3 to 4 feet; see Fig. 11), complete resetting may not have occurred; again, this tends to result in overestimated exposure ages.

(4) The sampled cliff was not shielded from cosmic rays by neighboring cliffs or the opposite canyon wall. Because of the irregularities of the canyon walls, this assumption is probably not completely valid, which results in somewhat lower actual ^{21}Ne production rates and leads to underestimates of exposure ages.

TABLE II
COSMOGENIC ^{21}NE ANALYSES FROM BV CANYON[a]

Sample Number	^{21}Ne Concentration (10^5 atoms/g)	Apparent Exposure Age (ka)
21-SLR-1	6.9 ± 1.4	19 ± 4
21-SLR-2	4.8 ± 1.1	14 ± 3
21-SLR-3	4.7 ± 1.0	13 ± 3

[a] Preliminary analyses by J. Poths, Los Alamos National Laboratory. Calculated exposure ages use a ^{21}Ne production rate of 35 atoms/g/yr for the latitude and altitude of Los Alamos and a vertical exposure; stated errors represent 1 standard deviation of the analytical uncertainties. Other uncertainties not encompassed by these errors are discussed in text.

Because of the above uncertainties, the apparent exposure ages in Table II should be used cautiously, although errors introduced by the simplifying assumptions would generally result in overestimates of exposure age. Two points are notable. First, the analyses and accompanying uncertainties suggest that typical ages for the last rockfall at the sample sites are less than 15,000 to 20,000 years, and therefore active cliff retreat occurred in BV Canyon within the latest Pleistocene and Holocene. Second, the apparent exposure ages are very similar, despite the fact that the sampled cliffs varied significantly in weathering characteristics and thus in inferred age. In the field, samples 21-SLR-1 and 21-SLR-2 appeared older than sample 21-SLR-3, yet the estimated ages are identical within the analytical uncertainty. This suggests that the measured ^{21}Ne concentrations may have resulted mainly from vertical penetration of cosmic rays through overlying rock. Alternatively, individual rockfall failures may be small enough along these cliffs to prevent complete resetting of the clock; this suggests that the ^{21}Ne concentrations may be better interpreted as a long-term erosion rate. Additional research is required to resolve these uncertainties and allow more confident interpretation of the results.

Topographic Analysis

Measurements of the width of Los Alamos, DP, and BV Canyons were made from 1:1200-scale FIMAD maps with 2-ft contours to evaluate spatial variations that may provide insight into cliff-retreat variations. Canyon width was measured perpendicular to a centerline down each canyon and from the break-in-slope on the resistant part of Tshirege unit 3 on the edges of the adjacent mesas. The measurement locations were chosen to ensure the maximum amount of variability, including both embayments where the canyons are widest and promontories where they are narrowest.

Measurements of canyon widths on the Pajarito Plateau have previously been used to calculate long-term cliff-retreat rates (Purtymun and Kennedy, 1971). The calculations assume that initial incision of the canyons occurred very soon after emplacement of the 1.22-Ma Tshirege Member of the Bandelier Tuff and that since that time cliff retreat rates have been constant. However, as discussed earlier, incision of the drainages through each cooling unit of the Bandelier Tuff could have occurred significantly after 1.22 Ma during progressive headward erosion of the

canyons. A significant part of canyon widening may have occurred during their early development. In addition, short- and long-term rates of cliff retreat could be related to other variables such as canyon depth, climate, and seismic activity, which would result in variable rates of cliff retreat over time.

All three canyons examined in the vicinity of TA-21 generally become narrower and shallower upcanyon (Fig. 15). These relationships are consistent with the headward development of the canyons over time, such that canyon incision began later upcanyon than downcanyon. Thus, local measurements of canyon width will only provide minimum values of cliff-retreat rate averaged over the past 1.22 Ma; the highest values would be calculated downcanyon, where the canyons are widest. East of TA-21 near the eastern limit of Tshirege unit 3 (the upper cliff-former at TA-21), the canyon reaches 1750 ft in width, providing a minimum-limiting average cliff-retreat rate of 0.72 ft/ky averaged over 1.22 Ma. Farther downstream, canyon width between the Tshirege unit 2 cliffs reaches 2600 ft west of State Route 4, providing a minimum-limiting average cliff-retreat rate of 1.07 ft/ky.

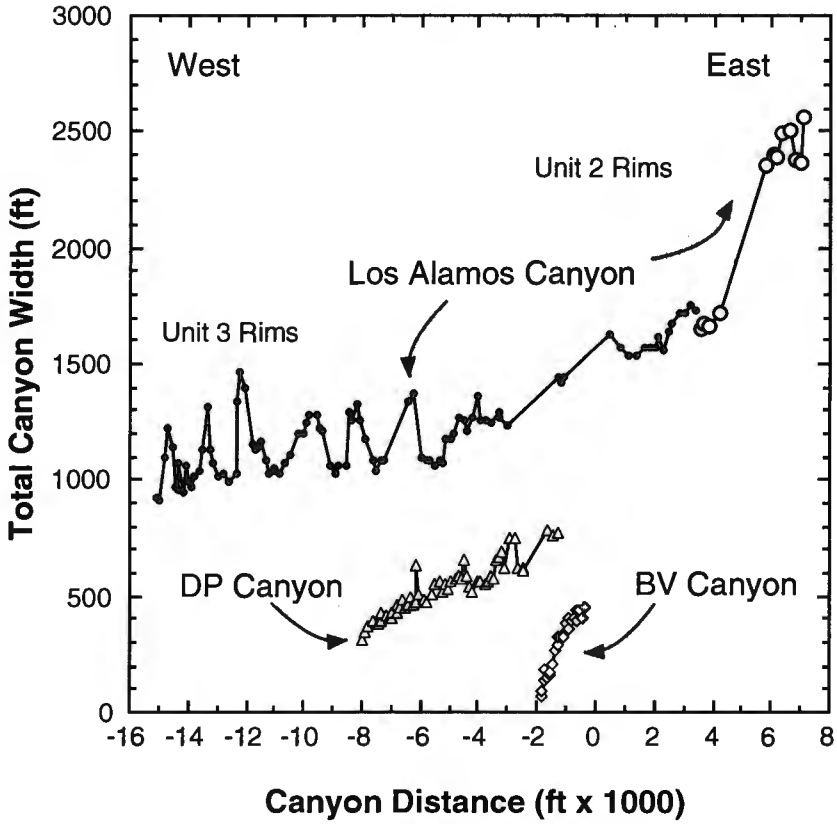

Fig. 15. Plots of total canyon width vs distance along Los Alamos, DP, and BV Canyons. Edge of canyon is defined as the break in slope at top of cliff or steep slope developed on resistant unit of Bandelier Tuff. Edge of canyon for DP, BV, and western part of Los Alamos Canyons is in Tshirege unit 3, and the edge of canyon in eastern part of Los Alamos Canyon is in Tshirege unit 2. Measurements made from FIMAD 1:1200-scale maps with 2-ft contour intervals. All canyons decrease in width to the west. Canyon distance uses junction of Los Alamos and DP Canyons as "0" point.

There may be local variability in average cliff-retreat rates that is associated with variations in fracture density. Significant local variations in canyon width occur along Los Alamos Canyon, and the wide parts often correspond with areas of increased fracture density along projected fault zones (Fig. 16). These include the Guaje Mountain fault zone (GMFZ) and two traces of the Rendija Canyon fault zone (RCFZ) west of TA-21, as mapped by Vaniman and Wohletz (1990). At TA-21, increased canyon width occurs near MDA V (Fig. 16), where exceptionally high fracture density has been documented (see Wohletz, Sec. III, this report). Two additional areas of higher cliff-retreat rates are suggested by increases in canyon width between MDA V and the GMFZ and between the RCFZ and the GMFZ at TA-41. The local increases in canyon width suggest that cliff-retreat rates in areas of more highly fractured tuff are 20 to 50% higher than in nearby cliffs.

A comparison was made of the distance from the approximate centerline of the valley bottoms to each canyon rim to evaluate evidence for any significant canyon asymmetry that would suggest greater retreat rates for either the north- or south-facing slopes. Specifically, if either rim was consistently a greater distance from the valley bottom, it would suggest that rim was retreating faster because of a difference in aspect. The term *valley bottom* used in this report is generally equivalent to the area of Quaternary alluvium (Qal), as mapped by Goff (Sec. II, this report).

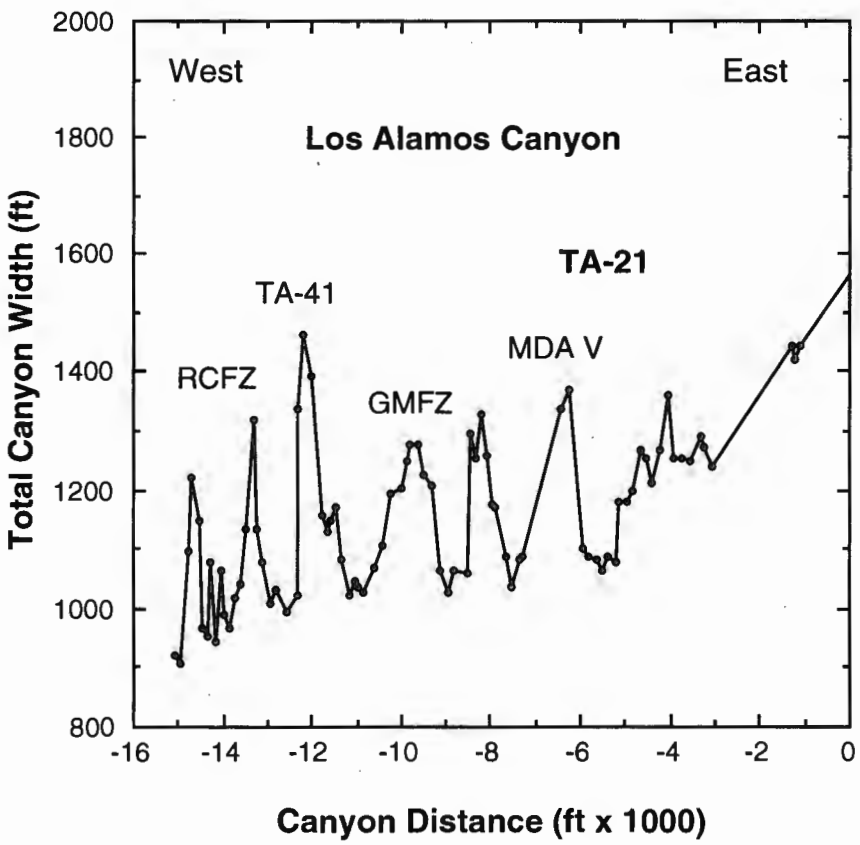

Fig. 16. Plot of total canyon width in Los Alamos Canyon near TA-21. Wide parts of canyon generally correspond to projected fault zones; GMFZ = Guaje Mountain fault zone and RCFZ = Rendija Canyon fault zone (from Vaniman and Wohletz, 1990). Canyon distance uses junction of Los Alamos and DP Canyons as "0" point.

Topographic measurements indicate that although significant asymmetry is present in places (Fig. 17), it is not systematic and most of the canyon lengths are roughly symmetric. In the western part of both Los Alamos Canyon and BV Canyon, the rims are roughly equidistant from the valley bottom, suggesting approximately uniform retreat rates. Canyons with significant asymmetry generally correlate with the presence of extensive valley fills on one side of the canyon, which provides evidence for lateral stream migration. These asymmetric reaches include the western part of DP Canyon (shown on Fig. 17), where deposits of older alluvium and slopewash occur on the southern side of the valley (Plate 4), and the eastern part of Los Alamos Canyon, where wide stream terraces are present ~100 ft above stream level south of the channel.

Measurements from topographic maps thus suggest that, despite differences in vegetation and the extent of cliffs between north- and south-facing canyon walls, there is no strong evidence for significant, systematic differences in the retreat rates of opposite canyon walls in the vicinity of TA-21. Estimates of cliff-retreat rates obtained from one canyon wall may therefore be generally applicable to the opposing wall.

Long-Term Canyon Evolution

Inferences about the long-term (post-1.22-Ma) evolution of the canyons adjacent to TA-21—based on the field mapping and analyses of topographic maps—have important implications for the timing and rates of cliff retreat. The occurrence of older alluvial deposits within the small tributary canyon to DP Canyon and along the margins of lower DP Canyon provides strong evidence that the tributary canyon was largely cut by a stream originating in the Sierra de los Valles and that little widening of this canyon has occurred since the old stream channel was abandoned. The

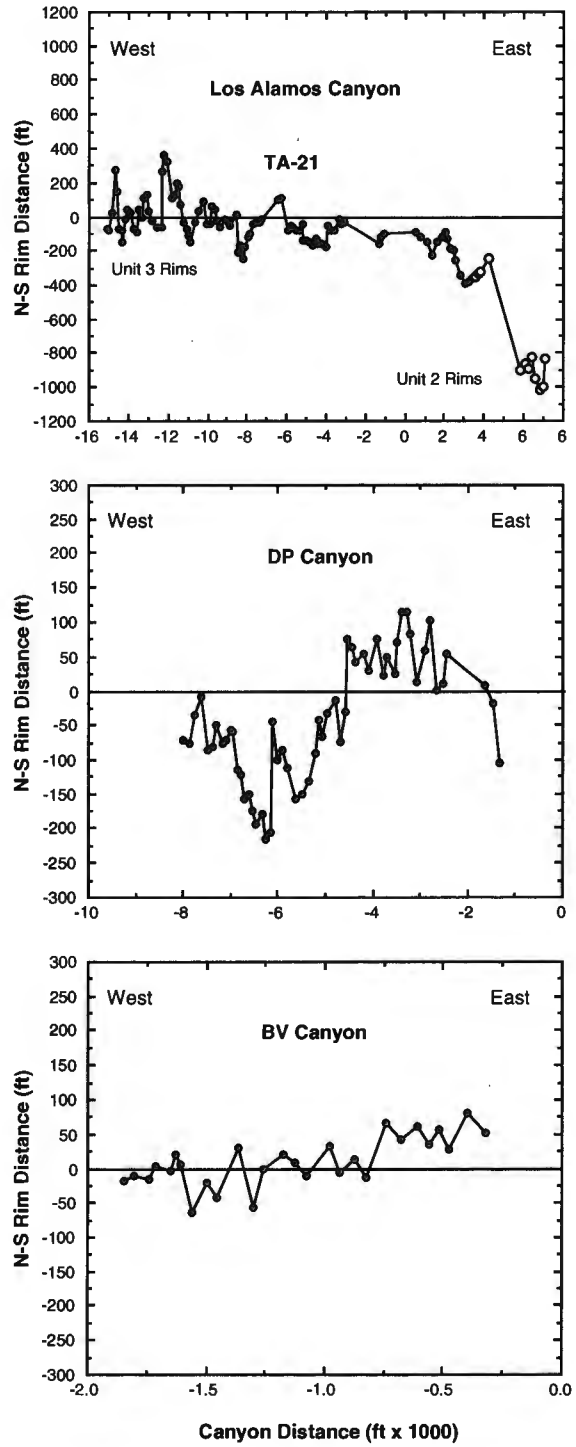

Fig. 17. Plots of differences between distance to north and south rims from approximate centerline of late Quaternary valley floor show canyon asymmetry. A positive value indicates that the north rim is farther than the south rim from the canyon floor. Western parts of both BV and Los Alamos Canyons are roughly symmetric, suggesting that retreat rates of the north and south rims are similar. Other parts of the canyons are asymmetric.

similarity between this small tributary canyon and DP and BV Canyons further suggests that DP and BV Canyons were also formed largely by streams originating in the Sierra de los Valles (Fig. 2). The age of these older stream channels that flowed over the mesas near TA-21 is unknown, but they may exceed 1 Ma.

These observations imply that minimal retreat of the cliffs adjacent to DP and BV Canyons has occurred since integration of the mesa-top channels (presumably along the present course of Los Alamos Canyon) and that the most significant canyon widening occurred during periods of lateral migration of the stream channel against the canyon walls. The significant increase in the width of Los Alamos Canyon downstream of DP Canyon (Fig. 8), which is associated with an extensive stream terrace ~100 ft above the channel that extends east to State Route 4, also suggests that the widening of Los Alamos Canyon in this reach was strongly related to lateral cutting by the stream when the terrace gravels were being deposited.

Precise cliff-retreat rates cannot be determined because the time when the earlier channels were abandoned is not known and the canyon width at that time is also not known. However, average long-term rates can be constrained by making reasonable assumptions about the age of the channels. Assuming ages of 0.5 to 1.22 Ma for the older alluvium of DP Canyon and using a maximum distance of 130 ft from these gravels to the Tshirege unit 3 canyon rim will provide maximum-limiting cliff-retreat rates of 0.11 to 0.26 ft/ky. If the 4.3-ft average block thickness measured along BV Canyon below MDA B (Fig. 7) is used, this is equivalent to removal of one block every 16,000 to 33,000 years on average. As coarse as these estimates are, they emphasize that rockfalls at any point along the tributary canyons are probably very infrequent.

GEOMORPHIC EVALUATION OF TA-21 MDAs

MDA B and MDA V

Sediment Transport and Deposition

MDA B and MDA V are both located on the south side of DP Mesa. All surface drainage from MDA B and the majority of the drainage from MDA V is to the south into BV Canyon (Plate 5).

Most runoff from MDA B is first channeled along the dirt road bounding the MDA on the south and later discharges off the south side of the road onto the rocky sloping mesa. Most of this runoff occurs at discrete locations, generally feeding into natural, shallow mesa-top drainages and flowing downslope over the Tshirege unit 3 cliffs into BV Canyon (Plate 5). The distinct drainages south from the MDA B dirt road occupy only some of the natural drainages on the mesa, and many of the natural drainages are bypassed by the road-related drainage system. These drainages mainly occur below the western, paved part of MDA B, implying that the present source for much of the runoff is the paved surface. Runoff from the main drainages can be traced over the gently sloping upper mesa southward to the steep rocky slopes and cliffs of Tshirege unit 3. This runoff is in part braided and takes multiple, meandering courses between fracture-bounded blocks of tuff. Bandelier Tuff bedrock is exposed along much of the drainage courses above the cliffs and few sediment-storage sites exist. Thus there are relatively few sites for infiltration of significant runoff into sediment or storage of contaminants, although some infiltration of runoff into fractures in the bedrock probably occurs.

Additional runoff, probably of much smaller volume, leaves the dirt road and diffuses rapidly onto the mesa; recognizable drainages cannot be traced far. The diffuse runoff south of the MDA B dirt road generally can only be

traced a few feet over the mesa surface and most of the water may infiltrate into the mesa-top soils. Also, the present locations of this diffuse runoff are strongly influenced by subtle features such as low berms along the road. These features are probably ephemeral, so that the location of diffuse runoff shifts over time. Much of the runoff may infiltrate into the shallow soil or into fractures on the rocky slope before reaching BV Canyon. Any contaminants that may have been transported by surface runoff away from MDA B are unlikely to have been concentrated on the slope. It is more likely that they would have been dispersed on the slope or transported down into BV Canyon.

The axis of BV Canyon contains many sites of potential sediment deposition—and, therefore, sites of potential deposition of contaminants. The bottom of BV Canyon, generally a grassy flat in the lower reaches, grades into patches of grass among rockfall boulders upstream. The canyon floor lacks a distinct channel for the lower 600 ft above the waterfall and has a discontinuous channel upstream. Notably, for the lower 1200 ft above the waterfall, the valley floor alternates between narrow, confined reaches (5 to 10 ft wide) and wider, unconfined reaches (20 to 30 ft wide). At present, the areas immediately downstream of confined reaches are the most significant sites of sediment deposition in BV Canyon. At these sites, runoff spreads and shallows over unchanneled grassy flats, losing its capacity to transport sediment. The presence of a grassy bed, which increases roughness, should also tend to slow the flow and encourage sediment deposition.

Four sites of sediment deposition in BV Canyon that are potential sediment sampling sites are shown on Plate 5. Two of these are sites of significant flow expansion, roughly 600 and 1200 ft above the waterfall at the lip of the hanging valley, where rapid shallowing of the flow should encourage sediment deposition. The third site is in a confined reach near the downslope end of the hanging valley, downstream of all side channels from both MDA B and the west side of MDA V. The fourth site is roughly 1700 ft above the waterfall, where a recent rockfall—burying most of a vintage car's hood—partially blocked the canyon and created a sediment trap.

Future sediment samples from BV Canyon should probably be obtained in transects across the valley flat because runoff spreads over these areas and likely would disperse any contaminants. Samples should also be acquired over a depth interval such as 0 to 6 in. because these are likely sites for burial of sediments and any associated contaminants.

Present surface runoff away from the perimeter of MDA V is generally diffuse and spreads over the mesa surface in unchanneled flow. Distinct surface channels are present only near the southeast corner of MDA V; surface runoff flows over the mesa and then drops over the steep, rocky Tshirege unit 3 slopes immediately east of the BV Canyon waterfall. There are no major sediment deposition areas associated with this runoff. Some of the diffuse runoff also concentrates in the shallow drainage west of MDA V, which drains into BV Canyon.

Cliff Retreat

The available data on cliff-retreat processes at TA-21 indicate that exposure of buried waste by cliff retreat south of MDA B is improbable within a time frame of 10,000 years or more. As discussed earlier, extensive pitting and erosional modification of the south-facing cliffs bordering the shallow tributaries to Los Alamos Canyon (BV and DP Canyons) suggest that failures are much less frequent here than on the south-facing cliffs bordering Los Alamos Canyon. In addition, the minimal retreat that could have occurred for cliffs adjacent to the older alluvial deposits provides evidence for maximum average retreat rates of 0.11 to 0.26 ft/ky, or 1.1 to 2.6 ft/10,000 yr. Using average rates can be misleading, however, because retreat probably occurs in discrete rockfall events.

The largest measured block south of MDA B is ~16 ft thick measured perpendicular to the cliff face (Fig. 11), and local retreat of this scale could presumably occur at any time—especially during earthquakes. Nevertheless, the closest the cliffs of BV Canyon approach MDA B is ~60 ft at the southeast end; thus exposure of the wastes by cliff retreat is extremely unlikely within a period of 10,000 years and could conceivably require in excess of 100,000 years.

The risk of exposure of buried wastes by cliff retreat at MDA V is more difficult to evaluate. The original cliff adjacent to MDA V probably was deeply embayed, as is the case further west along BV Canyon. Field and airphoto examination indicates that the head of an embayment was buried by artificial fill at the southwest corner of the MDA. The southwest corner of Absorption Bed 3 at MDA V may approach within 20 to 25 ft of the steep edge of this artificial fill (bed location from Fig. 16.7-2, TA-21 RFI Work Plan) and is possibly within several feet of the edge of the original cliff. The stability of the artificial fill is unknown, but the fill slope has a gradient of ~0.85 (40°), and noncompacted fill as probably occurs at this site is often unstable at such steep slopes. Failure of the fill slope and the buried edge of the former cliff during a triggering event like an earthquake or intense rainstorm should be considered possible with the consequent exposure of the southwest corner of Absorption Bed 3. Also, an increase in the width of Los Alamos Canyon near MDA V (Fig. 16) suggests locally higher cliff-retreat rates here, which are possibly associated with the increase in fracture density reported by Wohletz (Sec. III, this report).

MDAs A, T, and U

Sediment Transport and Deposition

MDAs A, T, and U are located on the north edge of DP Mesa and drain north into DP Canyon. It is known that radioactive contaminants, including plutonium, have been transported down DP Canyon in small concentrations (Purtymun, 1971, 1974; Purtymun *et al.*, 1990). The source of these contaminants is thought to be primarily outfalls from TA-21. It is possible that contaminants also have been derived partly from surface erosion at the MDAs and from air emissions at TA-21.

Surface drainage from all three MDAs is channeled along the access road adjoining TA-21 to the north and feeds into culverts that discharge below the road. The surface runoff from the three MDAs flows down the steep Tshirege unit 3 slopes before spreading over gentle, grassy slopes developed on alluvium and slopewash in the bottom of DP Canyon (Plate 4). These gentle slopes are likely sites of deposition for much of the sediment carried by the surface runoff and are appropriate sites for sediment sampling to determine whether significant amounts of contaminants have been deposited downslope of the MDAs. In addition, small areas of sediment deposition are present below MDAs A and U in narrow troughs in the tuff below the road (Plate 4). These are also appropriate sites for sediment sampling.

The bottom of DP Canyon is underlain in part by sediment that was deposited since development began in the watershed, as discussed earlier; the evidence for the young age is provided by the presence of exotic material within the sediments. This historic sediment can reach 7 ft in thickness upstream of the MDAs, although thicknesses of ~3 ft are more common in the reach affected by the MDAs and outfalls. Previous sampling of sediment in upper DP Canyon has been restricted to the presently active channel (Purtymun, 1971). It is possible that contaminants were deposited in the valley bottom sediments as they aggraded during historic time. There are natural streambank exposures of the historic sediments down-channel from the MDAs, immediately above where the channel steepens and cuts into Tshirege unit 2 bedrock. These exposures are appropriate sampling sites for determining whether significant amounts of

contaminants are stored in these sediments. One suggested sampling site, at an excellent north-south streambank exposure, is shown on Plate 4. Sampling to span this vertical exposure is recommended—such as in several depth intervals (for example, 0 to 6 in., 6 to 12 in., etc.). If contaminants are found, more detailed sampling of individual stratigraphic layers may be warranted because the contaminants may be concentrated in one or more discrete layers.

Cliff Retreat

Available data on cliff-retreat processes at TA-21 suggest that exposure of buried waste by the retreat of the slopes north of MDAs A, T, and U is unlikely within time frames of 10,000 years or more. No evidence of recent rockfalls was observed along the north-facing walls of DP and BV Canyons and, as discussed earlier, the distribution of the older alluvial deposits provides evidence for extremely slow retreat rates on the slopes bordering the shallow tributary valleys to Los Alamos Canyon (including upper DP Canyon). The northern margins of MDAs A, T, and U are about 200, 65, and 75 ft, respectively, from the break in slope at the top of the steep Tshirege unit 3 slopes and farther than MDA B; thus, exposure by cliff retreat caused by repeated rockfalls is considered unlikely.

The possibility of infrequent, larger scale mass-wasting on the north side of DP Mesa is suggested by the presence of anomalous arcuate troughs and steps north of MDAs A and U (Plate 4). These features are similar to steps and troughs that develop at the heads of large landslides. However, there is no other evidence for landsliding on this scale within the shallow canyons at TA-21, and it seems more reasonable that another mechanism created these features. Specifically, the arcuate steps occur west of and roughly on line with the paleo-stream channel that contains the older alluvial deposits (Plate 3), and the steps may have been carved by similar streams that once flowed over the top of DP Mesa. In addition, even if these steps were created by large-scale landsliding, future failures would most likely involve movement of the already detached blocks north of the MDAs (if they exist) and would not expose buried contaminants.

SUMMARY

The most significant pathway for surface transport of contaminants at TA-21 is erosion by surface runoff. Contaminants that are available for surface transport may be present in sediment previously eroded from MDAs or downslope of outfalls, or may be widely dispersed over the area as a result of air emissions. The most likely sites for deposition and temporary storage of contaminants downslope of the MDAs are shown on Plates 6 and 7. Below MDAs B and V, these sites are within BV Canyon, a shallow, low-gradient tributary to Los Alamos Canyon, where modern sediment deposition occurs on the grassy valley floor. Below MDAs A, T, and U, these sites are on grassy alluvial surfaces on the margins of the main DP Canyon channel and at local sediment-deposition areas upslope. Sediment deposited at each of these sites should be considered in temporary storage. The long-term record of sediment erosion and deposition in DP Canyon indicates that remobilization of this sediment can occur on time scales of years to thousands of years. In addition, the valley floor in DP Canyon has undergone aggradation by deposition of sediment in the last 50 years, and it is possible that contaminants eroded from MDAs or discharged from outfalls are retained within these sediments. The modern channel of DP Canyon has incised these historic sediments, and contaminants within previously deposited sediment may be supplied to the modern channel through bank erosion. Samples from these historic sediments exposed in streambanks in DP Canyon can be used to determine contaminant concentrations and possible contaminant sources for the stream.

All five MDAs at TA-21 are located near the edges of DP Mesa, and eventual exposure of buried contaminants by the retreat of cliffs is possible. Along the cliffs bordering Los Alamos Canyon, partially detached landslide blocks show that failure can occur up to at least 75 ft from the mesa edge. Single failures of this scale should be considered possible along the rim of Los Alamos Canyon, especially during earthquakes. However, the MDAs border shallow tributary canyons to Los Alamos Canyon, where the geomorphic characteristics provide evidence that rockfalls are very infrequent and that MDAs more than 50 ft from the cliffs should be considered stable with respect to mass-wasting for periods exceeding 10,000 years. Four of the five MDAs meet this criteria. The possible exception, MDA V, may have an absorption bed within 20 to 25 ft of the mesa edge. The mesa edge here consists of artificial fill that buries the head of an embayment along the canyon wall. Absorption Bed 3 may be within several feet of the original mesa edge, and exposure of the southwest corner of this bed through failure of the artificial fill or an adjacent buried fracture-bounded block of tuff should be considered possible during an earthquake or intense rainstorm. Local increases in canyon width (Fig. 16) and fracture density (see Wohletz, Section III, this report) near MDA V also suggest the potential for relatively fast rates of cliff retreat here.

DP Spring, which contains low concentrations of tritium, emerges from the base of an old valley fill in lower DP Canyon. This valley fill probably extends less than 300 ft upcanyon from DP Spring and is largely confined to the part of the canyon that is cut into the nonwelded units of the Bandelier Tuff. Because the spring is perennial—in contrast to the intermittent surface flow farther up DP Canyon—the water must have infiltrated into the tuff upstream, either directly from the stream channel or after first infiltrating alluvium. The favored model for the springwater flow path is that water from the alluvium in upper DP Canyon infiltrates the highly fractured Tshirege units 2 and 1v and emerges from the fractures into the upper part of the valley fill in lower DP Canyon. From there, the water flows through the valley fill before emerging at the contact between the valley fill and the Tshirege unit 1g at DP Spring.

ACKNOWLEDGEMENTS

This work was funded by the Los Alamos National Laboratory ER Program as part of site characterization activities for TA-21. The author thanks G. Eller, D. Broxton, and M. Devaurs for their support; J. Poths for cosmogenic ^{21}Ne analyses; D. Anderson, K. Anderson, J. Carney, and K. Reid for field and laboratory assistance; D. Walther for FIMAD map preparation; and D. Broxton, G. Eller, and J. Gardner for helpful review comments.

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