U.S Department of the Interior
U.S. Geological Survey

Preliminary Evaluation of the Landslide Potential in Capulin Canyon Following the Dome Fire, Bandelier National Monument, New Mexico

By Susan H. Cannon and W.L. Ellis

Open-File Report 97-141

Denver, CO 1997

CONTENTS

ILLUSTRATIONS

Figure

Tables

PRELIMINARY EVALUATION OF THE LANDSLIDE POTENTIAL IN CAPULIN CANYON FOLLOWING THE DOME FIRE, BANDELIER NATIONAL MONUMENT, NEW MEXICO

By Susan H. Cannon and W. L. Ellis

Abstract. The Dome fire burned 6,684 ha in Bandelier National Monument and the adjacent Sante Fe National Forest in New Mexico. To assess the present stability of the Boundary Peak and Base Camp landslides in Capulin Canyon, and to evaluate the potential for destabilization due to the removal of vegetation during the Dome fire, a program of mapping and soil-moisture monitoring was undertaken. The Boundary Peak landslide covers an area of approximately 2.9 km^2, and appears to be approximately 150 m thick, while the Base Camp landslide covers approximately 0.2 km^2. The thickness of the Base Camp landslide deposits is not known. The Boundary Peak landslide deposits experienced two areas of high burn intensity which cover a total area of approximately 0.15 km^2. The remainder of the deposits were mapped as moderate or low burn intensities. The Base Camp deposits show one area of low burn intensity which covers an area of 0.03 km^2.

Neither the Boundary Peak nor Base Camp landslide deposits exhibit evidence of recent movement or instability. Both landslide deposits are mantled by the 50,000- to 60,000-year-old El Cajete pumice; deposition of the pumice postdates the last movement on the landslides. The entire landslide topography is muted and subdued. No cracks, fissures, or shear zones were observed, and only a few tilted trees, too few and far between to indicate instability of the deposits, were observed. The present-day interaction of Capulin Creek and the landslide toes appear to be negligible, and no danger of destabilization of the deposits by undercutting appears to exist at this time.

The likelihood of reactivation of the Base Camp landslide deposits due to increased infiltration in areas burned by the Dome fire appears to be negligible due to the small area and low intensity of the fire on the deposits.

Qualitative evaluation of the preliminary soil-moisture data from the Boundary Peak landslide deposits indicates an apparent change in infiltration characteristics at the burned site, suggesting a slight potential for reactivation of deposits due to the Dome fire. The evaluation indicates that (1) rainfall infiltrates more readily, and to greater depths, at the burned site than at the unburned; and (2) the drying response of the sensors at the burned site is very gradual and over a limited range, while the pore pressures recorded by the shallow probes at the unburned site dissipate much more rapidly and to much higher tension values. These differences may be due to the lack of vegetation-induced transpiration at the burned sites, but continued monitoring is necessary to both confirm these relations and to quantify the differences in infiltration rates. Further evaluation is also necessary to determine if the increased infiltration rates could potentially destabilize the landslide deposits.

INTRODUCTION

The Dome fire of May, 1996, burned 6,684 ha in Bandelier National Monument and the adjacent Santa Fe National Forest in New Mexico. The report of the Burned Area Emergency Rehabilitation (BAER) team that evaluated conditions at the Monument immediately after the fire identified two Quaternary-age landslide deposits in Capulin Canyon as potentially unstable as a result of the fire, and they recommended further evaluation. The larger of the two landslide deposits is located on the north flank of Boundary Peak, while the considerably smaller deposit occurs just southwest of the Ranger Base Camp (fig. 1).

A potential consequence of the reactivation of either of these two landslide deposits is the creation of unstable ground that would pose a navigational hazard for recreating humans in the canyon. The integrity of archeological sites on the deposits would be threatened should movement continue for any extended period of time. The remote possibility also exists for the landslide deposits to move into Capulin Canyon and dam Capulin Creek. Should this occur, catastrophic failure of the dammed material and the resultant flooding could result in destruction of downstream archeological sites, as well as the loss of human life.

To assess the current stability of these deposits and evaluate the potential for destabilization due to the removal of vegetation, a two-phase study was initiated. The first phase involved both field and aerial-photographic mapping of the extent of the landslide deposits, paying particular attention to features that could indicate potential instability, such as tilting trees and cracks or fissures. Color infra-red aerial

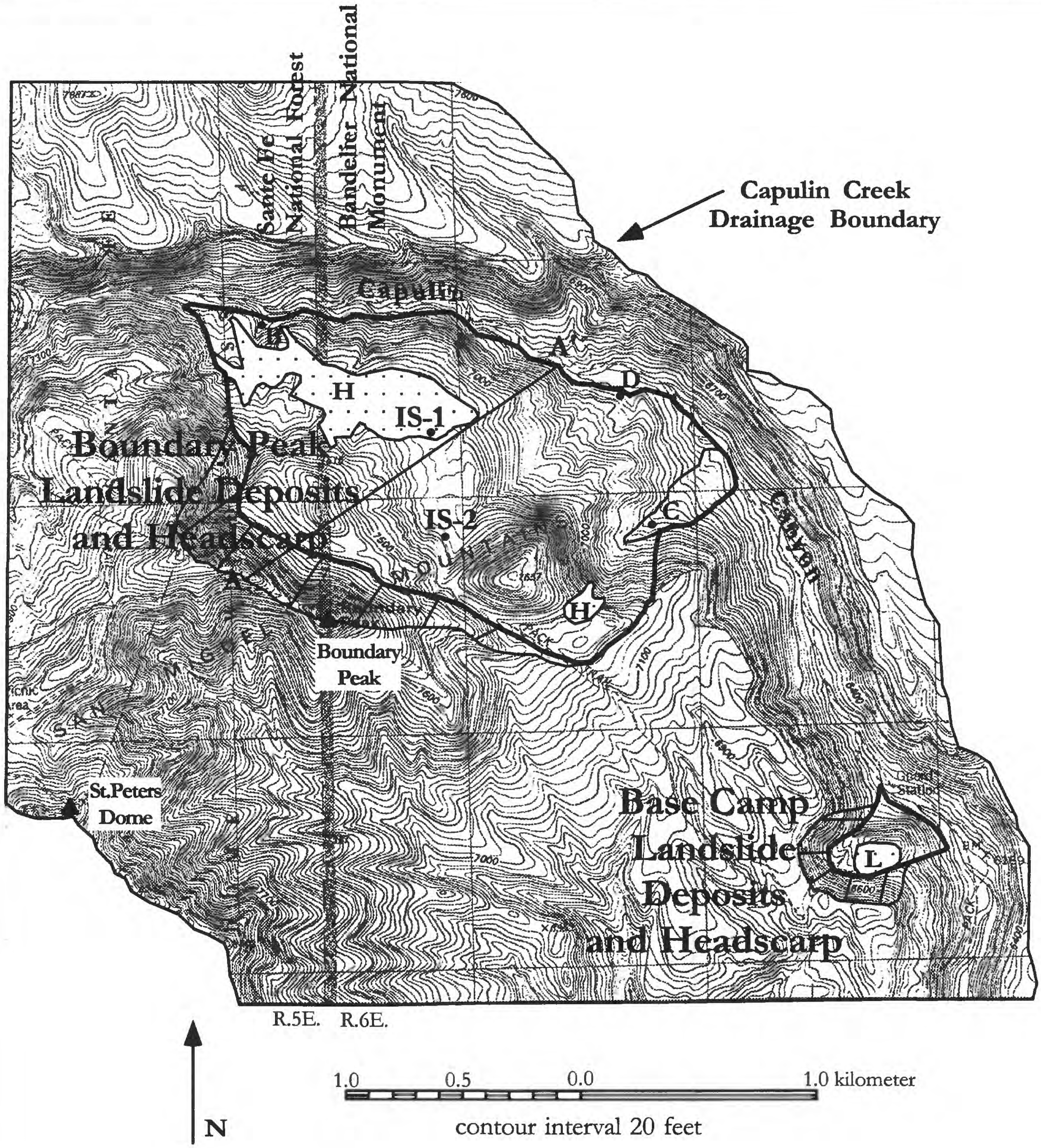

Figure 1. Topographic map of portion of Capulin Canyon in Bandelier National Monument showing locations of Boundary Peak and Base Camp Quaternary landslide deposits and instrumentation sites. Burned site is IS-1, while the unburned site is IS-2. Stippled areas denote areas of high (H) burn intensity on the Boundary Peak landslide deposits, and an area of low (L) burn intensity on the Base Camp landslide deposits. Letter B marks the location of a possible basal slip surface. Letter C denotes the location on the alluvial fan where C-14-dated samples were obtained. Letter D shows the location of surficial raveling of the landslide toe. Base is from U.S. Geological Survey Frijoles, New Mexico, 7.5' quadrangle map.

photographs taken on May 5, 1996, at 1:8,000-scale were utilized for the mapping. The potential for destabilization of the landslides due to channel incision at the base of the deposits was also assessed by examining conditions at the toe of the landslide deposits in Capulin Canyon.

The second phase of the evaluation addresses the issue of a potential change in stability of the landslide mass due to the removal of vegetation. To address this issue, two soil-moisture and rainfall monitoring sites were established, one on the burned slide mass and the other on similar unburned terrain. At each site, a series of soil-moisture sensors are used to document the infiltration of soil moisture into the soil during summer thunderstorm events. A preliminary comparison of the soil-moisture data at the burned and unburned sites, relative to rainfall accumulations, indicate varying infiltration characteristics of the two sites, some of which might be attributed to live tree transpiration rates.

This report consists of the following elements:

- Descriptions of the landslides, the observations made, and the conclusions drawn regarding their morphology, mode of failure, and present stability state
- Description of the soil-moisture monitoring experiment and preliminary results
- Preliminary conclusions regarding the likelihood of major landslide activity in the canyon

LANDSLIDE DESCRIPTIONS

The larger of the two landslides is located on the north flank of Boundary Peak and is referred to as the Boundary Peak landslide in this report (fig. 1). The other, considerably smaller landslide, occurs just southwest of the Ranger Base Camp and is called the Base Camp landslide (fig. 1). The landslides were identified by Goff and others (1990) on their geologic map of the area.

The Boundary Peak Landslide

Deposits from the Boundary Peak landslide, as outlined in figure 1, extend a distance of 1.2 km from the base of the headscarp to Capulin Canyon and are approximately 2.4 km wide in the canyon. Delineation of the landslide deposits was accomplished through examination of the 1:8,000-scale color IR aerial photographs taken on May 5, 1996, and field examination. The western and southwestern boundaries of the deposits were readily delineated based on topographic expression—the landslide deposits are generally smoother and have gentler slopes than the adjacent undisturbed ground. The southeastern boundary, however, required a little more investigation. The 7,657-foot-high peak located near the southern margin of the landslide deposits is composed of Paliza Canyon Formation hornblende dacite that dips 55° to the south with a N. 10° W. strike. This dip is considerably greater than that measured for the same unit to the south (Goff, and others, 1990) and is oriented back toward the headscarp, suggesting that this peak is not inplace material but rather a back-tilted rotational block that has moved downslope.

The southeastern boundary of the landslide deposits was further located by what might possibly be the remnants of a flank ridge, a feature commonly found along the margins of actively moving landslides (Fleming and Johnson, 1989). In addition, a contact between the Bandelier Tuff and landslide material was observed just east of this flank ridge, and the remnants of rotational slump blocks in landslide material were observed on the slopes below. The northeast margin of the deposits was delineated based on the topographic expression of a steep landslide toe in Capulin Canyon.

The headscarp of the landslide developed in the volcaniclastic rocks of the Cochiti Formation, although the landslide itself may have also involved the Canovas Canyon Tuffs, the sandstones and siltstones of the Sante Fe Formation, and the Paliza Canyon Formation hornblende dacites, all of which make up the flanks of Boundary Peak. The present-day headscarp has an average slope of 70%, although in places it is as steep as 86%. Slopes vary from 9% on the surface of the landslide to 50% on the steepest section of the toe where it rests in Capulin Canyon.

According to a map of burn intensity prepared by the U.S Forest Service from 1:12,000-scale aerial photography taken after the fire and limited field checking, the Boundary Peak landslide deposits experienced two areas of high intensity burn. These areas are shown as stippling on figure 1 and cover a combined area of 0.15 km^2. In these areas all pine needles, leaf litter, and branches up to 8 cm in diameter were consumed by the fire. Black and gray ash and charcoal deposits up to 5 cm deep were observed on the surface. The remainder of the deposits were mapped by the Forest Service as exhibiting moderate- or low-burn intensities.

What appears to be a basal failure zone of the Boundary Peak landslide is exposed in the west wall of a streamcut at map location B (fig. 1). This zone was measured to be 84 cm thick, is inclined at 3° to the north, and consists of a plastic, silty clay of variable color. This possible failure surface rests on what appears to be red Galisteo Sandstone. Given the location and geometry of the failure surface and the slope of the headscarp, a possible location of the failure surface beneath the landslide can be inferred, as shown in cross-section A-A′ (fig. 2). This reconstruction indicates that the deposits may be about 150 m thick. Given the imprecise values for the width and length of the deposits, a volume of the landslide deposits of approximately 530,000,000 m^3 is calculated.

Movement of the Boundary Peak landslide likely occurred along a deep-seated, convex-upward failure surface, which resulted in a rotational transfer of material downslope and out onto the valley floor. Material did not travel down Capulin Canyon for any distance. The topography of the landslide suggests that it moved primarily as one unit, although it appears that the main rotational block broke into a number of smaller, nested blocks at its lateral margins, resulting in a stepped topography on either side of the main block. No sedimentological evidence was observed upstream from the landslide deposit that would indicate that the landslide ever dammed Capulin Creek, suggesting that the rates of movement into Capulin Creek were sufficiently slow to allow the creek to maintain a channel.

An alluvial fan is located on the right margin of the landslide deposits; its outline is shown on figure 1. This fan consists of fluvially reworked landslide material, as well as material eroded from the headscarp. The fan surface is covered with abundant open-work boulder and cobble berms. The materials that make up these berms are often imbricated, indicating a surface-water transport mechanism, and the berms themselves lack the matrix material necessary to identify them as debris-flow deposits. In addition to the fan surfaces, boulder berms have been deposited where drainages off the headscarp intersect the landslide deposits.

Incision into the fan surface at map location C by recent surface flows revealed a stratigraphy that indicates that fires have occurred on or near the landslide deposits in the past. The surface of the fan is blanketed with approximately 2.5 cm of ash and charcoal from the Dome fire. Beneath this, exposed in a 2.50-m-high cut, are two sequences of older flu-

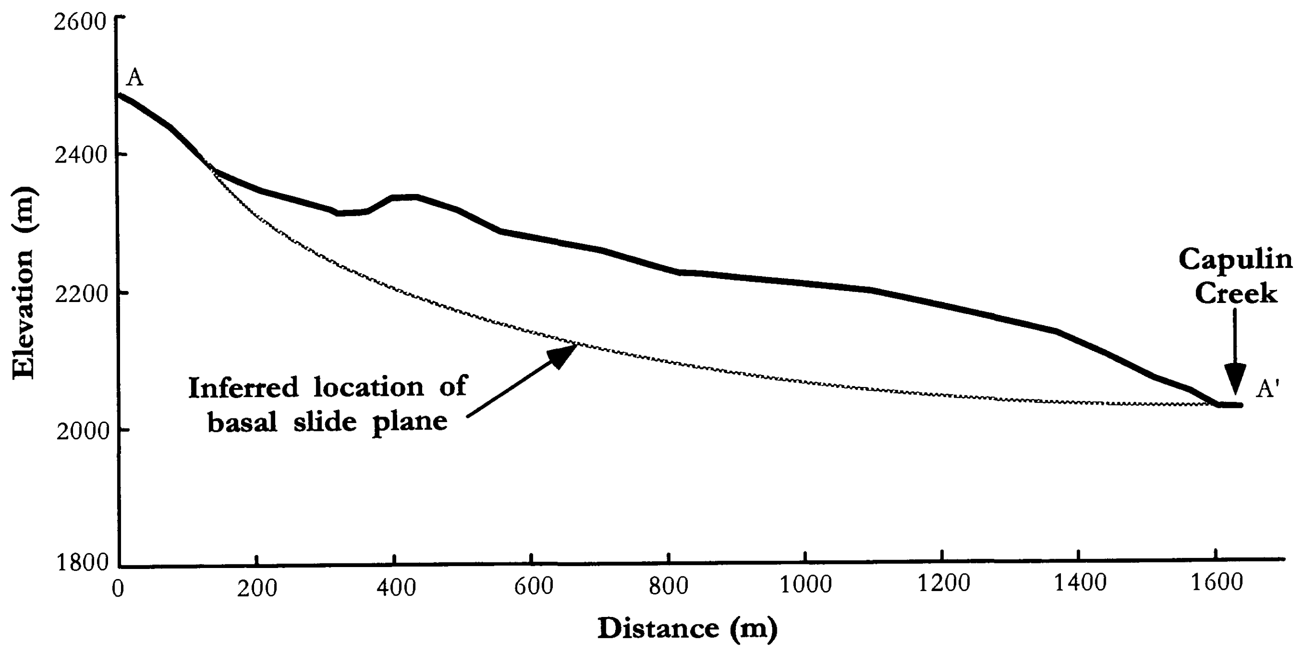

Figure 2. Cross section through Boundary Peak landslide deposits. Topography is from U.S. Geological Survey's Frijoles 7.5′ quadrangle.

vial deposits capped with soils containing abundant ash and charcoal fragments. These ash and charcoal-rich deposits represent depositional events following fires located upslope in the drainage. C-14 dates of A.D. 1650-1950 and A.D. 1280-1630 were obtained from charcoal in the upper, and lower soils, respectively. At this time, it is not possible to determine the response of the landslide deposits to these past fires.

The Base Camp Landslide

The Base Camp landslide deposits, as outlined on figure 1, extend 0.5 km from the headscarp to the canyon and are 0.4 km wide at their broadest point. The landslide appears to have formed in the Upper Bandelier Tuff. The arcuate headscarp is as steep as 85%, and the toe of the landslide also rests in Capulin Canyon, with a slope of 53%. This landslide also failed as a single rotational unit that left deposits on the hillside and in the canyon. Material did not travel down Capulin Canyon. No sedimentological evidence was observed upstream from the landslide deposit that would indicate that the landslide ever dammed Capulin Creek, suggesting that the rates of movement into Capulin Creek were sufficiently slow to allow the creek to maintain a channel.

One area of low-burn intensity that covers approximately 0.03 km^2, or one-sixth of the deposits, is shown on the U.S. Forest Service map of fire intensity (fig. 1).

PRESENT STABILITY STATE OF LANDSLIDE DEPOSITS

Both the Boundary Peak and Base Camp landslide deposits mantled the El Cajete pumice; geochronologic data suggests an age of about 50 to 60 ka for this deposit (Reneau and others, 1996). The superposition of the pumice on the landslide deposits indicates a minimum age of 50,000 to 60,000 years for the last movement of the landslides. The entire landslide topography is muted and subdued, also indicating an advanced age and lack of recent movement. We observed no cracks, fissures, or shear zones, or any other signs of instability on the landslide deposits. Although the thickness of the pumice mantle on the landslide deposits is unknown, the weathering of the pumice and degree of soil development is sufficient such that reactivation of the underlying landslide deposits could be reflected at the surface. Although our proposal suggested installing photographic-monitoring sites on the landslide deposits, this lack of evidence of active movement or unstable ground made it impossible to select sites for monitoring that would give informative results.

A few tilted trees were observed on the landslide deposits but they are too few and far between to indicate instability. The tilting of the few trees we observed can be explained as a phototropic response (Phipps, 1974), and a grouping of contiguous, similarly-aged tilted trees is necessary to indicate landslide instability.

The interaction of Capulin Creek and the toes of the landslides appears to be negligible, and no danger of destabilization of the deposits by incision appears to exist at this time. The stream bed of the creek in Capulin Canyon is quite broad and flat, and is not constricted by either of the landslide toes at this time. At one location (map location D) the steep front of the Boundary Peak landslide toe has failed as a surficial slip. The approximately 1-m-high scarp is subtle and smoothed by erosion, indicating that this is not a recent feature. The slip is approximately 15 m wide and 3 m high. The recent flooding on Capulin Creek has, however, incised slightly into this raveling surface, resulting in a 2-m-high cut into the channel bank. This was the only interaction of Capulin Creek with the either of the toes of the landslides observed in the canyon bottom, and its scale precludes any threat of destabilization of the landslide mass.

SOIL-MOISTURE MONITORING

This phase of the evaluation addresses the issue of a potential change in stability of the landslide mass due to the removal of vegetation. This analysis is based on the assumption that the only variable altered by the fire that affects the stability of the landslides is the infiltration of rainfall and snowmelt into the slide mass at the surface. Presumably, any other deep water source and the internal hydrologic characteristics of the mass were not altered by the fire. Two possible effects of the fire are: (1) a change in infiltration rates and amounts of rainfall and snowmelt as a result of removal of the mulching litter on the ground surface, and (2) a change in the rates and amounts of rainfall that can infiltrate to depth because of the decreased transpiration rates of the burned trees. To address these issues, two soil-moisture monitoring sites were established, one on the burned slide mass and the other on similar unburned terrain. Each site consists of a tipping bucket rain gage and two sets of four soil-moisture sensors installed to determine negative soil pore-water pressures, or soil tensions, at varying depths. This configuration was designed to document the infiltration of rainfall into the soil during summer thunderstorm events.

Soil tension is a measure of the forces holding soil moisture to the soil structure. When the soil is very dry, the small amount of inter-particle water in the voids is bound tightly to the soil particles. As the inter-particle voids in the soil are filled with moisture, the overall forces binding the moisture to the grains are lessened. Thus, in the simplest sense, lower soil tension values indicate a higher moisture content. Note, however, that the relation between soil tension and volumetric water content is not linear, but rather resembles a flattened S-shaped curve, as determined experimentally and shown on figure 3. The form and position of the curve depends on the grain-size distribution of the soil, or better yet, the pore-size distribution (Burdine, 1953). As represented by the tails of the S-shaped curves, the change in volumetric water content becomes negligible at varying values of soil tension, depending on the materials. Although the form of this moisture-retention curve is unknown for the materials at the instrument sites without further testing, preliminary analysis of the site materials indicates a silty sand to sandy gravel texture. For such materials, the change in volumetric water content can be considered to be negligible for soil-tension values less than -50 kPa.

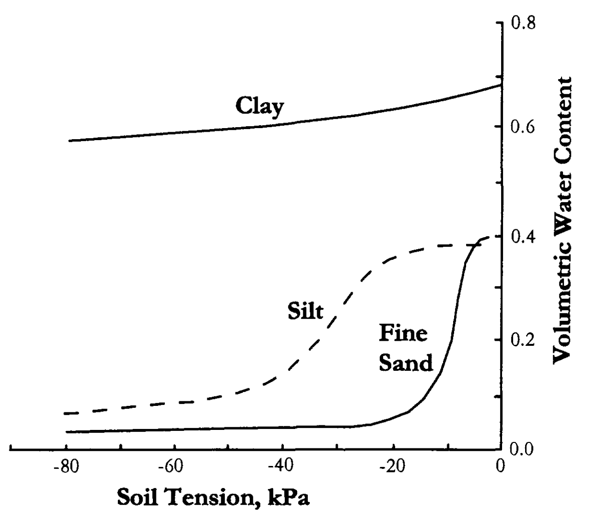

Figure 3. Soil water retention curves for clay, silt, and fine sand.

Instrumentation

Watermark model 200SS soil-moisture sensors, manufactured by Irrometer Company, Inc. of Riverside California, were selected for monitoring soil-pore water tension conditions at each site. The sensors consist of two concentric electrodes embedded in a granular matrix which has a consistency similar to fine sand. Included in the matrix is a gypsum block which minimize any effects of soil salinity on electrical conductivity. These granular-matrix sensors were developed in the early 1980's and have been used extensively in the agricultural industry for irrigation monitoring and control.

For purposes of this investigation, the granular-matrix sensors offer several advantages over other possible soil-moisture instrumentation. The cylindrical sensors, having dimensions of 2.25 cm in diameter and 8 cm in length, are easily installed in small-diameter hand-augered holes at various depths in the ground with a minimal disturbance of the existing soil column. Careful backfilling and tamping of the emplacement hole minimizes the possibility that it may provide an avenue of increased permeability for surface water to migrate to the sensors, although this possibility cannot be entirely eliminated. Other methods, such as TDR (time-domain reflectometry) or gypsum block sensors, would require greater disturbance of the overlying and surrounding soil column for emplacements of the sensing elements, and minimal disturbance of the natural soil column was considered to be a critical concern for this study. Further, the granular-matrix sensors can be placed in the ground for long periods of operation (even freezing) with no maintenance, and the cost is low relative to other instruments.

Additional instrumentation at each of the sites includes a tipping bucket rain gage capable of measuring rainfall in increments of 0.25 mm (0.01 in.), and soil-temperature sensors with an accuracy of ±1 °C installed at 15-cm and 61-cm depths. The soil-temperature sensors were installed to provide temperature correction in converting soil-sensor output to soil-tension values.

Data from the rain gages, soil-moisture sensors, and temperature sensors at each site are monitored and recorded by a datalogger/cellular telemetry system marketed by Environmental Cellular Inc. of Boulder, Colorado. The data recording and acquisition systems allow for data retrieval by remote computer dial-in. As currently configured, the systems record rainfall totals for 6-hour intervals, and the soil-moisture and temperature readings every 6 hours. In the event of accumulated rainfall that exceeds 2.5 mm (0.1 in.) in any 6-hour recording interval, the systems will switch to a fast-record mode wherein rainfall totals, soil moisture, and temperature readings are recorded every 15 minutes for the following 6 hours. The systems then return to the slow-record mode. This configuration allows for the rapid recording of soil-moisture conditions during significant rainfall events, and results in the savings of significant data storage space.

Soil-Moisture Sensor Calibration

The granular-matrix soil-moisture sensors provide an indirect measure of soil-water tension, and thus a series of calibrations are necessary to convert the sensor output to soil-tension values as a function of temperature.

Comprehensive research into the calibration of the Watermark sensors has been done at the Malheur Experimental Station which is operated by Oregon State University at Ontario, Oregon. Here, the Watermark sensors have been tested in both lab and field environments (for example, Eldredge, and others, 1993; Shock and Barnum, 1992; Stieber and Shock, 1995). The field calibration of Watermark sensors determined by Eldredge, and others (1993) is based on a comparison of sensor output to tensiometer readings, and produced a linear relationship between sensor output and soil tension. This relation is defined in the range between 0 and -80 kPa for 79 data points with an r^2 of 0.89. The relationship of soil tension to sensor output derived by Eldrege, and others (1993) is:

$$\psi = -6.44 - 0.738x \qquad \text{Eq (1)}$$

where ψ is soil-water tension in negative kPa and x is the reading obtained with the 30KTCD meter supplied by the manufacturer for reading the sensor output. The 30KTCD meter is designed such that the meter readings are related to sensor resistance and temperature by the equation:

$$x = \frac{R - 0.5}{0.1759(1 - 0.013T)} \qquad \text{Eq (2)}$$

where R is resistance in kΩ, and T is temperature in °C. By substitution of Eq (2) into Eq (1), the relation between soil-water tension and sensor resistance and temperature is:

$$\psi = \frac{-6.44 - 4.20(R - 0.5)}{(1 - 0.013T)} \qquad \text{Eq (3)}$$

Interface circuitry to convert a 12v DC power source to provide 5v AC excitation voltage to the soil-moisture sensors was built by the datalogger supplier. Because the sensors are an electrical resistive device, it is necessary to calibrate the sensors and interface circuitry to the datalogger output. To accomplish this calibration known resistances were applied to each analog input and the corresponding datalogger output in analog-to-digital counts recorded. This calibration resulted in a nonlinear relationship of the form:

$$R = \frac{0.0188C^2 + 11.288C}{1000} \quad (r^2 = 0.98) \qquad \text{Eq (4)}$$

where R is resistance in kΩ and C is datalogger output in counts. Substitution of Eq (4) into Eq (3) provides the following relationship for soil-water tension (in negative kPa) as a function of datalogger output and temperature:

$$\psi = \frac{-4.34 - 7.90 \times 10^{-5} C^2 - 0.047C}{1 - 0.013T} \qquad \text{Eq (5)}$$

Note that the reported calibration data is only in the range of 0 to -80 kPa. This constraint poses no serious limitation for this study as soil tensions in excess of -50 kPa are measured in soils that can experience very little changes in water content (fig. 3).

Instrument Locations and Installations

The location of the two soil-moisture monitoring sites (IS-1 and IS-2) on the Boundary Peak landslide deposit are shown on figure 1. Site IS-1 is located in an area that experienced a high burn intensity, and as a result is very open and exposed to sunlight. The surface is mantled by an unknown thickness of the El Cajete pumice. The ground surface at site IS-1 slopes 3° to the northeast, and the character of the subsurface materials was examined by digging a shallow pit and by augering with a 6.35-cm auger bit to a depth of 122 cm. The following materials and characteritics were revealed:

Site IS-1:

Depth (cm)	Description
0-4	dry ash, charcoal and pumice fragments
4-8	dry, light-tan silty sand with pumice fragments
8-30	moist, light-brown silty sand with pumice fragments
30-61	slightly moist, light-brown silty sand with pumice fragments
61-86	slightly moist, light-tan silty sand with pumice fragments
86-122	dry, white ignimbrite interbed

The fire intensity map prepared by the U.S. Forest Service shows the location of Site IS-2 in an moderately burned area. Field evidence, however, indicates that fire swept through the area, but with a very low temperature and a short residence time; some ponderosa pine trunks are singed to a height of 91 cm, but the needles remain green, the bark is healthy, and old pine needles remain on the ground. We thus consider this an essentially unburned site. Site IS-2 is considerably shadier than IS-1 due to the presence of abundant living ponderosa pine. The ground surface slopes 3.5° to the north-northeast, and although it is also mantled with El Cajete pumice, some cobbles and small boulders derived from the headscarp are scattered on the ground surface. The subsurface materials were examined by augering to a depth of 91 cm. The following materials and characteristics were described:

Site IS-2:

Depth (cm)	Description
0-15	dry, light-tan silt
15-38	moist, light-brown silty clay with pumice fragments
38-53	moist, lightly oxidized, light-brown silty sand with pumice fragments
53-91	dry, light-tan silty sand with some white ignimbrite fragments

It was more difficult to remove material from the auger tip at this site than at IS-1, presumably due to a slightly higher clay content of the materials. Grain-size distribution testing is presently underway to quantify the differences between the two sites.

Figures 4A and 4B are sketch maps showing the location of the soil-moisture sensor emplacement holes, thermistor emplacement holes, rain gages, dataloggers, and solar panels at each instrumentation site. The depths of installation of the soil-moisture sensors at each site are listed in table 1. The depth to which the deepest sensors were installed was controlled by the presence of unweathered pumice. Note also that sensors 5 through 8 at site IS-2 are not in the same sensor number-depth sequence as the other array due to installation constraints.

The raingages and soil-monitoring instrumentation were installed in late August 1996 and have operated nearly continuously since that time. Soil-temperature sensors were installed in early September allowing calculation of soil-tension values. Note that the temperature sensors were installed at depths of 15 and 61 cm. Temperature

Table 1. ***Soil-moisture sensor number and installation depth information at sites IS-1 and IS-2. Soil-temperature sensors at each site are installed at depths of 15 and 60 cm***

Site IS1 (burned)				Site IS-2 (unburned)			
Sensor No.	Depth (cm)	Sensor No.	Depth (cm)	Sensor No.	Depth (cm)	Sensor No.	Depth (cm)
1	15	5	15	1	15	7	15
2	30	6	30	2	30	5	30
3	60	7	60	3	60	6	60
4	79	8	84	4	71	8	100

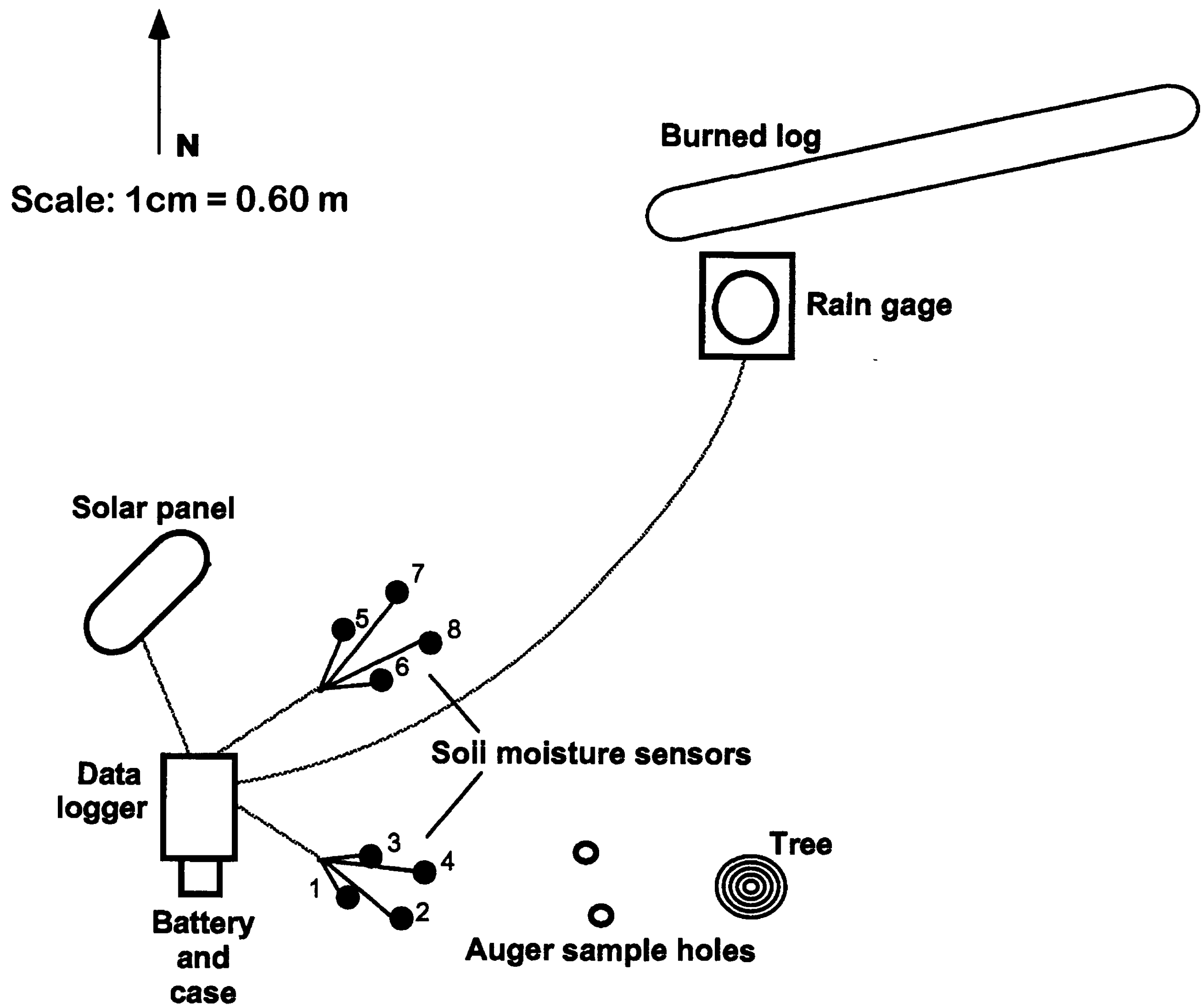

Figure 4A. Map of instrument installation IS-1 (burned site).

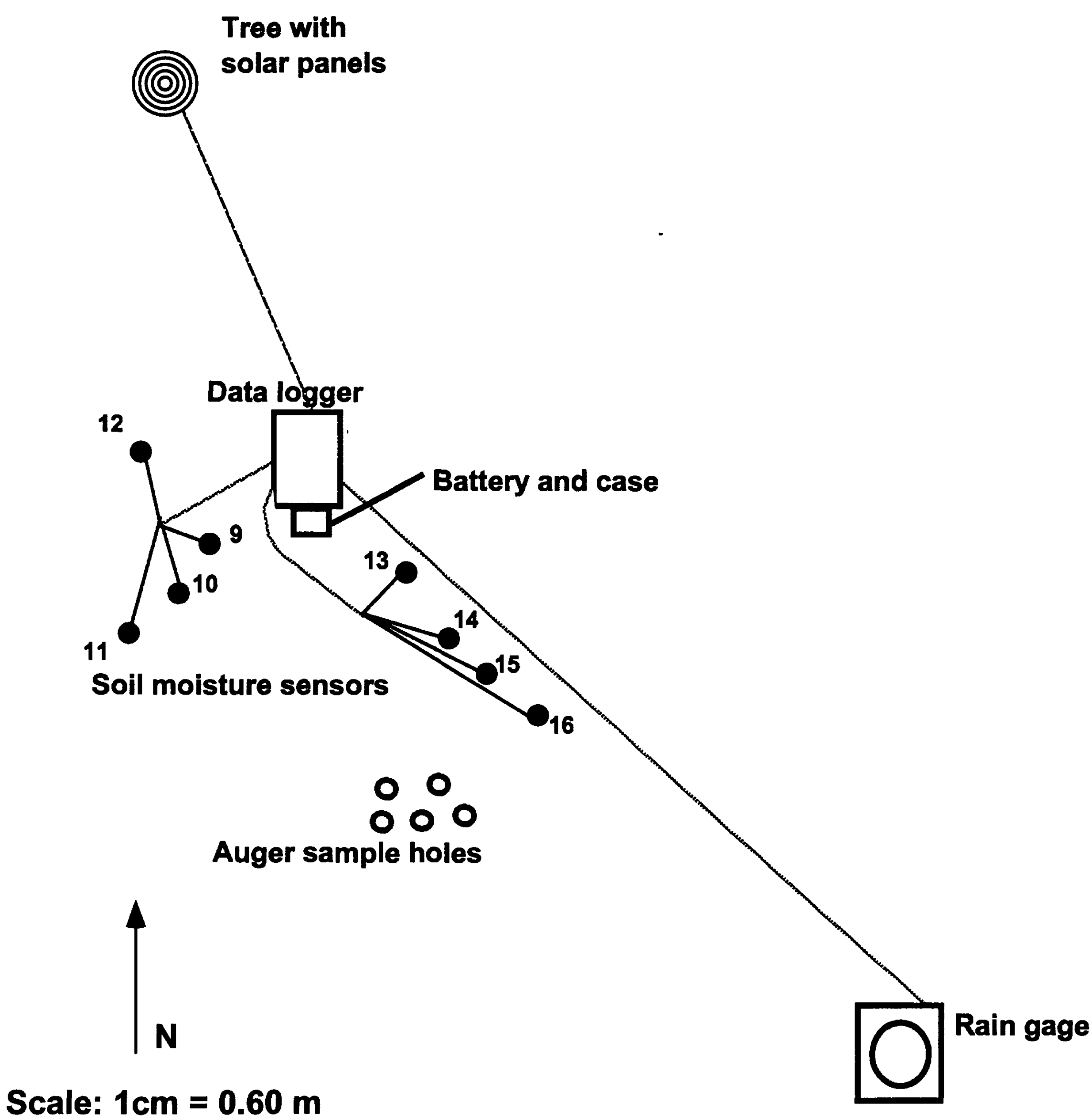

Figure 4B. Map of instrument installation IS-2 (unburned site).

data from the sensor at 15 cm was used in the calibration of soil-moisture sensors at 15 cm, and the temperature probe at 61 cm was used for all other soil-moisture sensors. Except for an approximately 2-week period in late October and early November of 1996, during which solar-power problems were encountered at site IS-2, essentially continuous records of rainfall and snowmelt events and soil-moisture conditions have been recorded at both sites.

Note that the soil-moisture sensors are wet when installed in the ground and are surrounded by a slurry of the soil in which they are installed. The slurry insures that air pockets are eliminated so that good contact between the soil and sensor is established. Some period of time is therefore required for the natural soil-moisture conditions in the proximity of the sensors to return to equilibrium, the length of which depends on the water content and properties of the surrounding soil. The soil surrounding the sensors was considerably drier than the installation slurry; thus, a period of drying was expected after sensor installation.

Preliminary Results

A qualitative comparison of the soil-tension responses of the burned and unburned sites (figs. 5 and 6), recorded from September 10 to November 30, 1996, indicates that rainfall infiltrates more readily, and to greater depths, at the burned site than at the unburned site. With some notable exceptions, most of the burned-site sensors responded immediately to the three moisture events recorded and show a repeated pattern of immediate wetting during a rainfall or snowmelt event, followed by gradual drying between events. In contrast, and also with exceptions, the sensors at the unburned site showed a continued drying trend until the late October event (which was a combined rainfall and snowmelt event spread over a few days), at which time only the four shallowest probes wetted (the 15 cm and 30 cm), and the deeper probes continued drying. Note that this drying trend may also be attributed to the moisture state of the soil and the sensors at the time of installation; the sensors, and presumably the surrounding soil, at the burned site were considerably wetter at installation than those at the unburned site. The permeability of soil is very low at such low moisture contents, and thus any wetting is a difficult proposition.

Further comparisons of the data from the two sites indicate that the wetting response to rainfall events at the burned site is much more rapid than that at the unburned site. For example, at the unburned site one of the sensors at 15 cm showed some wetting over an 8-day period in response to the September rainfall events, and the two probes at 15 cm and one probe at 30 cm also showed very slow wetting in response to the early October rainfall. These responses are in contrast with those at the burned site, which occurred over much shorter time periods and over a considerably smaller data range. This relation may again be due to the moisture state at the time of the rainfall events. Soil permeabilities are very low at the extremely low pore-pressure values recorded at the unburned site.

In addition, the drying responses for some rainfall events might be preliminarily taken to indicate the influence of active transpiration by the vegetation at the unburned site and a lack of transpiration at the burned site. The drying response of the sensors following the rainstorms at the burned site is very gradual and over only a limited range, while the pore pressures determined for the shallow probes at the unburned site dissipate much more rapidly, and to much higher tension values. Also note that the most-negative soil-tension values at the unburned site are considerably greater than those at the burned site. These differences might be due to the removal of soil water by the living vegetation at the unburned site.

Note that these data and interpretations are preliminary and continued monitoring through a complete summer thunderstorm season is necessary for their confirmation. In addition, to quantify the soil-moisture response, or to convert soil-tension values to volumetric water contents and permeabilities, further testing is necessary to establish the soil-moisture retention curves for the site materials (for example, Brooks and Corey, 1966; vanGenuchten, 1980). Further complicating the issue of determining volumetric water contents from soil-tension values, repeated wetting and drying cycles experienced by the soil result in a hysteresis in the soil water-retention curve. Laboratory testing of soil-permeability characteritics may be necessary to quantify this relation for the situation on the landslide deposits.

And finally, some aspects of the data remain to be explained. For example, at the burned site, one of the 30-cm sensors showed neither a wetting or drying response throughout the recorded period, while the other sensor at 30 cm showed only a drying response. In addition, one of sensors at 60 cm and the sensor at 84 cm did not respond to the September or early-October rainfall events, but did wet up dur-

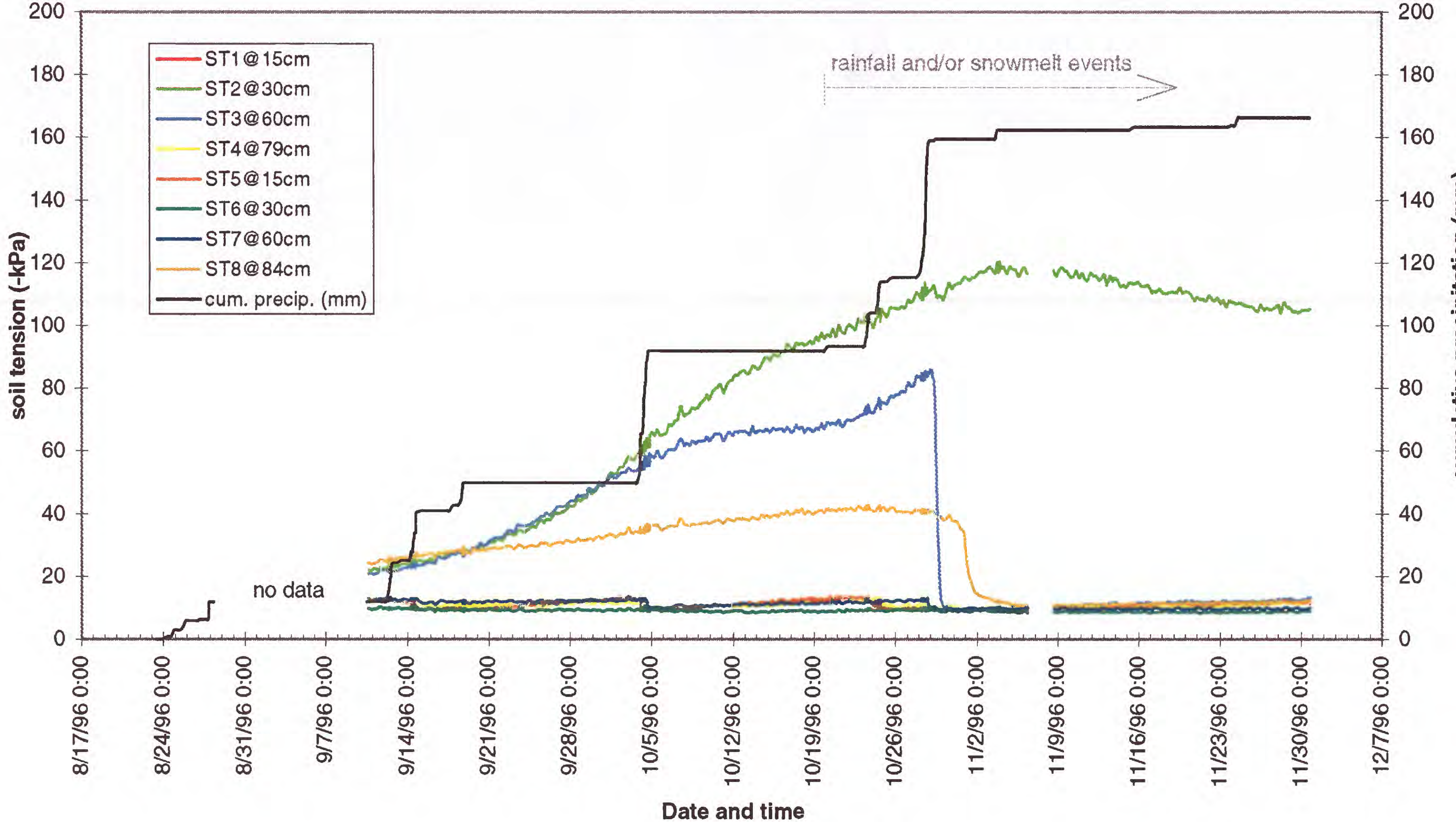

Figure 5. Plot of cumulative precipitation and soil-tension measurements with time for IS-1 (burned site). ST refers to soil-moisture sensors. Cumulative precipitation totals do not include data from rainfall events that occurred between August 29 and September 10, 1996. A total of 13.6 mm of rainfall was recorded at IS-2 between those dates.

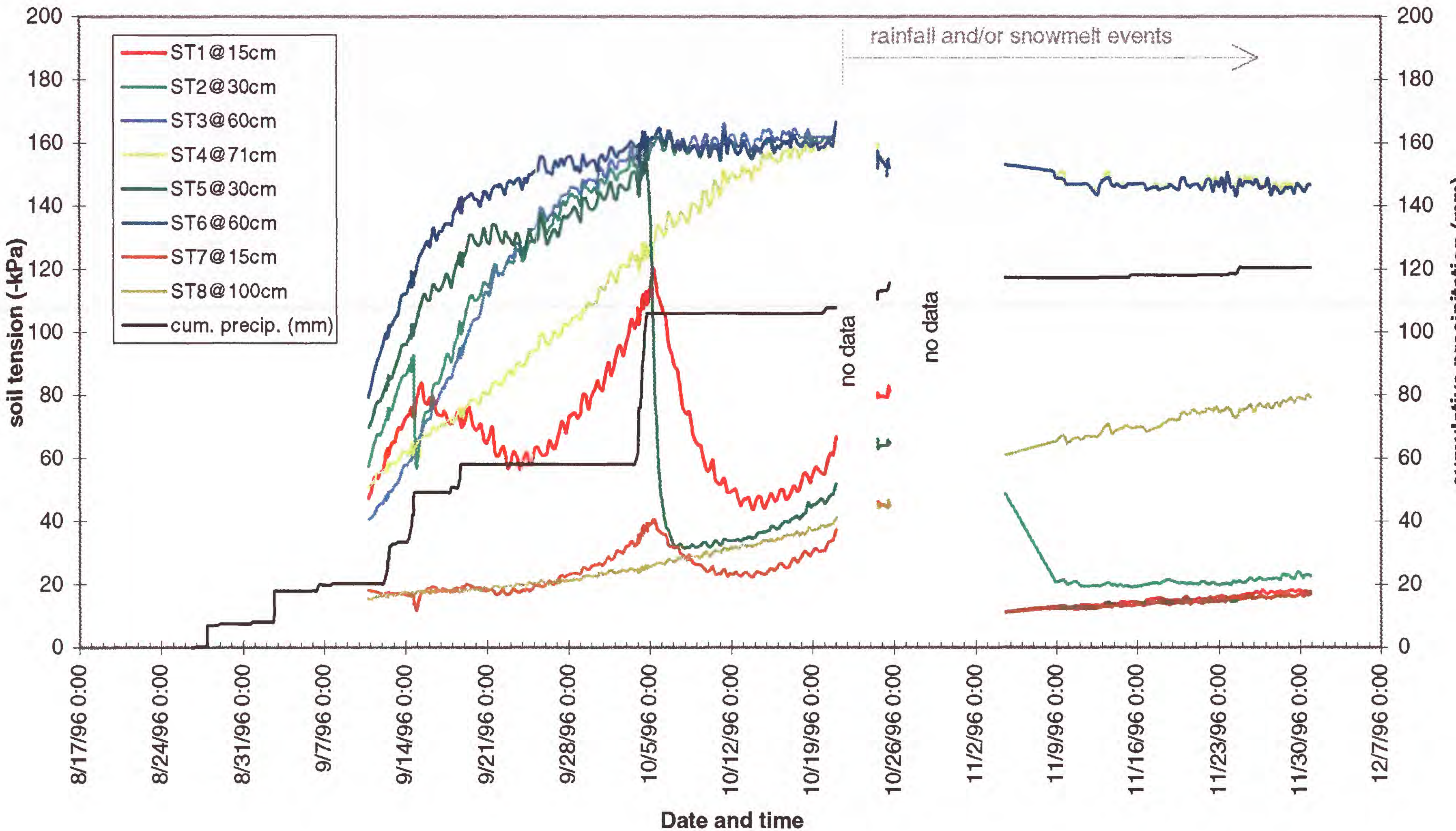

Figure 6. Plot of cumulative precipitation and soil-tension measurements with time for IS-2 (unburned site). ST refers to soil-moisture sensors. Records between October 21 and November 8, 1996, are discontinuous due to electrical power problems at the site. Cumulative precipitation totals do not include 56 mm of the 67.5 mm of precipitation from rainfall and snowmelt events recorded at IS-1 between those dates.

ing the late October combined rainfall and snowmelt event. The redundant 60-cm sensor and another sensor at 74 cm did, however, respond to all three moisture events. More data are necessary to interpret these results.

SUMMARY AND CONCLUSIONS

To assess the present stability of the Boundary Peak and Base Camp landslides in Capulin Canyon, and to evaluate the potential for destabilization due to the removal of vegetation during the Dome fire, a program of mapping and soil-moisture monitoring was undertaken.

The Boundary Peak landslide covers an area of approximately 2.9 km^2 and appears to be approximately 150 m thick, while the Base Camp landslide covers approximately 0.2 km^2. The thickness of the Base Camp landslide deposits is not known. The Boundary Peak landslide deposits experienced two areas of high burn intensity which cover a total area of approximately 0.15 km^2. The remainder of the deposits were mapped as moderate or low burn intensities. The Base Camp deposits show one area of low burn intensity which covers an area of 0.03 km^2. Initial emplacement of both the Boundary Peak and Base Camp landslide deposits occurred along deep-seated, convex-upward failure surfaces, which resulted in a rotational transfer of material downslope and out onto the valley floor. Material from either landslide did not travel down Capulin canyon for any distance. No sedimentological evidence was observed upstream from the landslide deposits that would indicate that the landslides ever dammed Capulin creek, suggesting that the rates of movement into Capulin creek were sufficiently slow to allow the creek to maintain a channel.

Neither the Boundary Peak nor the Base Camp landslide deposits exhibit evidence of recent movement or instability. Both landslide deposits are mantled by the El Cajete pumice, giving a minimum age of 50,000-60,000 years for the latest significant movement of the landslides. The entire landslide topography is muted and subdued. No cracks, fissures or shear zones were observed and only a few tilted trees, too few and far between to indicate instability of the deposits, were observed. Although the thickness of the pumice mantle on the landslide deposits is unknown, the weathering of the pumice and soil development creates a coherent layer that should reflect any reactivation of the underlying landslide deposits. The interaction of Capulin Creek and the landslide toes appears to be negligible, and no danger of destabilization of the deposits by undercutting appears to exist at this time.

The likelihood of reactivation of the Base Camp landslide deposits due to increased infiltration in areas burned by the Dome fire appears to be negligible due to the small area and low intensity of the fire on the deposits.

Qualitative evaluation of the preliminary soil-moisture data from the Boundary Peak landslide deposits indicates an apparent change in infiltration characteristics at the burned site, suggesting a slight potential for reactivation of the deposits due to the Dome fire. The evaluation indicates that (1) rainfall infiltrates more readily, and to greater depths, at the burned site than at the unburned site; and (2) the drying response of the sensors at the burned site is very gradual and over only a limited range, while the pore pressures recorded by the shallow sensors at the unburned site dissipate much more rapidly, and to much higher tension values. These differences may indeed be due to the lack of vegetation induced transpiration at the burned sites, but continuing monitoring through a minimum of one summer thunderstorm season is necessary to both confirm these relations, as well as to quantify the differences in infiltration rates. Further evaluation is also necessary to determine if the increased infiltration rates are sufficient to result in the destabilization of the landslide deposits.

A slight potential for the reactivation of the Boundary Peak landslide deposits due to the Dome fire is indicated by the apparent change in infiltration characteristics at the burned site. Movement on this type of deep-seated landslides is precipitated by infiltration of water deep into the deposits. Either a number of consecutive, very wet rainfall seasons, or a single large snowmelt event would be necessary to generate this condition.

The most likely potential consequence of the reactivation of this landslide deposit is the creation of unstable ground that would pose a navigational hazard for hikers on the deposits themselves. The integrity of archeological sites on the deposits would be threatened should movement continue for any extended period of time. The remote possibility also exists for the landslide deposits to move into Capulin Canyon and dam Capulin Creek, although there is no evidence to indicate that this occurred in the past. Should this occur, catastrophic failure of the dammed material and the resultant flooding could result in destruction of downstream archeological sites, as well as the loss of human life.

The likelihood of reactivation of these deposits appears to be so slight at this time that no restrictions of access to Capulin Canyon due to this threat appear to be necessary. However, continued evaluation of soil-moisture data collected through a minimum of one complete summer thunderstorm season is necessary to verify the apparent increase in rainfall infiltration into the burned area soils and to quantify the influence of this increase on the stability of the deposits.

Most importantly, a general state of awareness of the condition of the landslide deposits by those working in the canyon can be extremely useful in evaluating their continued stability.

- The steep section of the toe in Capulin Canyon should be observed for signs of steepening, and formation of cracks and shears within the deposits, particularly in the areas of stepped topography on the lateral margins of the primary block.
- The presence of new seeps or springs, or increased flow in existing seeps or springs along the toe of the landslide deposits in Capulin creek or at the heads of channels on the deposits, could indicate increased ground-water flow through the deposits in response to increased infiltration into the burned area.
- The development of areas with numerous tilted trees should be noted.

Should these conditions arise, access restrictions should be considered for Capulin Creek downstream from the landslide deposits.

REFERENCES

Brooks, R.H., and Corey, A.T., 1966, Properties of porus media affecting fluid flow: Journal of Irrigation and Drainage Division, American Society of Civil Engineers, v. 92., p.61-88.

Burdine, N.T., 1953, relative permeability calculations for pore-size distribution data: Petroleum Transactions, American Institute of Mining Metallurgy Engineering, v. 198, p. 71-77.

Eldredge, E.P., Shock, C.C., and Steiber, T.D., 1993, Calibration of granular matrix sensors for irrigation management: Agronomy Journal, v. 85. no.6, p. 1228-1232.

Fleming, R.W., and Johnson, A.M., 1989, Structures associated with strike-slip faults that bound landslide elements: Engineering Geology, v. 27, p. 39-114.

Goff, Fraser, Gardner, J.N., and Valentine, Greg, 1990, Geology of St. Peterís Dome Area, Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 69.

Phipps, R.L., 1974, The soil creep-curved tree fallacy: Journal Research U.S. Geological Survey, v. 2., no.3, p. 371-377.

Reneau, S.L., Gardner, J.N., and Forman, S.L., 1996, New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico: Geology, v. 24, no. 1, p.7-10.

Shock, C.C., and Barnum, J.M., 1992, Improving irrigation management of potatoes with granular matrix sensors: Proceedings of the 25th Oregon Potato Conference.

Stieber, T.D., and Shock, C.C., 1995, Placement of soil moisture sensors in sprinkler irrigated potatoes: American Potato Journal, v. 28, p. 533-543.

vanGenuchten, M.T., 1980, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils: Soil Science Society of America Journal, v. 44, p. 892-989.