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VOLUMETRIC ANALYSIS AND HYDROLOGIC CHARACTERIZATION OF A MODERN DEBRIS FLOW NEAR YUCCA MOUNTAIN, NEVADA

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U.S. GEOLOGICAL SURVEY

INFORMATION ONLY

Administrative Report

Prepared in cooperation with the
U.S. Department of Energy under
Interagency Agreement DE-AI08-92NV10874

102-8

VOLUMETRIC ANALYSIS AND HYDROLOGIC CHARACTERIZATION OF A MODERN DEBRIS FLOW NEAR YUCCA MOUNTAIN, NEVADA

By Jeffrey A. Coe, Patrick A. Glancy, and John W. Whitney

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Denver, Colorado
1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

COLOR FIGURES 6a, 6b
7a, 7b
are attached per NOTE
TO RECORDS.

TRC 4/20/95

For additional information write to:

Chief, Earth Science Investigations Program
Yucca Mountain Project Branch
U.S. Geological Survey
Box 25046, MS 421
Denver Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND ACRONYMS

Multiply	By	To obtain
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
millimeter (mm)	0.03937	inch (in.)
square meter (m^2)	10.76	square foot (ft^2)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Volumetric analysis and hydrologic characterization of a modern debris flow near Yucca Mountain, Nevada

ABSTRACT

On July 21 or 22, 1984, rainfall-triggered debris flows occurred on the south hillslope of Jake Ridge, about 6 kilometers east of the crest of Yucca Mountain. Rain gages near Jake Ridge recorded 65 millimeters and 69 millimeters on July 21, and 20 millimeters and 17 millimeters on July 22, respectively. Rainfall intensity rates ranged up to 73 millimeters per hour on the twenty-first, and 15 millimeters per hour on the twenty-second. Digital elevation models with 2.0 meter spatial resolution, measured from pre-storm and post-storm aerial stereo photographs, were used to map hillslope erosion and the downslope distribution of debris. Volumetric calculations indicate that about 7,040 cubic meters of debris was redistributed on the 49,132 square meter hillslope study area during the two-day storm period. About 4,580 cubic meters (65 percent) of the eroded sediment were deposited within the study area and the remaining 35 percent was deposited outside the study area in a short tributary to Fortymile Wash and in the wash itself. The maximum and mean depths of erosion in the study area were about 1.8 meters and 5 centimeters, respectively. Analysis of cumulative precipitation values in the context of the National Oceanic and Atmospheric Administration precipitation-frequency atlas suggests that precipitation from the main storm on July 21 was more than double that expected, on average, once during a 100-year period. Based on this estimate of precipitation-frequency, and the fact that some of the colluvium on the hillslope appears to have been stable for tens of thousands of years, we suggest that the long-term average recurrence interval for intense storms that cause debris flows at Jake Ridge is at least 100 years.

INTRODUCTION

Yucca Mountain, Nevada (fig. 1) was selected by the U.S. Congress for characterization as a potential repository for high-level nuclear-waste (U.S. Department of Energy, 1988). Two elements of the site characterization plan are: 1) determination of flood and debris-flow hazards to surface facilities and transportation routes that would be built in support of the repository, and 2) analysis of modern hillslope erosion.

FIGURE 1 NEAR HERE

Recent major floods within several hundred kilometers of Yucca Mountain have been documented by National Oceanic and Atmospheric Administration, 1974; Glancy and Harmsen, 1975; Katzer and others, 1976; and Randerson, 1976, 1986. Although these floods transported substantial amounts of debris and were inherently hazardous, none are known to have produced or been associated with true debris flows. Thus, they provide important data upon which to base interpretations regarding regional flooding, but they do not provide specific information regarding the potential for flooding and debris flows at Yucca Mountain.

Flooding potentials of selected drainages at Yucca Mountain were documented by Christensen and Spahr (1980) and Squires and Young (1984). Glancy (1994) documented multiple Quaternary debris-flow deposits exposed by trenches excavated in stream-channel sediments in Coyote Wash on the east flank of Yucca Mountain. These debris-flow deposits in the general area of the site indicate that debris flows should be expected in the future. The weather characteristics that caused these debris flows, however, are not known.

Figure 1. Index map showing Yucca Mountain and Jake Ridge. Lines around Yucca and Bare Mountains roughly correspond to the mountain front/piedmont juncture. SG is a stream gage in Fortymile Wash, altitude about 1,120 m. YR and YA were tipping-bucket rain gages operated by Sandia National Laboratories. Rain gage YR was at the crest of Yucca Mountain, elevation about 1,469 m. Rain gage YA was at the east base of Yucca Mountain, elevation about 1,143 m. 4JA is a weighing-bucket rain gage operated by the National Weather Service, elevation about 1,049 m. Gages YA and YR are no longer in operation.

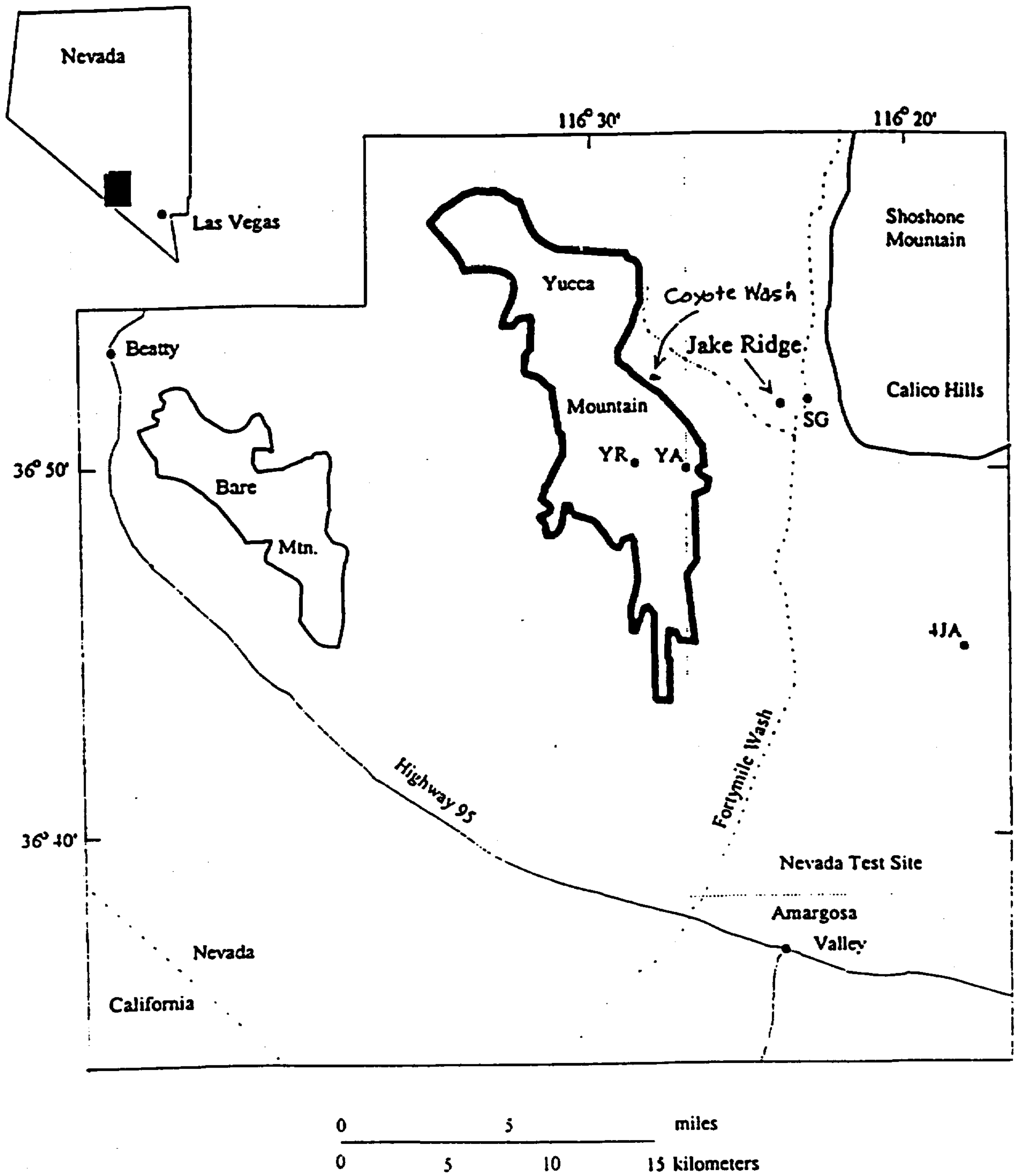

Nevada
Las Vegas
116° 30'
116° 20'
Shoshone Mountain
Yucca
Coyote Wash
Jake Ridge
Beatty
Mountain
Calico Hills
SG
YR
YA
36° 50'
Bare
Mtn.
4JA
Fortymile Wash
Highway 95
36° 40'
Nevada Test Site
Amargosa
Valley
Nevada
California
0
5
miles
0
5
10
15 kilometers

Fig 1

In investigations of modern hillslope erosion, as well as in potential flood and debris-flow hazards studies, it is important to correlate individual storm events with the corresponding volumes of sediment eroded by runoff. Field measurements of sediment eroded from hillslopes by runoff in arid to semiarid climates are difficult because precipitation events capable of causing erosion are infrequent and often localized. Measurement techniques that have been applied include repeated measurements of painted surface clasts or lines of stakes, and sediment traps on slopes or in channels (Goudie, 1990). Furthermore, measurements of debris eroded during single large storms are uncommon, and the above-mentioned traditional techniques of measurement are not well suited for recording large volumes of sediment eroded during sudden events. Typically, after large storms, the volume of eroded sediment is calculated by estimating or surveying the thickness and areal extent of debris deposited at the base of slopes or in channels (Glancy, 1968, Beaty, 1970, Glancy and Harmsen, 1975, Williams and Costa, 1988, Wohl and Pearthree, 1991).

The purpose of this report is to document modern hillslope erosion and debris flows that occurred on July 21 or 22, 1984, following intense rainfall on the south-facing hillslope of Jake Ridge (geographic name from Scott and Bonk, 1984), a flat-topped ridge about 6 km east of the crest of Yucca Mountain (fig. 1). These debris flows eroded unconsolidated colluvium from the upper hillslope, deepened and widened existing hillslope channels, created new channels on the lower hillslope, and deposited debris up to about 1.2 m thick on a dirt road at the base of the hillslope (fig. 2). Analytical photogrammetric techniques were used to map and determine the volumes of sediment eroded and deposited by these flows. These measurements of erosion and deposition made at the hillslope scale for a single event are rare, and are especially relevant in arid to semi-arid environments where infrequent debris flow events such as these are an important geomorphic agent. The volumetric results, combined with a review of weather systems that affect Yucca Mountain and a hydrologic analysis of the precipitation event that caused the debris flows, help characterize the potential debris-flow hazards and quantify modern hillslope erosion in the Yucca Mountain area.

FIGURE 2 NEAR HERE

Figure 2. Stereographic pair of aerial photographs taken in 1991 used for digital elevation model measurements. Approximate boundary of the study area is outlined. Original photo scale approximately 1:3,000. The road is about 5 m wide. Photograph frame numbers 326 and 327 taken by EG&G on 9/30/91 with Wild aerial camera 7167 (213.78 mm lens).

N ↑

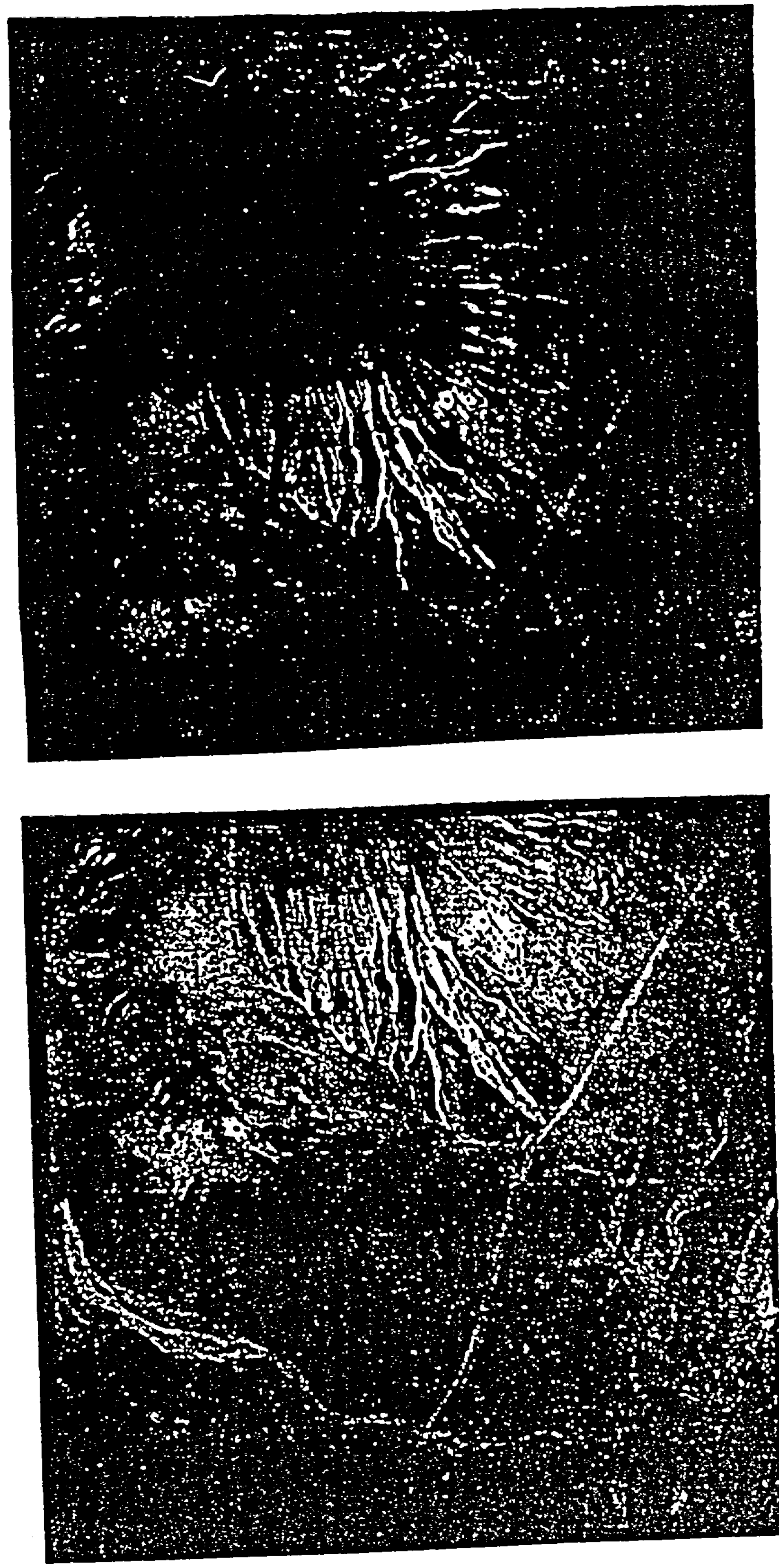


Figure 2

We gratefully acknowledge Keld Dueholm for his helpful suggestions regarding error analysis. Dan Cayan and Dale Ambos provided important meteorological reference material. We thank Scott Lundstrom, Dennis Grasso, Dave Moore, Thomas Bjerstedt, Mary-Margaret Coates, and three anonymous reviewers, for their critical reviews of the work. Sherman Wu and Elaine Ezra provided pre-flow and post-flow photography, respectively. Bob Fleming, Adel Zohdy, Anne McCafferty, Joe Hevesi, and Loren Crow had helpful suggestions during various stages of the project.

SETTING

Geology

Yucca Mountain (fig. 1) consists of several parallel, north-south trending ridges. These ridges rise abruptly above a piedmont alluvial surface that slopes southward toward the Amargosa River, about 45 km away. Jake Ridge (fig. 1) is at the southern extremity of a north-south trending ridge east of Yucca Mountain. Fortymile Wash, a major drainage of about 800 km^2, collects runoff from the east slopes of Yucca Mountain. Local relief is about 500 m between the crest of Yucca Mountain and the channel of Fortymile Wash. The steep-faced ridges of Yucca Mountain result from a dominantly north-south trending local fault system and the similarly aligned tributary drainage system of Fortymile Wash. Fortymile Wash and its Yucca Mountain tributaries flow ephemerally in response to strong regional or intense local rainstorms.

The Yucca Mountain area is underlain by a thick Tertiary volcanic sequence of silicic ash-flow tuffs that are chiefly underlain by interlayered rhyolite flows and non-welded tuffaceous beds that crop out predominantly in the Calico Hills area east of Fortymile Wash (Christiansen and Lipman, 1965, Frizzell and Shulters, 1990). The volcanic rocks of Calico Hills are part of a Tertiary sequence of rocks that form a regional aquitard. In contrast, rocks of the Paintbrush Tuff and the volcanic sequence above it form moderately transmissive aquifers (Winograd and Thordarson, 1975, p. 10). The crest of Jake Ridge, therefore, is capped by a moderately absorptive aquifer, but underlain by a nonabsorptive aquitard. This contrast in absorptivity may affect the runoff and erosive (debris flow) potential of the hillcrest and its underlying hillslope.

In general, hillslopes in the Yucca Mountain area are a combination of exposed bedrock and bedrock mantled by coarse-grained bouldery colluvium and fine-grained eolian deposits that are generally less than 2.5 m thick. Sparse hillslope vegetation is primarily cacti, creosote bush, saltbush, and other associated shrubs; grasses are scarce. Overall, vegetal cover provides little resistance to erosion caused by intense precipitation and the resultant runoff.

The south-facing hillslope at Jake Ridge is mantled by less than 2 m of bouldery colluvium and has a slope gradient that ranges from about 32° just below the caprock to about 4° at the base of the slope (fig. 2). The hillslope drains to a minor and relatively short tributary of Fortymile Wash. The top-surface of Jake Ridge, a dip-slope on resistant caprock, grades slightly (about 4°) to the southeast and is covered by a thin (less than 30 cm) mantle of cobbly colluvium.

Cation-ratio age estimates of varnished, relict, colluvial-boulder, hillslope deposits in the Yucca Mountain area range from about 150 thousand years (ka) to 1.2 million years (Ma) (Whitney and Harrington, 1994). The relatively old ages of these depositional surfaces suggests long-term slope stability throughout multiple climatic cycles of Quaternary time. Average slope degradation rates marginal to these dated deposits range from 0.2 to 7 mm/ka (Harrington and Whitney, 1991; Coe and others, 1993). These long-term erosion rates are similar to those calculated in the nearby western Mojave Desert (Oberlander, 1974).

Climate and Weather

The Yucca Mountain area is in a transitional climatic zone between the mid-latitude southern Great Basin desert, and the low-latitude northern Mojave desert (Houghton and others, 1975). It has a dry semi-arid continental climate with cool to cold winters and hot to very hot summers. For the years 1988-1989 mean-monthly temperatures ranged from 3.9°C in January to 28.9°C in July (Whitney and Harrington, 1994). Extreme temperatures during the same time period were -3.9°C in January and 40.6°C in July. Mean annual precipitation at and near Yucca Mountain ranges from about 125 to 150 mm (Quiring, 1983). Precipitation records from 13 U.S. Weather Service stations (Water Years 1965-81) indicate a bimodal distribution of precipitation (Quiring, 1983); about 70 percent of annual precipitation falls during the cool season (October-April) and the remainder during the warm season (May-September).

Four general types of weather systems affect the Yucca Mountain area: cold winter storms, warm winter storms, tropical cyclones, and convective summer storms. The last three of these systems have the potential to produce rainfall at rates sufficient to cause flooding. The Pacific ocean is the source of nearly all moisture for these storms (Hirschboeck, 1991), although Gulf of Mexico moisture can feed into the area at high altitudes (Hansen and Schwartz, 1981). Cold winter storms typically bring polar maritime moisture from the northwest. These storms usually bring snow, and rarely cause flooding except when rain following snowfall quickly melts the snowpack. The potential for rapidly melting snowpack to produce debris flows at Yucca Mountain is presently unknown. Occasional warm winter storms from the west and southwest can cause persistent heavy rainfall that results in major streamflows and flooding throughout the region. These warm winter storms also can spawn local cells of intense precipitation that cause severe runoff within small areas. Tropical cyclones during late summer and early autumn occasionally bring large amounts of moist, warm air over southern Nevada (Hirschboeck, 1991). These cyclones can also cause heavy rainfall of high intensity over large or localized areas and thus have the potential for causing debris flows. Tropical cyclones and warm-winter storms are relatively infrequent but probably generate the largest volumes of streamflow and floodwater throughout southern Nevada.

Severe convective summer storms are believed to be the dominant cause of debris flows and flash floods in small drainages of the Yucca Mountain area. For several days each summer, there is commonly a monsoonal flow of atmospheric moisture in southern Nevada; some years it is recurrent and more prolonged. This monsoonal flow often provides an abundant supply of atmospheric moisture needed to form intense and severe summer convective storms. Many of these convective storms are limited to small areas; some have unusually intense rainfall and, when reasonably isolated from surrounding rainstorms, are defined as "local storms" (Hansen and Schwarz, 1981). These local storms, commonly called thunderstorms, can yield rainfall in excess of of about 50 mm (the expected seasonal amount) in less than an hour and are capable of mobilizing debris flows. Precipitation from these storms can increase and intensify when convection occurs in conjunction with frontal convergence and orographic uplifiing. The largest of these storms, with regard to areal coverage and storm-yield potential, are characterized as mesoscale, convective-complex storms (Hirschboeck, 1991). These major convective storms can be especially intense and violent when warm, moist air masses are intercepted by through-moving frontal systems (for example, see Randerson, 1986).

Precipitation during 1984

Precipitation was unusual throughout southern Nevada during the 1984 Water Year (October 1983 - September 1984). It averaged about 1.3 times normal during the early cool season (October - December) but less than 10 percent of normal during the late cool season (January - April) and early warm season (May-June). July and August were extremely wet; overall rainfall was on the order of 600 percent of normal (U.S. National Weather Service, unpublished Nevada Test Site data). The 1984 annual precipitation total, however, was about 130 percent of normal; 1984 was a wet year but not unusually wet.

The uncommonly wet summer resulted from unusually strong monsoonal conditions that persisted between late July and early September. Numerous severe thunderstorms and resultant flash floods occurred across southern Nevada during this prolonged monsoonal period. The wet summer was not caused by the strong El Nino southern oscillation of 1982-83 (Bergman, 1984; Ropelewski, 1985). The persistent monsoonal conditions seem to have been the combined result of high-atmospheric pressure over the eastern United States and a persistent low-pressure atmospheric trough off the California coast. The combined effect of this dual pressure system promoted and maintained a southerly atmospheric flow that persistently injected abundant moisture into the atmosphere of the southern Great Basin and prompted numerous convective storms.

July rainfall at Yucca Mountain and Jake Ridge, prior to July 19, was minimal (U.S. National Weather Service, unpublished data). Two rain gages, one at the east base of Yucca Mountain, about 5.4 km southwest of Jake Ridge (gage YA, fig. 1), and the other (gage YR, fig. 1) near the crest of Yucca Mountain 7.5 km southwest of Jake Ridge, registered 0.25 mm and 4.8 mm, respectively, on July 19 (Hugh Church, Sandia National Laboratory, 1985, written communication). Neither these rain gages, nor National Weather Service rain gage 4JA (fig. 1), about 14 km southeast of Jake Ridge, registered any precipitation on July 20. Therefore, rainfall antecedent to July 21 at Jake Ridge appears to have been light, and a dry-colluvial mantle probably prevailed there and throughout the Yucca Mountain area.

THE JULY 21 AND 22, 1984 STORMS

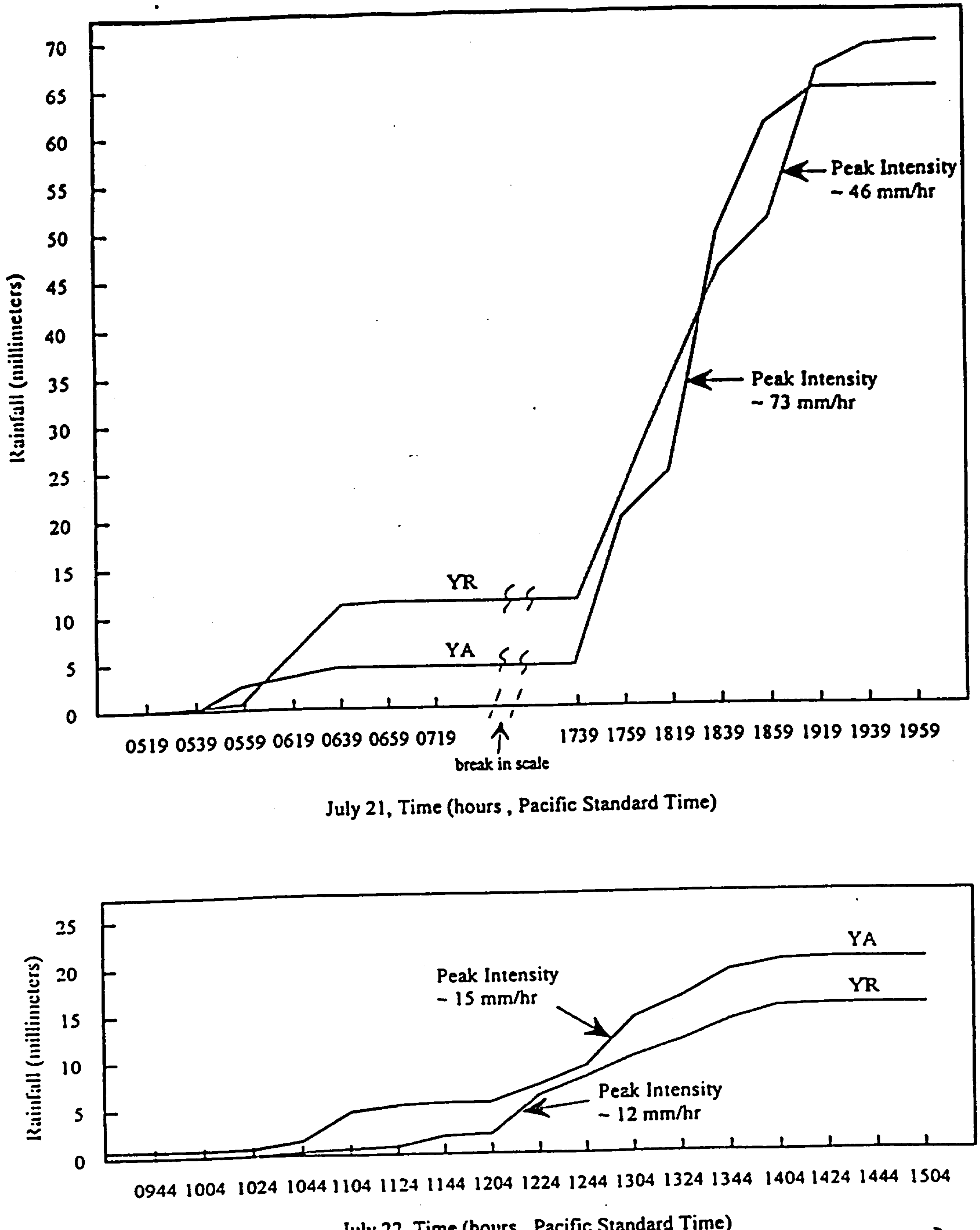
The storms that caused the July 21 or 22, 1984, debris flows at Jake Ridge were severe localized convective storms that occurred during the early part of the summer's monsoonal storm period. Daily satellite images from mid-June through August 1984 show that this storm system was part of a regional atmospheric flow system that brought moisture over a large area of the southern Great Basin, as described earlier.

Rainfall at Yucca Mountain began during the early morning hours of July 21 (fig. 3) when about 4 mm of rain fell at the eastern base of the mountain between 0544 hours and 0644 hours (Pacific Standard Time). About 11 mm fell at the crest (gage YR) between 0519 and 0719 hours. The next ten hours were dry. Heavy rainfall commenced during the late afternoon (about 1739 hrs.) and continued until about 1959 hours. Rainfall intensities reached 73 mm/hr at gage YA and 46 mm/hr at gage YR. Cumulative precipitation totals for the afternoon-evening storm were about 60 mm and 58 mm at the YA and YR gages, respectively. Heavy rainfall was apparently restricted to a small area because gage 4JA, about 15 km east-southeast of the Yucca Mountain gages, recorded only about 8 mm of rain during the entire day (U.S. National Weather Service Nuclear Support Office, written communication, 1984).

FIGURE 3 NEAR HERE

Rainfall began on July 22 during the early morning (0624-0644 hrs.) at gage YA and during mid-morning (1019-1039 hrs.) at gage YR (fig. 3). Rain continued until the mid-afternoon (1424 hrs.) at gage YA and until late-afternoon (1659 hrs.) at gage YR. Cumulative rainfall amounts and maximum intensities for the day were 20 mm and 15 mm/hr at gage YA, and 17 mm and 12 mm/hr at gage YR.

Figure 3. Cumulative rainfall records for July 21 and 22, 1984, storm events at rain gages YA and YR (fig. 1). Total accumulation at rain gage YR was 69.3 mm on July 21 and 16.5 mm on July 22 (0.8 mm of rain fell between 1504 and 1659 on July 22 that is not shown on the graph). Total accumulation at rain gage YA was 64.4 mm on July 21 and 20.4 mm on July 22 (0.5 mm fell between 0624 and 0644 hours on July 22 that is not shown on the graph).



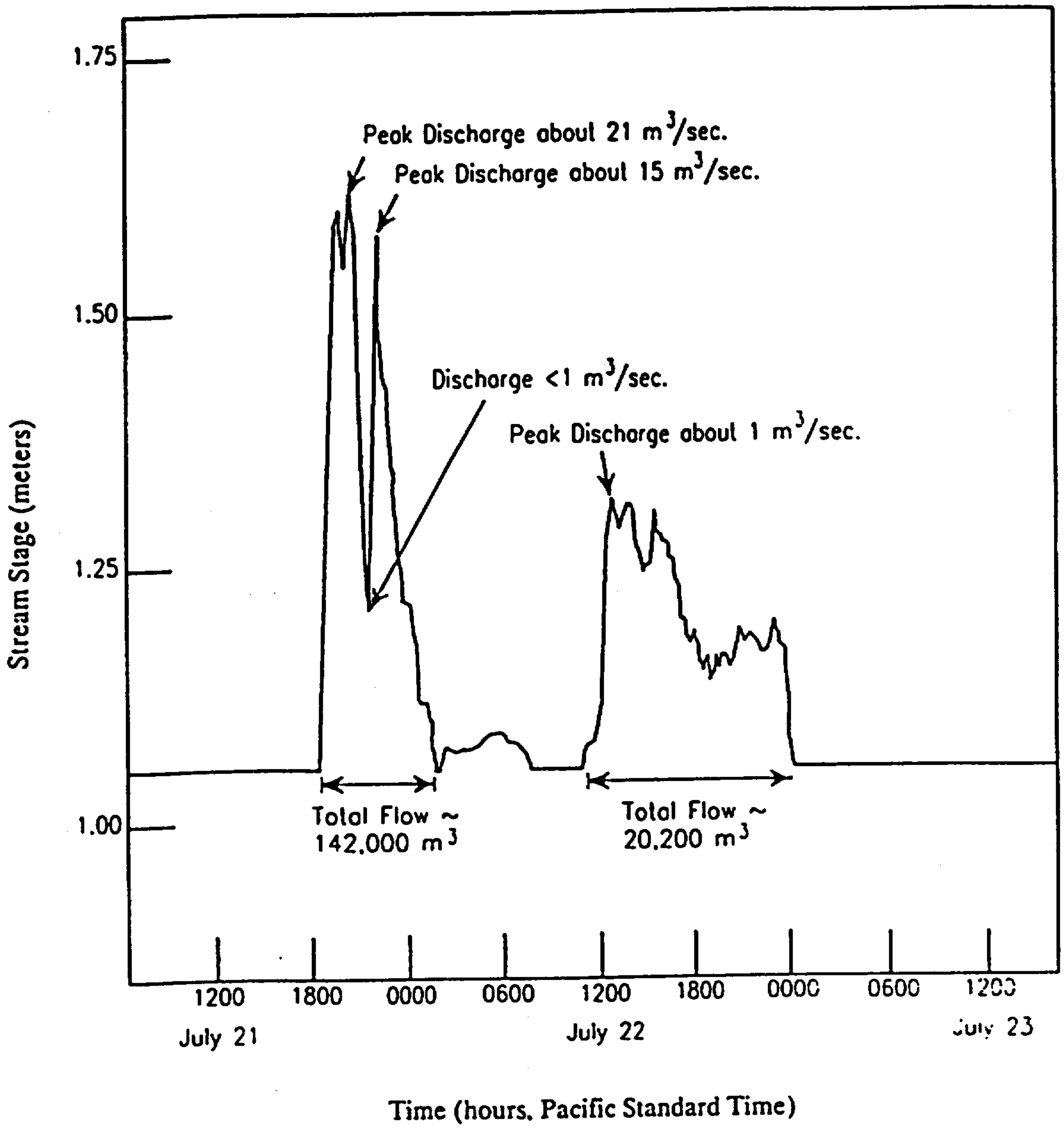
Rainfall (millimeters)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
YR
YA
Peak Intensity
~ 46 mm/hr
Peak Intensity
~ 73 mm/hr
0519 0539 0559 0619 0639 0659 0719
break in scale
1739 1759 1819 1839 1859 1919 1939 1959
July 21, Time (hours , Pacific Standard Time)
Rainfall (millimeters)
25
20
15
10
5
0
YA
YR
Peak Intensity
~ 15 mm/hr
Peak Intensity
~ 12 mm/hr
0944 1004 1024 1044 1104 1124 1144 1204 1224 1244 1304 1324 1344 1404 1424 1444 1504
July 22. Time (hours , Pacific Standard Time)

Figure 3

Some of the runoff from the storms was recorded by a stream gage in Fortymile Wash (SG. fig. 1) about 1.2 km east and slightly upstream from Jake Ridge (Pabst and others, 1993). Flow began at this gage on July 21 at about 1900 hours (fig. 4), peaked at 21 m^3/sec. within about 1 1/2 hours, and then began to rapidly recede. The flow receded to less than 1 m^3/sec. by 2200 hours (total flow time of about 3 hours), indicating this storm was quite local (total drainage basin area upstream from gage SG is about 650 km^2). A smaller runoff pulse of about 15 m^3/sec. followed at about 2230 hours. The precise location, timing, and magnitude of the rainfall that caused the second runoff pulse at the stream gage is uncertain. The second pulse may have been the result of a different storm cell, or from the same storm cell as it moved further upstream along Fortymile Wash: in either case, the runoff-pulse arrival could have been delayed by its greater distance of origin from the gage. A third streamflow pulse began on July 22 about 1130 hours and peaked at about 1 m^3/sec. at 1300 hours; this flow continued for 13 hours, ending about 0030 hours on July 23.

FIGURE 4 NEAR HERE

Figure 4. Streamflow record from stream gage SG [altitude about 1.120 m] in Fortymile Wash. SG consisted of a water-stage recorder and a crest-stage gage. The streamstage record was converted to stream discharge on the basis of several indirect measurements of peak streamflow during the summer of 1984 (Pabst and others. 1993).



Stream Stage (meters)
1.75
1.50
1.25
1.00
Peak Discharge about 21 m³/sec.
Peak Discharge about 15 m³/sec.
Discharge <1 m³/sec.
Peak Discharge about 1 m³/sec.
Total Flow ~ 142,000 m³
Total Flow ~ 20,200 m³
1200
1800
0000
0600
1200
1800
0000
0600
1200
July 21
July 22
July 23
Time (hours, Pacific Standard Time)

Figure 4

FIELD OBSERVATIONS

Fresh debris-flow scars and deposits were discovered at Jake Ridge on August 16, 1984. Precipitation records from gages YA and YR revealed that rainfall on July 21 and 22 was the sole candidate for initiating the debris flows. No evidence of other large-scale debris flows or mass movements at Yucca Mountain was found that appeared related to the July 21 and 22 storms. There was, however, abundant evidence of water-dominated sediment transport in many ephemeral stream channels.

Post-storm field observations on the top of Jake Ridge revealed that there was no evidence of intense runoff over the thinly mantled surface (fig. 2). The source area for much of the eroded debris at Jake Ridge was between 25 and 80 m below the top of the ridge. Water and debris widened and deepened existing channels on the upper and middle slope and cut new channels predominantly on the middle slope. Bouldery levees were deposited along channel margins on the middle and lower hillslope. The levees and bouldery lobe deposits contain a fine-grained matrix that indicates these flows were debris flows, rather than Newtonian, or water-dominated flows (Costa, 1984).

There were three primary zones of deposition: (1) a debris lobe located outside the study area about halfway down the large tributary channel that feeds into Fortymile Wash, (2) a debris lobe on the road at the base of the main hillslope channel (fig. 5), and (3) an elongated area of debris deposits along the southernmost, east-west trending channel that drains the hillslope (fig. 5). Debris in the tributary depositional lobe is poorly sorted and contains boulders (up to 0.5 m in diameter) from the Jake Ridge hillslope as well as from the Fortymile Wash alluvial terrace. The terrace gravels are cut by the tributary channel downstream from the base of the Jake Ridge hillslope. The lobe occurs as a fan where the tributary widens. The depositional lobe on the road is poorly sorted and contains a fine-grained matrix. It was deposited where the hillslope flattens to less than 4 degrees. Debris deposits on the road and along the east-west tributary contain boulders up to about 1 m in diameter. At the intersection of the tributary and Fortymile Wash, no debris larger than cobble size was observed.

FIGURE 5 NEAR HERE

Figure 5. Photograph of deposits at the base of the main and southern channels. View is to southeast from about half-way up the slope. The main lobe on the road is about 30 m wide and 75 m long at the widest and longest points. Fortymile Wash is visible in the distance. Additional lobes occur on the road to the left and in the tributary to Fortymile Wash. See pickup truck for scale. Photograph taken 8/16/84.

Figure 5

PHOTOGRAMMETRIC TECHNIQUES

Background

Photogrammetric measurements made from multiple sets of stereo photographs taken during successive time increments (multi-temporal) provide an ideal means of recording topographic change caused by mass movement processes, including debris flows (Brunsden, 1993). Geomorphological applications are by Brunsden and Jones (1976), Chandler and Moore (1989), and Baum and Fleming, (1991).

Digital elevation models (DEMs) are often derived directly from photogrammetric measurements. DEMs have been used for geomorphologic applications (Band, 1986; Tribe, 1991; Dietrich and others, 1992, 1993) but their spatial resolution is typically not adequate for large-scale studies of small individual landforms.

Volumetric analyses using photogrammetrically-derived altitude measurements are common in civil engineering, cut-and-fill problems, and stock-pile inventory applications (for example, Massa, 1958, Huberty and Anderson, 1990), but have just begun to be used for geomorphological applications (for example, Mills, 1992; Coe and others, 1993). Typically, such volumetric analyses involve the calculation of altitude differences between successive sets of cross-section or DEM measurements, and then numerically integrating these differences to calculate volumes of material lost or gained. We have used this approach, with DEMs of 2 m spatial resolution, to examine topographic changes at Jake Ridge.

Orientation of Stereo Pairs and Generation of Digital Elevation Models

DEMs were measured from pre-storm (1982, 1:8,000 scale) and post-storm (1991, 1:3,000 scale, fig. 2) stereographic pairs. The 1982 photographs contained a previously surveyed set of easting, northing, and altitude (xyz) ground-control points. The 1982 stereo pair was oriented (Slama and others, 1980; Ghosh, 1988) to these ground-control points in an analytical-stereo plotter. After the 1982 stereo pair was oriented in the plotter, the xyz coordinates of 16 points that were photo-identifiable in both the 1982 and 1991 photography, were recorded and transferred to the 1991 stereo pair. These points, which were evenly distributed and located in non-disturbed areas away from the debris flows, were then used as ground-control points to orient the 1991 stereo pair in the plotter. Using this orientation procedure, the 1982 and 1991 photographs were registered to each other to within an overall xy-standard deviation of 0.14 m and an overall z-standard deviation of 0.14 m. Orientation residuals on individual points were normally distributed about a mean of zero. Because the 16 control points were evenly distributed and include much redundancy (only three points are needed to orient a stereo model) we conclude that: (1) errors associated with subsequent DEM measurements were random (systemmatic errors are negligible). and (2) the computed 1σ value of 0.14 m is a reasonable estimate of the horizontal and vertical resolution of the altitude difference DEM (described later in this section) derived from the measured DEMs.

Each DEM, which consisted of an xyz grid with 2.0 m xy-spatial resolution, was measured from within a 49,132 m^2 study area (fig. 2) in each stereo pair. The analytical plotter and associated grid-measurement software were used to measure altitudes at approximately 12,300 identical xy-grid-node locations. Because altitude data were measured on a regularly spaced xy grid, no grid interpolation was necessary to create the DEMs. IDRISI Geographic Information System software (Eastman, 1992) was used to generate thematic maps from the DEMs.

To calculate net volumetric changes caused by the debris flows, an elevation-difference DEM was created by subtracting the 1982 DEM from the 1991 DEM. The elevation-difference DEM was used to generate an elevation-difference map of the study area (fig. 6). Based on the relative amounts of deposition and erosion shown on this map, the study area was divided into upper, middle, and lower hillslope zones (fig. 6). The upper-hillslope zone is dominated by erosion. The middle zone is dominated by channel widening and deepening as well as by deposition. The lower zone is dominated by deposition. The boundary between the upper and middle zone corresponds to about a 12 degree slope gradient, whereas the boundary between the middle and lower zones corresponds to about a 4 degree slope gradient (fig. 7).

FIGURE 6 NEAR HERE

FIGURE 7 NEAR HERE

Figure 6. Elevation-difference map. Hillslope zones shown are defined in the text. (a) Elevation-difference map created by subtracting the 1982 DEM from the 1991 DEM. Red and blue areas experienced positive and negative elevation change, respectively. Yellow areas showed no elevation change. (b) Perspective view of elevation-difference map overlaid on topography. Topographic relief from the base of the hillslope to the top of the ridge is approximately 130 m. View direction is along an azimuth of 330°. View angle is 25° above horizontal.

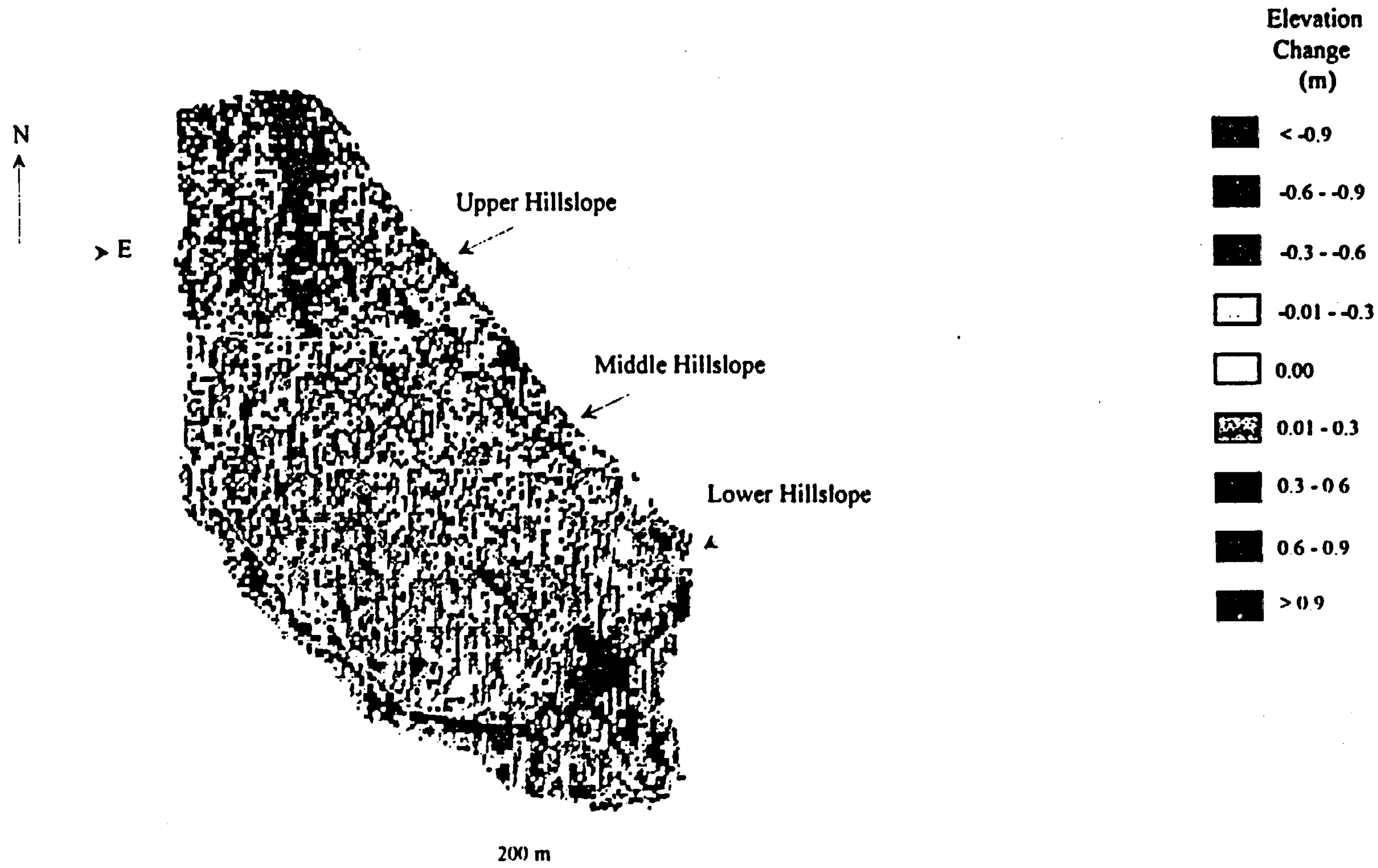

N
E
Upper Hillslope
Middle Hillslope
Lower Hillslope
200 m
Elevation Change (m)
< -0.9
-0.6 - -0.9
-0.3 - -0.6
-0.01 - -0.3
0.00
0.01 - 0.3
0.3 - 0.6
0.6 - 0.9
> 0.9

Fig. 6A

2 1 5 3 2 5 0 1

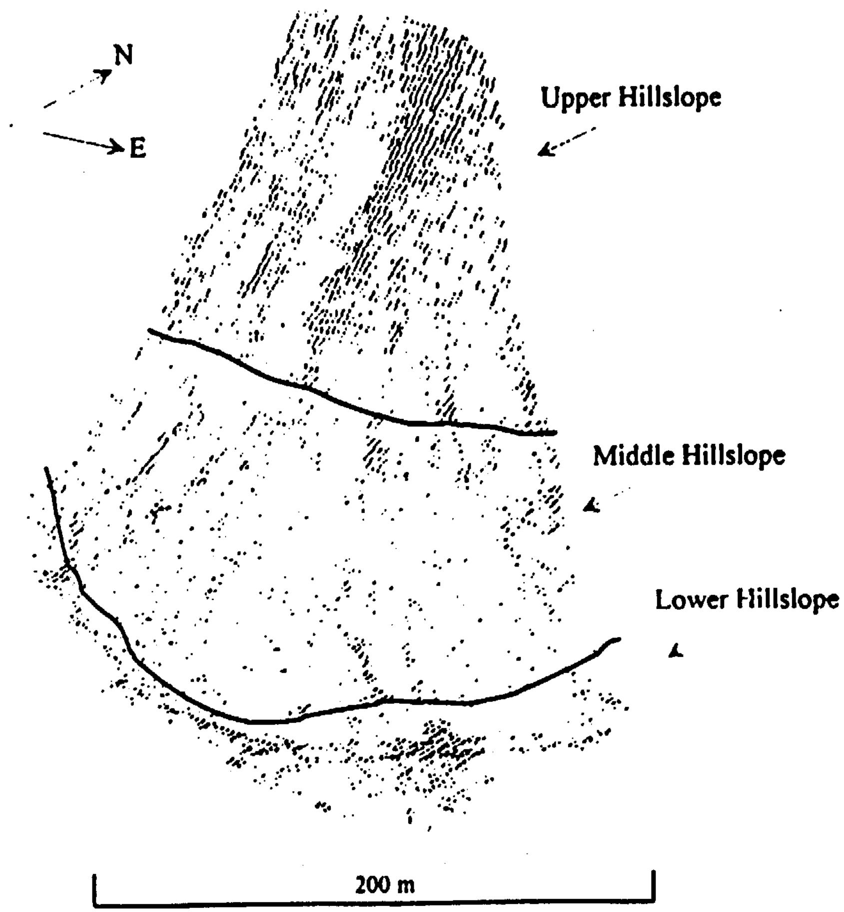


Fig 6B

Figure 7. Slope map derived from 1982 digital elevation model. Hillslope zones shown are defined in the text. A, slope map. B. perspective view of 1982 slope map overlaid on topography. Topographic relief from the base of the hillslope to the top of the ridge is approximately 130 m. View direction is along an azimuth of 330°. View angle is 25° above horizontal.

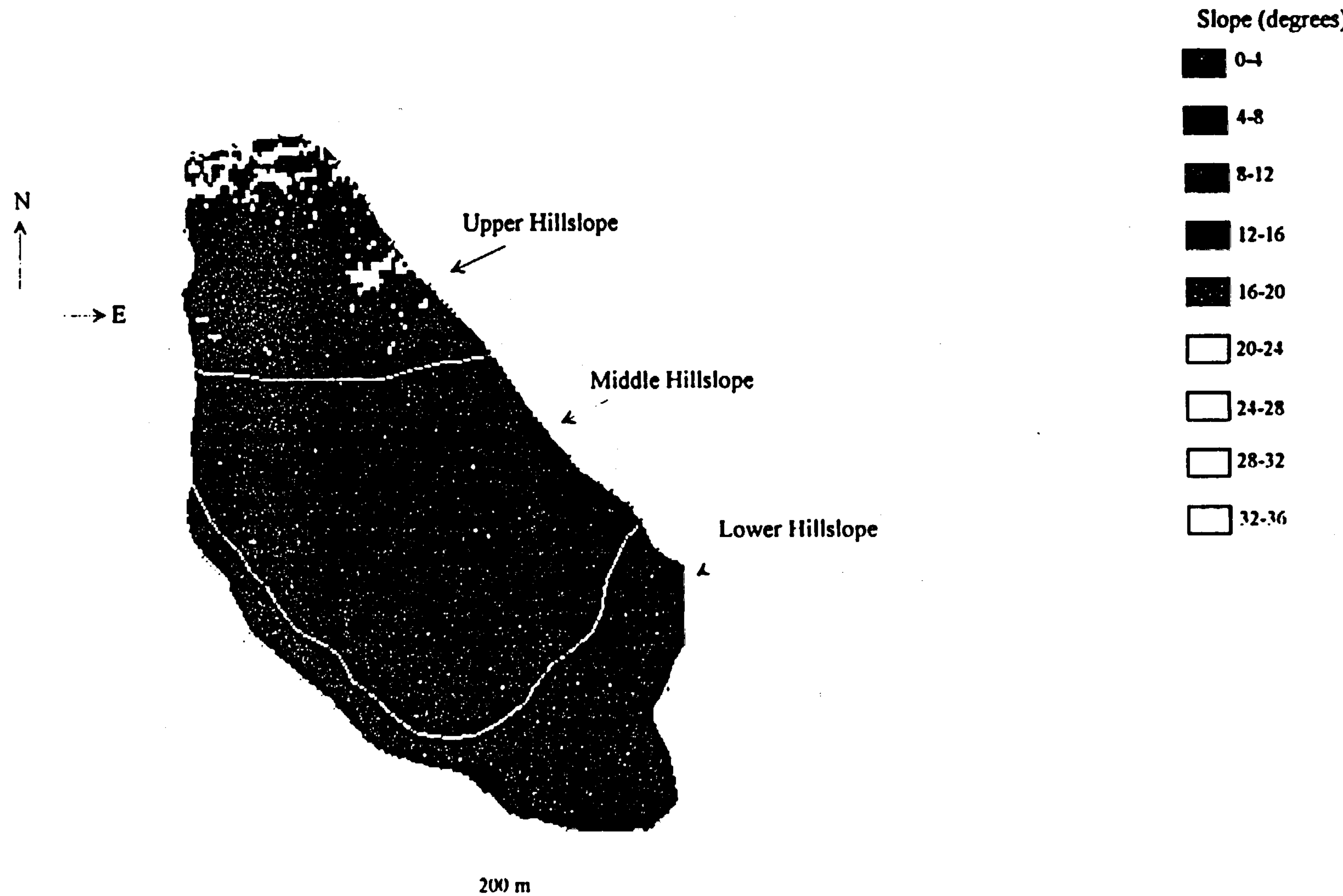

Slope (degrees)
0-4
4-8
8-12
12-16
16-20
20-24
24-28
28-32
32-36
N
E
Upper Hillslope
Middle Hillslope
Lower Hillslope
200 m

Fig. 7A

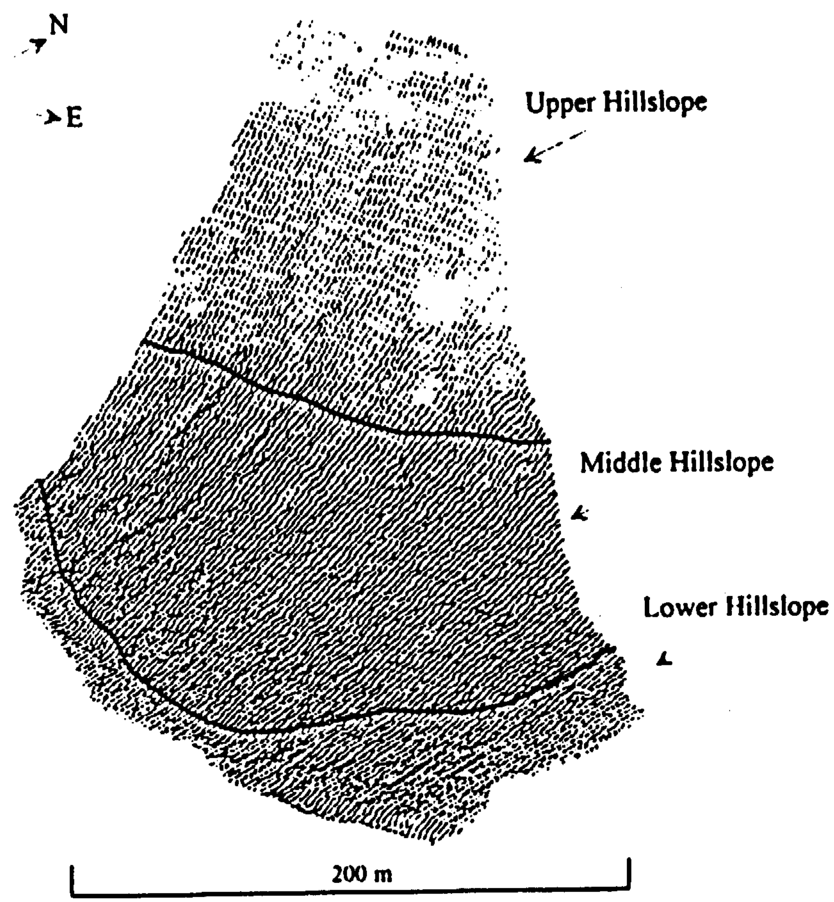


fig 7b

VOLUMETRIC ANALYSIS

Net volumes for each hillslope zone were calculated as follows:

$$V = \frac{A}{n}\sum_{i}^{n}\Delta z_i \qquad (1)$$

where V is volume, A is area, n is the number of 2x2 m cells, and Δz is the elevation difference value (1991 elevation - 1982 elevation). In order to estimate errors for the calculated volumes, equation 1 is further developed as follows:

$$V = A\frac{1}{n}\sum_{i}^{n}\Delta z_i \qquad (2)$$

which can be rewritten as

$$V = A\cdot\overline{\Delta z} \qquad (3)$$

where $\overline{\Delta z}$ is the mean Δz value. The standard deviation of V (σ_v) derived from equation 3 is given by ?:

$$\sigma_v = A\cdot\sigma_{\overline{\Delta z}} \qquad (4)$$

where $\sigma_{\overline{\Delta z}}$ is the standard error of $\overline{\Delta z}$. Substituting in equation 4 according to the equation for standard error of the mean ($\sigma_{\overline{\Delta z}} = \frac{\sigma_{\Delta z}}{\sqrt{n}}$) yields:

$$\sigma_v = \frac{A}{\sqrt{n}}\sigma_{\Delta z} \qquad (5)$$

Equation 5 was used to calculate the 2σ errors for the calculated volumes. As established previously, the 2σ value used for $\sigma_{\Delta z}$ in this equation was 0.28 m. Inherent in this volumetric analysis process was the assumption that erosion and deposition from other storms between 1982 and 1991 is negligible relative to that caused by the 1984 debris flows.

RESULTS

About 7,040 m^3 ±92 m^3 of colluvium was redistributed within the 49,132 m^2 Jake Ridge study area by the debris flows (table 1). About 2,460 m^3 ±124 m^3 (35%) of this colluvium was removed from the study area and about 4,580 m^3 ±81 m^3 (65 %) was deposited within the area. Thus, the overall study area was lowered by erosion an average of 5 cm. The colluvium that was removed was deposited in the short tributary to Fortymile Wash, and in the wash itself.

Erosion was greatest on the upper hillslope where slope gradients were generally greater than 12°. About 3,520 m^3 ±55 m^3 of colluvium was eroded from the upper hillslope, whereas only 310 m^3 ±15 m^3 was redeposited (table 1). At least 81 percent of the upper hillslope was affected by erosion. The two areas of maximum erosion (1.2 - 1.8 m) are on the upper hillslope (darkest blue, fig. 6) where large pieces of bedrock were removed. The mean depth of erosion on the upper hillslope was 27 cm. The middle hillslope, where slope gradients generally ranged from 4 to 12 degrees, was more equally affected by both erosion and deposition. About 55 percent of the middle hillslope was affected by erosion and 43 percent by deposition. The elevation of the other 2 percent of the area remained unchanged. The mean depth of erosion on the middle hillslope was about 4 cm. Most of the lower hillslope (68 percent) was affected by deposition. The main depositional areas on the lower hillslope are near the road and along the east-west-trending southern channel (fig. 6). The maximum thickness of deposition at the base of the hillslope was about 1.2 m. Small areas within the main depositional lobe at the road that show more than 1.2 m of deposition are the result of road grading after the storm. The mean depth of deposition on the lower slope was 16 cm.

TABLE 1 NEAR HERE

DISCUSSION

Processes

There were probably several initation mechanisms for the debris flows. Some water may have percolated down through the cobble mantle on the hilltop into the underlying fractured caprock and then exited the fractures at the cliff face. Several triangular stripped areas increase in size downslope from fractures in and just below the face. These light colored areas at the cliff face are visible in the 1991 photographs (fig. 2). This suggests that at least some debris movement was initiated by streams of water flowing from the caprock and applying a 'fire hose' effect (Johnson and Rodine, 1984) to the hillslope colluvium. The relatively low permeability of the underlying bedrock, probably combined with an already saturated colluvial mantle, would have prohibited this water from dispersing into the slope, and encouraged shallow mass movement failures or 'soil slips' (Campbell, 1975, Ellen and Fleming, 1987). With the inclusion of additional water, these initial soil slips would have then flowed downslope in the available channels on the upper hillslope. The presence of levees suggests these flows were fairly rapid.

Table 1. Volumetric change for each hillslope zone shown in figure 6. Percentages are of the total area for each zone.

Polygon	Area (m^2)	Negative Volume (m^3)	Area with negative cell volumes (m^2)	Positive Volume (m^3)	Area with positive cell volumes (m^2)	Area with cell volumes = 0 (m^2)	Volume Sum (m3)
Upper Slope	11748	-3520 ±55	9532 (81%)	+310 ±15	1184 (16%)	332 (3%)	-3210 ±61
Middle Slope	25688	-2970 ±67	14200 (55%)	+1890 ±58	10908 (43%)	580 (2%)	-1080 ±90
Lower Slope	11696	-550 ±32	3228 (28%)	+2380 ±50	8012 (68%)	456 (4%)	+1830 ±61
Study Area	49132	-7040 ±92	26960 (55%)	+4580 ±81	20804 (42%)	1368 (3%)	-2460 ±124

The creation of new channels and the deepening of existing channels on the middle and lower hillslopes suggests that at least some erosion took place by channel scour before and after the debris flows. Additionally, inspection of interchannel areas (fig. 2) on the elevation difference map (fig. 6) suggests that substantial erosion and deposition took place by surface wash.

Recurrence Interval

Precipitation rates described above and shown in figure 3 indicate that the most intensive period of recorded rainfall occurred during a 2-hour period on the evening of July 21. The magnitude of a 2-hour storm with a probable 100-year recurrence interval was calculated as about 29 mm using methods prescribed in the Precipitation-Frequency Atlas of the western United States (Miller and others. 1973). Thus. the 2-hour totals of 60 and 58 mm recorded by gages YA and YR, respectively, are about twice those expected with a 1 percent probability of occurrence in any given year. A probable maximum precipitation rate calculated for a 2-hour duration storm in the arid southwestern U.S. is about 307 mm (Hansen and others. 1977); or about five times greater than that recorded by the Yucca Mountain rain gages on July 21.

The accumulation and intensity of rainfall at Jake Ridge, about 5.4 km northeast of rain gages YA and YR, is unknown. It is unlikely, however, that the maximum rainfall during the storms occurred at gages YA and YR. The established record of debris flows in the vicinity of these gages (Glancy, 1994) and the absense of flows during the 1984 storms reinforces the likelihood that rainfall amounts and intensities were greater at Jake Ridge than those recorded at gages YA and YR.

The 100-year flood peak (Q_{100}) of Fortymile Wash at gage SG (fig. 1) is estimated at about 330 m^3/sec. using an equation developed by Squires and Young (1984). Peak discharge recorded by gage SG during the storms of July 1984 of 21 m^3/sec. (fig. 4) is only about 6 percent of the predicted Q_{100}. Using equations developed by Christensen and Spahr (1980), Q_{100} is about 650 m^3/sec. and Q_{10} is about 96 m^3/sec. Accordingly, the peak discharge of 21 m^3/sec. is only about 20 percent of Q_{10}. This relatively minor runoff of Fortymile Wash, in spite of the intense rainfall at Yucca Mountain and the debris flows at Jake Ridge, emphasizes the local nature of the July storm.

About 2,460 m^3 of sediment was removed from the south-facing hillslope of Jake Ridge. The entire south-facing hillslope study area is 49,132 m^2. Field observations indicate that non-channelized areas of the south-facing hillslope are generally mantled by 0-2 m of colluvium. If a mean value of 1 m is assumed for the amount of unconsolidated colluvium cover, then approximately 49,000 m^3 of debris would have existed on the south-facing hillslope prior to the July 1984 storms. Therefore, about 5 percent of the available colluvium was removed from the hillslope during the two-day storm.

Because precipitation gaging sites in the southern Great Basin are widely scattered and have not been in operation for long periods of time (generally less than 50 years) it is difficult to access the recurrence of a storm comparable to that of July 21 and 22, 1984. If storms of similar magnitude and intensity as the July 1984 storm were to revisit Jake Ridge every 100 years, for example, and the hillslope was eroded by similar debris flows, then most of the pre-July 1984 colluvium (about 49,000 m^3) would be stripped in a few thousand years. A 300-year storm interval would strip the available colluvium in about 6,000 years. These scenarios assume that no new hillslope colluvium is weathered from the underlying bedrock during that time. Whitney and Harrington (1988) suggest that most of the coarse hillslope colluvium that mantles hillslopes in the Yucca Mountain area was weathered during cooler, pluvial climates. Additionally, they observe that weathering processes operating under the present dry, interpluvial climate are not capable of producing coarse hillslope colluvium. Some of the colluvium on Jake Ridge appears to have been stable for at least tens of thousands of years, as evidenced by accumulations of dark rock varnish on the surface of boulders in the colluvium. Comparison of the average lowering of the Jake Ridge study area (5 cm) to existing estimates of long-term erosion rates at Yucca Mountain (0.2 to 7 mm/ka, Harrington and Whitney, 1991; Coe and others, 1993) suggests that the Jake Ridge debris flows were a rare occurrence for the Yucca Mountain area. Based on the arguments outlined above, and from the probability of comparable storm occurrence suggested by the precipitation frequency atlas, the probable recurrence interval of intense debris-flow erosion at Jake Ridge, similar to that of 1984, is at least 100 years.

SUMMARY

A photogrammetric method has been used to volumetrically calculate net erosion and sediment redistribution on an individual hillslope. About 2,460 m^3 (5 percent) of the available colluvium was removed from the Jake Ridge study area during a two-day period of convective rainstorms. The mean depth of erosion for the overall study area was about 5 cm. The maximum depth of localized erosion and deposition was about 1.8 m and 1.2 m respectively. Nearby rain gages recorded up to 69 mm of rain at intensities that reached 73 mm/hour. Analysis of cumulative precipitation from the main storm on July 21 indicates that it was more than double that expected to occur once, on average, in 100 years. Based on this estimate of precipitation frequency, the percentage of available colluvium eroded during the storms, and the stable nature of the remaining undisturbed colluvium, the long-term average recurrence interval for large scale, debris-flow erosion at Jake Ridge is estimated to be at least 100 years. The interval may be significantly longer. It is likely that the amount of rain that fell at Jake Ridge and triggered debris flows, was greater and/or more intense than that recorded at the rain gages, where debris flows did not occur. The recurrence interval of this more intense storm would be longer than that estimated here on the basis of gaged precipitation.

The photogrammetric approach used in this study is dependent upon the availability, scale, and resolution quality of pre-event stereographic photographs. The accuracy of the method is principally controlled by the scale of the pre-event photographs because post-event photography can be flown at any desired scale. We consider the 1:8,000 scale pre-event photography used in this study to be at the scale limit that is practical to accurately detect elevation changes associated with erosion and deposition less than about 10 cm.

REFERENCES CITED

Band, L.E., 1986, Topographic partition of watersheds with digital elevation models: Water Resources Research, v. 22, no. 1, p. 15-24.

Baum R.L., and Fleming, R.W., 1991, Use of longitudinal strain in identifying driving and resisting elements of landslides: Geological Society of America Bulletin, v. 103, p. 1121-1132.

Beaty, C.B., 1970, Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, USA: American Journal of Science, v. 268, p. 50-77.

Bergman, K.H., 1984, The climate of autumn 1983--featuring the conclusion of a major el Nino event: Monthly Weather Review, v. 112, p. 1141-1456.

Brunsden, Denys, 1993, Mass movement, the research frontier and beyond--A geomorphological approach: Geomorphology, v. 7, p. 85-128.

Brunsden, Denys, and Jones, D.K.C., 1976, The evolution of landslide slopes in Dorset: Philosophical Transactions: Royal Society of London, v. A283, p. 605-631.

Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Chandler, J.H., and Moore, R., 1989, Analytical photogrammetry--a method for monitoring slope instability: Quarterly Journal of Engineering Geology, v. 22, p. 97-110.

Christensen, R.C., and Spahr, N.E., 1980. Flood potential of Topopah Wash and tributaries, eastern part of Jackass Flats, Nevada Test Site, southern Nevada: U.S. Geological Open-File Report 80-963, 26 p.

Christiansen, R.L., and Lipman, P.W., 1965. Geologic map of the Topopah Spring Northwest quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-444, scale 1:24000.

Coe, J.A., Whitney, J. W., and Harrington, C.D., 1993. Photogrammetric analysis of Quaternary hillslope erosion at Yucca Mountain, Nevada: Geological Society of America Abstracts with Programs, v. v. 25, no. 5, p. 22.

Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa J.E., and Fleisher, P.J., eds., Developments and applications of Geomorphology: Berlin, Springer, pp. 268-317.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., and McKean, James, 1993, Analysis of erosion thresholds, channel networks, and landscape morphology, using a digital terrain model: The Journal of Geology, v. 101, p. 259-278.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, James, and Bauer, Romy., 1992, Erosion thresholds and land surface morphology, Geology, v. 20, p. 675-679.

Eastman, J.R., 1992, IDRISI GIS technical reference guide: Worcester, Massachusetts, Clark University Graduate School of Geography, 213 p.

Ellen, S.D., and Fleming, R.W., 1987, Mobilization of debris flows from soil slips, San Francisco Bay region, California, *in* Costa, J.E., and Wieczorek, Flows/avalanches--process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 31-40.

Frizzell, V.A. and Shulters, Jacqueline, 1990, Geologic map of the Nevada Test Site, southern Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2046, scale 1:100,000.

Glancy, P.A., 1968, A mudflow in the Second Creek drainage, Lake Tahoe Basin, Nevada, and its relation to sedimentation and urbanization: U.S. Geological Survey Professional Paper 650-C, p. C195-C200.

Glancy, P.A., 1994, Evidence of prehistoric flooding and the potential for future flooding at Coyote Wash, Yucca Mountain, Nevada. U.S. Geological Survey Open File Report 92-458, 31 p.

Glancy, P.A. and Harmsen, L., 1975, A hydrologic assesment of the September 14, 1974, flood in El Dorado Canyon, Nevada: U.S. Geological Survey Professional Paper 930, 28 p.

Ghosh, S.K., 1988, Analytical photogrammetry, 2nd ed., New York, Pergamon Press, 308 p.

Goudie, A.S., 1990, Geomorphological techniques, 2nd ed., London, Unwin Hyman, 570 p.

Hansen, M.E., and Schwartz, F.K., 1981, Meteorology of important rainstorms in the Colorado River and Great Basin drainages: U.S. Department of the Army Hydrometeorological Report 50, 167 p.

Hansen, M.E., Schwartz, F.K., and Riedel, J.T., 1977, Probable maximum precipitation estimates, Colorado River and Great Basin drainages: U.S. Department of Commerce and U.S. Department of the Army Hydrometeorological Report 49, 161 p.

Harrington, C.D., and Whitney, J.W., 1991, Quaternary erosion rates on hillslopes in the Yucca Mountain region, Nevada: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A118.

Hirschboeck, K.K., 1991, Hydrology of floods and droughts, climate and floods, *in* National Water Summary 1988-89--hydrologic events and floods and drought: U.S. Geological Survey Water Supply Paper 2375, p. 67-88.

Houghton, J.G., Sakamoto, C.M., and Gifford, R.O., 1975, Nevada's weather and climate: Nevada Bureau of Mines and Geology, Special Publication 2, 78 p.

Huberty, Brian, and Anderson, Carl, 1990, Coal pile inventory using 35-mm oblique terrestrial photogrammetry: Photogrammetric Engineering and Remote Sensing, v. 56, no. 8, p. 1169-1171.

Johnson, A.M. and Rodine, J.R., 1984, Debris flows, *in* Brunsden, Denys, and Prior, D.B., eds., Slope instability, Chichester, Wiley, p. 257-361.

Katzer, T.L., Glancy, P.A., and Harmsen, Lynn, 1976, A brief hydrologic appraisal of the July 3-4, 1975, flash flood in Las Vegas Valley, Nevada: Clark County Flood Control Division, Department of Public Works, 40 p.

Massa, W.S., 1958, Inventory of large coal piles, Photogrammetric Engineering, v. 24, no. 1, p. 77-81.

Miller, J.F., Frederick, R.H., and Tracey, R.J., 1973, Precipitation-frequency atlas of the western United States, NOAA Atlas 2, Volume VII-Nevada: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, Maryland, 43 p.

Mills, H.H., 1992, Post-eruption erosion and deposition in the 1980 crater of Mount St. Helens, Washington, determined from digital maps: Earth surface processes and landforms, v. 17, p. 739-754.

National Oceanic and Atmospheric Administration, 1974, Report on the flash flood of September 14, 1974, in El Dorado Canyon, Nevada: National Weather Service, Western Region, Special Report, 20 p.

Oberlander, T.M., 1974, Landscape inheritance and the pediment problem in the Mojave desert of southern California: American Journal of Science, v. 274, p. 849-875.

Pabst, M.E., Beck, D.A., Glancy, P.A., and Johnson, J.A., 1993, Streamflow and selected precipitation data for Yucca Mountain and vicinity, Nye County, Nevada, Water Years 1983-85: U.S. Geological Survey Open-File Report 93-438, 66 p.

Quiring, R.F., 1983, Precipitation climatology of the Nevada Test Site: U.S. Weather Service, Nuclear Support Office Publication WSNSO 351-88, 34 p.

Randerson, Darryl, 1976, Meteorological analysis for the Las Vegas, Nevada flood of 3 July 1975: Monthly Weather Review, v. 104, p. 719-727.

Randerson, Darryl, 1986, A mesoscale convective complex type storm over the desert southwest: US National Weather Service, NOAA Technical Memorandum NWS WR-196, 54 p.

Ropelewski, C.F., 1985, Seasonal climate summary--the global climate June-August 1984-A return to "normal" in the tropics: Monthly Weather Review, v. 113, April 1985, p. 664-679.

Scott, R.B. and Bonk, Jerry, 1984, Preliminary geologic map of Yucca Mountain, Nye County, Nevada with geologic sections: U.S. Geological Survey Open-File Report 84-494.

Slama, C.C., Theurer, Charles, and Henriksen, S.W., 1980, Manual of photogrammetry: Bethesda, Maryland, American Society of Photogrammetry and Remote Sensing, 1056 p.

Squires R.R., and Young, R.L., 1984, Flood potential of Fortymile Wash and its principal southwestern tributaries, Nevada Test Site, Southern Nevada: U.S. Geological Survey Open-File Report 83-4001, 33 p.

Tribe, Andrea, 1991, Automated recognition of valley heads from digital elevation models: Earth Surface Processes and Landforms, v. 16, p. 33-49.

U.S. Department of Energy, 1988, Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development, Nevada, U.S. Department of Energy, DOE/RW-0199: Washington, D.C.

Williams, G.P. and Costa, J.E., 1988, Geomorphic measurements after a flood: *in* Baker V.R., Kochel R.C., and Patton P.C., eds., Flood geomorphology, New York, Wiley, p. 65-77.

Whitney, J.W., and Harrington, C.D., 1988, Middle Pleistocene colluvial boulder flows on Yucca Mountain in southern Nevada: Geological Society of America, Abstracts with Programs, v. 20, no. 7, p. A348.

Whitney, J.W. and Harrington, C.D., 1994, Relict colluvial boulder deposits-indicators of climatic change and long-term slope stability in the Yucca Mountain region, southern Nevada: Geological Society of America Bulletin, v.105, p. 1008-1018.

Winograd, I.J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.

Wohl, E.E., and Pearthree P.P., 1991, Debris flows as geomorphic agents in the Huachuca Mountains of southeastern Arizona: Geomorphology, v. 4, p. 273-292.

3/8/95

NOTE TO RECORDS:

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Figure 6a, 6b, 7a, and 7b from this U.S.G.S. Administrative Report need to be in color for the interpretations in this report to be communicated clearly. A version of this publication with these four figures, in color, can be located at:

Yucca Mountain Site Characterization Office
Research and Study Center, P-106
101 Convention Center Drive
Las Vegas, NV 89019

9136200 2520

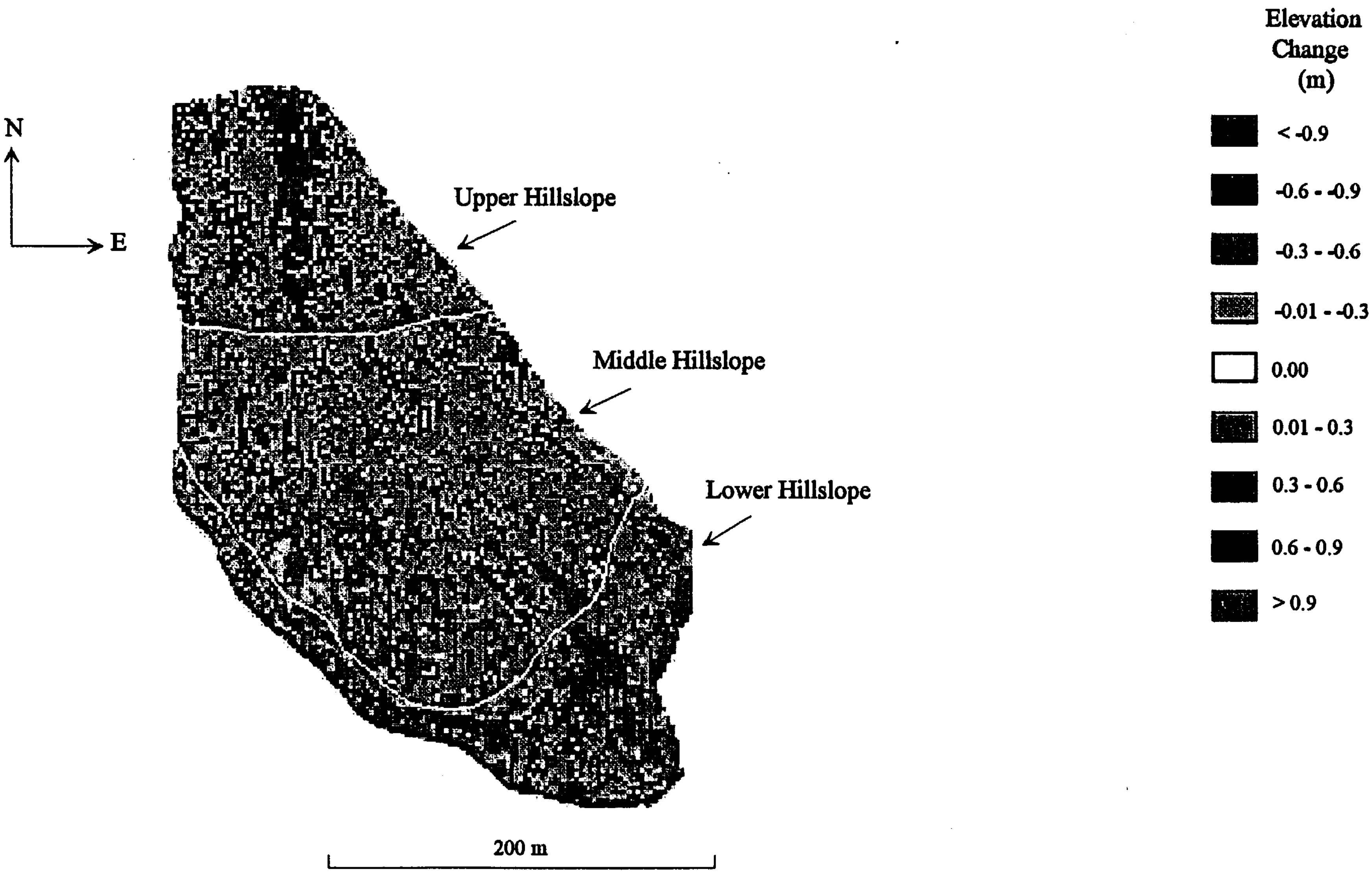
N
E
Upper Hillslope
Middle Hillslope
Lower Hillslope
200 m
Elevation Change (m)
< -0.9
-0.6 - -0.9
-0.3 - -0.6
-0.01 - -0.3
0.00
0.01 - 0.3
0.3 - 0.6
0.6 - 0.9
> 0.9

Figure 6a.

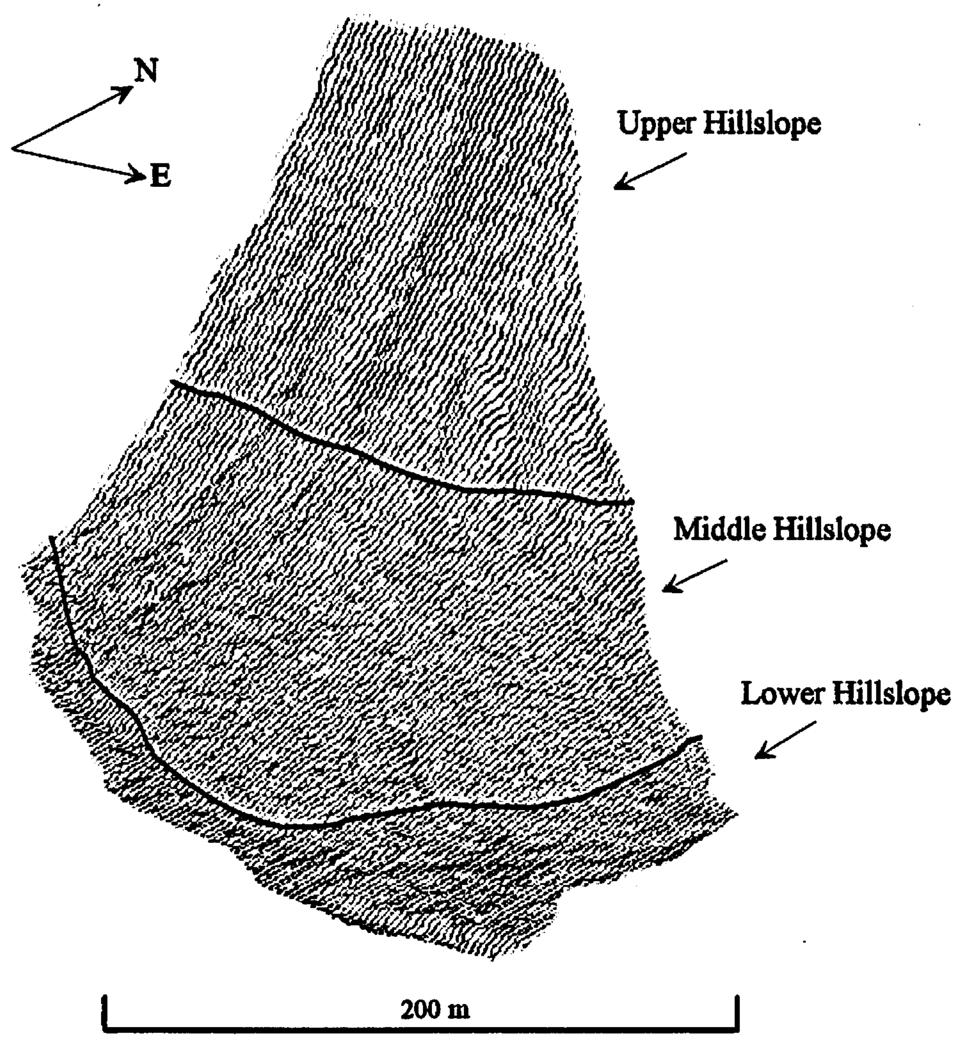

Figure 6b.

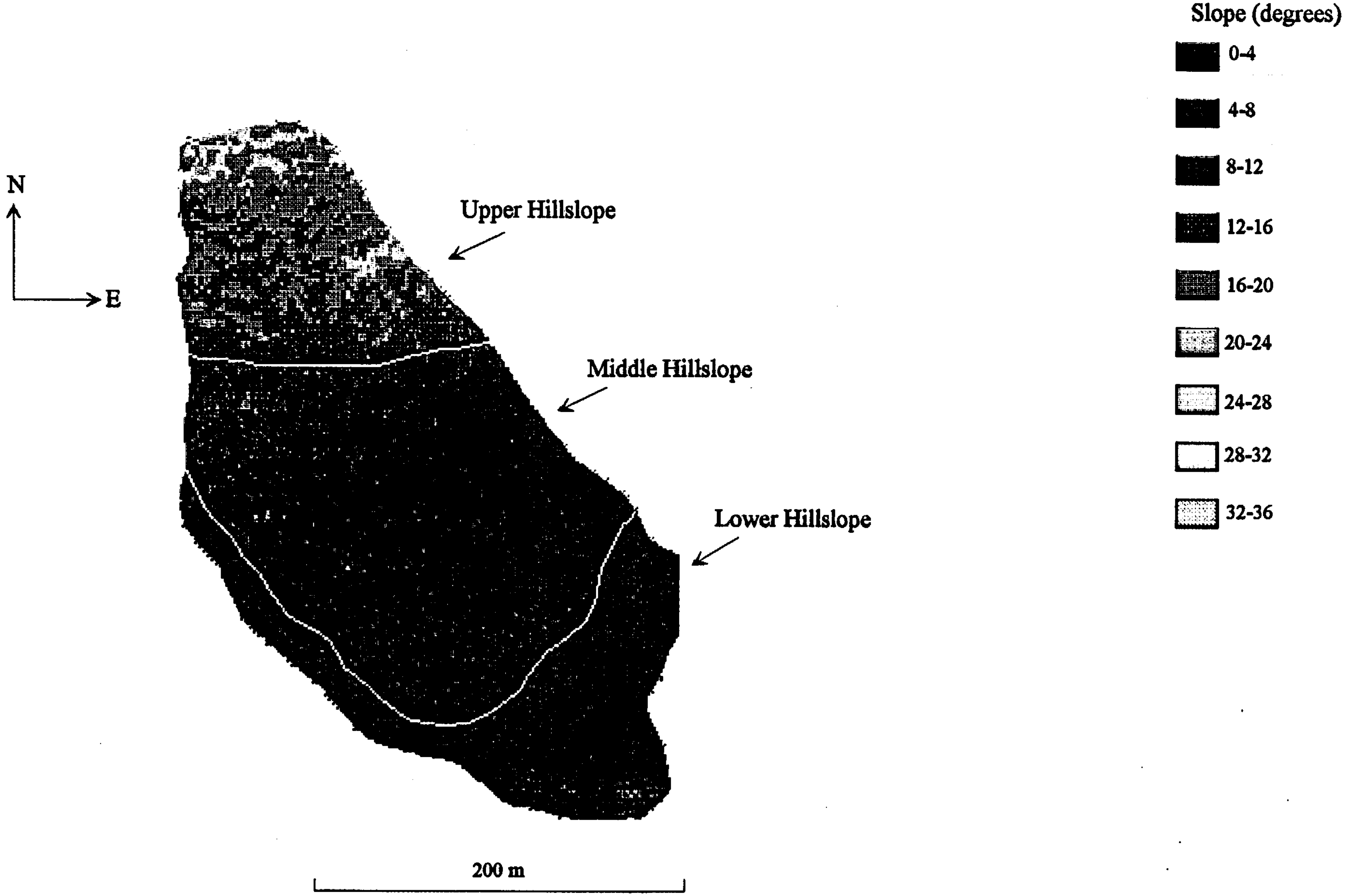
N
E
Upper Hillslope
Middle Hillslope
Lower Hillslope
200 m
Slope (degrees)
0-4
4-8
8-12
12-16
16-20
20-24
24-28
28-32
32-36

Figure 7a.

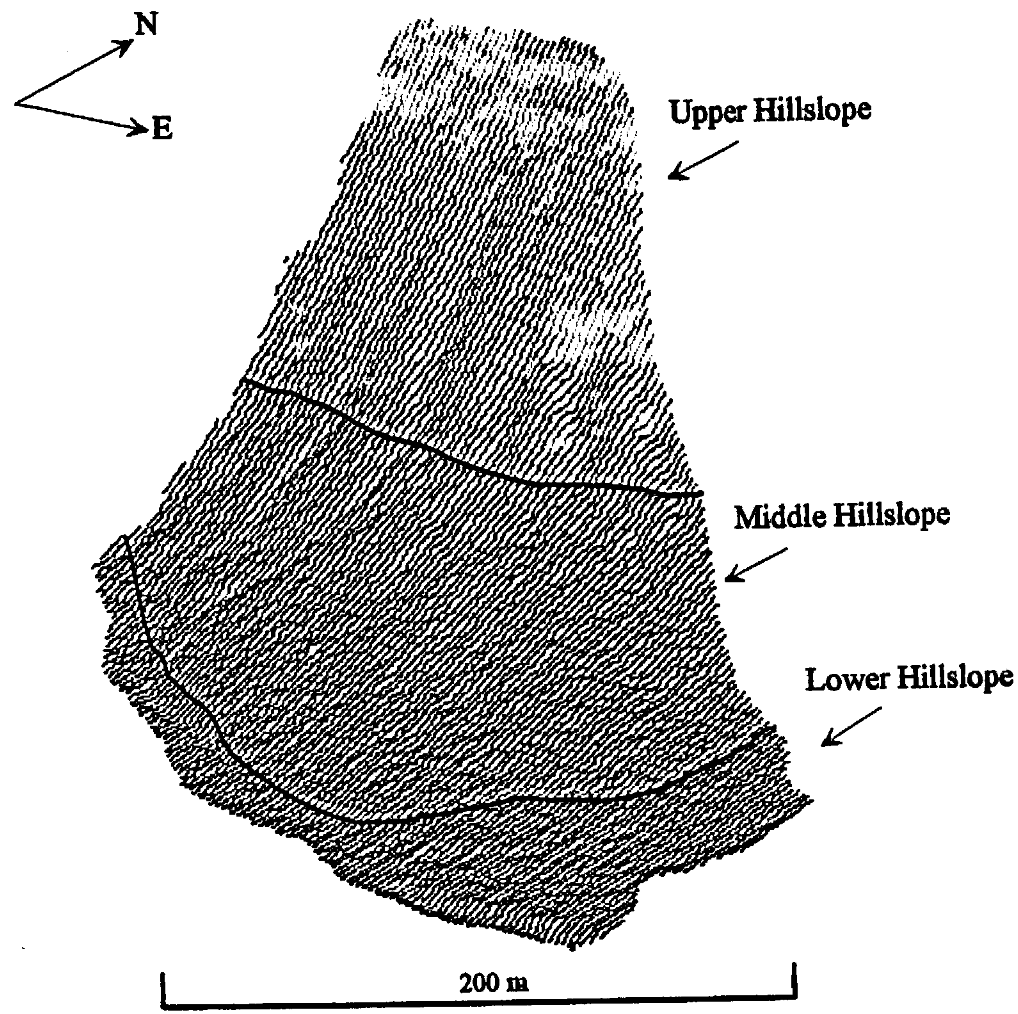

Figure 7b.