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GEOLOGICAL SURVEY
3215 Marine Street
Boulder, CO 80303-1066
September 12, 1994

Greg Toll, Operations Superintendent
City of Boulder Open Space Operations
66 S. Cherryvale Rd.
Boulder, CO 80303

Dear Mr. Toll,

Enclosed is a copy of a draft manuscript that I wrote based on work in Boulder ~~County~~ City Open Space. You may recall that you gave me permission last November to collect data at Rabbit Mt. Open Space. This work was done for the CU Department of Geography and has not been published so it is not citeable. Please call me if you have any questions, at 541-3011. Thanks again for your assistance.

Cordially,

Matt Larsen

Matt Larsen,
Hydrologist

Soil Development and Relative Age Dating of Quaternary Landslide Deposits in the Boulder-Lyons Front Range area

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An analysis of soil development on Quaternary landslide deposits provides a useful tool for estimating the age of the deposits. Certain requirements must be met for this approach to be successfully employed: 1. the analyzed soil must be one that has developed on material that was freshly exposed or deposited at the time the mass movement occurred; and, 2. soil on an adjacent, undisturbed slope (with comparable bedrock, vegetation, elevation, aspect, angle, and moisture conditions) should be analyzed to confirm significant differences in developmental stage. When these conditions can be met, the approximate age of the landslide can be determined.

Soils at two landslide sites in the Boulder-Lyons Front Range area were described and sampled. Cox horizons in the undisturbed soils adjacent to the landslides were redder in color-- light-reddish-brown to brown (7.5YR to 5YR) than their younger counterparts on the landslides, which were yellowish-brown (10YR). These colors indicate that that the landslide soil may be 3,000 to 5,000 years old. Cox horizon density for the landslide soils was higher than Cox horizon density on the undisturbed, adjacent soils, possibly because of illuviation of clay and silt.

Storm precipitation data for the 20th century indicate that low intensity storms of sufficient duration to trigger large earthflows are not common. Simplified estimates of soil geotechnical characteristics suggest that the earthflows at the two study sites would require moisture infiltration equivalent to several years of present-day mean annual rainfall, assuming zero evaporation losses. Many Front Range earthflow scars and deposits in the Boulder-Lyons area may therefore date from mid Holocene or earlier, when moisture conditions were wetter, and evaporation and temperature was lower than at present.

INTRODUCTION

Ancient mass-wasting episodes leave a stratigraphic record that can be used to estimate past climate conditions. Seismic activity and anthropogenic disturbance are locally important causes of extensive landsliding (Varnes, 1978). However, landslides triggered by precipitation, often in conjunction with an antecedent moisture requirement (Campbell, 1975) are common in many areas of the world. In those areas where the landslide deposits or scars are still exposed, these features provide a substrate on which a soil may develop. This soil development begins after the mass-wasting event has occurred and may provide a measure of the approximate age of the feature.

Numerous Quaternary landslide deposits along the Front Range urban corridor have been mapped by Crosby (1978). Little work has been done to estimate the age of these deposits. Some of the landslide deposits are historic and related to anthropogenic activity. Others, however, may be much older (R. Madole, USGS, personal communication) perhaps dating to early Holocene or to the Pleistocene. It is probable that the older landslides occurred during a period when mean annual precipitation was higher than the present 47 cm.

A method for determining the approximate age of Quaternary Front Range landslide deposits would be valuable for several reasons. Although widely used in the Rocky Mountains and elsewhere for age estimation of various types of geomorphic surfaces (Birkeland, 1984; Harden, 1982; Machette, 1975; Shroba, 1977; Scott, 1963) the use of soil development to determine the age of landslide deposits has not been widely documented in the scientific literature. Demonstration of the practicality of this approach may lead to better assessment of Quaternary mass-wasting features. If the landslide deposit age can be approximated the mass movement can then be related to the climatic conditions existing at that time and an improved understanding of these deposits can be developed. In addition, a regional inventory of the locations, dimensions, and ages of Quaternary landslide deposits would be of interest in the calculation of Quaternary hillslope denudation rates and fluvial sediment budgets. Finally, human encroachment on Front Range hillslopes is a worsening problem, necessitating improved hazard assessment. Estimates of precipitation conditions that may trigger future episodes of landsliding are needed to mitigate threats to life and property.

STUDY AREA

A site located west of Boulder, Colorado (105° 18', 40°, elevation 1,737 m) and another site, east of Lyons, Colorado (105° 13', 40° 15', elevation 1,769 m) were selected for analysis of soil and geomorphic characteristics (fig. 1). The two sites contain landslides (earthflows) mapped by Crosby (1978). These particular sites were chosen because of good access, reasonably well-defined landslide features, and intersite comparable topographic, soil, and geologic characteristics.

Geology

The Colorado Front Range is the easternmost range of mountains that comprise the Rocky Mountain cordillera where it passes through the state of Colorado in central-western United States. The Front Range in the Boulder-Lyons area is composed of a series of Tertiary sedimentary rocks that underlie north-south trending narrow parallel ridges. The ridges are mainly composed of well-cemented sandstones-- principally the Dakota Group, Lyons Sandstone, and the Fountain Formation. The valleys between the ridges are mostly shale and softer sandstone-- the Pierre Shale and the Benton Formation (Worcester, 1950). Because of the steep eastward bedrock tilting that formed the Front Range ridges, the hillslopes, particularly where mantled with Pierre Shale, are prone to mass movements and numerous large (10,000 m^3 to >100,000 m^3) have occurred.

Soils

Soils mapped by the U.S. Soil Conservation Service (SCS) include five orders: Entisols, Inceptisols, Aridsols, Mollisols, and Alfisols (Moreland and Moreland, 1975). Mollisols (Lithic Haplustolls) represented by the Baller soil series are the soils mapped in the area of the landslides examined in this study. The SCS described the Baller soil series as shallow, well drained loamy residuum weathered from sandstone, common on 9 to 35 percent slopes with weakly expressed horizons-- A and C horizons without B horizon development. According to the SCS, soils in the Boulder area reflect a previous lengthy history of conditions under which soil moisture exceeded that of the present day (Moreland and Moreland, 1975).

Climate

Annual precipitation in the Boulder area is 47 cm (fig. 2), 70 percent of which occurs as spring and summer rainfall and thunderstorms resulting mainly from Pacific monsoonal air masses (Hansen, *et al.*, 1978). The remainder falls as winter snow. The maximum annual precipitation recorded during the past 100 years in the Boulder-Lyons region is 79 cm, or about 168 percent of normal. In 1921 however, the local maximum annual precipitation recorded near Indian Peaks, 26 km west of Boulder, was 174 cm (Hansen, *et al.*, 1978). The mean annual evaporation of 140 cm is about 300 percent of mean annual precipitation. Mean monthly temperature ranges from 0° Celsius in January to 21° Celsius in July.

METHODS

Field methods

Soil profiles were characterized on two landslide deposits and on the relatively undisturbed hillslopes adjacent to the deposits according to techniques described by Birkeland (1984) and Buol *et al.*, (1973). The soil profiles were named according to their location-- Hawthorne-old (Ho) and Hawthorne- young (Hy) were upslope of, and on a landslide deposit, respectively (fig. 3). Rabbit Mountain- old (RMo) and Rabbit Mountain- young (RMy) had the same geography. Rabbit Mountain- side (RMs) was located on a slope of comparable elevation and angle, about 100 m north of Rmy.

Soil master and subhorizons, Munsell color (Munsell Color Company, 1954), structure, gravel percent, consistence, texture, clay films, and horizon boundaries were noted in the field. Compressive strength was estimated using a penetrometer. In addition, the profiles were photographed and landslide deposit dimensions were sketched. Samples were collected at 20 to 30 cm intervals for laboratory analysis of texture, dry color, bulk density, ambient moisture percent, loss on ignition, and pH.

Laboratory methods

Laboratory work included the determination of: 1. clay, silt, sand percent using hydrometer technique; 2. gravimetric soil moisture percent; 3. soil bulk density for use in calculation of clay formation; 4. dry soil Munsell color determination; 5. loss on ignition, from which organic carbon was estimated by dividing loss on igntion by 1.724, and 6. soil pH using colorimetric method. Standard laboratory procedures were followed as described by Birkeland (1984) and Soil Survey Staff (1951).

Climate and geotechnical estimates

A summary of 20th-century Denver-area Front Range maximum precipitation totals and storm durations (Hansen *et al.*, 1978) was compared to a worldwide rainfall threshold for landsliding (Caine, 1980). Comparison of the storm precipitation data with the threshold provides insights into Front Range landslide potential. Using landslide scar and deposit thickness, width, length, and slope angle, rudimentary calculations of rainfall required to initiate failure conditions were estimated using Mohr-Coulomb theory (Terghazi and Peck, 1967).

RESULTS AND DISCUSSION

Landslide morphology and dimensions

The Hawthorne earthflow scar, located on an east-facing, 23° slope, has a head scarp that measures 34 m in width and a vertical offset of about 2.4 m (fig. 3). The earthflow deposit is located 25 to 50 m downslope and covers an approximate area of 850 m^2. The estimated drainage area upslope of the headscarp is 6,800 m^2. The Rabbit Mountain earthflow is located on a southwest-facing slope of 14°. The headscarp is highly eroded and presently has a vertical offset of less than 1 m. The earthflow deposit, located about 140 m downslope, consists of two *en echelon*, downslope-oriented, 5 m-thick lobes, covering an area of about 875 m^2. The smoothed, subdued morphology and comparable vegetation of earthflow deposits and scars at both sites suggests that they are at least 100's of years old.

Soils characteristics

Because of the small sample size, only limited conclusions can be drawn from the soils data. Using dry Munsell colors, the ages of the soils can be roughly estimated. The Ho Cox horizon soil color is 7.5YR while the Hy color is 10YR throughout the profile (table 1; fig. 4). The RMo soil Cox horizon is 5YR in color and the RMy color is 10YR throughout (table 1; fig. 5). The Rms soil falls between Rmo and Rmy with a Cox color of 7.5YR.

A generalized progression in age from younger to older soils derived from river sediment in the Colorado Piedmont follows a color sequence from 10YR--7.5YR--5YR--10R (Birkeland, 1984). These colors represent ages of zero, 10^4, 10^5, and 10^6 years, respectively. An additional age estimate using the color 10YR 6/4 for glacial till in Rocky Mountains, Colorado, assigns an age of 10^3 years (Shroba, 1977). These color-age correlations suggest the Ho soil may be as old as 10,000 years and the the Rmo soil may be as old as 100,000 years. The Rms soil probably provides a more reliable age estimate for the Rabbit Mountain site of 10,000 years as the near-ridge top location of the Rmo site is not likely to have been stable enough to allow a soil to develop in place for 100,000 years. The Cox horizon colors for the Hy and Rmy soils indicate that they are likely to be somewhere between 1,000 and 10,000 years old.

Color-age correlations by Scott (1963) on Front Range Quaternary and Pleistocene alluvium indicate that the landslide soil Cox colors may represent an age that is near the late Pleistocene/early Holocene boundary of 10,000 years. In addition, Scott (1963) described several Front Range earthflows in Pierre shale in an area about 80 km south of the Boulder. He estimated their ages to be late Holocene, stating that they displaced Piney Creek alluvium which has an age of approximately 3,000 years. This age places the earthflows on his boundary between a dry interglacial and wet glacial climate cycle (fig. 6).

The younger soils (Hy, Rmy) at both sites had relatively higher density in the Cox horizon than did their older counterparts (Ho, Rmo, respectively). The lower Cox-horizon density in the older soils may result from translocation of clay down-profile as the soil ages. Down-profile clay weight per unit volume at the Rmo and Rmy sites support this possibility as the younger soil has a relatively lower amount of clay overall, as well as at depth. Clay weight per unit volume at the Ho and Hy sites did not show the same trend, due possibly to the general mixing of soil material that occurs on colluvial hillslopes.

Average values for unconfined compressive strength, pH, and estimated organic carbon were inconclusive in differentiating between older and younger soils at both sites.

Storm rainfall

The storm rainfall required for triggering of earthflows (Varnes, 1978) may not be as common as 20th-century storm magnitude and frequency data at first suggest. Recorded short-duration, high-intensity storms are impressive in their magnitude and plot above the worldwide landslide threshold (fig. 7). However, the longer duration storms-- those exceeding 24 h, are at or below the worldwide landslide threshold. Moderate- to deep-seated earthflows are a type of mass wasting that is slow- to moderate in velocity, usually requiring lengthy periods of low intensity precipitation. This moisture regime allows the buildup of soil pore-water pressure needed to destabilize the hillslope at depth (Wilson, 1991; Iverson and Major, 1986). If the intensity-duration characteristics of the Front Range storms drawn from the data base of Hansen *et al.*, (1978) are representative, deep-seated earthflow movements should not be a common phenomena at present.

Geotechnical characteristics

The potential for landslide failure to occur in a soil-mantled hillslope can be estimated using Mohr-Coulomb theory to calculate the factor of safety. The factor of safety is defined as the ratio of the resisting force (due to the shear strength of soil along the failure surface) to the driving force (due to the weight of the sliding mass). As soil approaches saturation, weight (W) increases, and cohesion (c) decreases, and the factor of safety approaches unity. The equation is expressed as:

$$F = \frac{cL + W \cos \alpha \tan \phi}{W \sin \alpha}$$

where:
c = soil cohesion,
L = length of failure plane,
W = weight of the soil above the failure plane,
α = angle of the failure plane (parallel or subparallel to the hillslope angle), and
ϕ = internal friction angle.

Conditions required for failure estimated using the Mohr-Coulomb theory indicate that moisture conditions significantly higher than those of the present-day may have been required to induce failure at both sites. Using measured soil density (table 1), landslide scar width, length, and thickness (noted above), estimated values from Huang (1983) for soil cohesion (1367 kg/m^2) and friction angle (28°), and upslope rainfall catchment area, about 1 year and 4 years of mean annual precipitation would be required to trigger the Hawthorne and Rabbit Mountain earthflows, respectively. This precipitation estimate does not include the evaporation losses and assumes that 100 percent of annual precipitation saturates the soil down to the 2.4 and 5 m failure depths at the Hawthorne and Rabbit Mountain sites, respectively. Because dense clay loam (Hawthorne) and clay soil (Rabbit Mountain) have extremely low permeability (10^{-8}m/s, Terghazi and Peck, 1967), the amount of required precipitation is probably much higher, unless significant macropore soil-water flow occurs at these sites. In addition, the mean annual evaporation rate of 140 cm exceeds mean annual precipitation by about 200 percent, suggesting that large rainfall-triggered earthflows are unlikely to occur under present climate conditions.

CONCLUSIONS

Comparison of soils on and adjacent to landslide deposits demonstrates that landslide soils are relatively younger than their counterparts on undisturbed hillslopes. Munsell color, soil density, and down-profile clay concentrations are the simplest characteristics supporting this conclusion. The Cox age-color correlations suggest that the landslides occurred between 1,000 and 10,000 years ago.

Twentieth century storm-rainfall characteristics were analyzed in conjunction with Mohr-Coulomb estimates of moisture conditions required to reduce soil shear strength sufficiently to induce hillslope failure. These analyses indicate that present day climate may be too dry to have triggered the numerous, extensive earthflow deposits mapped along the Front Range. However, if the earthflows are slightly older than Scott's (1963) 3,000 year estimate for the earthflows south of Boulder, the Hawthorne and Rabbit Mountain earthflows would have occurred during a wet glacial cycle that occurred just prior to the period when Piney Creek alluvium was deposited. The earthflow Cox colors indicate that this is a reasonable possibility and that the Boulder-Lyons landslides described in this study may be 3,000 to 5,000 years old.

Determining the age of a feature or deposit is one of the most difficult tasks faced in Quaternary stratigraphy. Quantitative dating methods such as ^{14}C, can be prohibitively expensive and beyond the scope of many research budgets. Relative dating methods such as degree of soil development are therefore attractive alternatives when they can be shown to be reasonably accurate. Comparison of soil development on landslide deposits with adjacent topographically similar, but undisturbed soil is a useful approach. However, to be statistically sound, a number of soils on the landslide deposit must be compared with an equal number on the adjacent undisturbed site.

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Table 1. Results of field and laboratory analyses showing soil moisture, bulk density, porosity, compressive strength, pH value, sand, silt, and clay percentage, estimated organic carbon percent, dry Munsell color, and clay weight per unit volume at varying depths for five soils sites.

Soil	Depth cm	Moisture %	Bulk density, g/cc	Porosity %	Unc Str kg/cm^2	pH	Sand %	Silt %	Clay %	Clwt g/cc	OrgC %	Color
Ho	3	21	1.24	53	<.1	6.8	54	22	24	0.29	2.8	10YR4/2
Ho	14	26	1.28	52	<.1	7.2	40	25	36	0.46	3	10YR3/4
Ho	35	29	1.32	50	1.5	7.6	31	29	40	0.53	2.7	7.5YR4/2
Ho	80	22	1.37	48	1.5	7.4	35	37	27	0.37	2.1	7.5YR5/4
Ho	105	21	1.31	50	1.6	7.4	37	35	28	0.37	1.8	7.5YR5/4
Hy	3	24	1.08	59	<.1	7.4	46	31	23	0.25	5.8	10YR4/1
Hy	16	24	1.23	54	<.1	7.6	42	24	34	0.42	3.1	10YR4/1
Hy	38	18	1.59	40	1.75	7.4	44	23	33	0.52	2.1	10YR5/3
Hy	85	22	1.44	46	3.25	8	20	23	58	0.83	2.7	10YR5/3
RMo	5	16	1.47	45	nd	7.8	44	19	38	0.55	3.3	7.5YR5/2
RMo	18	12	1.4	47	nd	7.2	33	19	48	0.68	3.1	7.5YR6/6
RMo	40	14	1.19	55	nd	8.2	19	19	62	0.73	2.9	5YR6/3
RMs	9	20	0.99	63	0.8	7.4	46	26	28	0.28	2.8	10YR4/2
RMs	24	24	1.38	48	3	7.4	27	29	44	0.61	3.3	7.5YR3/2
RMs	40	16	1.44	46	>6	7.4	23	28	49	0.71	2.5	7.5YR4/2
RMy	3	26	1.01	62	1	7.4	43	25	32	0.32	4.7	10YR4/2
RMy	17	21	1.49	44	1.6	7.4	36	18	46	0.69	3.6	10YR4/3
RMy	33	11	1.24	53	2	7.4	38	17	45	0.56	2.8	10YR5/4

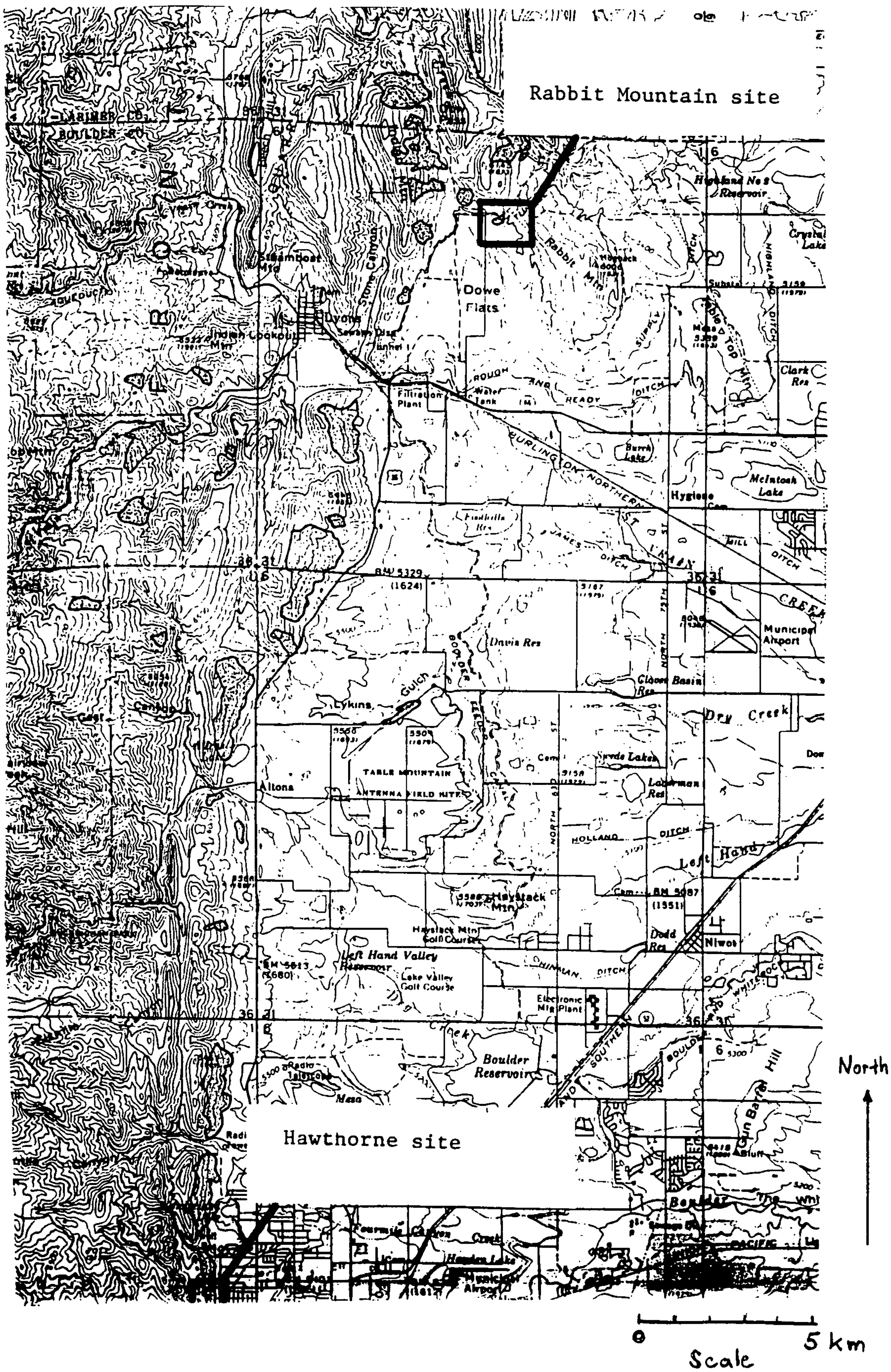

Figure 1. Map of Boulder-Lyons, Colorado area showing study sites. Stippled areas are landslide locations from Crosby (1978).

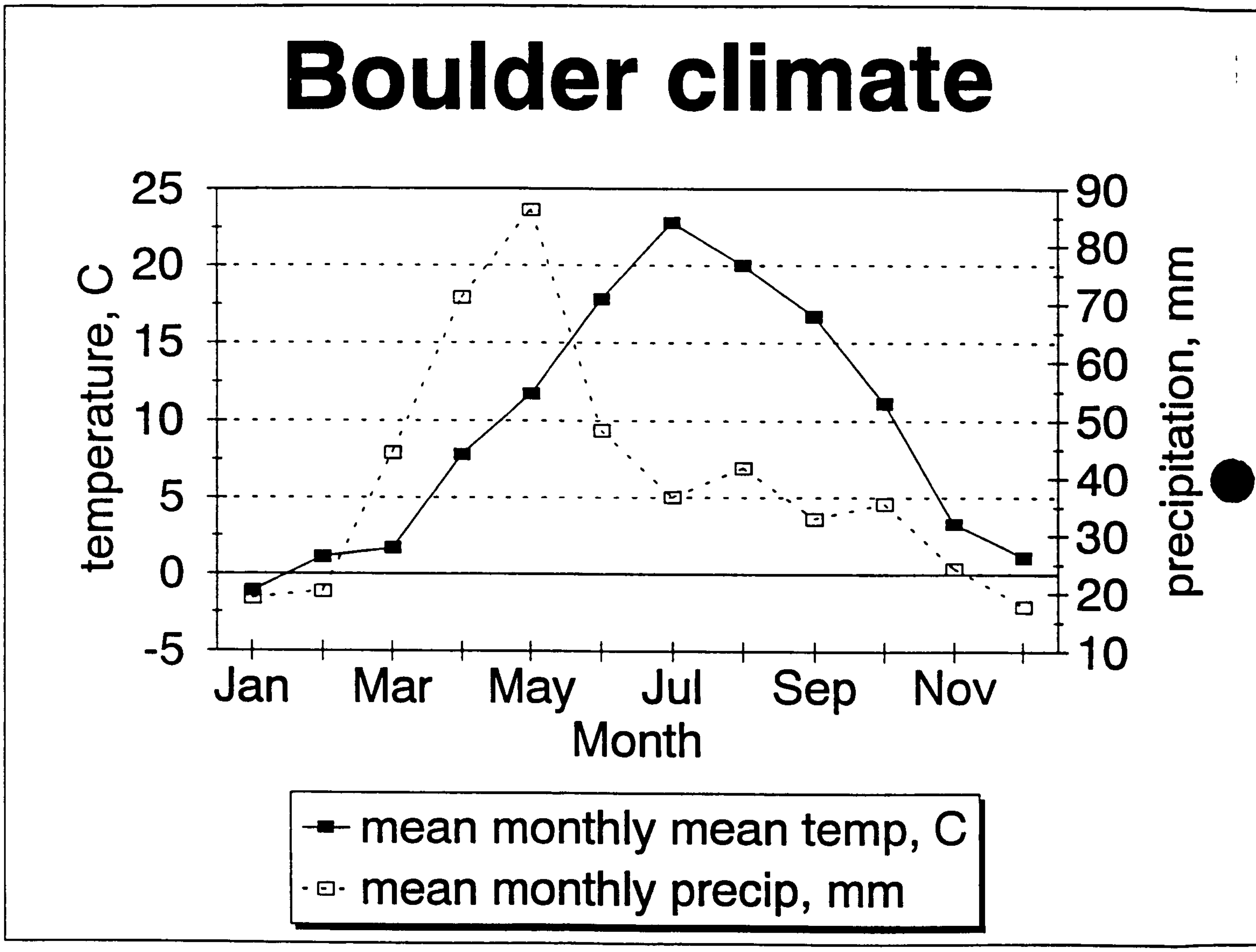

Figure 2. Plot of mean monthly precipitation and temperature for Boulder, Colorado. (data from Hansen, et al., 1978).

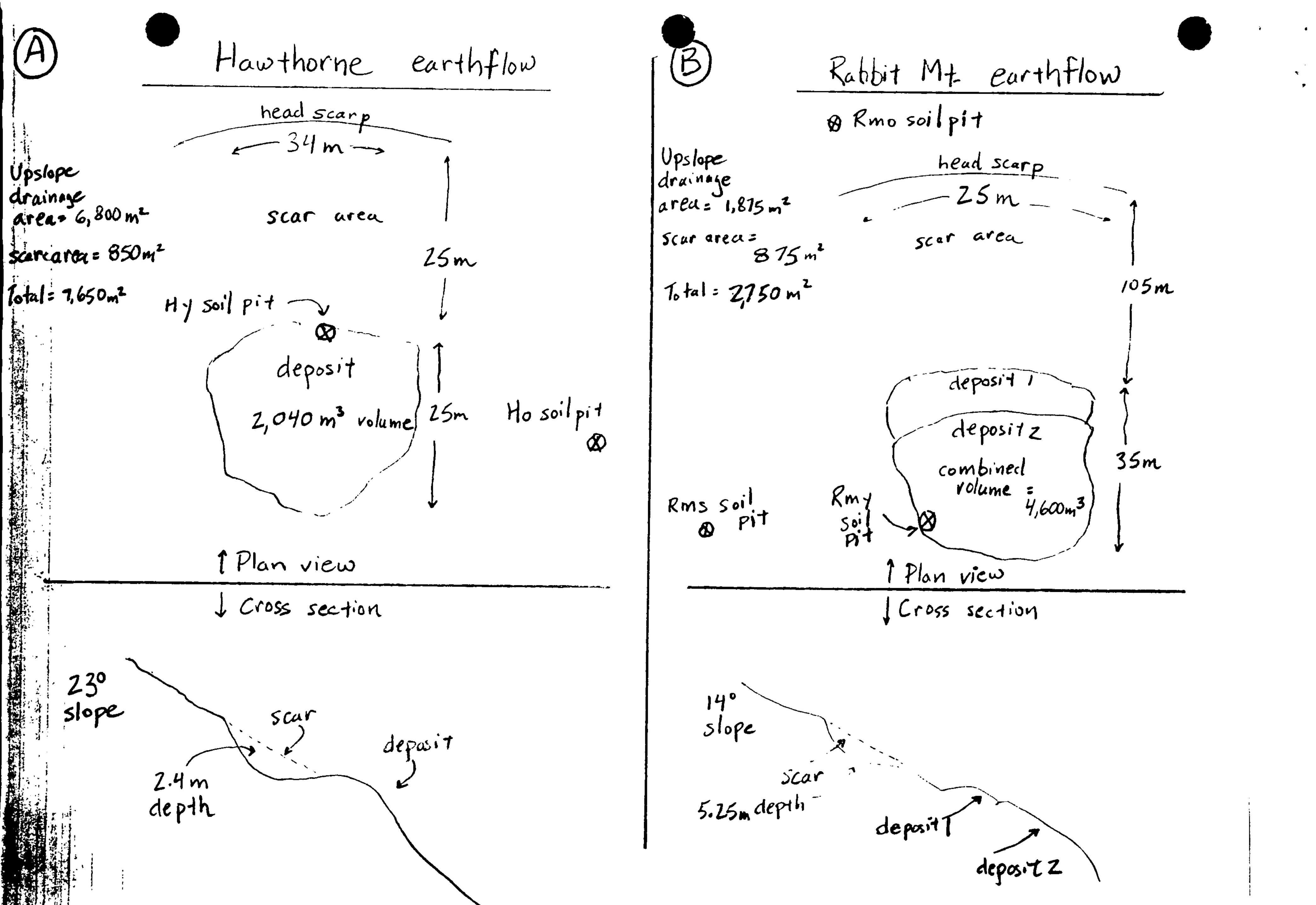

Figure 3. Schematic representation of Hawthorne and Rabbitt Mountain earthflows.

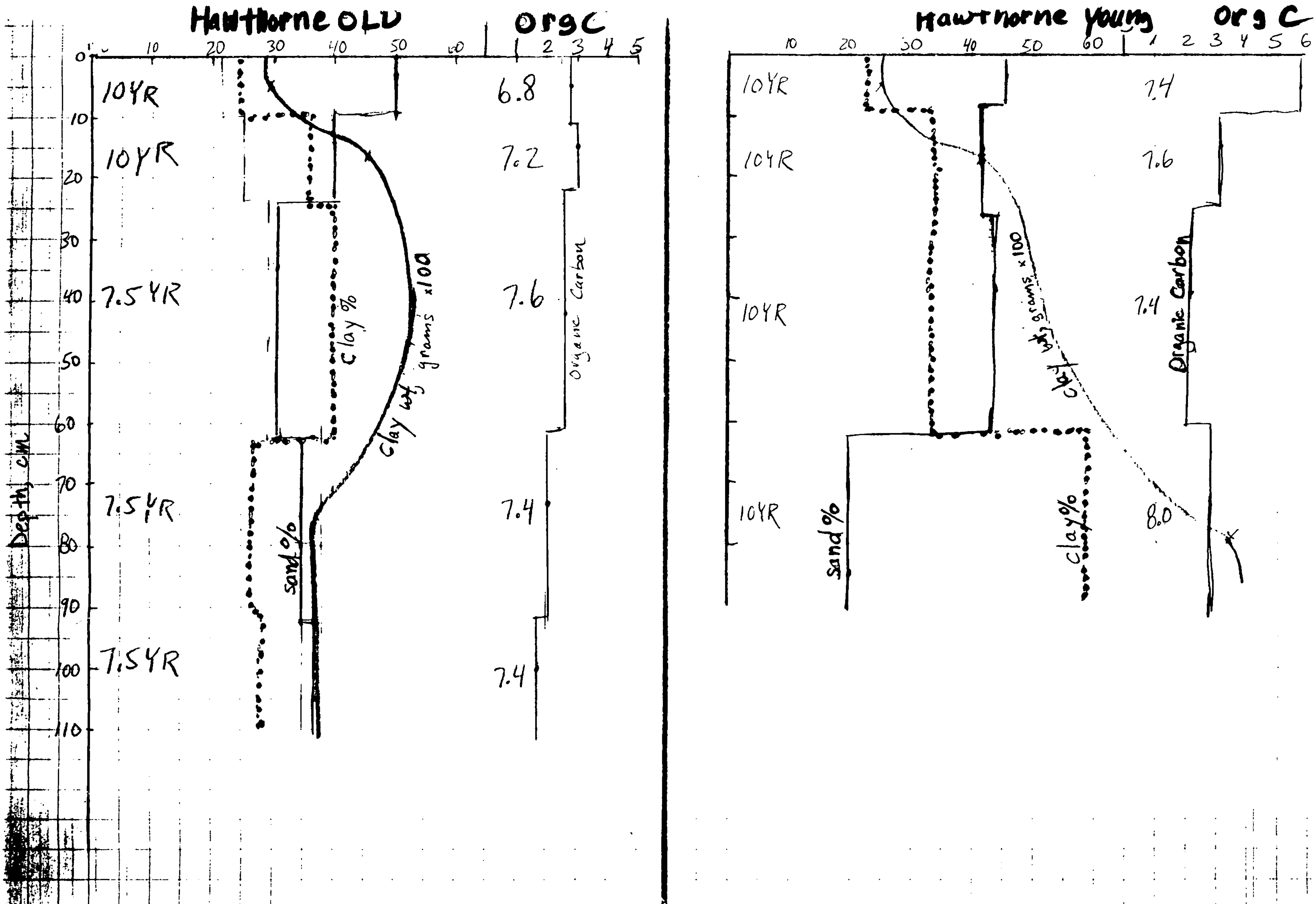

Figure 4. Simplified soil profiles for Hawthorne earthflow site.

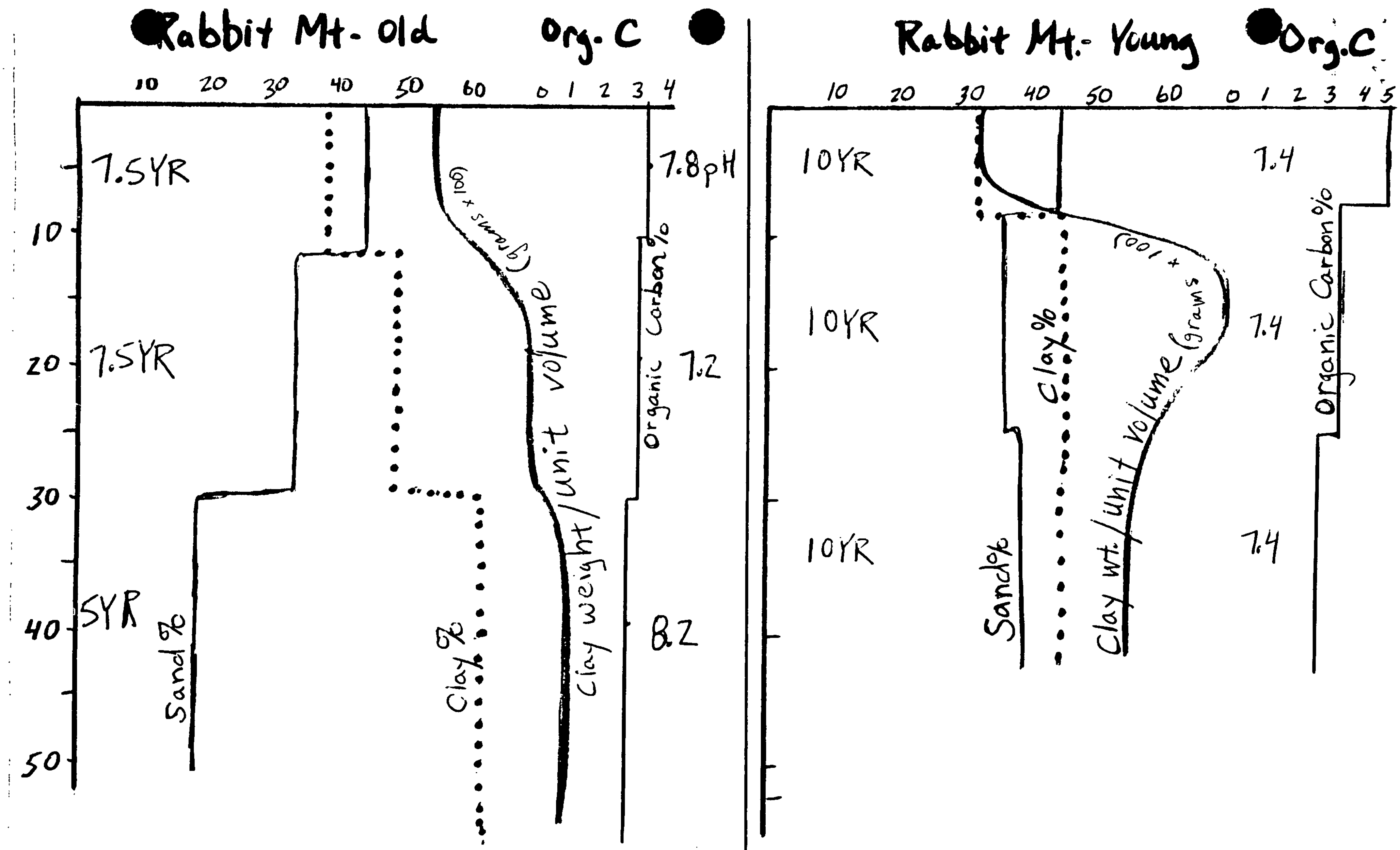

Figure 5. Simplified soil profiles for Rabbit Mountain earthflow site.

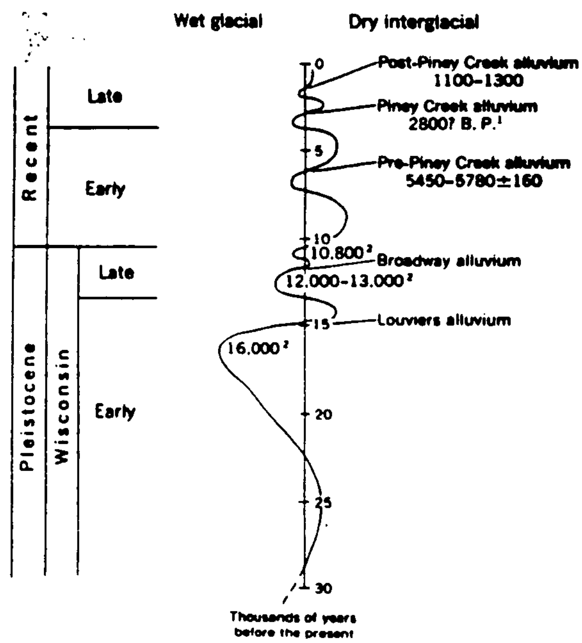

Figure 6. Graph of late Quaternary climate cycles and related deposits. Curve shows interpretation of degree and duration of wetness and dryness (from Scott, 1963).

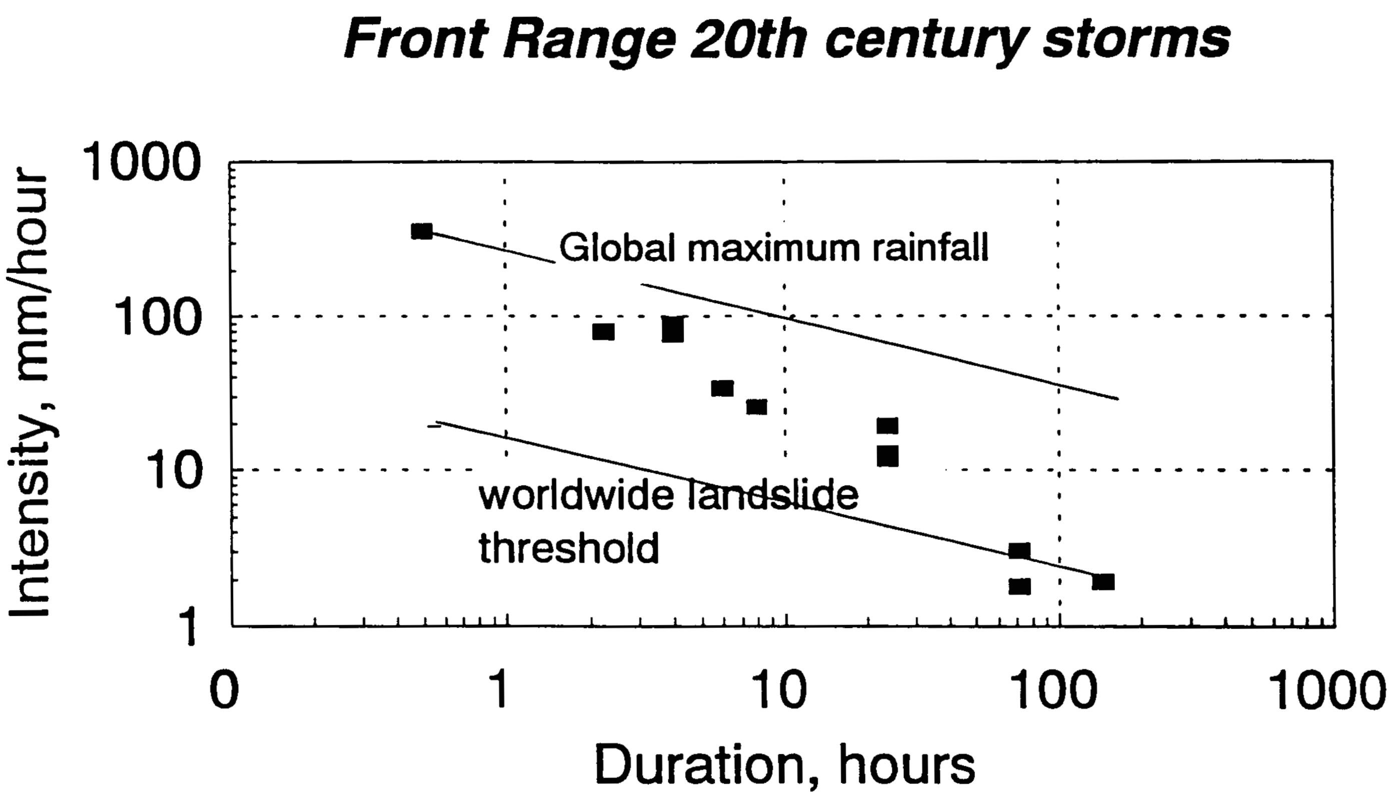

Figure 7. Plot of selected 20th-century storms in the Denver Front Range area showing rainfall intensity versus duration (data from Hansen, et al, 1978). Worldwide rainfall threshold for triggering of landslides from Caine (1980). Global maximum rainfall from Jennings (1950).