LANDSLIDES AND OTHER MASS MOVEMENTS NEAR TA-33, NORTHERN WHITE ROCK CANYON, NEW MEXICO--FINAL REPORT, SUBCONTRACT 9-LC3-6519F-1

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ABSTRACT

Massive slump complexes and at least two rock avalanches flank the eastern rim of the Pajarito Plateau along northern White Rock Canyon, north of TA-33. Landslides failed along mechanically weak rocks in the Santa Fe Group, within the Puye Formation, or in Pliocene alluvial and lacustrine units. The landslides are mainly of early or middle Pleistocene age. The toe area of at least one slump complex has been active in the late Pleistocene, damming White Rock Canyon near the mouth of Water Canyon. Lacustrine sediment that filled this lake, or series of lakes, to an elevation of at least 1710 m is preserved at a number of upstream sites, including a deposit near the Buckman townsite that exposes 30 m of lacustrine sediment. Charcoal collected at several sites has been submitted for ^{14}C dating. Landslides, however, probably do not represent a significant short-term threat to the material disposal areas at TA-33. Bedrock that lies beneath the TA-33 mesa is relatively stable, the mesa shows no signs of incipient failure, and past periods of slide activity were responses to rapid downcutting of the Rio Grande and climate change, probably over periods of several decades, at least.

Rockfall and headward erosion of gullies do not represent significant decadal hazards on canyon rims near TA-33. Gully migration near MDA-K is a potential threat, but the gullies were not examined in detail. A system of north-trending faults, at least one of which displays Pleistocene activity, bisects the TA-33 mesa. If these faults are capable of producing significant seismic shaking, generalizations about landslide and rockfall hazards must be reevaluated.

INTRODUCTION

White Rock Canyon (WRC) was cut by the Rio Grande from Otowi bridge to near Cochiti Dam (Fig. 1) in Miocene through early Quaternary rocks. The northern part of the Canyon is flanked by extensive landslides and small areas of Quaternary alluvial, fluvial and lacustrine deposits. The landslides, mostly massive slumps and flows derived from the slumps, extend from near the Rio Grande to the canyon rims along more than 80% of the area between Ancho Canyon and Otowi bridge. Slides are smaller and more widely spaced to the south. Most slides incorporate basalt and resistant rock types that underlie the basalt; several slides, the most prominent southwest of Water Canyon, include coherent beds of upper Bandelier Tuff. Soils containing Stage IV B_{ca} horizons and covering deposits of the el Cajete tephra (~150,000 years before present(?)) suggest that most slides failed in the early or middle Pleistocene. Reactivation of at least one and probably several slump complexes dammed northern White Rock Canyon (NWRC) near the mouth of Water

Canyon, forming lakes that extended tens of kilometers upstream. The youngest period of lacustrine deposition is probably late Pleistocene, and may be as young as a few tens of thousands of years ago.

The history of NWRC and the stratigraphy, age and geologic history of bedrock and surficial materials are summarized by Dethier (1993a). Bedrock geology is discussed in more detail by Spiegel and Baldwin (1963), Griggs (1963), Aubele (1978), and Dethier (1993b). This report summarizes field data collected in the vicinity of TA-33 during field studies with S. Reneau in 1993; age control based on ^{14}C and other techniques will be reported in a later paper.

SETTING

Northern White Rock Canyon (NWRC), for purposes of this report, begins at Otowi bridge and extends south to the vicinity of Chaquehui Canyon in the southern Espanola basin. This section of White Rock Canyon is bounded by the Pajarito Plateau to the west, the Cerros del Rio to the east and the broad flood plain of the Rio Grande to the north. Topography is steep and rugged in the canyon and along major tributaries that drain the Pajarito Plateau (Fig. 2) such as Mortandad and Ancho Canyon. Local relief ranges from 170 to more than 300 m and cliff areas as high as 100 m are common.

CLIMATE AND VEGETATION

Slope stability along NWRC is probably a function of climate, particularly effective moisture, the magnitude and duration of erosive peak flows on the Rio Grande, and periods of rapid canyon cutting induced by shifts in canyon position. Present climate near NWRC is not monitored, but is arid to semi-arid with annual precipitation of about 250 mm and mean annual temperature of about 15° C along the floor of the canyon (see Spaulding, 1992). Many tributaries to the Rio Grande, such as Los Alamos Canyon, drain areas that receive at least 50% more precipitation and are 3 to 5 °C cooler. Precipitation in the Jemez Mountains exceeds 500 mm. In most years about half of the annual precipitation occurs during intense convective storms associated with the summer monsoon season of July and August. During the rest of the year precipitation is associated with frontal passage and tends to be less intense. Before extensive upstream damming and diversion for agriculture, peak discharge in the Rio Grande tended to occur in two periods (Nordin and Beverage,1965). The summer storm season was characterized by peak flows of relatively short duration whereas the snowmelt season of April -June produced sustained flows and high peak discharges. Channel scour and at least local lowering of base level is thus most likely during the latter flows.

Vegetation is sparse near the Canyon, to the east for tens of km and for several km to the west. Sagebrush, rabbit brush, grasses and cactus are common near the bottom of the Canyon, giving way to a mixture of pinon, juniper and grassland on Canyon slopes and in the lower reaches of tributary canyons and to pinion and Ponderosa pine to the west of the Canyon (Spaulding, 1992). Vegetation is generally most dense on north-facing slopes, and most sparse on slopes with south aspect.

PALEOCLIMATE

Late Cenozoic climates are not well documented in the southwestern U.S.; even latest Pleistocene and Holocene changes in temperature and precipitation are not well constrained. Wolfe (1978) suggests that Pliocene climate of the northern hemisphere was similar to that of the late Holocene. In the southern U.S., Pliocene climate may also be similar to that of the late Holocene. Fossil records from northern latitudes (Wolfe, 1978) show that these areas were warmer than at present during the Pliocene, but that differences were minimal at lower latitude such as that of New Mexico. Thick, buried B_{Ca} horizons within the upper Puye Formation (Waresback, 1986) and on some Pliocene basalt flows near White Rock suggest that extended warm, dry periods characterized at least some of Pliocene time.

Pleistocene climates presumably have alternated between colder and wetter (?) pluvial periods and warmer, drier interpluvials, but the scale of these changes is not well known. Records of climate change extracted from pluvial lakes (for instance Smith,1984) and from speleothems or vein calcite offer the best hope for reconstructing terrestrial Pleistocene paleoclimate, although records and dating for the early Pleistocene are incomplete. Winograd and others (1992) suggest that pluvial periods during the past 180,000 years may have been cooler than older pluvial periods. The late Pleistocene in northern New Mexico, for instance, has been characterized as dry and cold (Galloway, 1970) or as moist and cool (Bachhuber, 1989). Geologic evidence demonstrates that the upper Rio Grande drainage in New Mexico and Colorado supported extensive alpine glaciers during the middle and late Pleistocene and that water input to nearby pluvial lakes was synchronous with glacial maxima (Allen and Anderson, 1993). Maximum discharges along the Rio Grande during peak melt periods must have been greater than those that occurred during the late Holocene.

AGE CONTROL FOR QUATERNARY DEPOSITS

Age control for Quaternary landslides and other deposits is not yet well-established, but one marker unit, the 150 ka el Cajete tephra, offers radiometric control and charcoal fragments in lacustrine sediment have beeng submitted for dating by ^{14}C techniques. Amino-acid ratios from fossil gastropods, particularly *Succinea* and *Vallonia*, in sediment associated with landslides, can be used to calculate an approximate age for the sediment (Dethier and McCoy, 1993). I have also made semiquantitative age estimates for deposits based on the degree of soil development, particularly the morphology of B_{Ca} horizons. Age estimates based on cation ratios in rock varnish (see Dethier and others, 1988) are noted below, but the accuracy of ages from this technique is not known.

Three other techniques have potential application in the NWRC area. Thermoluminescence (TL) or electron-spin resonance (ESR) techniques could be applied to some of the sedimentary sequences, using age control derived from elsewhere in the Espanola basin. The paleomagnetic signature, particularly intensity, of lacustrine deposits at Buckman might permit correlation with dated paleomagnetic sequences from other sites in the western United States. Techniques based on the accumulation of cosmogenic isotopes such as Al, Be, Ne, or Cl have already been applied to questions of erosion rate in the vicinity of NWRC(Albrecht and others, 1993). When the validity of such techniques is better established, they could be used to calculate exposure ages for large blocks on some of the landslides, or possibly rates of cliff retreat along the edge of the Pajarito Plateau.

METHOD

I mapped the geology of the area NW of the Rio Grande between Chaquehui Canyon and Water Canyon at a scale of 1:6,000, and performed reconnaissance investigations of landslides and lacustrine deposits as far north as Otowi bridge. I also did a detailed survey of the stability of the canyon rim NE of Chaquehui Canyon and along the south-facing portion of the TA-33. In the detailed survey, I recorded the location of all young (late Holocene) rockfalls that contained two or more blocks. Rockfalls were judged to be young when they met the following criteria : (1)one edge of each fallen block > 50 cm; (2) blocks generally unstable; (3) absence of lichen cover, rock varnish, or weathering "patina" on fresh surfaces exposed by the rockfall; (4) presence of caliche on most joint surfaces exposed by rockfall and (5) no rounding of fresh surfaces of fallen blocks. I examined size characteristics of 23 areas where rockfalls had occurred and hunted along the rim for areas of widened joints, fresh fractures, and other evidence of incipient failure. I also recorded the location of all late Holocene gullies cut > 40 cm deep into Pleistocene or Holocene sediment in the vicinity of the TA-33 rim, and on a reconnaissance basis SE of MDA-K at TA-33.

RESULTS

Plate 1 (sent under separate cover to Steve Reneau, LANL) shows the location of landslides and other surficial deposits, rockfall and gully locations, and reconnaissance bedrock geology in the vicinity of TA-33.

BEDROCK GEOLOGY

Cliffs and scarps of landslides along WRC expose as much as 250 m of horizontal to slightly dipping Miocene, Pliocene, and lower Quaternary rocks. Principal units, from oldest to youngest (see Table 1), include the sedimentary rocks of the Santa Fe Group, volcaniclastic and quartzite-rich gravel of the Puye Formation, older alluvial deposits, basaltic flows and phreatomagmatic deposits of the Cerros del Rio volcanic field, and the lower and upper Bandelier Tuff (Griggs, 1964; Dethier, 1993b). Figure 3 shows the interfingered relationships among the bedrock units near the northern end of WRC. Each of the bedrock units is incorporated, at least locally, into the massive slides that flank the Rio Grande. Most failure surfaces are apparently within the Santa Fe Group, Pliocene alluvium, or the volcanic deposits. The stratigraphy and selected characteristics of the bedrock units are summarized in Table 2; stratigraphic significance is described by Dethier (1993a;b).

PRE-MIDDLE PLEISTOCENE HISTORY OF WHITE ROCK CANYON AND VICINITY

Lateral shifts in the position of the ancestral Rio Grande during the mid-to late Pliocene were contemporary with net aggradation of almost 200 m near WRC, but thick, canyon-filling basalt flows suggest that local relief must have been at least 60 m at times during this period. The lower Bandelier Tuff lies locally on landslide debris, demonstrating that at least some mass movements took place during the late Pliocene. This is not surprising, given steep local slopes, and exposure of some of the same planes of failure that also caused slides during the Pleistocene. South of White Rock, the Rio Grande apparently flowed in a sinuous paleocanyon within 60 m of present grade before eruption of the lower Bandelier Tuff. Steve Reneau (LANL) has mapped remnants of the paleocanyon 1 to 2 km W. of the modern Rio Grande between Frijoles Canyon and Water Canyon. The paleocanyon apparently was shallower or absent north of White Rock, based on the elevation of the lower Bandelier Tuff near the present river. Both of the pyroclastic eruptions filled the paleocanyon and northern White Rock Canyon, damming the Rio Grande, at least briefly. A shift of the Rio Grande from its early Pleistocene paleocanyon and downcutting of 125- 250 m probably occurred rapidly after eruption of the 1.1 Ma upper Bandelier Tuff, but isolated gravel deposits from this time, located along the edge of the canyon and on some interfluves, have not been mapped in detail. Such mapping would be useful in analysis of landslide stability in the Pajarito Plateau area, since rapid incision by the Rio Grande and at least some of it tributaries probably induced massive slumping of unstable bedrock units.

LANDSLIDES IN THE VICINITY OF TA-33

Distribution

Pervasive landslides are among the most striking geologic features of White Rock Canyon north of the TA-33 area. Between TA-33 and Otowi bridge, a distance of about 16 km, slump complexes cover some 20 km^2, with an average distance between rims of about 1.8 km . In the 20 km south of Chaquehui Canyon, the distance between rims averages < 1 km and landslides cover <20% of this area (D.P. Dethier, unpublished mapping, 1985-86). Landslide zones between Chaquehui Canyon and Otowi bridge have been examined in reconnaisssance west of the Rio Grande and can be divided into 11 groups (Fig. 4;Table 3). Values for landslide size, defined as area/rim length, range from extremely small near Chaquehui Canyon to > 1.5 km^2/km between Ancho Canyon and Water Canyon. Plate 1 shows landslides and other deposits in the vicinity of TA-33 and TA-70 at a scale of 1:6,000. A cover of colluvial material, much of it older than ~150 ka, may conceal more extensive landslides south of the TA-33 mesa; bedrock could also lie beneath the colluvium.

Description and Age

Most landslides along NWRC are massive slump complexes covered with basaltic boulders, flanked by colluvium and talus, and best exposed between Ancho and Pajarito Canyons. Deposits consist of large slump blocks with coherent internal stratigraphy near canyon rims and progressively more deformed slumps that grade into debris flows closer to the Rio Grande (Table 3). Dips in massive slump blocks range from 8° to 70° toward head scarps. Many of the slump complexes consist of individual blocks separated by scarps that may have formed at different times. The eastern edge of Water Canyon W. (Fig. 4; Plate 1), for instance, includes several individual slumps that were active after deposition of the el Cajete tephra, possibly in late Pleistocene time. Slumps to the west are covered with the tephra, and may have formed during middle Pleistocene time.

Two slides, particularly one north of the mouth of Ancho Canyon, are topographically complex and have low height/length values, suggesting that they originated as avalanches or flows (Hsu, 1975). Gently sloping upper surfaces of slump blocks in many slide complexes are sites of fluvial, colluvial and eolian deposition and are separately mapped by Dethier (1993b). Small debris slides and areas of rockfall are common along the Rio Grande, particularly in areas affected by fluctuations in the pool elevation of Cochiti Lake. Small areas of recent rockfall are also scattered along steep canyon rims, particularly on the western side of NWRC.

Four small landslides (probably debris flows) consisting exclusively of Bandelier Tuff are exposed in Chaquehui Canyon SW of MDA-E. The slides rest on alluvial deposits of Chaquehui Canyon at the same elevation as that of the modern arroyo and do not seem to be covered with el Cajete tephra. The slides appear to be part of debris aprons shed from adjacent cliffs of upper Bandelier Tuff, but may be remnants of a larger mass that flowed from upstream. Neither the slide material nor the stratigraphic context is similar to other slides I have examined in the area

Slide material covers rocks of the Santa Fe Group, the Puye Formation, or landslide deposits at most sites. Morphology of most failures and inclusions of Bandelier Tuff in some (Water Canyon W.,for instance), suggests that slides were active in early to middle Pleistocene time, but that many became relatively stable in the middle or late Pleistocene. El Cajete tephra lies on landslide deposits in areas south of Chaquehui Canyon, where fall deposits were thickest. The tephra occurs as isolated deposits on most landslides and on many colluvial slopes north of Chaquehui Canyon, but is apparently not present on others. Fluvial reworking of the thin, pumiceous deposits makes geologic evidence equivocal at many sites. Contact relations with lacustrine deposits, discussed below, offer additional possibilities for age control.

Soils on landslide deposits are generally 0.8 to 1.4 m thick. Carbonate morphology (Birkeland, 1984; Machette, 1985) is Stage IV at some sites and Stage III carbonate is present in most exposures. Cation ratios in rock varnish (Dethier and others, 1988) on clasts from massive slumps at the SW edge of La Mesita and in the Mortandad Canyon and Overlook zones suggest that those slides stabilized at least 250,000 years ago.

Causes of Landslides

Landslides exposed along White Rock Canyon result from the steep slopes and removal of lateral support produced by canyon cutting, the occurrence of mechanically weak rocks such as layers of clayey altered volcanic rock, and fluctuations in the elevation of regional and perched water tables. Climate changes such as the greater effective moisture and more rapid downcutting associated with pluvial periods and shifts in canyon position probably helped to destabilize slides. Formation and sudden draining of lakes and earthquakes may have acted as short-term triggers for slide activity. The lower parts of failure planes are seldom exposed in NWRC. Dips of planes between slump blocks near the canyon rim are 70 to 85°, but slope morphology and mechanical considerations suggest that deeper parts of those planes must have shallow dips. In general, massive failures have occurred along: (1) steeply dipping planes rooted in the Santa Fe Group; (2) 10 to 30 ° planes (where measured) within the Puye Formation, fanglomerate facies; (3) subhorizontal planes in clayey silt layers found at several levels of Pliocene fluvial and lacustrine deposits; and (4) steep planes, possibly joints, in the Bandelier Tuff. Slump complexes along NWRC become smaller south of Ancho Canyon, and are limited features of the landscape south of Chaquehui Canyon.

LANDSLIDE DAMS AND LACUSTRINE SEDIMENTATION IN NORTHERN WHITE ROCK CANYON

Lacustrine silt, clay and sand accumulated at elevations as high as about 1707 m in NWRC in a series of lakes trapped behind landslide dams in the vicinity of the mouth of Water Canyon. In this discussion I assume that there were at least two to as many as 4 different lakes trapped behind landslide dams and representing separate episodes of sedimentation. It is also possible that preserved sediment accumulated in a single lake with a dam that failed in stages, or in a series of lakes of similar age. Most field evidence suggests multiple lakes separated in time by thousands to several tens of thousands of years. The landslide dam that impounded the lakes was located about one km southwest of the mouth of Water Canyon, at the toe of the Water Canyon W. slump complex (Figs. 4;5). In the dam area, boulder gravel containing Rio Grande lithologies, bars composed of large boulders, abandoned channels, and lacustrine sediment are stranded at a series of levels as high as 60 m above the modern channel. El Cajete tephra occurs in the B horizon of a soil buried by one of the lacustrine sequences in the dam area, at a site called "Rattlesnake" (Fig. 5), demonstrating that at least some of the lake sediment is late Pleistocene. At this site and in most of the dam area, field evidence suggests that the slump blocks that impounded the lakes had been active before formation of the lakes, and after their drainage as well, complicating correlations based on elevation. At one upstream site (SW Otowi bridge), deformed lake sediment rests on a slump block that has dropped at least 20 m since their deposition. Reconnaissance field data suggest that slumps may also have dammed the Rio Grande in late Pleistocene time in the Pajarito Canyon zone (Fig. 4), perhaps at elevations of a few tens of meters above the modern Rio Grande. It seems reasonable that canyon-cutting by the Rio Grande has episodically dammed White Rock Canyon. What is more surprising, perhaps, is that fine sediment from the lacustrine episodes has been preserved at several localities above the dam area.

Lacustrine deposits as thick as 30 m provide evidence for the style of sedimentation in the slide-dammed lakes of NWRC. The sites noted on Fig. 5 are the most extensive exposures of lacustrine sediment found to date, the largest of which occurs at the mouth of Canada Ancha, near the Buckman townsite (Fig. 2). Lacustrine sediment at the Buckman site (Fig. 6)is exposed over a lateral distance of almost 200 m, and extends 30 m vertically. The lower 15 m of sediment is rich in silt and clay, whereas the upper part of the section is sandier. The unconformable contact suggests that the silts were exposed subaerially or that strong bottom currents eroded the deposits before deposition resumed in a shallower lake. Charcoal fragments at the base of the silt-rich sequence have been submitted for ^{14}C dating. More than 20 m of similar fine-grained deposits crop out southwest of Otowi bridge.

Thinner sequences of lacustrine sediment are exposed near the intersections of the Blue Dot and Red Dot Trails with the Rio Grande (Figs.7; 8). The base of both deposits is 8 to 10 m above the present Rio Grande. Both deposits and those in the Rattlesnake area are capped with Rio Grande gravels. Thin-bedded, silt-rich fine sand is the most common sediment. Cross-laminated to cross-stratified beds suggest moderate to strong currents swept the bottom of the lake at irregular intervals, perhaps when nearby arroyos were in flood. Neither the Blue Dot nor the Red Dot sections expose other evidence for breaks in sedimentation. The gravel cap in both areas shows the the Rio Grande locally deposited gravel before returning to its prelacustrine base level. Mapping of gravel deposits near these areas and at Rattlesnake, however, suggests that the upper gravels are remnants from channels filled by the Rio Grande as it aggraded over the lacustrine deposits before failure of the landslide dam. If this interpretation is correct, landslide dams must have been stable for at least tens of years, if not much longer.

In the area downstream from Water Canyon, a fluvial deposit filled with boulders several meters in diameter and other reconnaissance field evidence indicates that the dam area may have failed catastrophically during at least one event. I have mapped similar bouilder-rich deposits downstream in the Cochiti Dam quadrangle, but most evidence there suggested that the fluvial deposits were older than the el Cajete tephra. Additional field mapping could help indicate the age of these deposits and whether flood released during a dam failure produced significant downstream scour or undercutting of deposits near the channel.

ROCK AVALANCHES

Two deposits, one of substantial size, appear to have originated as rock falls or avalanches from the western rim of White Rock Canyon (Fig. 5). I have not studied one of the deposits, located along the northern margin of the Pajarito zone (Fig. 5 , but in air photo views it superficially resembles the much larger slide at Ancho Canyon. The Ancho Canyon rock avalanche has a surface area of ~ 0.50 km^2, and using 40 m as a minimum average thickness, the apparent volume is 20 x 10^6 m^3. Assuming that the avalanche originated near the present rim, it fell >300m vertically and travelled about 1500 m laterally to the Rio Grande. The excessive travel distance, the low surface angle, and presence of surface features such as lateral ridges all indicate rapid , flowing motion of the rock debris. Field mapping (Plate 1) suggests that the rock avalanche covers an older slide complex, but colluvium and talus obscure contacts. El Cajete tephra covers the upper slopes and toe areas of the slide, indicating that despite its fresh appearance, it is older than about 150 ka. I have not seen any field evidence that suggests the origin of the rock avalanche. The basaltic andesite of which it is composed is highly fractured and platey, and two scarps near the rim (Plate 1) suggest the potential for additional failures. Suuden acceleration of the rock mass, produced by an earthquake on a nearby fault, is a plausible trigger for the rock avalanche, but it could also have been a stochastic event.

DISCUSSION

LANDSLIDE HAZARDS AT TA-33

Landslides do not appear to represent a decadal hazard to MDAs or structures located at TA-33, barring the unknown effects of a major earthquake located on a fault near TA-33. Slump complexes that line NWRC upstream from TA-33 become narrower along the edge of TA-33 and to the south. This change in slide size and style is apparently a result of bedrock stratigraphy. Pliocene alluvial and lacustrine deposits, zones in the Santa Fe Group, and altered zones in the Puye Formation fanglomerate, the three units asssociated with massive slope failures to the north, become thin or absent south of Chaquehui Canyon. Some phreatomagmatic deposits exposed to the south are sufficiently weak to produce slumping, but the scale of failure is relatively small. The scale of canyon cutting required to initiate slumping by removal of lateral support is apparently ten or more meters, an amount of erosion unlikely to occur in 10 to 100 years. The duration of climate change required to raise the position of the water table substantially needs to be addressed through modeling, but it would probably take several decades of dramatically increased effective moisture. Finally, there is no indication that large slumps move rapidly in the vicinity of rim areas.

OTHER GEOLOGIC HAZARDS NEAR TA-33

Rockfalls

Detailed mapping of the mesa rim near the TA-33 MDAs demonstrates that rockfalls have not been common in the Upper Bandelier Tuff in this area during at least the past few decades. In the 6900 m of rim that I examined, I mapped 23 areas of rockfall, all of them small (Plate 1). All mapped failures occurred in a zone within 3 m of the mesa rim and most involved a characteristic failure width of < 2 m and included less than 5 blocks. One of the largest failures, on the mesa rim south of MDA-E, appears to have resulted from grading activities at the site. Grading and drainage diversion may also have contributed to some of the small rockfalls 50 m south of MDA-D. Evidence of incipient failure surfaces is also minimal. I found two zones, neither near MDAs (Plate 1), where intersecting fracture sets outlined areas of potential failure between 3 and 4 meters wide. If I assume that all mapped rockfalls occurred randomly over the past 100 years, there is < 50 % chance of a rockfall from any kilometer of rim during a ten year period. Rockfall events are probably not random, but the characteristic failures are sufficiently small to keep impact on the MDAs small over any short time period.

Faults

Mapping of the canyon rim near TA-33 suggests that a near-vertical fault striking 350±10 ° apparently offsets the Upper Bandelier Tuff (1.1 Ma) by > 3.5 m. The Pleistocene fault is exposed about 650 m west of MDA-D and 1100 m east of MDA-E (Plate 1). At least two additional north-striking faults cut the Pliocene bedrock that lies beneath the south-facing mesa rim at the edge of White Rock Canyon. These faults may also have had Pleistocene activity, but reconnaissance mapping did not indicate that fault planes cut through the Upper Bandelier Tuff. This fault zone should be mapped in detail, since the triggering effect of seismic shaking on landslide stability cannot be evaluated without local acceleration values.

Headward erosion along gullies

I mapped gullies that showed evidence of recent headward erosion along the parts of the TA-33 mesa that overlook lower Ancho Canyon, White Rock Canyon, and the northeastern edge of Chaquehui Canyon. Active gullies were widely separated along most of the rim area (Plate 1). Two of the deepest gullies were cut into the Upper Bandelier Tuff by water diverted from roads near MDA-E and MDA-D. Since the Tuff is reasonably resistant to erosion, neither gully appeared to represent a short-term threat to these disposal areas. The gully system on the upland east of MDA-K is more extensive. Gullies there are dissecting Quaternary sediment and appear to have been active in late Holocene time. Headward erosion may represent a long-term threat to MDA-K, but I did not evaluate the possibility.

SUMMARY

Massive landslides and slumps along White Rock Canyon are a result of zones of weak rock material exposed by downcutting, removal of lateral support during canyon cutting, and increased pore pressures during periods of pluvial climate. The slides were active during at least late Pliocene through middle Pleistocene time, and probably more recently. A lacustrine deposit 30 m thick near the mouth of Canda Ancha provides the best evidence for damming of White Rock Canyon, probably by landslides, in middle or late Pleistocene time. Alluvial deposits rich in large boulders, exposed downstream may have resulted from floods related to repeated failures of upstream dams. Landslides, however, probably do not represent a significant short-term threat to the material disposal areas at TA-33. Bedrock that lies beneath the TA-33 mesa appears to be relatively stable, the mesa shows no signs of incipient failure, and past periods of slide activity were responses to rapid downcutting of the Rio Grande and climate change, probably over periods of several decades, at least.

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LIST OF TABLES

Table 1. Age of lithostratigraphic units exposed in the vicinity of White Rock Canyon, New Mexico.

Lithostratigraphic unit	Age	Location and Significance	Reference
Santa Fe Group, undivided	mid-to upper Miocene (vertebrate fossils; fission track on tephra)	No dated localities in vicinity of White Rock Canyon	Galusha and Blick (1971) Manley (1976; 1979)
Puye Formation	4 Ma	Age estimate for basal Puye Fm	Waresback and Turbeville (1990)
	2.9 ±0.5 Ma (fission track)	Age for tephra in basal Puye Fm NW of mouth of Garcia Canyon	Manley (1976)
	1.8 ± 0.1 Ma (Ar/Ar)	Age for tephra at top of Puye Fm in upper Guaje Canyon	Waresback and Turbeville (1990)
Cerros del Rio basalt[1]	2.7± 0.1 Ma (K/Ar)	Massive flow from La Mesita	Dethier (1993b)
	2.5 ± 0.1 Ma (K/Ar)	Otowi flow of Galusha and Blick (1971), which flowed west, parallel to Los Alamos Canyon	Dethier (1993b)
	2.3 ± 0.1 Ma (K/Ar)	Forms S. rim of Caja del Rio Canyon. Flowed west under area of White Rock	Dethier (1993b)
Pliocene alluvial and lacustrine deposits[2]	2.7 ± 0.4 Ma (fission track)	Dacitic tephra within Ancha Fm along Canada Ancha, Horcado Ranch Quad.	Manley (1976)
	2.0 ± 0.3 Ma (K/Ar)	Cerros del Rio andesite flow capping Ancha Fm along Canada Ancha	Manley (1976)

"Pajarito Plateau" tholeiitic basalt	1.8 ± 0.2 Ma (K/Ar)	Flow south of Buey Canyon nr. White Rock. Dates E. flowing tholeiitic basalt and age of lake dammed at 6200'	Dethier (1993b)
	2.4 ± 0.3 Ma (K/Ar)	Flow at intersection of Los Alamos and Pueblo Canyons Flow entered lake at 6200'	Luedke and Smith (1978)
Bandelier Tuff, Otowi Member	1.50 ± 0.01 Ma (Ar/Ar)	Fills canyons cut in tholeiitic basalt and other Pliocene units	Spell and others (1989)
Bandelier Tuff, Tshirege Member	1.13 ± 0.01 Ma (Ar/Ar)	Fills canyon and covers Bandelier Tuff, Otowi Member	Spell and others (1989)
El Cajete tephra	0.15 ± 0.04 (Ar/Ar)	Locally covers landslides and other Pleistocene surfaces	Self and others (1988)

1. Basaltic andesite, hawaiite, andesite and phreatomagmatic deposits of basaltic composition (see Dethier, 1993b).
2. In part older alluvium of Griggs (1964) and Ancha Formation of Spiegel and Baldwin (1963).

Table 2. Description of bedrock units in the vicinity of White Rock Canyon, New Mexico

Stratigraphic unit (Age)	Description	Thickness	Contact relations	Interpretation
Santa Fe Group, undivided (Middle Miocene to early(?) Pliocene)	Pinkish grey to buff-colored, poorly to moderately lithified, planar-bedded to massive silty sandstone and cross-bedded pebbly sand in sparse channels. Sandstone beds< 4m thick; channels< 1m. Arkosic matrix. Thin beds of altered dacitic tephra abundant locally. Dips <8° NW in N. White Rock Canyon. Paleocurrents 170° to 270°. Correlates, in part, with Tesuque Fm of Galusha and Blick (1971) and the Ancha Fm of Spiegel and Baldwin (1963).	>185 m in surface >600 m in the subsurface	Base not exposed. Puye Fm or phreatomagmatic deposits unconformably overlie unit	Sheetflood and stream channel deposits on alluvial plain
Puye Formation, ancestral Rio Grande facies (Pliocene)	Mainly grey, poorly to moderately lithified, locally cemen. massive and channel crossbedded pebble to cobble gravel rich in clasts of Precambrian rock, and beds of silt and silty sand, exposed mainly W. of the Rio Grande. Gravel beds generally 0.5-3.0 m thick; locally planar bedded; silt beds < 2m thick in White Rock Canyon, but thicker NW of Otowi Br. Maximum thickness and extensive exposures in Sandia and Mortendad Canyons. Paleocurrents 160° to 220°. Mainly equivalent to Totavi Lentil of Griggs (1964).	5 to 45 m	Fills channels in and locally interbedded with Puye Fm, fanglomerate facies or Santa Fe Grp. Pliocene alluvium or phreatomagmatic deposits unconformably overlie unit	Axial channel (braid-plain) and lacustrine deposits

Puye Formation, fanglomerate facies (Pliocene)	Pinkish grey to grey, locally cemented, weakly lithified pebble to bldr. gravel, boulder-rich debris flows, massive to planar-bedded sand, thin beds of dacitic tephra and pumiceous alluvium and beds of fine sand and silt, exposed mainly W. of White Rock Canyon. Gravel beds 0.5-3.0 m thick; debris flows 0.3-5.0 m thick; Clast and matrix lithology mainly dacite and related rocks derived from the Tschicoma Fm of the Jemez Mtns. Paleocurrents 90° to 200° and average about 150°. Equivalent to Puye Fm of Griggs (1964).	5 to 30 m near White Rock Canyon;>60 m NW of Otowi bridge	Unconformably overlies Santa Fe Group, or, locally Puye Fm, ancestral Rio Grande facies. That facies, Pliocene alluvium or phreatomagmatic deposits unconformably overlie unit	Stream-channel, sheetflood, debris flow and local lacustrine deposits on alluvial fan.
Fluvial and lacustrine deposits (Pliocene)	Buff to brownish-yellow unlithified crossbedded sand, pebbly sand rich in rocks from the Sangre de Cristo Range, thin-bedded silt and silty sand and beds of cinders and debris flows along Canada Ancha and N. of Water Canyon, W. of the Rio Grande. Paleocurrents from 180°-270°. Correlates with older alluvium of Griggs (1964) and, in part, with the Ancha Fm of Spiegel and Baldwin (1963).	0 to 30 m	Unconformably (locally conformably) overlies phreatomagmatic deposits along Canada Ancha, unconformably overlies Puye Fm or basalt flows near the Rio Grande. Interlayered with and overlain by phreatomagmatic deposits and basalt	Stream-channel, sheetflood and lacustrine deposits

Cerros del Rio basalt and related rocks (Pliocene)	Greenish black and black to dark grey, locally brownish red olivine basalt, hawaiite, basaltic andesite and andesite flows of the Cerros del Rio field. Thin (<5m) to thick (>40 m) flows containing 2-8% quartz xenocrysts. Flow tops are generally vesicular, locally rubbly and flow interiors display columnar joints with spacing that ranges from 0.3-5 m or are nearly massive. Flow directions variable, but toward W for older flows near Otowi Br. and S. for some massive flows south of White Rock.	20 to 170 m	Unconformably overlies phreatomagmatic deposits Puye Fm, Pliocene alluvium or Santa Fe Group. Lies beneath Pliocene alluvium Puye Fm or Bandelier Tuff.	Flows from shield, vents maars and cinder cones
Cerros del Rio phreatomagmatic deposits (Pliocene)	Banded light gray to black, locally reddish brown to red, bedded to massive fall, surge and flow deposits composed of basaltic tuff and cinders and accidental fragments of Santa Fe Group or Puye Fm. Fall beds 0.3-3.0 m thick, composed of banded ash and lapilli deposits. Surge beds are planar and crossbedded, locally rippled coarse silt to pebbly sand, generally 0.1-0.4 m thick. Flow deposits mainly matrix-supported pebble to boulder gravel in discontinuous beds 1-4 m thick. Locally sheared, slumped, or brecciated. Moderately lithified.	<60 m; thickest near maars such as La Mesita	Unconformably overlies Puye Fm, Santa Fe Group or interlayered basalt and phreatomagmatic deposits. Lies beneath Cerros del Rio basalt or cinder and agglomerate from cinder cones in most areas	Deposits from explosive eruptions at maars

"Pajarito Plateau basalt" (late Pliocene)	Dark green to black tholeiitic olivine basalt flows, pillow basalt, and palagonitic breccia exposed W. of the Rio Grande, N. of Chaquehui Canyon. Flows <10 m thick with sharp to rubble-rich contacts. Flow directions on foreset deposits average about 110° and range from 70° to 150°. Topset/ foreset contacts in deltas composed of basaltic debris occur at an elevation of 6200'. Basalt flowed from vent W. and NW of White Rock Canyon, and buried by Bandelier Tuff.	10-30 m	Overlies Pliocene alluvium and lacustrine deposits N. of White Rock and older basalt to the S. Thin fluvial and lacustrine deposits locally separate flows from over-lying Bandelier Tuff	Flows and deposits formed when basalt entered a lake in White Rock Canyon
Bandelier Tuff, Otowi Member (early Pleistocene)	Light gray (pink, pinkish brown or brown on weathered surfaces), slightly welded pyroclastic flows of pumiceous rhyolite and a compound, pumiceous fall unit (Guaje Member) as thick as 6m, also of rhyolitic composition. One or two thick flows lie above the Guaje member which is absent at most exposures near White Rock Canyon.	<50 m	Fills canyons as deep as 60 m cut into Pajarito Plateau basalt, Cerros del Rio basalt or phreatomagmatic deposits. Lies disconformably beneath the Bandelier Tuff, Tshirege Member	Pyroclastic flows and fall deposits derived from the Valles Caldera

Bandelier Tuff, Tshirege Member (early Pleistocene)	Light gray (pink, pinkish brown or brown on weathered surfaces), Slightly welded pyroclastic flows and a pumiceous fall unit (Tsankawi pumice bed) <1 m thick, both of rhyolitic composition. 2 to 5 flows, separated by pumice concentrations of thin, sorted partings, crop out along deep canyons W. of White Rock Canyon.	30-60 m except 90 m at one site E of White Rock Canyon	Lies disconformably above the Bandelier Tuff, Otowi Member. Forms surface or lies beneath alluvial deposits a few m thick.	Pyroclastic flows and fall deposits derived from the Valles Caldera

Table 3 . Selected characteristics of slide zones along northern White Rock Canyon, New Mexico

Designation	Classification	Size Area(Km2)/ Rim length (Km)	Dip of slump blocks	Failure surface	Notes
Chaquehui Canyon	Rock slides (3); small slumps	0.05	--	Bandelier Tuff	Small failures probably late Pleistocene
TA-33	Slump complex	0.51	30°-50°	Phreatomagmatic deposits(?) or Puye Fm fanglomerate	Slumps >300m from rim
Ancho Canyon	Rock avalanche	1.69	--	Santa Fe Grp(?)	Volume> 18 x 10^6 m^3
Water Canyon W.	Slump complex	1.87	~50°	Puye Fm or Santa Fe Grp.	Blocks > 300 m wide. SE slump blocks active in late Pleistocene. Dam and spillway area for late Pleistocene lakes
Water Canyon	Slump complex	0.57	30°-70°	Puye Fm. or Santa Fe Grp.	Slump blocks along Rio Grande may have been active in late Pleistocene
Pajarito Canyon	Slump complex; small rock avalanche (?)	0.87	30°-70°	Puye Fm. or Santa Fe Grp.	Largest slump block >300 X 500 m
Overlook	Slump complex	0.61	10° (near rim) to 70° nr. river	Puye Fm or Pliocene alluvium	Slump blocks <150 m wide; locally 50 m
Mortandad Canyon	Slump complex	0.22	10°-30°	Pliocene alluvium	Failure planes subhoriz.
Sandia Canyon	Slump complex	0.51	30°-50°	Pliocene alluvium and Santa Fe Grp	
N. Sandia Canyon	Slump complex	0.45	30°-70°	Pliocene alluvium and Santa Fe Grp	3 or 4 tiers of coherent slumps
SW Otowi Bridge	Slump complex	0.53	30°-70°	Pliocene alluvium and Santa Fe Grp	3 or 4 tiers of coherent slumps locally

LIST OF FIGURES AND PLATES

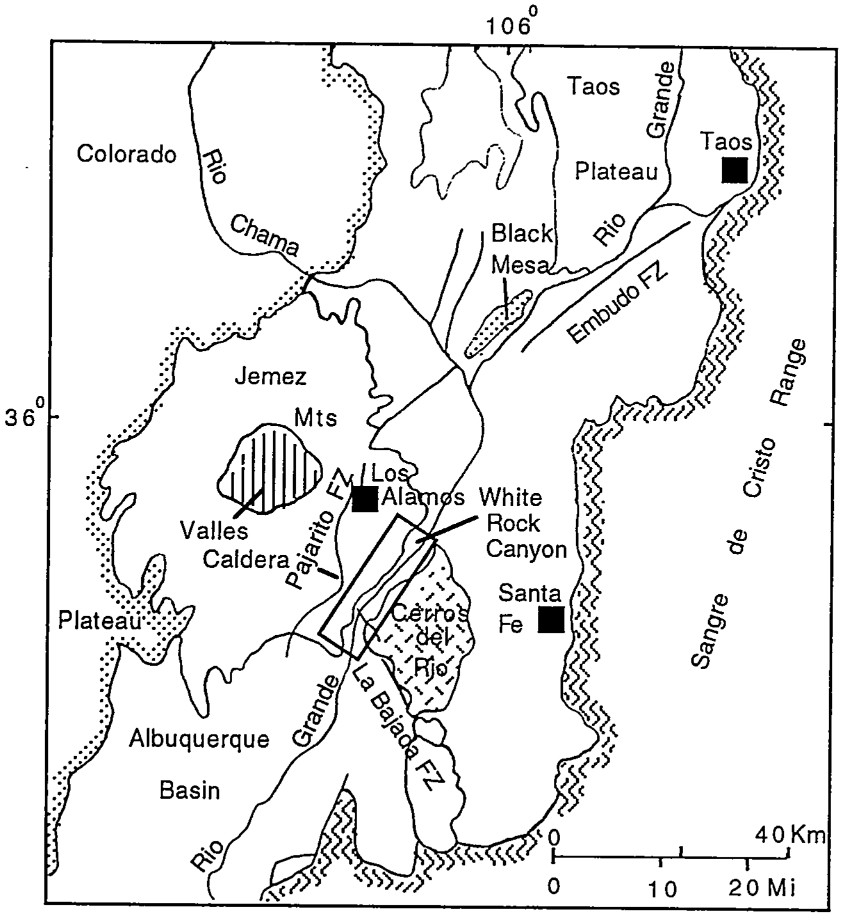

106°
36°
Colorado
Plateau
Rio
Chama
Taos
Plateau
Taos
Rio
Grande
Black
Mesa
Embudo FZ
Jemez
Mts
Valles
Caldera
Pajarito FZ
Los
Alamos
White
Rock
Canyon
Santa
Fe
Cerros
del
Rio
Sangre de Cristo Range
La Bajada FZ
Albuquerque
Basin
Rio
Grande
0
40 Km
0
10
20 Mi

Figure 1.

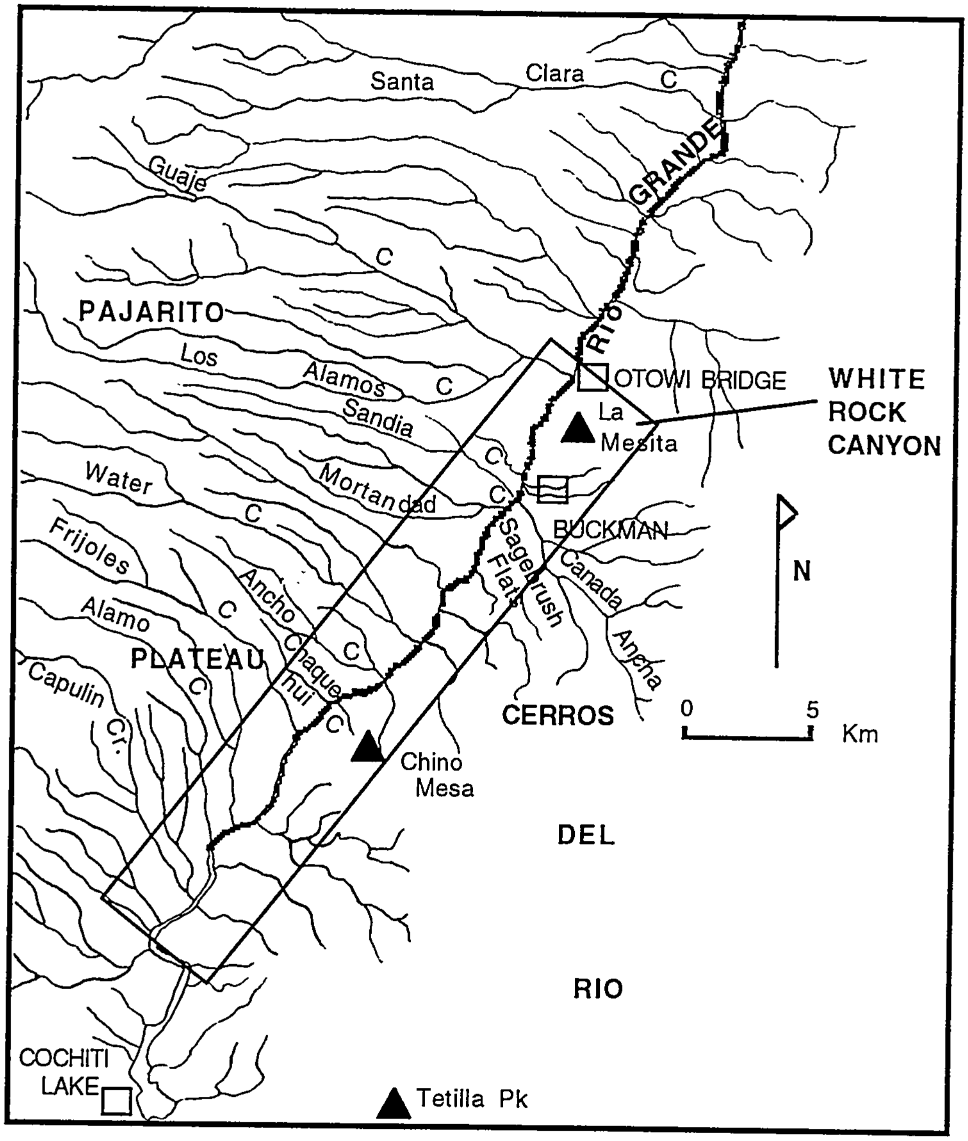
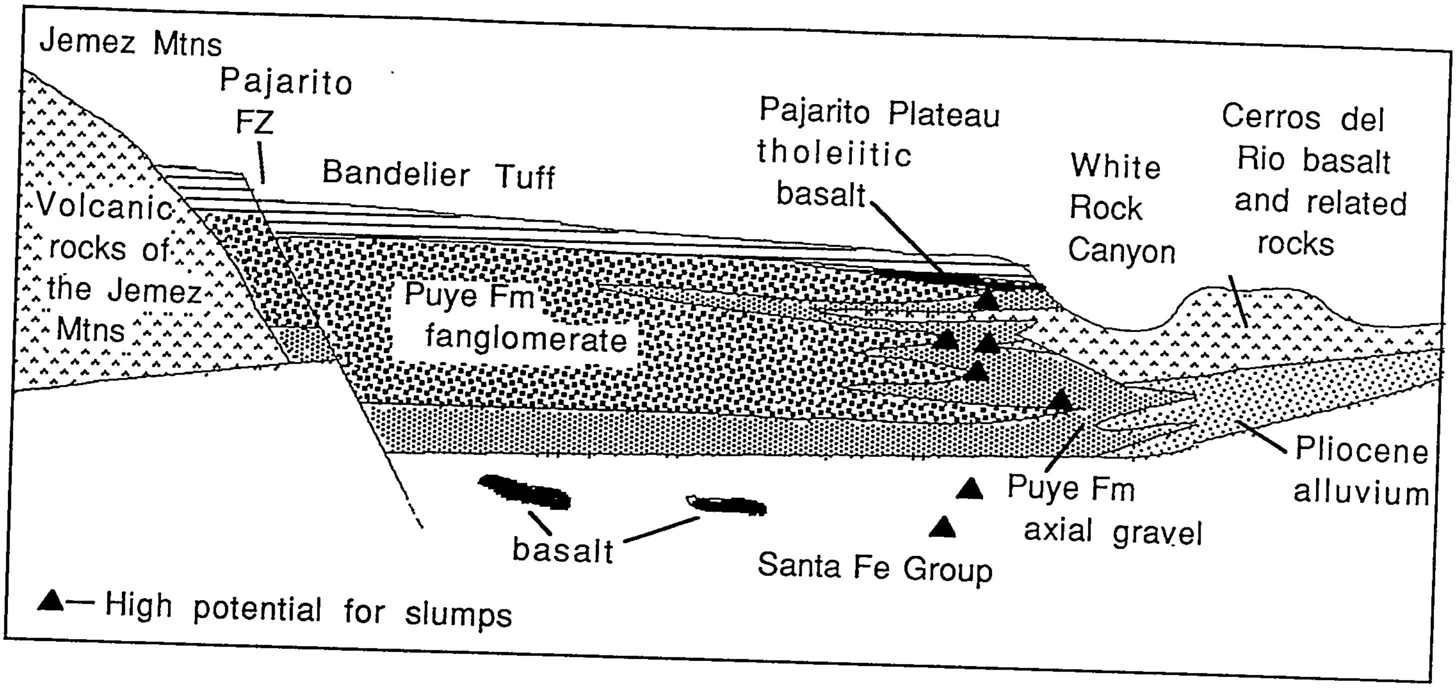

Santa
Clara
C
Guaje
GRANDE
C
PAJARITO
RIO
Los
Alamos
C
OTOWI BRIDGE
WHITE
ROCK
CANYON
Sandia
La
Mesita
Water
Mortandad
C
C
C
BUCKMAN
Frijoles
Ancho
Sagebrush
Flats
Canada
N
Alamo
C
PLATEAU
Chaquehui
C
Ancha
Capulin
C
C
Cr.
CERROS
0
5
Km
Chino
Mesa
DEL
RIO
COCHITI
LAKE
Tetilla Pk

Figure 2.



Jemez Mtns
Pajarito FZ
Bandelier Tuff
Pajarito Plateau tholeiitic basalt
White Rock Canyon
Cerros del Rio basalt and related rocks
Volcanic rocks of the Jemez Mtns
Puye Fm fanglomerate
Pliocene alluvium
Puye Fm axial gravel
basalt
Santa Fe Group
▲— High potential for slumps

Figure 3.

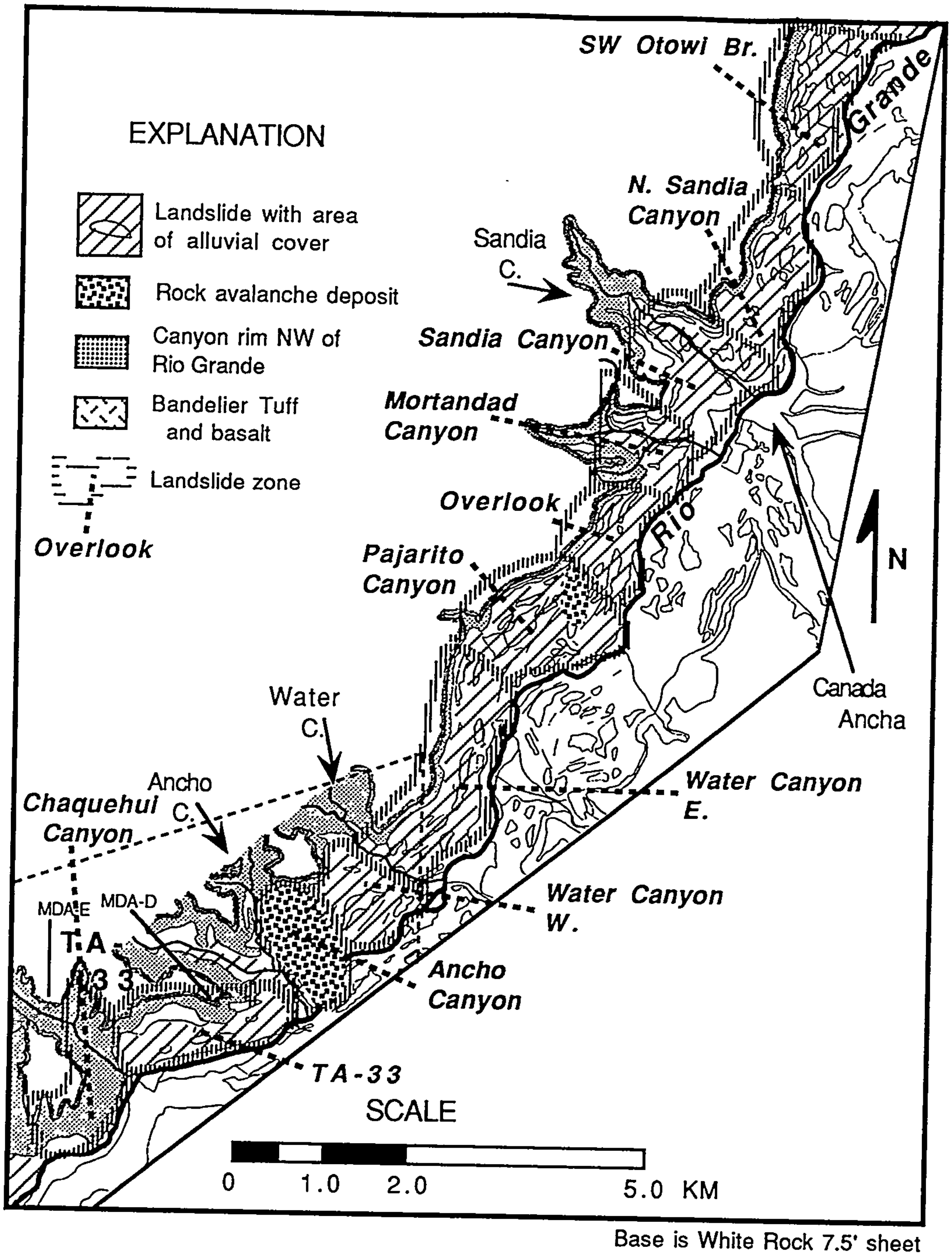
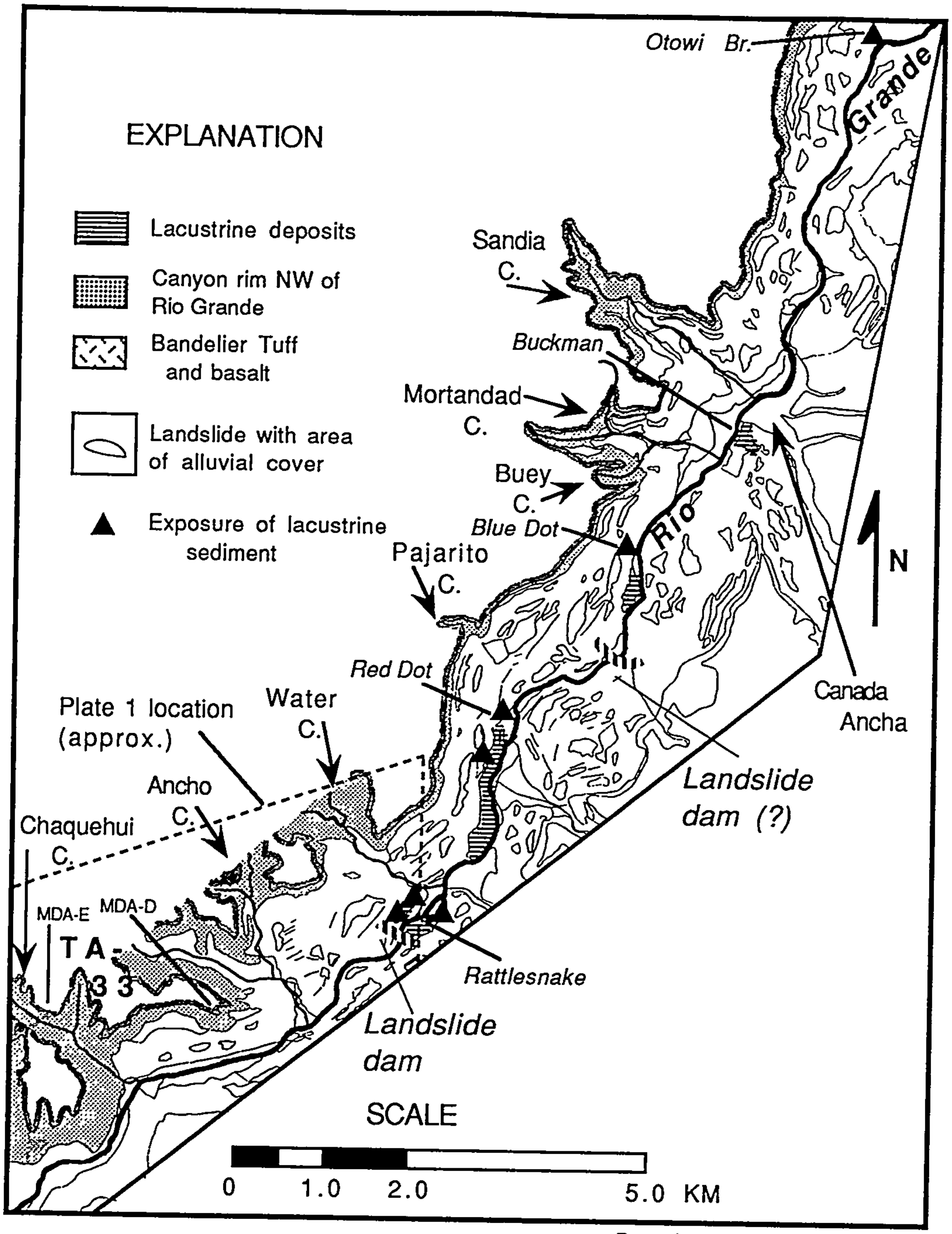
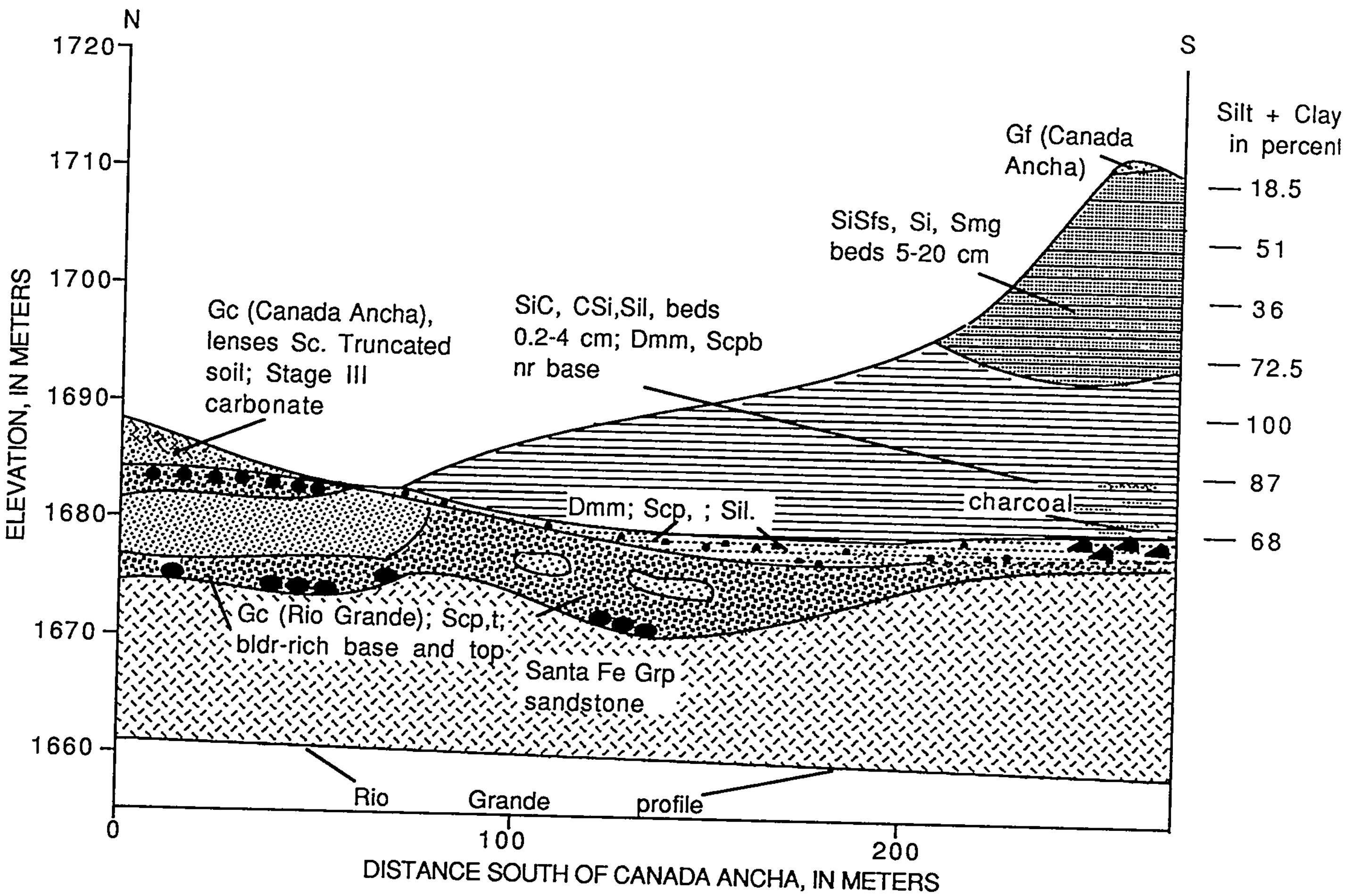

EXPLANATION
Landslide with area of alluvial cover
Rock avalanche deposit
Canyon rim NW of Rio Grande
Bandelier Tuff and basalt
Landslide zone
Overlook
SW Otowi Br.
Grande
N. Sandia Canyon
Sandia C.
Sandia Canyon
Mortandad Canyon
Overlook
Rio
Pajarito Canyon
N
Canada Ancha
Water C.
Ancho C.
Chaquehui Canyon
Water Canyon E.
Water Canyon W.
MDA-E
MDA-D
TA 33
Ancho Canyon
TA-33
SCALE
0
1.0
2.0
5.0 KM
Base is White Rock 7.5' sheet

Figure 4.



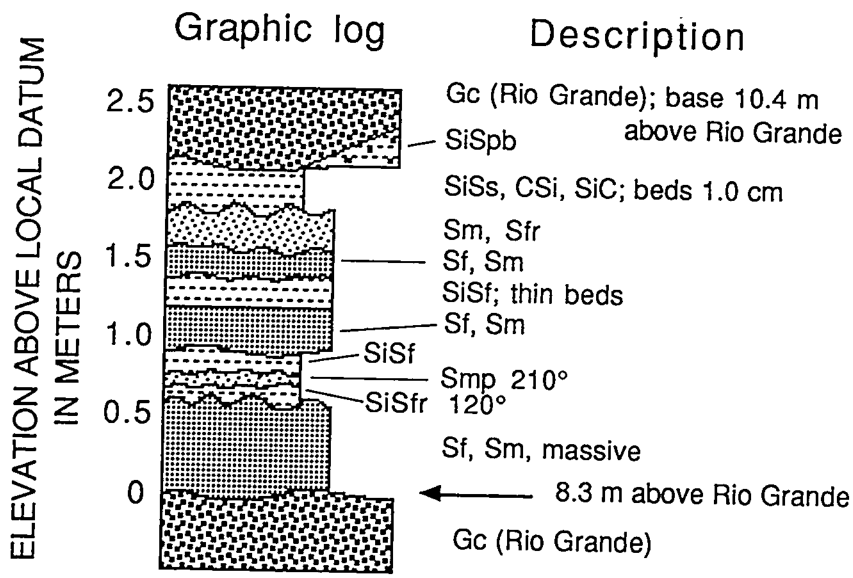
Base is White Rock 7.5' sheet

Figure 5.



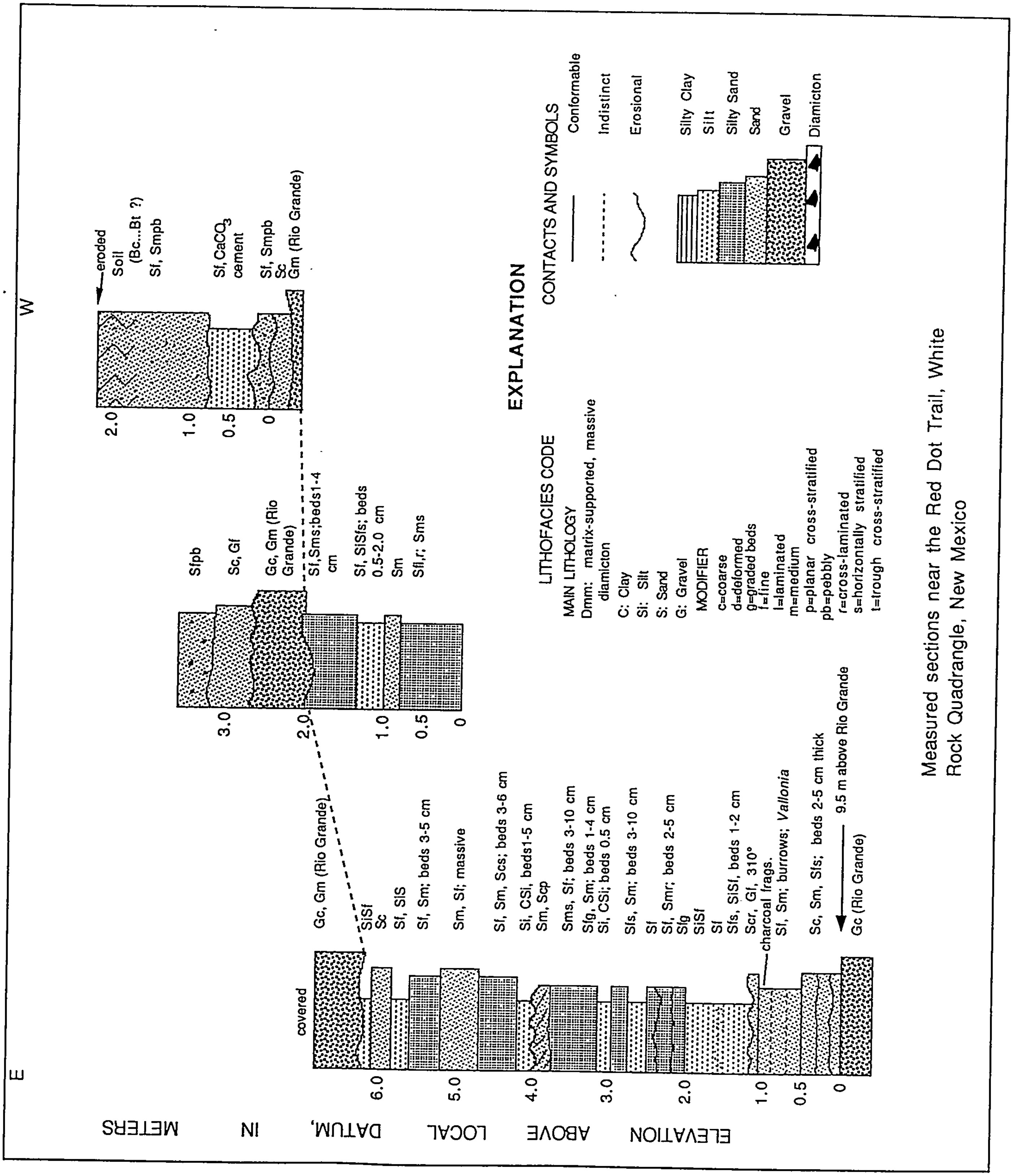
N
S
1720
1710
1700
1690
1680
1670
1660
ELEVATION, IN METERS
Silt + Clay in percent
18.5
51
36
72.5
100
87
68
Gf (Canada Ancha)
SiSfs, Si, Smg beds 5-20 cm
SiC, CSi,Sil, beds 0.2-4 cm; Dmm, Scpb nr base
Gc (Canada Ancha), lenses Sc. Truncated soil; Stage III carbonate
Dmm; Scp, ; Sil.
charcoal
Gc (Rio Grande); Scp,t; bldr-rich base and top
Santa Fe Grp sandstone
Rio Grande profile
0
100
200
DISTANCE SOUTH OF CANADA ANCHA, IN METERS

Figure 6.



Measured section near the Blue Dot Trail,
White Rock Quadrangle

Figure 7.



Measured sections near the Red Dot Trail, White Rock Quadrangle, New Mexico

Figure 8.