MASS WASTING IN THE SWAUK WATERSHED, WASHINGTON

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Abstract: Mass wasting evidence is common along the margins of the Columbia River Basalts. I identified, mapped, dated, and assessed the environment of nearly 160 discrete slope failures (excluding rockfall) along the margins of the Columbia River Basalts in the Swauk watershed of central Washington. Rotational slides, translational slides, flows, and complex slide-flows were identified via topographic map, airphoto, and field analysis. Geographic information systems analysis revealed that these features cover 38% of the watershed. Translational slides are the most numerous of the slope failures, whereas complex slide-flows cover the most area. I placed each slope failure into a relative age category (active, inactive-young, inactive mature, and inactive-old) based on the characteristics of the main scarp, lateral flanks, internal morphology, vegetation cover, and toe relationships. Most Swauk watershed slope failures are inactive-mature. Organic sediments from an inactive-mature sag pond formed ~6880 ^{14}C yr BP, whereas inactive-young sediments dated at ~5930 ^{14}C yr BP. Inactive slope failures are often associated with steep slopes, inclined beds, incompetent geologic units, or streamcuts. Streamcuts, roadcuts, or clearcuts typically accompany active slope failures. Rain-on-snow events and associated mass wasting in winter 1996 provide a plausible trigger analog for inactive mass wasting. Rockfall deposits cover ~29% of the watershed, range from inactive to active in age, and occur atop pre-existing slope failures in well-jointed Columbia River Basalts. Mass wasting has played a key role in shaping the topographic and hydrologic patterns of the watershed.
[Key words: mass wasting, watershed, Washington state, Columbia River Basalts, rain-on-snow.]

INTRODUCTION

Evidence of mass wasting is common along the margins of the Columbia River Basalts in Washington and Oregon. The Swauk watershed lies at the western boundary of these Miocene basalt flows in central Washington state (Fig. 1). Swauk watershed mass wasting has long been the subject of general comments (e.g., Russell, 1900; Smith, 1904; Rector, 1962). Previous researchers mapped mass wasting in the watershed to varying degrees (e.g., Rosenmeier, 1968; Othberg et al., 1979; Tabor et al., 1982; Wenatchee National Forest, 1997). Most previous discussion and mapping ignored the different types and timing of mass wasting in the watershed. Incompetent underlying sedimentary beds have most often been cited as the cause of Swauk watershed slope failures (e.g., Rector, 1962; Tabor et al., 1982; Campbell, 1988; Wenatchee National Forest, 1997). Wenatchee National Forest (1997) briefly discussed the implications of mass wasting in the upper portion of the watershed. Whereas previous researchers examined individual aspects of Swauk

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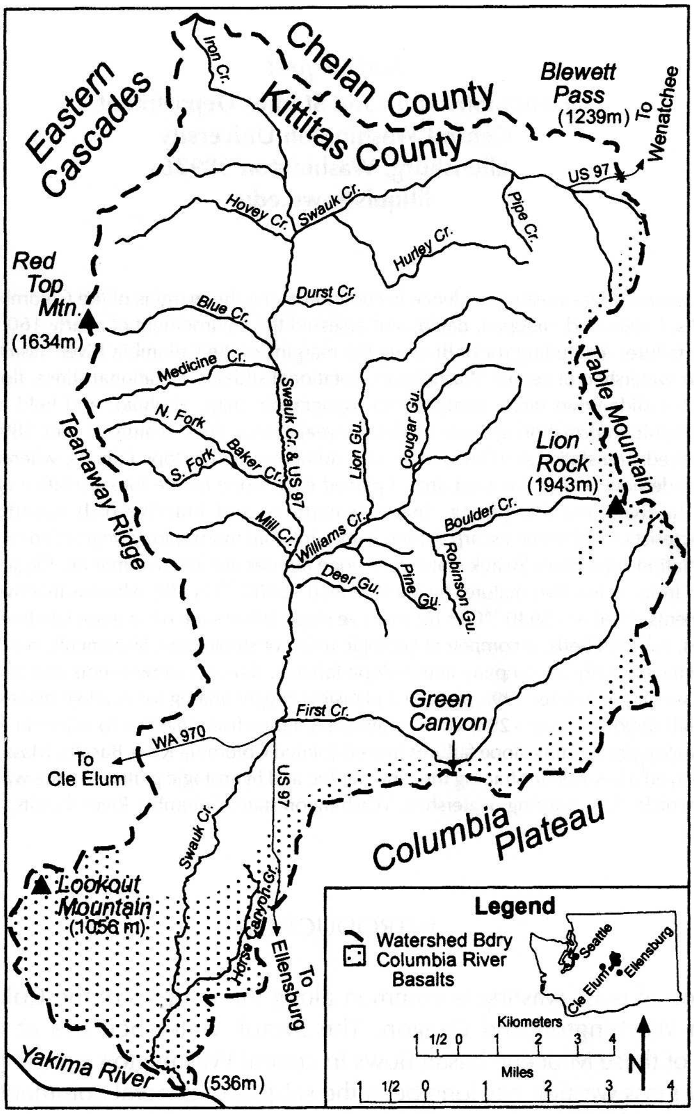

Fig. 1. Swauk watershed, central Washington state. Stipled area represents the extent of Columbia River Basalts in the study area.

watershed mass wasting, no single watershed-wide study has holistically addressed the above issues.

In this paper, I present a detailed, watershed-scale analysis of mass wasting in the Swauk watershed that specifically addresses: (1) the spatial patterns of mass wasting; (2) the types of slope failures; (3) the factors affecting these slope failures; (4) the relative and absolute timing of mass wasting; and (5) the implications of mass wasting.

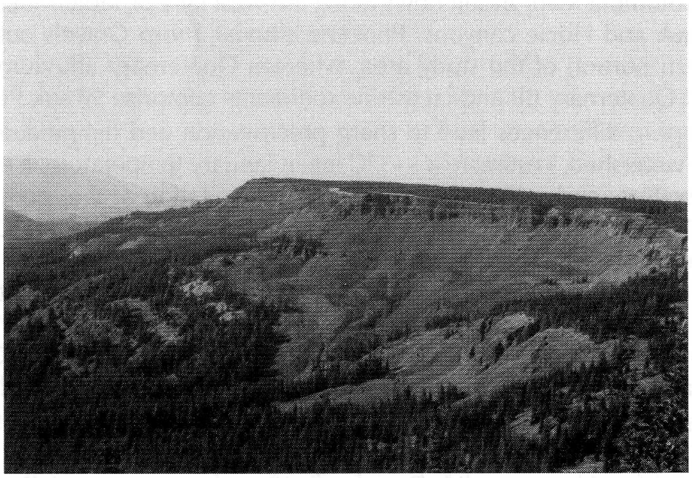

Fig. 2. View north from Lion Rock along the west face of Table Mountain at rockfall deposits mantling hummocky rotational slides.

STUDY AREA

The Swauk watershed is located in north-central Kittitas County, Washington, on the south side of the Wenatchee Mountains, an eastern outlier of the Cascade Range (Fig. 1). The approximately pear-shaped, 258 km^2 watershed is bounded by the Kittitas–Chelan county border to the north, Table Mountain to the east, the Yakima River to the south, and Teanaway Ridge to the west. Elevations in the watershed range from 1943 m at Lion Rock to 1634 m at Red Top Mountain to 536 m at the confluence of Swauk Creek and the Yakima River.

The watershed consists of upper and lower basins. The rugged upper basin extends from Lauderdale Junction upvalley (Fig. 1). Cliff and talus topography and hummocky terrain at the base of these steep slopes (Fig. 2) characterizes the upper basin. Thin, linear valleys flanked by steep, narrow-crested ridges form the landscape at lower elevations in the upper basin. The lower basin, extending from Lauderdale Junction to the mouth of Swauk Creek, is characterized by the gently undulating surfaces of Swauk Prairie and the gradual east-trending slopes of Lookout Mountain.

Tabor et al. (1982) has summarized the key geologic units of the watershed. The sedimentary Eocene Swauk Formation dominates the central portion of the watershed. Teanaway Basalt lava flows, pyroclastic flows, and ash flow tuffs overlie the Swauk Formation, especially along the western and southern boundaries of the upper basin. Scores of Teanaway basalt and diabase dikes intrude the Swauk Formation throughout the study area. The sedimentary late Eocene Roslyn Formation overlies the Teanaway dikes outcropping along the east side of the watershed and immediately east of Lauderdale Junction. Columbia River Basalts of Miocene age overlie the sedimentary Roslyn Formation in the eastern and southern portions of the watershed (Fig. 1). The Ellensburg Formation occurs as sedimentary beds between Columbia River Basalt flows along the west face of Table Mountain and in lower Swauk and Horse canyons. Pliocene alluvial Thorp Gravels outcrop in the southeastern portion of the study area, whereas Quaternary alluvium fills valley floors, and Quaternary till and lacustrine sediments comprise Swauk Prairie.

Topographic differences lead to sharp precipitation and temperature gradients within the watershed. I estimate a ~–3°C mean January temperature, a ~19°C mean July temperature, and ~40 cm mean annual precipitation at the mouth of Swauk Creek (~536 m), based on Ellensburg's and Cle Elum's climate data (NOAA, 1998). Using an environmental lapse rate of 6.4°C/1000 m, I further estimate mean temperatures of ~–12°C and ~10°C for January and July, respectively, at Lion Rock (1943 m). Mean annual precipitation at Blewett Pass (1248 m) over the period 1961–1990 was 89 cm, with the majority falling as winter snow (NRCS, 1995). I assume that precipitation patterns at Lion Rock are similar to those at Blewett Pass.

Five distinctive vegetation zones occur between the highest elevations of the watershed and its mouth. The forested areas include the subalpine fir (*Abies lasiocarpa*), grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menseizii*), and ponderosa pine (*Pinus ponderosa*) zones. A shrub-steppe (*Artemisia tridentata/ Agropyron*) zone is located at the lowest elevations (Schneider, 1971; Franklin and Dyrness, 1973).

Swauk Creek is the primary stream of the watershed. No glaciers are present within the basin, but snowfields persist late into the year at higher, sheltered locations. Streams within the watershed fluctuate primarily because of snowmelt—either "rain-on-snow" events occurring from late fall to early spring, or warm weather–induced snowmelt in the late spring (Wenatchee National Forest, 1997). Dry weather and water diversions result in low late summer flows in local streams. Ponds and wetlands are common, especially in the hummocky terrain at the bases of the Teanaway Ridge and Table Mountain escarpments.

Historic land uses in the Swauk watershed include grazing, recreation, lode mining, placer mining, logging, and transportation (Wenatchee National Forest, 1997). Most significant for mass wasting are the latter three land uses. Sluicing, dredging, and hydraulic techniques have been used since 1873 to mine placer gold deposits (Wenatchee National Forest, 1997). Over 60% of the watershed has been logged at least once, often by clearcutting, since 1891 (Wenatchee National Forest, 1997). U.S. Highway 97 and a dense network of logging roads have replaced the wagon routes and railroad grades associated with early mining and logging.

METHODS

I relied on four key methodological components in this study: (1) identification, (2) mapping, (3) dating, and (4) assessment of environment. Mass wasting features were identified on U.S. Geological Survey 7.5' topographic maps; U.S. Forest Service 1992, 1:16,000, natural color air photos (upper basin); Washington Department of Natural Resources 1984/1985, 1:12,000, natural color air photos (lower basin); Agricultural Stabilization and Conservation Service 1954, 1:20,000, panchromatic air photos (upper and lower basin); and in the field. Following Soeters and van Westen (1996), I identified mass wasting features based on *morphology* (e.g., concave/convex slope features, step-like morphology, semi-circular headscarps, backtilted steps, hummocky terrain, and in-filled valleys with slightly convex bottoms), *vegetation* (e.g., vegetation absent from scarps, tilted or dead vegetation, and different vegetation associated with drainage conditions), and *drainage* (e.g., areas of stagnant, deranged, anomalous, interrupted, and excessive drainage).

Once identified, I mapped slope failures on 7.5' topographic maps. Mass wasting features include the uppermost zone of depletion (i.e., top of headscarp) to the lowermost portion of the zone of accumulation (i.e., toe) (Cruden and Varnes, 1996). Mass wasting polygons were subsequently digitized and attributed in ARC/INFO®. I ultimately completed the maps using Freehand® software.

Following Cruden and Varnes (1996), mass wasting types were classified as falls, rotational slides, translational slides, flows, and complex slide flows. In cases where more than one mass wasting process shaped a polygon, I used the dominant morphology to assign that polygon to a particular type class.

I grouped slope failures in a four-category, relative-age chronology developed by McCalpin (1984) and Keaton and DeGraff (1996) (Table 1). This chronology is based on the premise that the main scarp, lateral flanks, internal morphology, vegetation cover, and toe relationships of mass wasting features become less distinct from adjacent terrain over time. Basal organic deposits collected from mass wasting–created depressions (e.g., Diez et al., 1996) provide absolute temporal control to the relative dating scheme. Absolute dates are considered minimum because a lag time may have occurred between the development of a depression and the deposition of organic matter, and the sampled units may not have been at the base of the mass wasting–created depressions.

Using topographic-map, air-photo, and field observations, I identified the factors potentially contributing to mass wasting over time, and the topographic and hydrologic implications of mass wasting. The potential factors include those that lead to high shear stress—(1) removal of lateral support, (2) overloading, (3) transitory stresses, (4) removal of underlying support, (5) lateral pressure, and (6) increase in slope angle—and those that lead to low shear strength—(1) composition and texture, (2) physico-chemical reactions, (3) effects of pore water, (4) changes in structure, (5) vegetation, and (6) relict structures (Selby, 1993).

RESULTS AND DISCUSSION

Types of Mass Wasting

Excluding rockfall, 156 discrete slope failures cover ~98 km^2 (or ~38%) of the study area. Individual mass wasting features range in area from <0.01 km^2 to 22.6 km^2. Slides (translational and rotational), flows, complex slide-flows, and falls are present, especially along the eastern and western margins of the Swauk watershed's upper basin (Fig. 3). Mass wasting is also common in the Swauk Creek corridor in the lower basin. I mapped but did not determine the type of mass wasting at two additional sites identified by U.S. Forest Service Personnel (Wenatchee National Forest, 1997; Bill Ehinger, pers. comm., October 1999).

Table 1. Preliminary Mass Wasting Age Classification

Activity class	Main scarp	Lateral flanks	Internal morphology	Vegetation	Toe relationships
Active	Sharp; unvegetated	Sharp; unvegetated; streams at edge	Hummocky topography with lakes in depressions; angular blocks separated by unvegetated cracks/ scarps	"Jack-strawed" trees/ "drunken forest"	Main valley stream shifted by mass; floodplain covered by debris; lake behind mass wasting dam
Inactive-young	Sharp; partly vegetated	Sharp; partly vegetated; small tributaries to lateral streams	Hummocky topography with ponds and marshes in depressions; subangular blocks separated by vegetated cracks/ scarps	Different age, type or density than adjacent terrain; bent older tree trunks	Same as active class but toe modified by modern stream
Inactive-mature	Smooth; vegetated	Smooth; vegetated; tributaries extend into main body	Smooth, rolling topography; no undrained depressions; deranged drainage pattern	Different type and density than adjacent terrain but same age	Mass wasting debris covers terraces but cut by modern streams; modern stream has widened floodplain upstream
Inactive-old	Dissected; vegetated	Vague lateral margins; vegetated; no lateral drainage	Smooth, rolling topography; no undrained depressions; dendritic drainage pattern	Same age, type and density as adjacent terrain	Terraces or moraines cut into slide debris; uniform modern floodplain

Sources: Adapted from McCalpin, 1984; Keaton and DeGraff, 1996.

Translational slides. Translational slides develop on linear shear planes (Cruden and Varnes, 1996). They typically consist of: (1) a roughly linear escarpment within the zone of depletion (Cruden and Varnes, 1996); (2) a main body typically lacking in steps;(3) a hummocky zone of accumulation that includes ponds and wetlands; and (4) a toe around which streams and roads sharply bend. Translational slides are the most numerous mass wasting features found in the watershed (79) (Fig. 3; Table 2), collectively covering ~16 km^2. Individual translational slides in the watershed range from <0.01 km^2 to 1.24 km^2. Classic translational slides occurred on Teanaway Basalt dip slopes in upper Hovey Creek on the west side of the study area, and in the First Creek drainage of the eastern portion of the watershed (Fig. 3).

Translational slides, as well as rotational slides, flows, and complex slide-flows, in the Swauk watershed are spatially and temporally associated with increased precipitation. Rapid snowmelt is the primary source of water triggering contemporary

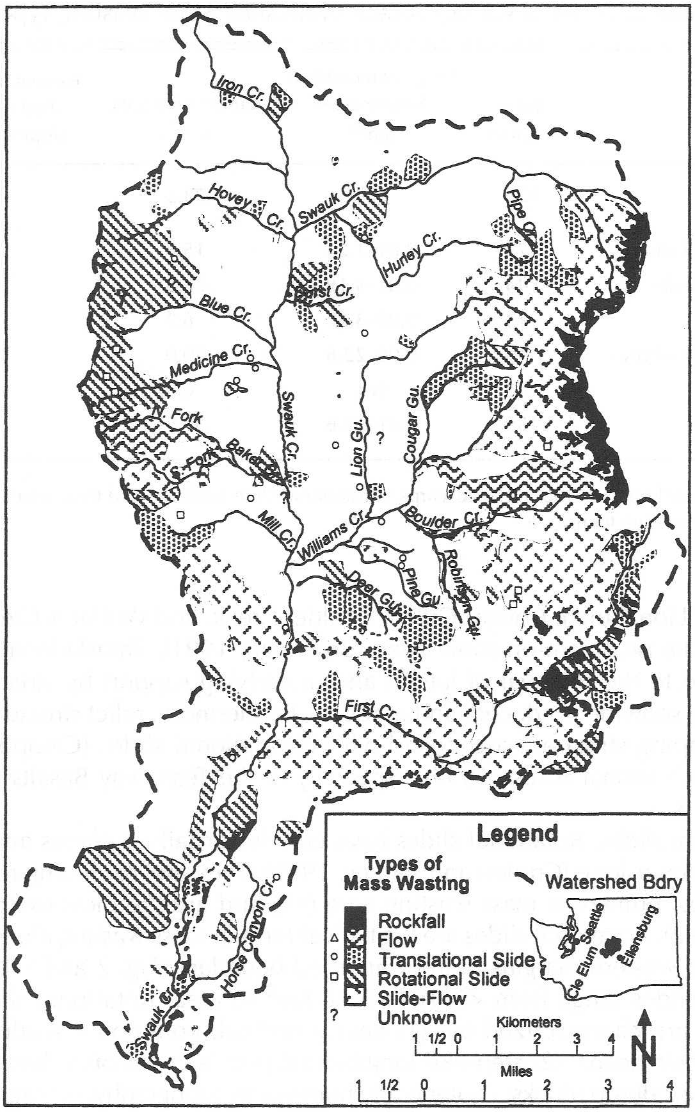

Fig. 3. Swauk watershed mass wasting types.

watershed mass wasting. The winter 1996 rain-on-snow events and the associated 24 mass wasting features (Wenatchee National Forest, 1997) provide a modern analog of a possible mass wasting trigger over time. Rain-on-snow events generally occur from November through February when warm, moist air masses move into the Pacific Northwest, raising the freezing level and dropping large amounts of rainfall onto the snowpack. Intermediate elevations of the watershed, including Swauk Creek from near Lauderdale Junction to the mouth of Hurley Creek, and the lower

Table 2. Totals of Various Swauk Watershed Mass Wasting Types

	Total number	Range in individual feature areas (km^2)	Cumulative area (km^2)	Percentage of watershed covered by slope failures (%)
Falls[a]	126	?	73.5	28.5
Translational slides	79	0.01–1.24	15.8	6.1
Rotational slides	44	0.01–5.18	25.5	9.9
Flows	13	0.02–3.27	6.2	2.4
Complex slide-flows	18	0.06–22.6	50.0	19.4
Unknown	2	NA	0.01	<0.1
Total	156	0.01–22.6	97.51	37.9

[a] Falls commonly occur atop the headscarps of rotational slide surfaces, and thus are not included in the mass wasting totals.

portions of Lion Gulch, Cougar Gulch, Boulder Creek, and Williams Creek (Fig. 1), lie within the peak rain-on-snow zone (Brunengo, 1991). Translational slides are also related to the removal of lateral and underlying support by stream erosion (commonly snowmelt-induced) and roadcuts. Furthermore, relict structures such as steeply dipping strata are associated with translational slides (Campbell, 1988; Wenatchee National Forest, 1997), especially in the Teanaway Basalts along First Creek (Fig. 3).

Rotational slides. Rotational slides have curvilinear failure planes and rotate as they slide downslope (Cruden and Varnes, 1996). They are, excluding rockfall, the second most numerous mass wasting type (44) and are the most extensive (~26 km^2) (Table 2). Rotational slides are the typical form of mass wasting along the steep eastern and western margins of the watershed boundary (Fig. 2 and 3). Individual rotational slides range from <0.01 to 5.18 km^2 in area. Rotational slides in the watershed are characterized by: (1) nearly vertical, commonly scalloped main scarps at their heads; (2) step-like longitudinal profiles with often backtilted and talus-covered slump blocks; (3) generally hummocky topography; (4) sag ponds and wetlands in the depressions of the hummocky topography; (5) streams and roads that bend around the toes of the slides; and (6) a generally deranged drainage pattern.

Rector (1962), Rosenmeier (1968), and Tabor et al. (1982) noted large, isolated basalt blocks that parallel the abrupt western escarpment of Table Mountain. These sometimes backtilted, and typically talus-covered, basalt blocks are separated from adjacent large basalt blocks by <1 m to >100 m wide "moat-like" gaps. Smith (1904, p. 3) further described the topography at Table Mountain where "...not only are the boundary cliffs fringed with these detached masses of basalt which lie in confusion below, but above, paralleling the present escarpment, can be seen gaping cracks which mark the first state in the development of future landslides." I have noted similar topography on the west face of Table Mountain, where the forms and relationships suggest that the "blocks" are deep-seated rotational slides and the open "moats" indicate ongoing rotational slide processes. Rotational slides typically occur where the Columbia River Basalts overlie the incompetent Roslyn and Ellensburg formations on the eastern margin of the watershed and where the Teanaway Basalts overlie the incompetent Swauk Formation on the western margin (e.g., Russell, 1900; Smith, 1904; Foster, 1957; Rector, 1962; Tabor et al., 1982; Campbell, 1988).

Flows. A flow is a "spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved" (Cruden and Varnes, 1996, p. 64). Flows in the watershed are present as stand-alone features (discussed in this section), and as complexes with slides (discussed in the following section). Thirteen stand-alone flows cumulatively cover ~6 km^2 of the watershed (Table 2). Flows result in broad, low-gradient, and smooth valley floors in upper Blue and Baker creeks on the east face of Teanaway Ridge, and in upper Deer Gulch in the central portion of the watershed (Fig. 3). Steep-sided, linear to sinuous topographic highs flanked by streams represent old valley-fill flows that are classic illustrations of inverted topography. Two such flows formed in the Teanaway Basalts of upper Baker Creek and extend approximately 3 km downvalley (Fig. 3). The largest flow in the watershed originated in the Swauk Formation high on the west face of Table Mountain and stretches more than 5 km down a tributary of Williams Creek (Fig. 3).

Thomson (1932) noted the thin (typically <2 m), angular, poorly sorted debris of "gulch washings" in intermittent stream channels. He attributed these deposits to slope wash from spring runoff but, based on his description, I suspect that they are debris-flow deposits. I have also observed fans at the mouths of numerous streams in the study area composed of an unsorted mix of subangular boulders suggesting a debris-flow origin. The "gulch-washings" and fans warrant further research before they are included in the data set.

The relationship of the winter 1996 rain-on-snow events to flows suggests that rapid snowmelt events have likely triggered flows over time. The nine active mass wasting features located within or immediately downslope of recently logged areas further suggest that diminished root strength associated with logging may have played a role in historic flows.

Complex slide-flows. Eighteen mass wasting features in the watershed (Table 2) are rotational slides that grade into flows in preexisting valleys. Because the resulting features involved both movement types, they are better described as complex slide-flows (Cruden and Varnes, 1996). These features appear similar to the rotational slides discussed previously but are associated downvalley with broad, low-gradient, smooth valley floors or steep-sided, linear to sinuous topographic highs flanked by streams (i.e., inverted topography). Complex slide-flows cover much of Table Mountain's west face north of Lion Rock and the east face of Teanaway Ridge. Cumulatively, complex slide-flows cover 50 km^2 of the study area and include the largest individual mass wasting feature of the watershed (22.6 km^2), covering much of the west face of Table Mountain north of Lion Rock (Table 2; Fig. 3).

The lower portions of complex slide-flows often resemble end and lateral moraines. These features commonly: (1) are located downslope of cirque-like amphitheaters; (2) form linear ridges that jut out perpendicular to the slope; (3) enclose small ponds or wetlands; (4) occur as nested features; and (5) are composed of diamicton. Similarities between alpine glacial and mass wasting features have been noted by other researchers (e.g., Bailey, 1972). The following points argue against a glacial origin for these features in the Swauk watershed: (1) the downvalley faces of the linear ridges are steeper than the upvalley faces; (2) other glacial features are lacking—for example, valley train deposits downvalley and lateral moraines trending nearly continuously upvalley to cirques; and (3) the exposed west face of Table Mountain was probably not sufficiently high for glacier accumulation.

Fall. Fall occurs when rock or sediment is detached from a steep slope and falls, bounces, or rolls to its new location (Cruden and Varnes, 1996). I identified 126 discrete rockfall deposits covering ~74 km^2 (Table 2). The spatial extent of rockfall is likely an underestimate, as I mapped only those deposits visible on air photos, whereas limited field observations indicate rockfall deposits are often present beneath forest cover. Rockfall deposits are characterized by accumulations of individual clasts typically ranging from 5 to 50 cm in diameter. Large (>30 m^3) basalt blocks amidst the talus slopes either fell or slid from above (Rector, 1962). Rockfall deposits occur as talus beneath steep slopes, talus cones at the mouths of couloirs, protalus ramparts paralleling the base of slopes, and rock glaciers oriented perpendicular to the slopes. Because of the watershed scale of this analysis, I lumped all rockfall deposits together as the products of "fall."

Most rockfall deposits occur at the base of steep escarpments atop rotational slides and complex slide-flows in the well-jointed Columbia River Basalts along the western margins of Table Mountain, and along Swauk Creek in the lower basin (Fig. 3). Rockfall deposits are less common in the Teanaway Basalts on the eastern and southern margins of the upper basin. Joint-weakened rocks eventually fall, especially: (1) after rotational slides periodically steepen the margins of the watershed, thus removing lateral and vertical support; and (2) when water freezes in the joints, thus increasing lateral pressure.

Timing of Mass Wasting

I identified four relative age categories of mass wasting (excluding rockfall) in the Swauk watershed—active, inactive-young, inactive-mature, and inactive-old (Table 3). Generally, inactive features are larger, more numerous (116), and collectively cover more area (~96 km^2) of the watershed than do active mass wasting features (40 and ~2 km^2, respectively). Each age category includes the various mass wasting types (excluding fall) found in the watershed.

Active. Active mass wasting features (Table 1) total 40 yet cover only ~2 km^2 of the study area (Table 3; Fig. 4). These features are generally small, ranging from <0.01 km^2 to 1.17 km^2. Active mass wasting features are those that show evidence of movement during the past century. The small size of most active slope failures and the resulting poor resolution of such features on air photos suggests that active mass wasting is likely underrepresented in the data set.

Inactive-young. Fourteen inactive-young mass wasting features (Table 1) are present in the study area, covering ~13 km^2 (Table 3; Fig. 4). Individual inactive-

Table 3. Relative and Absolute Ages of Swauk Watershed Mass Wasting (Excluding Rockfall)

Relative age	Total number	Range in individual feature areas (km^2)	Cumulative area (km^2)	Preliminary radiocarbon results (^{14}C yr B.P.)
Active	40	<0.01–1.17	1.70	
Inactive-young	14	0.03–3.65	12.91	5930
Inactive-mature	84	0.01–22.63	71.73	6880
Inactive-old	18	0.03–3.27	11.18	
Total	156		97.5	

young slope failures are larger than active features, ranging from 0.03 km^2 to 3.65 km^2. Charcoal from a buried soil O/A horizon in a wet depression behind an inactive-young rotational slide block in upper Medicine Creek (A on Fig. 4 and 5) dated at 5930 ± 100 ^{14}C yr B.P. (Beta 125973) (Table 4).

Inactive-mature. Inactive-mature mass wasting features (Table 1) are the most numerous (84) and cover the most area (~72 km^2) of the mass wasting age groups (Table 3; Fig. 4). These features range in size from 0.01 km^2 to 22.63 km^2. A buried O horizon in an inactive-mature wet depression on upper Pipe Creek (B on Fig. 4 and 5) yielded an age of 6880 ± 70 ^{14}C yr B.P. (Beta 125974) (Table 4).

Inactive-old. Inactive-old mass wasting (Table 1) is characterized by greater geomorphic, biotic, and hydrologic similarity to the surrounding terrain than is inactive-mature or inactive-young mass wasting (Table 1). I identified 18 inactive-old mass wasting features covering a total of ~11 km^2 in the study area (Table 3; Fig. 4). These slope failures range from 0.03 km^2 to 3.27 km^2. Inactive-old mass wasting terrain is the most subdued and similar to surrounding non-mass wasted terrain, and thus is the most difficult to recognize of the four relative age classes (Table 1). No absolute dates were determined for this age class.

Rockfall timing. Rockfall deposits are a mix of relative age categories. Vegetation-free areas (Smith, 1904; Rector, 1962), unstable deposits (Rector, 1962), and fresh-faced, percussion-scarred, perched basalt boulders at the base of the Table Mountain escarpment suggest that some rockfall is actively occurring. The predominance of weathered and lichen-covered boulders suggests that most rockfall is inactive-young or inactive-mature, but likely not inactive-old, because of unfilled boulder voids and a lack of vegetation cover. Active, inactive-young, or inactive-mature ages are further indicated by the presence of talus on the main scarps of the common inactive-mature rotational slides (Fig. 2). Rector (1962) advocated repetitive talus formation/talus removal cycles on the west face of Table Mountain. Such cycles would require periodic rotational slide–induced steepening of the west face of Table Mountain. The cliff and talus topography and underlying hummocky terrain of the west face of Table Mountain and the east face of Teanaway Ridge support this interpretation.

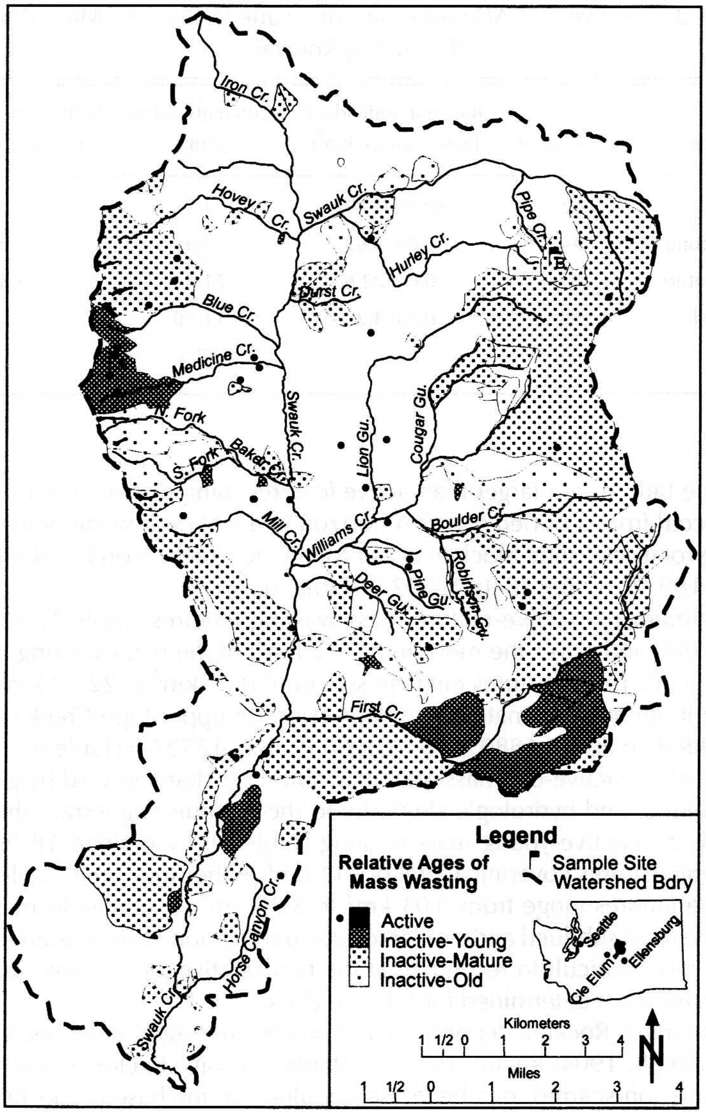

Fig. 4. Swauk watershed mass wasting ages (excluding rockfall).

The relative and absolute timing of mass wasting is clouded by the issue of multiple mass wasting events within the same feature. McCalpin's (1984) and Keaton and DeGraff's (1996) relative age classification addresses only the most recent movement of a particular slope failure. It is probable, however, that mass wasting deposits are repeatedly reactivated over time. For example, Tabor et al. (1982) hypothesized that diamictons situated at various elevations downslope of the large blocks indicate debris flows of various ages. Furthermore, multiple blocks within

Table 4. Swauk Watershed Slope Failure Radiocarbon Dates

ID[a]	General locality	UTM coordinates (x,y,z)	Lab #[b] (beta)	Age ± s.d. (^{14}C yr BP)	Material	Stratigraphic/ geomorphic context	Type of date[c]
A (#354)	Upper Medicine Creek drainage ~1km SE of Red Top Mountain	5239750m N 0669800m E 1366 m	125973	5930 ± 100	Charcoal	Buried soil O/A horizon in depression behind slump block	Ext
B (#478)	Upper Pipe Creek ~3km SW of Blewett Pass	5242175m N 0681050m E 1408 m	125974	6880 ± 70	Organic sediment	Buried soil O horizon in depression behind slump block	Std

[a] Refers to letter shown on Figure 4.

[b] Beta Analytic, Inc. laboratory number.

[c] Abbreviations: ext = extended counting radiocarbon dating; std = standard radiocarbon dating.

rotational slides on the west face of Table Mountain may suggest multiple slide events.

Implications of Mass Wasting

Mass wasting has impacted various aspects of the Swauk watershed's physical and human environment. In this section, I focus on the topographic and hydrologic implications of mass wasting.

Topographic patterns. Mass wasting has resulted in the formation of distinct topography in the Swauk watershed. The abrupt cliff and talus faces of Table Mountain and Teanaway Ridge (Fig. 1 and 2), and the hummocky deposits at the bases of these slopes resulted from a variety of mass wasting processes. The watershed is gradually enlarging from rotational slide–, translational slide–, complex slide-flow–, and rockfall-induced recession of Table Mountain and Teanaway Ridge (e.g., Rector, 1962; Tabor et al., 1982). However, the "west of center" location of middle Swauk Creek suggests that headward recession has occurred more rapidly in the Columbia River Basalts of the eastern margin than in the Teanaway Basalts of the western margin. Recession is not laterally consistent on a micro-scale; rather, it selectively exploits weaker geologic strata resulting in typically amphitheater-like "scallops" in the west face of Table Mountain, and scallops and "passes" in the east face of Teanaway Ridge. This pattern of basalt-edge mass wasting and slope recession is not restricted to the Swauk watershed. Others have noted such mass wasting in areas adjacent to the watershed (e.g., Artim, 1974; Othberg, 1975; Tabor et al., 1987), in the region (e.g., Vallier and Miller, 1974; Palmer, 1977; Beaulieu, 1985), and globally (e.g., Evans, 1984).

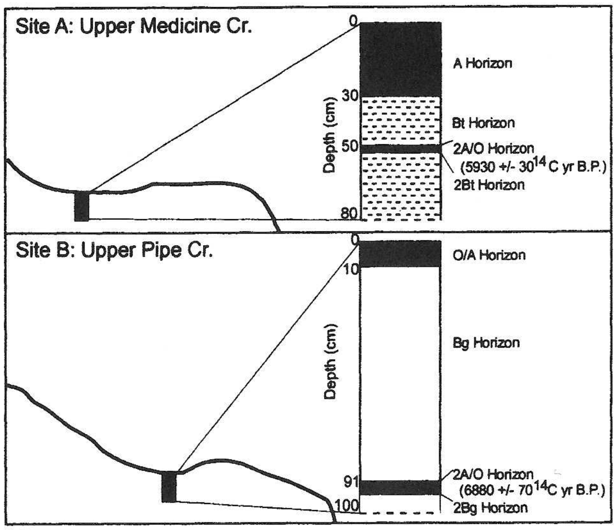

Fig. 5. Cross-section view of soil stratigraphy and general topographic setting of two slope failures dated by radiocarbon methods. Topography not to scale.

Hydrologic patterns. Mass wasting has dramatically impacted wetland, pond, and stream patterns in the watershed. Most of the numerous wetlands and ponds lie in the hummocky topography at the base of Table Mountain and Teanaway Ridge (Fig. 1). Deranged drainage patterns characterize the active, inactive-young, and inactive-mature mass wasting features, especially on the west flanks of Table Mountain (Fig. 3). Valley fill from large debris flows resulted in totally displaced streams (e.g., Baker Creek and a tributary to Williams Creek) (Fig. 2) and inverted topography. Numerous streams bend around the toes of mass wasting deposits (e.g., Lower Hurley Creek, Lower Hovey Creek) (Fig. 2), thus increasing channel sinuosity. Lower First Creek conspicuously bends around the toe of an inactive-mature complex slide-flow near the mouth of Green Canyon (Fig. 1). Russell (1900) and Smith (1904) interpreted the sharp bend in First Creek as the elbow of capture and the large size of adjacent Green Canyon, relative to its modern stream, as the canyon of a stream that was captured by First Creek. I postulate that the inactive-mature complex slide-flow west of Green Canyon (Fig. 4) initiated the capture by shifting the existing channel of Green Canyon Creek northward. This complex slide-flow increased the gradient of lower First Creek, thus enhancing its ability to erode headwards. Headward expansion of First Creek also led to a larger drainage area, thus discharge and headward erosion increased. The minimum date of 6880 ± 70 ^{14}C yr B.P. from an inactive-mature slope failure in upper Pipe Creek (Fig. 5; Table 4) suggests that the capture occurred more than ~6900 ^{14}C yr B.P. Sediments from the complex slide-flow west of Green Canyon, the First Creek channel, and Green Canyon need to be dated before a mass wasting origin of the stream capture may be verified.

CONCLUSIONS

Approximately 38% of the Swauk Watershed has been directly impacted by rotational slides, translational slides, complex slide-flows, and flows. Translational slides are the most numerous of the slope failures and complex slide-flows cover the most area. Rockfall deposits cover ~29% of the watershed, often occurring atop pre-existing slides, flows, and complex slide-flows. Most mass wasting features are found on the steep eastern and western margins of the watershed's upper basin. Over time, these processes commonly operate in concert on a particular slope—for example, rotational rockslides periodically oversteepen basalts, causing rockfalls. Active mass wasting is triggered by precipitation and snowmelt derived primarily from rain-on-snow events, and occurs where slopes have been steepened by roadcuts and streamcuts and where vegetation has been removed by logging. Inactive mass wasting is primarily related to streamcuts, relict structures (e.g., dipslopes), steep slopes, and incompetent beds, all likely triggered by pore water effects associated with direct precipitation and snowmelt.

Active, inactive-young, inactive-mature, and inactive-old relative age classes of slope failures (excluding rockfall) are present in the watershed. Mass wasting is primarily inactive, with most classified as "inactive-mature." Active mass wasting features are typically much smaller, less numerous, and cover less total area than inactive features. Radiocarbon dating indicates that an inactive-young rotational slide formed in upper Medicine Creek before ~5930 ^{14}C yr BP, whereas an inactive-mature feature developed in upper Pipe Creek before ~6880 ^{14}C yr BP. Further radiocarbon ages should clarify these relative age categories. I did not differentiate between the ages of the various rockfall deposits.

Mass wasting has played a key role in shaping the topographic and hydrologic patterns in the watershed. The abrupt faces of Table Mountain and Teanaway Ridge and the hummocky deposits at the bases of these slopes resulted from a variety of mass wasting processes. Most of the watershed's numerous wetlands and ponds lie in the hummocky topography at the base of Table Mountain and Teanaway Ridge. Mass wasting has further resulted in deranged drainage patterns, especially in the active, inactive-young, and inactive-mature mass wasting features on the west flanks of Table Mountain. Mass wasting also likely played a role in the capture of Green Canyon Creek by First Creek.

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