AERIAL-PHOTOGRAPHIC INVENTORY AND ANALYSIS OF LANDSLIDES IN NORTHEASTERN YELLOWSTONE NATIONAL PARK, WYOMING

THESIS

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CHAPTER I

INTRODUCTION

A landslide is a movement of material downslope (Cruden 1991). Landslide material varies, from rocks toppling down a canyon wall to a fluid mass of soil and water. Landslide type is related to the material composition of the landslide with Varnes (1978) and Dikau et al. (1996) recognizing six types: fall, topple, slide, lateral spread, flow, and complex. Landslides are identified and mapped through fieldwork and aerial photographs as well as other types of remote sensing, like satellite imagery. Depending on the scale of the aerial photographs, it is possible to classify landslides into these six different types, with falls and topples the most difficult types to identify.

The Rocky Mountain region has been the location of several landslide studies using aerial photographs to map landslides (e.g. Dow et al. 1981, Walsh and Butler 1997, Cannon et al. 2001, Brardinoni et al. 2002). However, landslide research in the mountainous terrain of Yellowstone National Park, Wyoming, has generally been ignored in the literature. Carrara and O'Neill (2003) examined landslide movements through tree-ring dating in southwestern Montana, near Yellowstone National Park. Meyer (2001) briefly mentioned landslides in Yellowstone in his study of large-magnitude floods. Fritz (1985) also mentioned a few large landslides as well as the general location of the larger landslides on geologic maps in northeastern Yellowstone.

With this research, aerial photographs were used to identify and create an inventory map illustrating the location and spatial distribution of landslides in two adjoining watersheds, Soda Butte Creek and Cache Creek, in northeastern Yellowstone National Park (figure 1). The inventory map provides a visualization of the geomorphic impact of landslides in the area. The physical attributes of the landslide slopes were compared to the landslide distribution, identifying the dominant lithology, soil, and land cover of the landslides. Comparisons were also made between the topographic characteristics of the landslides, which included the landslide aspect and the angle of landslide deposit.

In this study, vertical aerial photographs were used to identify landslides; however there are two types of aerial photographs that can be used in landslide identification: oblique and vertical. Oblique aerial photographs include a part of the horizon. Vertical aerial photographs lose distinguishing and easily recognizable landform characteristics that can be seen on oblique photographs, but are a more reliable source of measurements and information since hillslopes and rolling topography are not facing the camera at an angle, distorting height displacement and obscuring potentially important features (Rabben et al. 1960).

Although landslides in the study area can be mapped through fieldwork, the area has rugged terrain and is very isolated with only one main paved road in the area. Using aerial photography to identify and map landslides, while not meant to replace the value of fieldwork, was less time-intensive and will later be complemented with fieldwork. Maps showing the location of some of the landslides in the area exist (Spatial

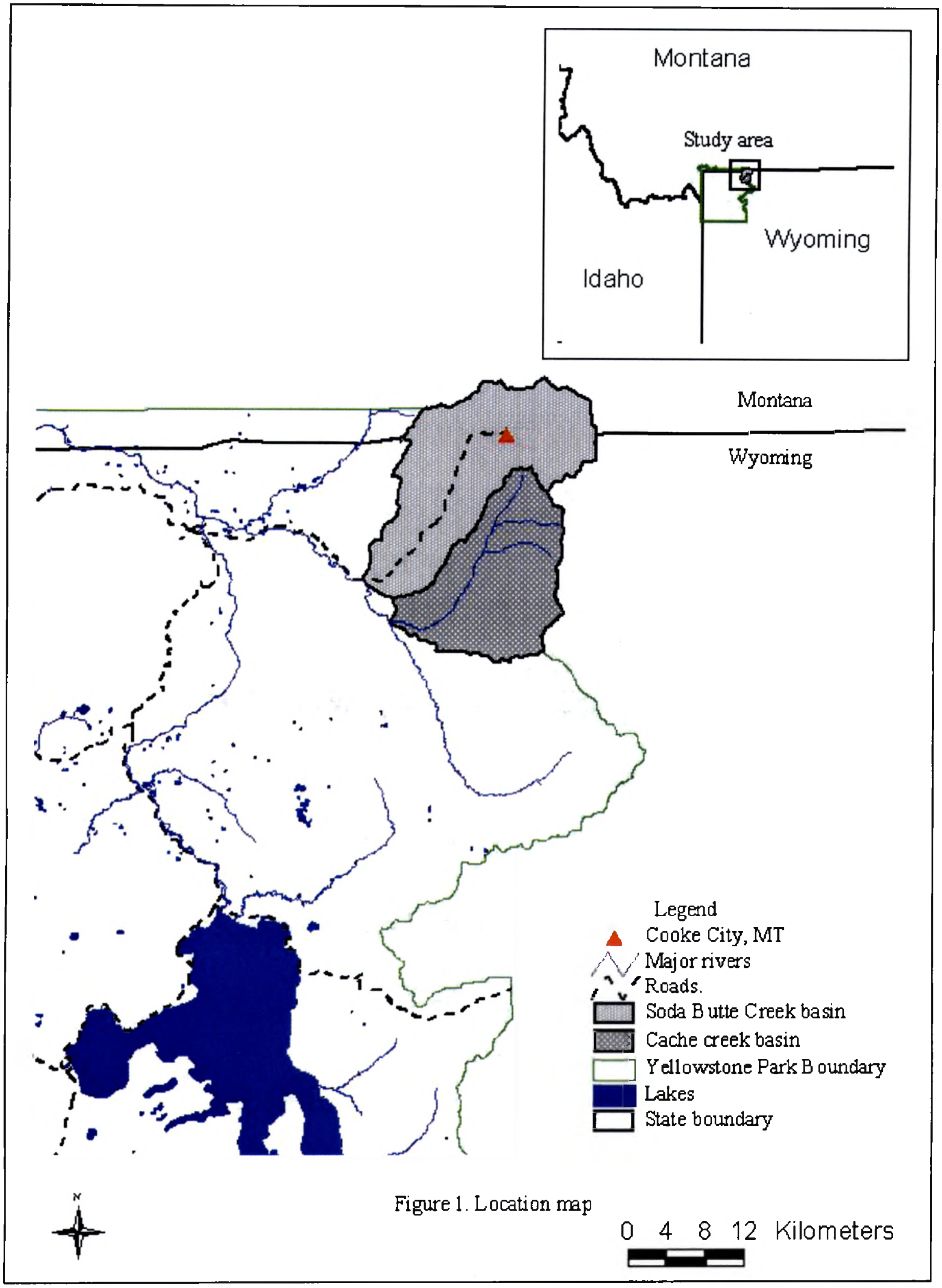

Figure 1. Location map

Analysis Center 1996, 1997), but research has not been published on the landslide distribution and the passive indicators of the landslides inside Yellowstone National Park.

This research was based on systems theory. Hall and Fagen (1958) identified two integral parts of the theory, a set of objects and their attributes. Using systems as the basis of the research, the hillslopes that are affected by landslides were considered the set of objects that interacted and reacted in a relationship with the physical attributes of the objects or hillslopes. The system reacted to the physical attributes of the slopes. An integral part of systems theory is the threshold limit. Changes or transitions are made at a threshold of an open system when a boundary or trigger point is reached (Brunsden 1973). Internal thresholds were considered in this research, as the passive attributes that were the influence on the slopes (Coates and Vitek 1980). Gardner (1980) provided an excellent example of a theoretical discussion relating the threshold theory to the frequency and magnitude of rockfalls and rockslides. Consequently, threshold theory, in conjunction with systems theory, provided an excellent framework to base this study of landslides and their passive attributes of failure.

This study's main objective was to use aerial photographs to identify and map landslides in the Soda Butte Creek and Cache Creek watersheds to answer two central questions:

- What is the distribution of landslides?
- What are the passive indicators associated with landslides?

The first question addressed sought to find where the landslides are in the study area. Landslides are mapped for different purposes, including inventory, activity (temporally), density, hazard (or susceptibility) and vulnerability maps (Guzzetti el al.

2000, Parise 2001). This research created an inventory map of the study area upon which other types of landslides maps can now be created. The spatial clustering of the landslides, in connection with aspect and valley orientation, was considered the possible answer to the first question.

The second question sought to identify the attributes present in the study area that influenced landslides. This study focused on the passive attributes related to the area, as opposed to temporal triggering mechanisms, like precipitation and earthquakes, that are linked to the occurrence of a landslide at a point in time. Passive attributes included in the study were angle of landslide deposit, landslide aspect, land cover and use, lithology, and soil. Slope instability related to structure and morphology was reviewed in the literature and discussed in the results, but were not analyzed.

The data collected in this study should be used in future research to identify the temporal occurrence of landslides in the area. The temporal analysis of landslides will be based on the inventory map created in this research to produce an activity map analyzing the age and triggering mechanisms of the landslides in the study area. Other attributes, such as earthquakes and precipitation, should be incorporated into this future study.

CHAPTER II

LITERATURE REVIEW

The literature supported the methodology and research agenda. The supporting literature was classified into three main sections: aerial photograph landslide detection, other types of remote sensing in landslide detection, and the passive indicators of slopes instability: slope angle, aspect, land cover and use, lithology, structure, and morphology.

Aerial photographs have been used in landslide research in a wide range of studies, including identification, mapping, analysis, and initiation factors (e.g. Aniya 1985, Gao 1993, Su and Stohr 2000, Cannon et al. 2001). Aerial photographic landslide detection concerns several elements of air photo interpretation including the methodology behind identifying landslides, air photo scale, the confidence level of landslide identification, and the size of landslides accurately identified.

Landslide initiation is dependent on factors that change over time (triggering mechanisms) and static forces (passive indicators or attributes) that are part of the landscape. The passive attribute's influence on slope stability varies depending on location and interaction between the attributes; therefore, it is difficult to specifically identify which attributes contribute to slope instability; however, some patterns of failure can be found in the geomorphic literature.

Aerial photography in landslide research

Several studies have used air photos to identify landslides (table 1). No consensus was found in the literature on the photographic scale needed in landslide identification. Air photo scale was usually between 1:10,000-1:20,000; however, scales in a range from 1:3,000-1:66,000 were used. Amiya (1985) used a scale of 1:20,000 to detect landslides on air photos while Hermanns and Strecker (1999) used scales ranging from 1:20,000-1:60,000.

The literature showed that the size of the landslide detected was dependent on the air photo scale and the extent and type of vegetation present, both of which limited the accuracy of landslide mapping from air photos. Lueder (1959) suggested using both large (1:5,000) and small-scale (1:20,000) imagery, when available, to accurately map landslides. Belcher et al. (1960) recommended a scale of 1:15,000 to 1:30,000 for general landslide mapping and 1:5,000 to 1:10,000 for areas with smaller landslides. However, the use of large-scale air photos was usually in combination with small-scale photos (Belcher et al. 1960). Few studies mention any limitations placed on the size of the landslides detected. Brardinoni et al. (2002) and Rood (1984) limited the size of the landslides mapped to areas larger than 200 m^2 with scales ranging from 1:11,000 to 1:20,000. Brardinoni et al. (in press), in comparing the rate of landslide detection between fieldwork and air photos, determined the age of the landslide in recently-logged areas having a detection size of 150 m^2 and old landslides, a maximum area of 650 m^2 on air photos from 1:12,000-1:15,000. Schwab (1988b) identified landslides larger than 400 m^2 with 1:10,000 aerial photographs. Hermanns and Strecker (1999) used a much larger landslide area, 1,000,000 m^2, with small-scale air photos (1:50,000).

Table 1. Locations and sources of studies using aerial photographs to identify landslides.

Source	Location	Scale Used
Aniya (1985)	Amahata River Basin, Japan	1: 20,000
Brardinoni et al. (in press)	Capilano Basin, British Columbia, Canada	1:12,000:1:15,000
Brardinoni et al. (2002)	Coastal British Columbia, Canada	1:11,000-1:20,000
Butler and Walsh (1994)	Glacier National Park, Montana	Not given
Cannon et al. (2001)	Storm King Mountain, Colorado	1:8,000
Chang and Slaymaker (2002)	Ho-she River Basin, Taiwan	1:17,000-1:18,000
Chigira (2002)	Nishigo Village, Japan	1:8,000
Cruden and Eaton (1987)	Kananaskis Country, Alberta, Canada	1:15,840
Dai and Lee (2002)	Lantau Island, Hong Kong	1:20,000-1:40,000
Dai et al. (2001)	Lantau Island, Hong Kong	Not given
Dow et al. (1981)	Monarch Lake, Colorado	Not given
Gao (1993)	Nelson County, Virginia	1:25,000-1:40:000
Guariguata (1990)	Luquillo Mountains, Puerto Rico	1:24,000
Guzzetti et al. (2000)	Umbria and Marche Regions, Italy	1:20,000
Hermanns and Strecker (1999)	Andes Mountains, Northwest Argentina	1:20,000-1:60,000
Jibson and Keefer (1989)	New Madrid Area, Tennessee and Kentucky	1:50,000
Kull and Magilligan (1994)	White Mountains, New Hampshire	Not given
Lorente et al. (2002)	Aragon and Gallego River Basins, Pyrenees Mountains Spain	Not given
Mollard (1986)	S. Saskatchewan and Qu'Appelle River Valleys, Saskatchewan, Canada	1:16,000
Montgomery et al. (2000)	Mettman Ridge, Oregon	Not given
Nossin (1999)	Villavicencio, Columbia	1:16,000
Pachauri and Pant (1992)	Aglar River Basin, Himalayas	Not given
Parise (2001)	Southern Apennines Mountains, Italy	1:10,000-1:35,000
Parise and Wasowski (1999)	Southern Apennines Mountains, Italy	1:9,000-1:36,000
Polemio and Petrucci (2001)	Sele River Basin, Italy	1:7,000-1:13,000
Reid (1998)	Simas Valley, California	1:9,200-1:24,100
Rood (1984)	Queen Charlotte Islands, British Columbia, Canada	1:11,000-1:13,000
Schmidt and Meitz (2000)	Cottonwood Canyon, Colorado	1:3,000
Schwab (1988b)	Queen Charlotte Islands, British Columbia, Canada	1:10,000
Su and Stohr (2000)	New Madrid Area, S. Illinois	1:20,000
Van Weston and Getahun (in press)	Belluno, Italy	1:15,000-1:66,000
Walsh and Butler (1997)	Glacier National Park, Montana	1:34,400-1:48,000
Wieczorek (1984)	Cruz Mountains, California	1:6,000-1:30,000

Many studies discussed the identification factors that indicated the presence of landslides on air photos. Overall, these studies provide a comprehensive list of proven factors for landslide identification. Gao (1993) looked for areas with a lighter tone, steep walls, and a contrasting texture at the bottom of a slope. Lorente et al. (2002) studied debris flows through air photos and identified a flow if the landscape had a small scar (a scarp illustrating where the slope failed) and a lobate tongue or landslide toe with levees. Pachauri and Pant (1992) also used bright tones on air photos, in addition to hummocky topography. In addition to some of the above-mentioned factors, Parise and Wasowski (1999) also looked for cracks in the terrain and a sudden change in the drainage network. Bechler et al. (1960), in addition to hummocky topography and ponded drainage, noted the lack of vegetation on an air photo, although that feature was usually included with tonal changes in other studies since a lighter tone indicated a lack of vegetation. Su and Stohr (2000) provided the most extensive list of indicators, divided into two categories: distinguishing and ambiguous. Distinguishing characteristics included hummocky topography and scarps while ambiguous characteristics included a curve in a road and deadfall.

Few studies rated the level of confidence of landslide detection, although not all landslides can be confirmed without a secondary means of identification, such as fieldwork. Dow et al. (1981) created six confidence levels of debris flow identification on air photos with a potential landslide site ranked the lowest confidence of identification and confirmed landslide ranked the highest confidence of identification. Jibson and Keefer (1989) used three levels of confidence, from questionable to definite. Su and Stohr (2000) provided the best example on ranking confidence levels of landslide detection. Three levels of confidence were ranked by the specific characteristics of the landslide, divided between ambiguous and distinguishing indicators. For instance, a possible landslide had ambiguous indicators while a certain landslide had at least one distinguishing characteristic and several ambiguous characteristics.

Remote sensing in landslide research

Satellite imagery and digital elevation models (DEM) are widely used remote sensing techniques in landslide detection studies (table 2). As with air photos, scale was not always stated in these studies, making it difficult to judge the scale needed to accurately detect landslides. Many studies used air photos in conjunction with other types of remote sensing to detect landslides (Dow el al. 1981, Pachauri and Pant 1992, Gruber and Haefner 1995, Hermanns and Strecker 1999, Nossin 1999, Cannon et al. 2001). Cannon et al. (2001) used DEM's and digital line graph's (DLG) to identify topographic

Table 2. Studies using other types of remote sensing (other than aerial photographs) to detect landslides.

Source	Location	Remote Sensing Media
Cannon et al. (2001)	Storm King Mountain, Colorado	DEM and Digital Line Graph
Dow et al. (1981)	Monarch Lake, Colorado	Landsat Color IR
Gruber and Haefner (1985)	Swiss Alps	Satellite and DEM
Hermanns and Strecker (1999)	Andes Mountains, Northwest Argentina	Landsat TM
Nossin (1999)	Villavicencio, Colombia	Satellite imagery
Pachauri and Pant (1992)	Aglar River, Himalayas	Landsat imagery
Temesgen et al. (2001)	Wondogenet, Ethiopia	SPOT and Landsat
Van Westen and Getahun (in press)	Belluno, Italy	DEM
Walsh and Butler (1997)	Glacier National Park, Montana	Landsat and DEM

controls present in an area of debris flows, although the specific types of topography, such as aspect, were not identified. Walsh and Butler (1997) incorporated GIS and remote sensing technology, including DEM's and satellite imagery, to acquire information on slope angle, elevation, and other factors relating to debris flows. Butler and Walsh (1994) and Gao (1993) provided good examples on the use of terrain characteristics gathered from DEM's.

Slope Angle

The angle of the slope influences the shear strength of the material on the slope, with an inverse relationship existing between the angle and shear strength. Multiple studies concluded that starting slope angles varying between 15°-35° are related to slope instability. In a New Hampshire study, Kull and Magilligan (1994) found the mean slope angles varied from 30.4° to 35.3°. Carrara et al. (1982) reported angles of failure between 10.4° and 34.5° in the Southern Italy. Jibson and Keefer (1989), looking at three kinds of landslides, found a median slope angle of 16°-23° relating to slope failure. Lorente et al. (2002) concluded that debris flows in the Spanish Pyrenees failed at angles ranging from 20°-35°. Gao (1993) found a majority of slope failure between 19°-31°. However, on research in the Himalayas, Pachauri and Pant's (1992) results disagreed with other studies, concluding that slopes steeper than 35° generally failed. Aniya's (1985) results also disagreed with other studies, concluding a susceptibility of slope failure at 40°-45°. Anbalagan (1992) ranked slope angles above 36° having the highest slope instability on landslide hazard maps. Temesgen et al. (2001) reported two units of slope angles, in units of 10, where failure was the highest: 10°-20°, and 30°-40°. However, this study's classification method of slope units may have introduced rounding errors into the conclusion. Zezere et al. (1999) analyzed slope angle by two methods: slope failure by density (25°-30°) and percentage of failed area (10°-15°), with density analysis referring to the same type of analysis as the above-mentioned studies, whereas percentage of failed area is the percentage of land volume at each angle unit that failed. Zhou et al.'s (2002) analysis confirmed the majority of other studies' conclusions that slopes tended to fail between 25° and 35°.

Slope Aspect

Slope aspect is the azimuthal direction a slope is facing, usually divided into eight azimuthal classes in research. External influences, such as wind direction, weather front tracks, and sun angle, will have different degrees of influence on slopes depending on the azimuthal direction. Therefore, different conclusions will be noted on the affect of aspect on slope failure. Aniya (1985) found north-facing slopes had a low failure rate primarily because of climatological factors. Gao (1993) concluded from research in Virginia that landslides were more common on aspects ranging from west to northeast. Jibson and Keefer (1989) studied slopes that failed after the New Madrid earthquakes of 1811-12. Most landslides were on west to northwest facing slopes, which the authors felt correlated with the earthquake epicenter. Kull and Magilligan's (1994) research in New Hampshire found landslides primarily on the east and west slopes, reflecting a strong climatological influence. Temesgen et al. (2001) used only four azimuthal classes whereas the other studies used eight, concluding highest frequency of landslides on west-facing slopes and the lowest frequency on south-facing slopes.

Land use and land cover

Land use and cover is observed in landslide research to determine the influence of human impact and vegetation on slope stability. Invariably, in an area impacted or controlled by humans, the land cover will be reflective of the land use. In general, the research supported the theory that root strength contributed to the overall slope stability; however, a consensus was not found on the type of vegetation that contributed the most to slope stability (Schmidt et al. 2001, Wu and Sidle 1995). Aniya (1985) divided slope vegetation into six categories, of which two, planted forests and brush, both related to human change on the landscape, were linked to slope failure. Dai et al. (2001) divided land cover into four categories: bareland, grassland, shrubland, and woodland. Grassland was found to have the highest incidence of landslides with bareland associated with the lowest density of landslides in the study area. No explanation was given on the correlation of root strength to the low occurrence of landslides on the area classified as bareland. Zhou et al.'s (2002) conclusions seem to contradict Dai et al.'s (2001) results on research completed in the same area. The same four categories were used, showing 66% of the landslides occurred in bareland and shrubs, with the mixed vegetation category second with 26% of landslide occurrence. Lorente et al. (2002) divided land cover into six classifications: shrubs, pine afforestation, oak or evergreen oak, beech and fir, pine, meadows, and farmed area. The pine category, with shrubs second, was related to slope failure the most frequently. Pachauri and Pant (1992) used three categories: sparse vegetation, cultivated land, and forest, of which sparse vegetation was most closely associated with landslides.

Lithology

In landslides studies, lithology is the composition of the rocks and sediments of the slopes. Anabalagan (1992) rated the passive attributes for hazard mapping and based the rating of the slope lithology on the rock type, erodibility and resistance to weathering of the rocks. Dai et al. (2001) gave a through description and ages of the lithology of their study area; however, the classes relating to slope failure were poorly described. Volcanic rocks were highly associated with slope instability, but the type and age of the volcanic rocks (intrusive and extrusive were both in the area) were not identified. Zezere et al. (1999) identified five categories of lithology where landsliding had occurred. Basalts and volcanic tuffs, and secondarily limestones, had the most slope failures in their Portugal study area. Pachauri and Pant (1992) had four categories of lithology with quartzite highly associated with slope instability.

No overall patterns or trends were identified with the lithology, because the composition and age of each rock type were different depending on the particular study area. However, there were general rock types, such as volcanic rocks, identified and associated with slope stability.

Morphology

Morphologic controls refer to the shapes of the slope, which are generally categorized into straight, convex, or concave. Aniya (1985) reconstructed the slope profile and slope form in an area of Japan. Analysis of the slope profile determined that straight slopes, not concave or convex, were more likely to fail and that the convergent slope form was most unstable. Zezere et al. (1999) concluded that concave slopes and convergent slope form have some influence on stability. Lorente et al. (2002) found little evidence of slope profiles influencing landslides; however, debris flows did have a slightly higher occurrence on concave slopes.

Structure

Slope structure includes joint intersections, thrusts, intrusions and faults in the rocks, which create areas of weakness (Anabalagan 1992) and affect other factors like slope angle. Cruden and Eaton (1987) found that slope types, such as dip and overdip, frequently have a higher incidence of rockslides. Temesgen et al. (2001) looked at the landslide distribution and collapsed structures (a caldera was located in the study area), faults, and lineaments, generally finding that the greater the distance from these factors, the more stable the slope.

CHAPTER III

STUDY AREA

This research focused on two adjoining watersheds located in northwestern Wyoming and southwestern Montana (figure 1). Cache Creek watershed is approximately 209.9 km^2, and Soda Butte Creek watershed is approximately 270.9 km^2 (Fonstad and Marcus 2003). Most of the study area is in Yellowstone National Park, with only small portions outside the park boundary (in national or private holdings). The study area is within the Absaroka Mountains of the Northern Rocky Mountains. The highest elevation is Pilot Peak at 3566 meters, located at the eastern edge of the study area. The lowest elevation is 1987 meters at the confluence of Soda Butte Creek and Lamar River at the western edge of the study area. Soda Butte Creek watershed's mean elevation is 2589 meters, whereas the Cache Creek watershed's mean elevation is 2551 meters (Fonstad and Marcus 2003). The area is generally characterized by areas of high relief and steep cliffs, although the western portion of the study area has U-shaped valleys with lower gradients.

The bedrock is primarily composed of Precambrian basement rock with extensive volcanic lava flows with sediments, gneiss, and limestone from the Paleozoic and Tertiary time periods. Friable andesitic volcaniclastic rocks of the Eocene Absaroka Volcanic Supergroup (ca 27-58 million years ago) are found on the upper slopes of the study area (Prostka et al. 1975). Numerous seismically active faults run through the area (Fritz 1985). Soils are primarily from the mollisol order and are derived from rhyolitic and andesitic parent materials, which are from lava flows of the same name with andesite being the oldest. Soils derived from rhyolite are very acidic whereas andesitic soils are more nutrient-rich (Despain 1990).

Conifers are the primary vegetation in the study area with the pine genus (*Pinus spp.*) dominant. Whitebark pine (*Pinus albicaulis*) and subalpine fir (*Abies lasiocarpa*) are usually found above 2621 meters elevations on the eastern side of the study area (Despain 1990). Douglas fir (*Pseudotsuga menziesii*) is typically located on north-facing slopes. Lodgepole pine (*Pinus contorta*) is the dominant species in the area and is found in the southern portion of the study area, generally preferring elevations of 2134 to 2591 meters (Despain 1990). In the Cache Creek watershed, 70.9 percent of the watershed is forested while 68.2 percent of the Soda Butte watershed is forested (Fonstad and Marcus 2003). Bare rock is found at the highest elevation, especially near the eastern edge of the study area where there are glacial horns and arêtes. Grassland occupies portions of valleys throughout the area. Logging occurs in the national forest in the northeastern portion of the study area. Numerous unpaved logging roads can be seen on aerial photographs in this area. This same area has a history of mining activity, which is currently inactive; however, old mining camps are still present. Other human activity has been kept at a minimum due to presence of the national park. Small human settlements exist in the far northeast corner of the study area. Fire activity maps show a majority of the study area was burned in the 1988 fires (Jeffery 1989, 264-265); however, in comparing the two watersheds, only 13% of Soda Butte Creek was burned, whereas Cache Creek burned 56.9% of its area (Fonstad and Marcus 2003).

The monthly climate normals for 1971-2000 for Cooke City, Montana show a January mean minimum temperature of –11°C and a July mean maximum temperature of 23°C (figure 2). The first snowfall is usually in late August with the last snowfall in late May or early June. Freezing temperatures and snowfall are possible in every month. Normal precipitation is 647 millimeters, distributed relatively uniformly in all months of the year (NCDC 2000).

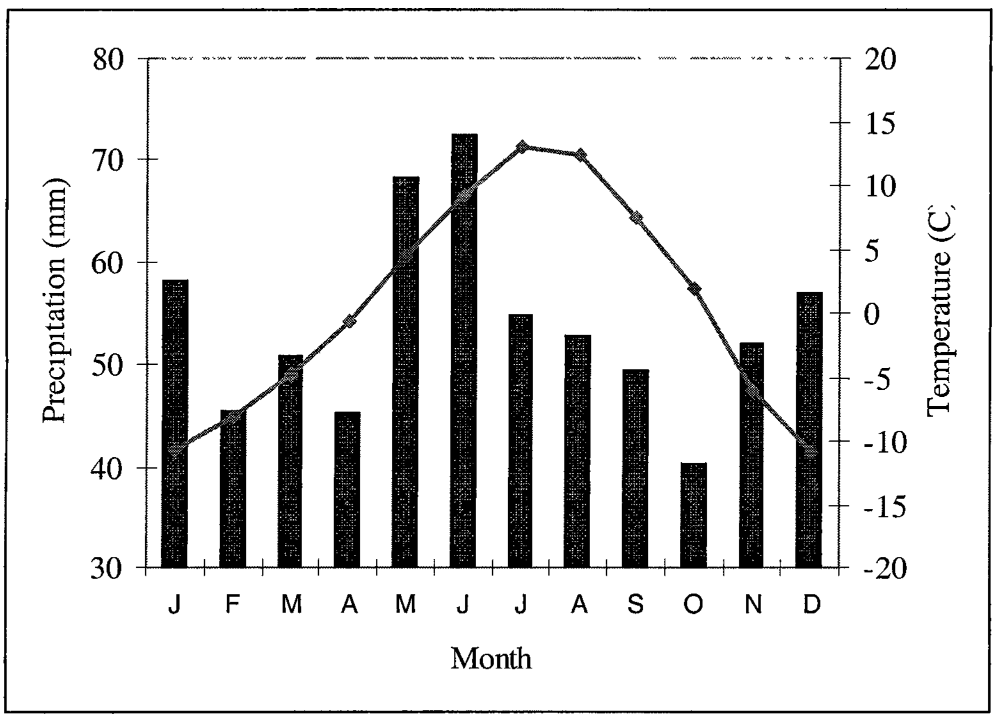

Figure 2. Cooke City 2 W station, Montana climograph.

CHAPTER IV

METHODS

In order to analyze the spatial distribution of landslides in the study area, landslides in the study area were identified on vertical aerial photographs and subsequently mapped. Topographic and geologic attributes of the landslides were used to identify controls of the spatial patterns of the landslides. Aerial photographs were the primary source of data used to identify landslides and were obtained from the U. S. Geological Survey (USGS), which had panchromatic photographs taken in 1994 with leaf-on vegetation at a 1 meter by 1-meter scale with the distortion removed.

The corrected aerial photographs, or digital orthophotos quarter quads (DOQQ), were obtained from the USGS by the Geographic Information and Analysis Center (GIAC), which mosiaced them into a single map of the Greater Yellowstone area (USGS 1999b). GIAC scanned and mosaiced 1:24,000 scale USGS topographic maps (USGS 1999a) of the Greater Yellowstone area into a digital raster graphic. Thirty-meter gray-scale DEM's was used to supplement the aerial photographs. GIAC (1999) created a DEM of the area from USGS topographic maps.

Stereo viewing was used to supplement the detection of landslide scars and deposits that may have otherwise been undetectable by other methods. The aerial photographs that were available had previously had the distortion removed, so that conventional viewing in stereo was not possible. To obtain stereo images of the study area, digital orthophotos were re-sampled from a 1-meter by 1-meter resolution to a 4-meter by 4-meter resolution for stereo viewing. A gray-scale 30-meter DEM was overlaid with the digital orthophotos, which were registered to the DEM. The combined image was then color stretched to emphasize the contrast between the color values. This technique was important to illustrate the tonal differences of the scarps and disturbed vegetation. Parallax was induced in the digital orthophotos and was based on the relative height of each pixel, which was determined from the DEM. This was done with Terra Firma, a digital terrain modeling software package (Eyton 2003), which was then used to interpolate two shifted perspective views from the orthophotos. The resulting digital images were viewed in Paint Shop Pro, an image-editing software capable of displaying raw pixel data into stereo images.

Landslides were identified using characteristics noted in the literature (table 3). Stereo viewing corrected some of the identification problems associated with vegetation cover addressed in Brardinoni et al. (2002) and Hermanns and Strecker (1999).

Table 3. Characteristics of landslide identification on aerial photographs.

Characteristics	Sources
Scarps	Belcher (1960); Lorente et al. (2002); Lueder (1959); Su and Stohr (2000)
Hummocky topography	Belcher (1960); Lueder (1959); Pachuri and Pant (1992); Su and Stohr (2000)
Concave slopes/slope shape	Bechler (1960); Gao (1993); Temesgen et al. (2001)
Tonal changes and texture	Belcher (1960); Gao (1993); Lueder (1959); Pachuri and Pant (1992); Temesgen et al. (2001)
Disturbed vegetation	Belcher (1960); Temesgen et al. (2001)
Ponded drainage	Lueder (1959); Su and Stohr (2000)
Toe/lobate tongue	Lorente et al (2002); Su and Stohr (2000)
Large blocks of detached rocks	Temesgen et al. (2001); Su and Stohr (2000)

Maps from Yellowstone National Park (YNP) and the Natural Resources Information System of Montana (NRIS) were used to identify the attributes of the landslides. Using maps from state and federal government agencies introduced different reporting styles. In general, the maps from YNP were in greater detail and provided more information than the NRIS maps. To compensate for the lack of resolution from the state maps, some information on the landslides outside of YNP was hypothesized from a compilation of sources and are reviewed below.

Digital geologic maps of YNP (Spatial Analysis Center 1999) were used to identify the lithology and structure of the area. The adjoining YNP geology map (Fritz 1985), and the digital geology map of Montana (USGS 1998) were used to identify the landslides to the east of YNP. Digital soil maps of YNP were obtained from the Spatial Analysis Center (1997). In areas where the soil type varied, the soil type in and around the scarp was used. For the area east of YNP, a digital soil survey map of Carbon County, Montana (U. S. Department of Agriculture 2003) was used. A digital land cover map (Spatial Analysis Center 1990), categorized by vegetation species, was used to map the vegetation present on and around the landslides. Land cover for the landslides to the east of YNP was inferred and interpolated from aerial photographs, stereo images, slopes with similar characteristics, and the adjoining YNP land cover map. Future fieldwork should confirm the soil, lithology, and land cover attributes for these landslides.

Landslides were mapped in ArcView, a geographical information system (GIS). Information on the individual landslides, including angle of landslide deposit, landslide aspect, length, lithology, land use and land cover, location, and soil, were entered into the database.

The topographic attributes of the landslides were calculated from the topographic maps. The topographic maps and digital orthophotos were used in the calculation of the angle and aspect of the landslide deposits. Aspect was determined by measuring a line drawn in the perceived direction of flow from the top of the landslide to the toe. The line's aspect was then measured with a protractor. The relief of the landslides was measured from the contour intervals on digital topographic maps and was used to calculate the angle of landslide deposits. Discrepancies in the calculations could be from the position of some of the contour lines, which were close together due to a scarp or cliff. The length of the landslides was measured in ArcView using the measure tool in the direction of the flow from the top of the landslide deposit to the landslide toe. In some cases, the landslide material was not in a direct line from the top of the slide and therefore parts of the landslide may have reached lower elevations than were reported. The angles of landslides deposits were calculated from the landslide length and deposit. The location of the landslides was calculated in ArcView by converting Universal Transverse Mercator (UTM) coordinates into latitude and longitude.

Descriptive statistics were used to analyze the landslide attributes, using histograms and the Rose diagram. The attributes were analyzed separately and then compared in order to identify any spatial patterns.

CHAPTER V

RESULTS AND ANALYSIS

Twenty-two landslides were mapped in the study area (figure 3). All of the landslides are located in the Soda Butte Creek watershed and were numbered so reference could be made to specific landslides (figure 4). Two main clusters of landslides exist. One cluster is at the southwestern edge of the study area and is comprised of eleven landslides. The other cluster is at the northeastern edge of the study area and consists of six landslides. Other landslides are found sporadically throughout the Soda Butte Creek watershed.

Several possible landslides were identified in both watersheds. These possible landslides were small and generally thought to be debris flows. Ambiguous characteristics were found on these sites; however, there were not any distinguishing characteristics to positively identify these sites as landslides. They were not included in this study; however, a map was created to identify possible landslides for future fieldwork.

Landslides were expected to be found in both watersheds. As mentioned above, there are several possible landslides in the Cache Creek watershed; however, none could be positively identified as a landslide. Similarities exist between the two watersheds.

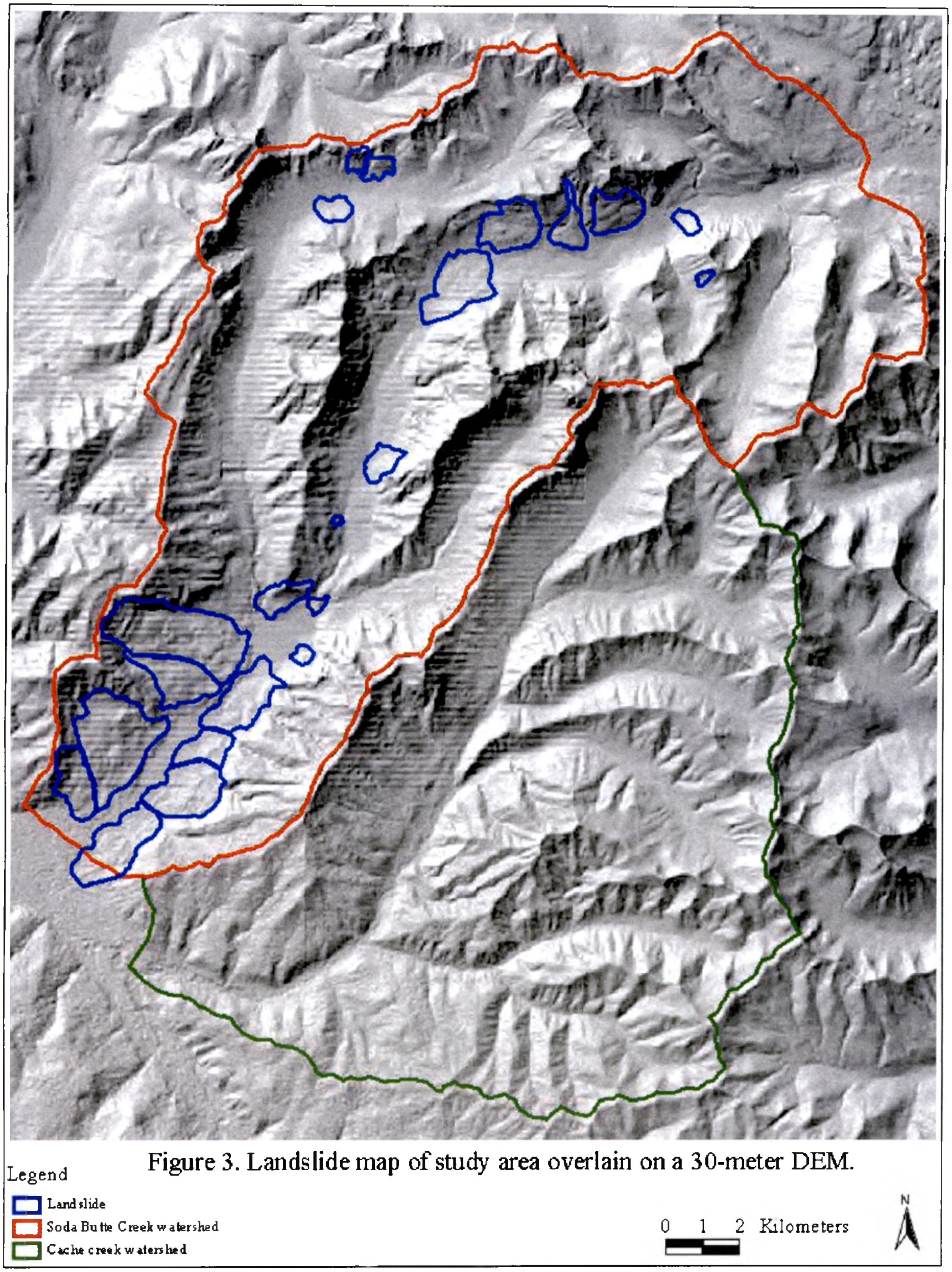

Figure 3. Landslide map of study area overlain on a 30-meter DEM.

The largest valley within the Cache Creek watershed has the same orientation as the main valley in the Soda Butte watershed, which is where a majority of the landslides are located. However, Cache Creek has several smaller valleys that are oriented east to west whereas Soda Butte had a few larger valleys primarily oriented north to south. As noted in chapter three, the sizes of watersheds are similar. Cache Creek is smaller by approximately 70 meters. Comparing the two watersheds, Cache Creek has a slightly larger area covered by forests. While slope stability is influenced by the type of land cover on the slopes, the percent difference between the two watersheds is too small to be significant. The mean basin elevation is also very similar, with Cache Creek having a slightly higher mean elevation.

There is a large difference between the watersheds when comparing the percent burned areas from the 1988 fires. Cache Creek had over forty-percent more area burned than Soda Butte Creek. Generally, there are more landslides in burned areas than non-burned areas as debris flow initiation can increase after a forest fire moved through an area (Cannon et al. 2001). Because of their similarities to avalanche paths, debris flows could not be mapped in this study. Therefore, Cache Creek may have had debris flows that were not identified. Although landslide types were not part of this study, some general types of landslides can be noted. The landslide deposits in the Soda Butte watershed appeared to be slides and flows. None of the mapped landslides had the characteristics of debris flows. Therefore, even if there are debris flows in the Cache Creek watershed, other types of landslides should also have been identified. Images with increased resolution are needed to identify landslides in Cache Creek that were too small to be identified with the imagery used in this study. Finally, if the landslide map is

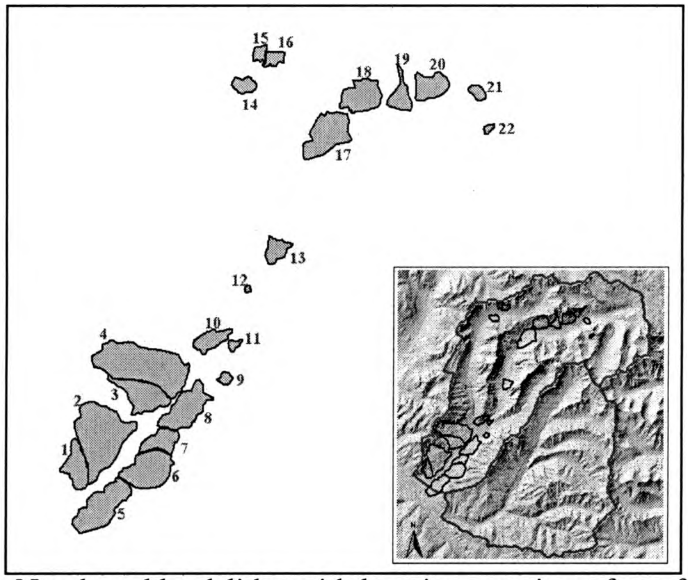

Figure 4. Numbered landslides with location map inset for reference.

accurate and Cache Creek does not have any landslides, other differences between the watersheds must be identified. These possible differences between the watersheds include the lithology, soil, type of land cover, and climate.

Comparing the different imagery used to identify the landslides, the gray-scale DEM's were largely ineffective. Only two landslides could be identified solely on the DEM's (landslides 2 and 4); however, with the stereo image, those same landslides were found to be comprised of multiple landslides. Given the 30-meter resolution of the DEM's, it was not surprising that more landslides were not found. The landslides that were found were possibly the largest landslides identified in this study. However, identifying characteristics associated with landslides, such as hummocky topography, are usually less than 30 meters in size. Identifying landslides 2 and 4 was possible as the scarps were larger than 30 meters and were clearly recognizable, as was the hummocky topography. The general conclusion was that to use DEM's in landslide identification, a higher resolution is needed.

Characteristics that identified landslides on the landscape could be seen on the aerial photographs, which were at a 1-meter resolution. However, the majority of the landslides could not have been identified and mapped with confidence without the stereo images of the area. They provided a 3-dimensional view of the area that was necessary to associate particular landforms with the landslides. The 4-meter resolution of the stereo images was still a sufficiently high resolution to identify the characteristics associated with a landslide. A limitation of having only images from 1994, instead of a series of dates spaced over several years, was the inability to detect landslides that have eliminated earlier, smaller landslides or multiple landslides in the same area. Fieldwork and older aerial photographs are necessary to find the remnants of some of these landslides.

Some of the landslides are possibly one, two, or several small slides that lack lateral features to distinguish them. In particular, two landslides in the northern section of the study area (numbers 15 and 16) showed some evidence of multiple landsliding; however, as they had some delineation between the two masses, they were marked as two landslides. All of the landslides had some type of vegetation on them, with the exception of numbers 15 and 16, which are on steep slopes.

Terrain characteristics of the landslides were consistent with what was reported in the literature (table 3). In general, an area that had two or more of the identifying characteristics was mapped as a landslide. Landslide 17 had many of the characteristics seen of the landslides in the study area (figure 5). Scarps were the most common characteristic used to identify landslides. Many landslides had hummocky topography; however, due to the area's glacial history, that characteristic was used with caution. Disturbed vegetation was commonly seen with the landslides and when combined with

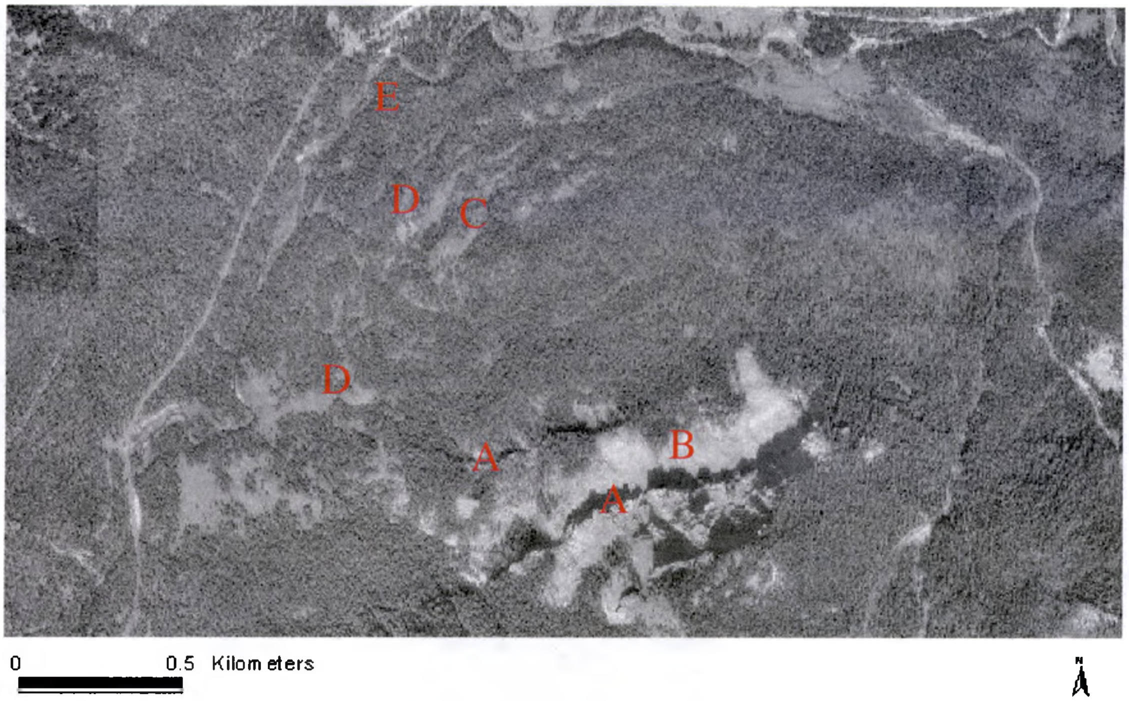

Figure 5. Identifying characteristics of landslide 17. The letters indicate the following features: A. scarp (partially in shadow); B. tonal differences; C. hummocky topography; D. disturbed vegetation; E. toe.

hummocky topography on the stereo images, was an excellent indicator of a disturbance in an area. The shape of the slope was not an indicator of landslides; however, some of the scarps had a concave form that helped identification. Tonal changes and textures of the landscape, when viewed in stereo, were often found to be associated with the vegetation-bare scarps of the landslides. However, small stands of quaking aspen (*Populus tremuloides*) were seen on several landslide toes and had a decidedly different, lighter tone that distinguished them from conifer stands. Quaking aspen has been associated with disturbed ground (Price 1981) and the difference between vegetation provided an added indicator of a disturbance. Toes or lobate tongues were seen on many landslides and served as a very distinctive indicator of a landslide. Landslide characteristics not used in this study were ponded drainage and detached rocks. In the case of detached rocks, the resolution of the imagery made this characteristic unusable. There would have had to been large rocks and boulders as well as a large overall combined pile of rocks to have been detected. Ponded drainage would probably have been a greater use in areas of recently disturbed slopes. The resolution of the imagery may have also affected the use of this characteristic to identify landslides.

A digital landform map (Spatial Analysis Center 1996), digital soil map (Spatial Analysis Center 1997), and USGS surficial geologic map (Pierce 1974) showed either earth flows or landslides as a category. These maps were compared to the final landslide map in this study. Some landslides mapped in this study were found on the other maps (figure 6). For example, landslides 17, 18, and 19 were mapped on the soil map.

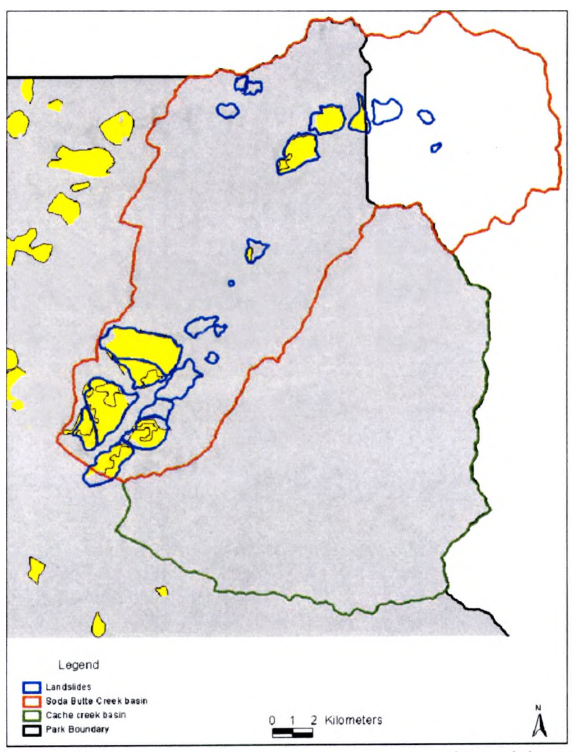

Figure 6. Comparison of landslide maps. Landslides mapped in this study (in blue) and landslides identified on the soil map (in yellow). The soil map was only for YNP and ended at the Park boundary (in black).

However, landslides 1 and 2 are mapped as one landslide on the soil map, instead of the two landslides that were identified in this study. The landform map identified more landslides than the soil map. That map also identified parts of landslides 11 and 12. The attributes of the landslides were not identified or analyzed in association with these maps. Meyer (2001) identified landslide four as the Trout Lake landslide; however, no attributes of the landslide were mentioned. Additional landslides are probably located in the study area. Aerial photographs with increased resolution and fieldwork are required to identify them. It is possible that additional landslides are present in the Cache Creek watershed as well as the Soda Butte Creek watershed. In particular, smaller debris flows and rock falls will probably be found within both watersheds.

There are several reasons why other landslides were not identified. Vegetation may have obscured the scarp and slide area. Shadows caused by the sun angle obscured some slopes on the aerial photographs and the stereo images. Shadows on north-facing slopes and slopes in the shadow of higher slopes or cliffs were seen on aerial photographs. This was especially a problem in locating scarps and determining the extent of the landslide (figure 5). Rockfalls and small landslides may have been too small to be detected from the aerial photographs. Particular types of landslides can look like other types of mass movements. For instance, several areas in the Pebble Creek valley (the northernmost valley in the study area) had evidence of either debris flows, debris flow paths, or avalanche paths. However, debris flow paths resemble avalanche paths and can be one and the same. Without any depositional material, which is rare given the fluidity of debris flows, these areas could not be positively identified as landslides. Another problem is the past glacial activity that has occurred in the study area (Fritz 1985). Some features of glacial activity, such as moraines and disturbed drainage system, can interfere with landslide identification. Finally, as Parise (2001) noted, the inventory map is a static view of landslides present when the aerial photographs were taken. Landslides may also have occurred since the photographs were taken.

Landslide characteristics

Databases of the landslide attributes were created to analyze and identify characteristics associated with slope instability in the study area (tables 4 and 5). The topographic attributes were first studied separately, then compared as a group to observe any patterns. Table 4 gives the basic characteristics of the landslides: location, aspect, angle, length, deposit relief, and total relief.

The landslides ranged from 251 to 3,684 meters in length with an average of 1,244 meters (table 4). In some cases, the landslides reached a lower elevation by flowing to the side of primary direction of flow; however, in order to achieve measurement consistency, the length was measured in a straight line from the top of the landslide in the direction of the flow to the bottom.

The deposit relief reflects the amount of elevation the landslide traveled. The deposit relief ranged between 49 and 671 meters with an average of 288 meters. The relief was measured to the nearest contour interval, which at 40 feet (12 meters), introduced some error. The total reliefs of the landslides were calculated in order to observe differences between the total areas affected by the landslide and the landslide deposit. The total relief ranged from 49 to 854 meters with an average of 444 meters.

Table 4. Topographic attributes of the landslides.

ID	Location Latitude	Longitude	Slope Aspect (°)	Angle of deposit (°)	Length (m)	Deposit relief (m)	Total Relief (m)
1	44.885	-110.176	173	8	1,971	281	378
2	44.886	-110.162	136	9	2,369	366	854
3	44.908	-110.158	120	13	2,424	256	610
4	44.902	-110.138	130	10	3,684	671	756
5	44.858	-110.155	304	12	1,050	226	299
6	44.871	-110.127	293	8	1,582	232	354
7	44.884	-110.122	290	11	1,141	220	305
8	44.899	-110.104	286	12	1,222	256	378
9	44.905	-110.094	285	23	486	207	512
10	44.924	-110.103	178	15	778	210	296
11	44.919	-110.089	296	6	471	49	49
12	44.939	-110.087	100	14	251	61	122
13	44.952	-110.064	285	30	770	439	659
14	45.011	-110.085	355	19	629	214	336
15	45.028	-110.077	180	22	614	244	317
16	45.026	-110.070	180	9	930	146	207
17	44.991	-110.039	342	13	1,413	317	561
18	45.016	-110.025	178	16	1,309	378	537
19	45.020	-110.005	175	15	1,772	376	622
20	45.017	-109.989	176	20	1,210	439	793
21	45.008	–109.961	315	23	797	384	531
22	44.998	-109.956	243	28	496	268	293
		Landslide means	228	15	1,244	288	444
		Standard deviation	78	7	812	141	215

The length of the landslides was plotted against the deposit relief and the total relief (figure 7). The scatterplot diagram shows a weak, but positive relationship between the deposit relief and the landslide length, with an r^2 of 0.45. The scatterplot diagram shows a weaker, but still positive, relationship between the total relief and the landslide length, with an r^2 of 0.40. This positive relationship would be expected except when landslides are confined in a narrow valley or a slump where the deposit slipped down but moved relatively little. There was a difference of 156 meters between the two

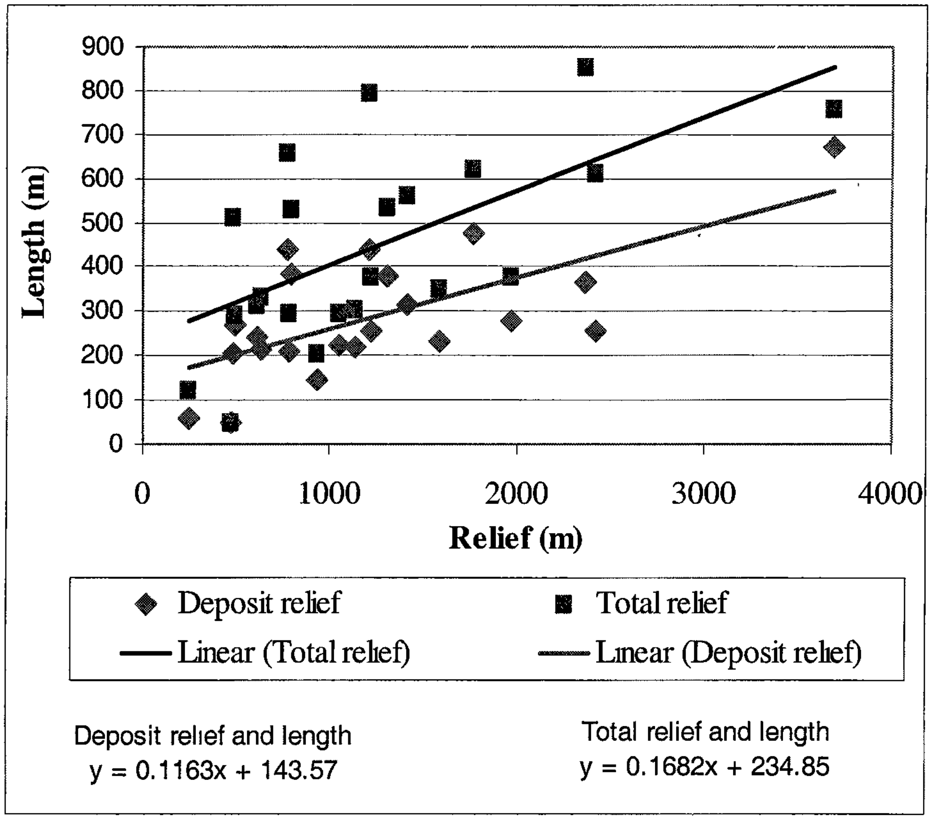

Figure 7. Scatterplot diagram of relief (deposit and total) versus length. The coefficient of determination (r^2) for the deposit relief and length was 0.45. The coefficient of determination (r^2) for the total relief and length was 0.40.

was possible as it was difficult to accurately mark the top or source of the landslide on the topographic maps. Fieldwork is needed to identify the exact height of the scarps. Looking at the range of the landslide elevations, the tops of the landslide were from 2,135 to 2,916 meters and had an average elevation of 2,473 meters (figure 8). The toes of the landslides ranged in elevation from 2,013 to 2,647 meters with an average elevation of 2,184. Some similarities were seen in the ranges of elevations of the landslides that were close in proximity. For instance, landslides 5 through 10, which are located along the same valley, have similar elevations, as do landslides 19 through 21.

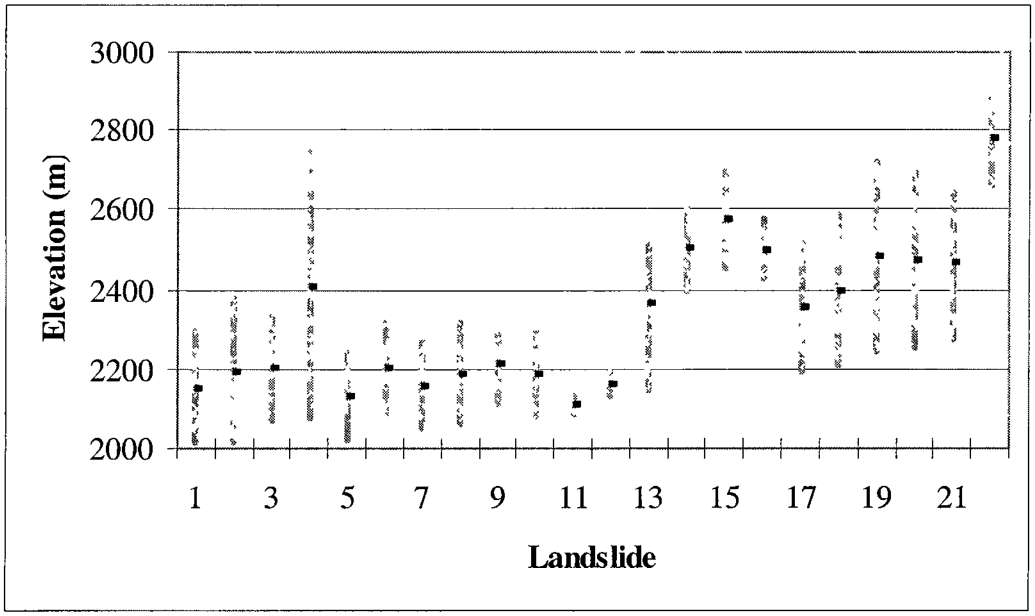

Figure 8. Elevation of the landslides. The top of each line marks the elevation at the head of the landslide, and bottom of the line is the landslide toe. The black dot marks the mean elevation.

Landslide aspect

Landslides generally occurred in the southeast and northwest (figure 8). The mean aspect was 228°. The strongest orientation of the landslides was in the south with seven landslides occurring between 170°-180°. As the Rose diagram illustrates, no landslides were found between 0° - 45° (northeast) and 180° - 248° (southwest).

Landslides occurring on the southwest and northeast slopes may be a result of the orientation of the valleys in the study area. The major valleys were primarily oriented northeast to southwest with southeast and northwest-facing slopes. Several smaller basins in the Cache Creek watershed were oriented east to west. Few slopes in the study area faced northeast and southwest. In order to test whether the southeastern and northwestern slopes are likely to fail or if the failures are merely a product of the valley orientation, future research should include studying basins with east to west orientation.

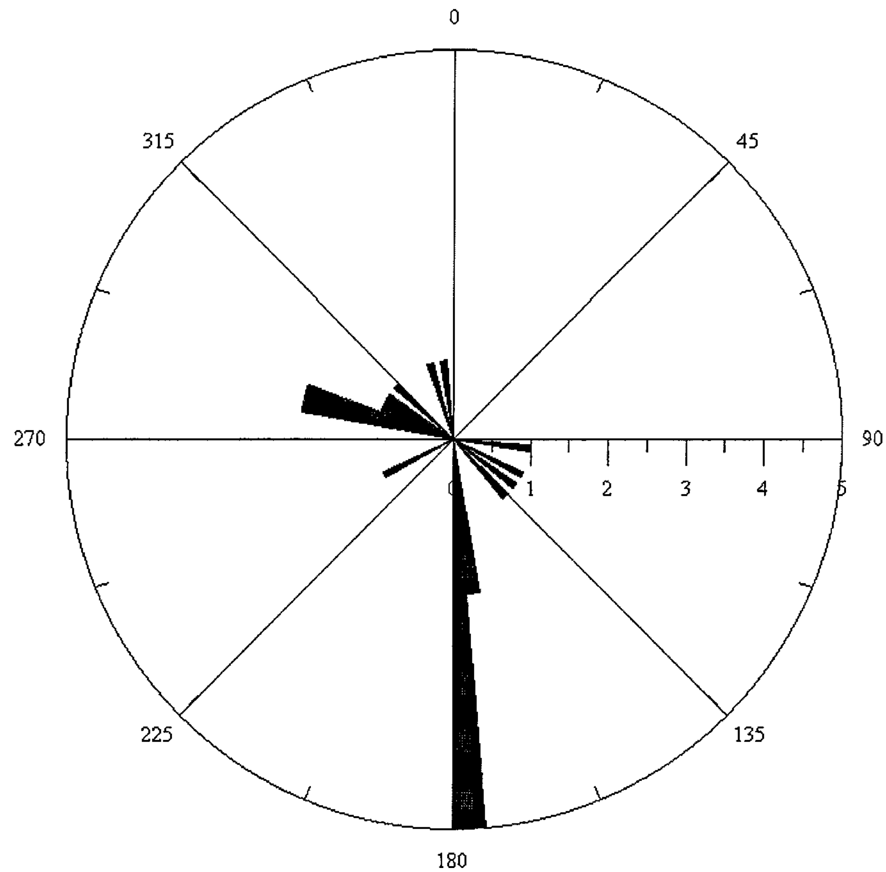

Figure 9. Rose diagram of the landslides aspect.

Climate and solar radiation influence the conditions on the slope and vary according to the slope aspect. Solar radiation influences the amount of heating that occurs on a slope and is affected by slope aspect, latitude, and the time and day of the year (Swift 1976). Southwestern slopes, followed by southern and southeastern slopes in the northern hemisphere, are characteristically the driest and warmest (Gao 1993, Blumer 1910). Future temporal studies of the landslides will possibly determine the time of the year they failed

The types of climatological influences that could affect slope stability were not included in this study. In the future, the effects of wind and weather fronts on the slopes will be analyzed in conjunction with the changes in solar radiation to determine how the stability of the slopes are influenced by its aspect.

Slope angle of landslide deposits

Measurements were taken of the landslides rather than the slopes before they failed, thereby resulting in angles of the landslide deposits. Angles ranged from 6° to 30° with a majority of the slopes having an angle under 20° (figure 9). The mean angle was 15°. This was significantly lower than reported pre-failure slopes angles of 25°-35° (e.g. Kull and Magilligan 1994, Lorente et al. 2000, Zhou et al. 2002). However, the literature was reporting on the angles of the slopes before failure. The angles of these slopes would have been much steeper than the post-failure slope angles. The current slope angle of landslide deposits has now reached the angle of repose or the maximum angle at which the deposit is stable (Summerfield 1991). Angles of landslide deposits that are

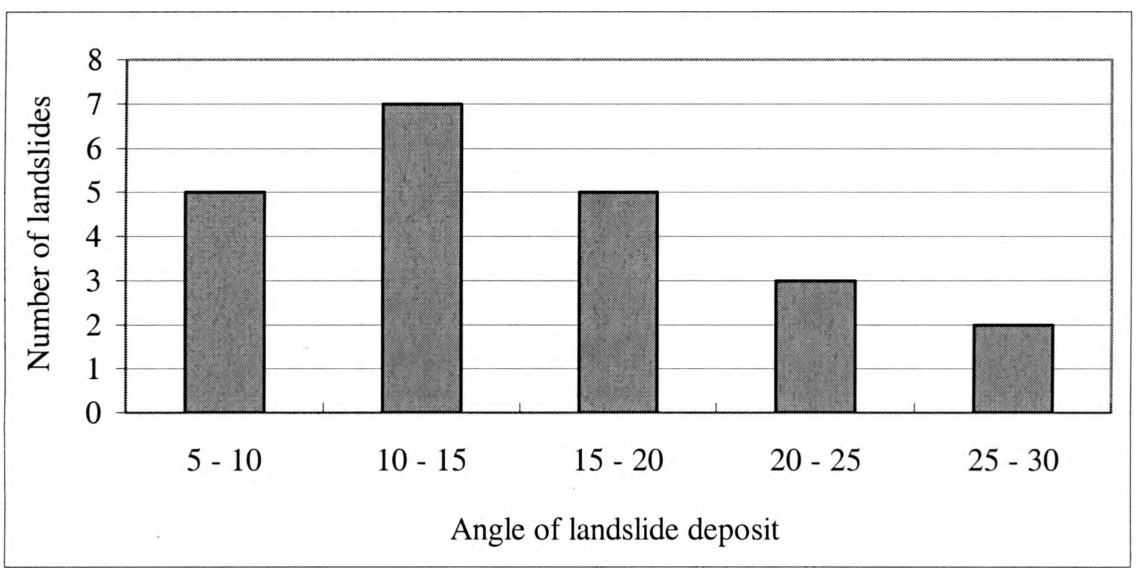

Figure 9. Histogram of the angle of landslide deposits.

representative of slopes that have not failed, such as landslide 14 with a 30°angle, may not be at an angle of repose. Future landslides may be possible on these sites.

The angles of landslide deposits were compared against the length of the landslides to observe any patterns of length versus angle (figure 10). Overall, the scatterplot diagram shows a weak inverse relationship between landslide deposits and angles of deposits, with an r^2 of 0.20. Longer landslides generally came to rest at lower angles than shorter landslides. In some cases, the landslides may rest at steep angles due to the type of landslides (e.g. creep), if the shear stress was stronger that the shear strength of the slope, or if there was a lack of liquid during movement.

Passive attributes of the landslides

The passive attributes of the landslides - lithology, land cover and use, and soil - were identified to observe any patterns that may be associated with failure (table 5). Lithology was studied as it is linked to the strength of the rock types as well as influencing the composition of soils. Land use and cover can be important as stabilizing forces on the slopes. Soils will affect the vegetation present on the slopes, which can contribute to the overall strength of the slope.

Lithology

Except for two landslides, the rock types found on the landslides were similar in type and age (figure 11). Tertiary andesites and basalts were found on the most landslides in the study area. Tertiary rocks date from approximately 1.6 to 66 million years ago.

Table 5. Passive attributes of the landslides.

ID	Lithology	Land cover	Soil
1	Tertiary andesites/basalts	Douglas fir	Bedrock and skeletal mollisols
2	Tertiary andesites/basalts	Douglas fir/non-forested	Skeletal mollisols with root-limiting layers/bedrock
3	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols with root-limiting layers/bedrock
4	Tertiary andesites/basalts	Whitebark pine/non-forested	Skeletal mollisols with root-limiting layers/bedrock
5	Tertiary andesites/basalts	Douglas fir/non-forested	Skeletal mollisols with root-limiting layers
6	Tertiary andesites/basalts	Lodgepole pine/non-forested	Skeletal mollisols with root-limiting layers
7	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols with root-limiting layers/bedrock
8	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols with root-limiting layers/bedrock
9	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols with root-limiting layers/bedrock
10	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols and bedrock
11	Tertiary andesites/basalts	Douglas fir	Mollisols and alfisols
12	Tertiary intrusives	Douglas fir	Skeletal mollisols
13	Tertiary andesites/intrusives	Whitebark pine/non-forested	Mollisols with root-limiting layers
14	Mississippian sediments	Whitebark pine/Lodgepole pine	Mollisols and inceptisols
15	Tertiary andesites	Whitebark pine	Mollisols and bedrock
16	Tertiary andesites	Whitebark pine	Mollisols and inceptisols
17	Devonian sediments	Whitebark pine/non-forested	Skeletal mollisols with root-limiting layers
18	Devonian sediments	Whitebark pine	Skeletal mollisols with root-limiting layers
19	Tertiary andesites/basalts	Douglas fir	Skeletal mollisols with root-limiting layers
20	Tertiary volcanics	Douglas fir	Skeletal mollisols with root-limiting layers
21	Tertiary volcanics	Lodgepole pine/non-forested	Skeletal mollisols with root-limiting layers
22	Tertiary volcanics	Non-forested/Whitebark pine	Bedrock/skeletal mollisols

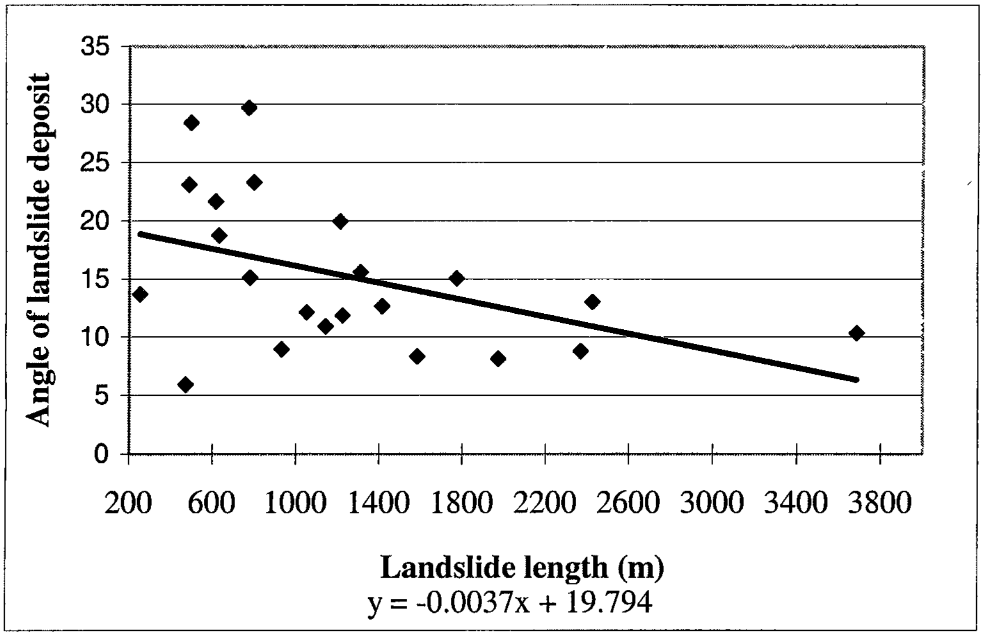

Figure 11. Scatterplot diagram of landslide length versus the angle of landslide deposit. The correlation of determination (r^2) was 0.40.

Prostka et al. (1975) stated that volcanic rocks of the study area were deposited during the Eocene epoch (approximately 27 to 58 million years ago). One study did link basalt to slope failure (Zezere et al. 1999). However, finding this rock type in the area may not be significant, because andesites and basalts are volcanic extrusives, and are the most abundant types of lava-originated rocks in the world (Hamblin and Christiansen 1999).

The Tertiary volcanics found in the study area refer to extrusive rocks whose type could not be further identified. Given the proximity to areas where andesites and basalts are found, these rocks might be either. It is not likely to be rhyolite, the other primary extrusive rock in YNP, as it generally occurs in the southwest portion of the Park (Fritz 1985). However, if it were rhyolite, it would be important to note that rhyolite results in different soils and vegetation types, which may affect slope stability. The Tertiary intrusive rocks noted in figure 12 may be part of a complex of dikes and sills from the

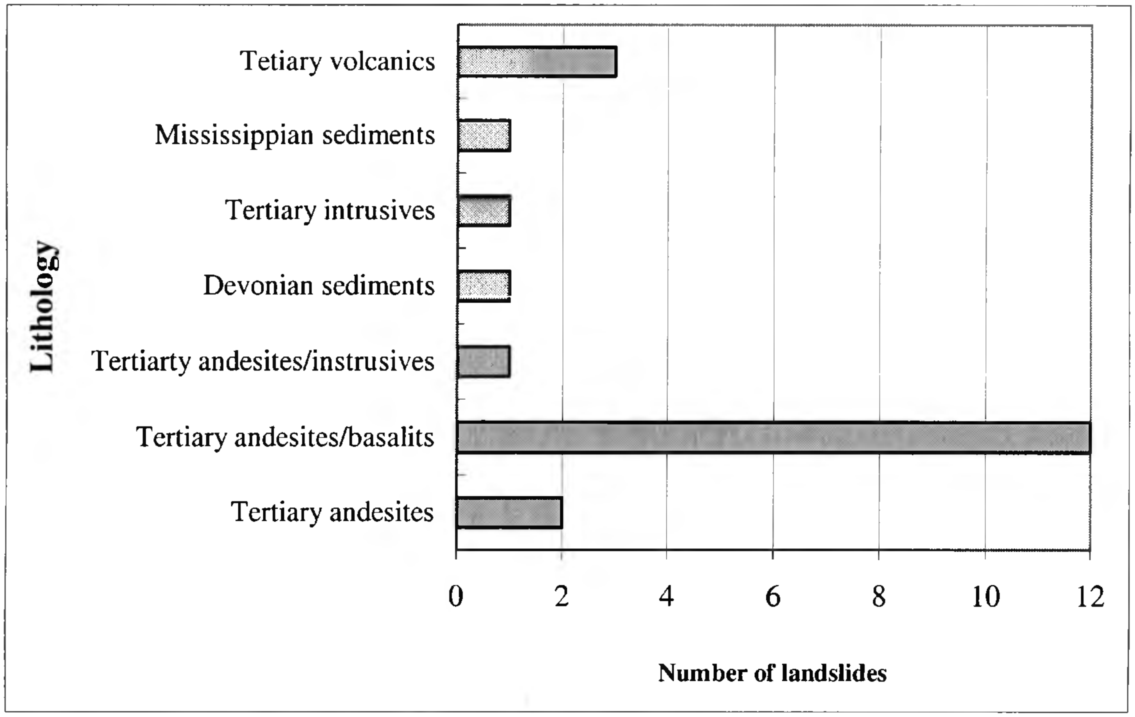

Figure 12. Histogram of the lithology of the landslides.

Eocene period.

The literature showed that limestone and schists are linked to slope failure (Anabalagan 1992). Despain (1990) noted that sedimentary rocks from the Paleozoic era are generally composed of limestone, sandstone, and shales. However, only two landslides in the study area can be linked to these rock types. Both of these rock types are from the Paleozoic era. Devonian rocks are approximately 360 to 408 million years old while Mississippian rocks are approximately 320 to 360 million years old.

The lithology of the landslides was very similar. Extrusive and intrusive igneous rocks were the most prevalent and are from the same geologic period. Intrusive rocks may be a source of weaknesses in joints, depending on weathering and structural differences between the intrusive and the surrounding rocks as well as the angle of the intrusion. The rock type is important in the formation of soil, which can influence the type of vegetation found on the slopes.

Soil

The landslides had similar soil types (figure 13). Soils on the landslides were identified by their soil order. The soil order is the first of five levels of soil taxonomy described by the U.S. Department of Agriculture (1998). Three soil orders were on the landslides: mollisols, alfisols, and inceptisols. Mollisols were found on all the landslides. Three landslides contained mollisols and either alfisols or inceptisols. Soils classified as mollisols have a dark colored layer at the surface (U. S. Department of Agriculture 1998). Inceptisols are less-developed soils (Buol et al. 1997), whereas alfisols have a sodium or clay horizon (U. S. Department of Agriculture 1998).

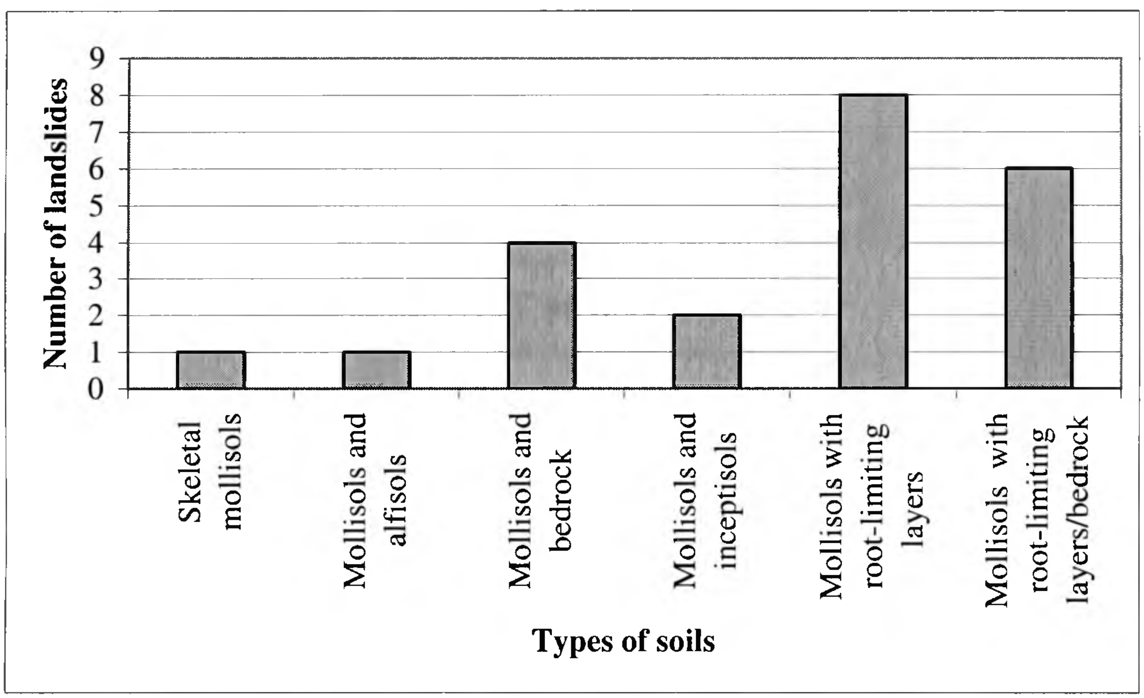

Figure 13. Histogram of the soil types found on the landslides.

Mollisols with root-limiting layers were found on many of the landslides. Skeletal mollisols with root-limiting layers and bedrock were on ten of the twelve landslides where the landslide length was over 1,000 meters. Root-limiting layers have the potential to prevent vegetation from establishing deep roots as well as preventing nutrients and identified moisture from being mixed into the deeper soil layers. Roots from vegetation are considered a stabilizing force on slopes (Schmidt et al. 2001, Wu and Sidle 1995). In order to determine the influence of the root-limiting layers on slope instability, future studies will need to include the depth of these layers and the extent of them on the slopes in the area.

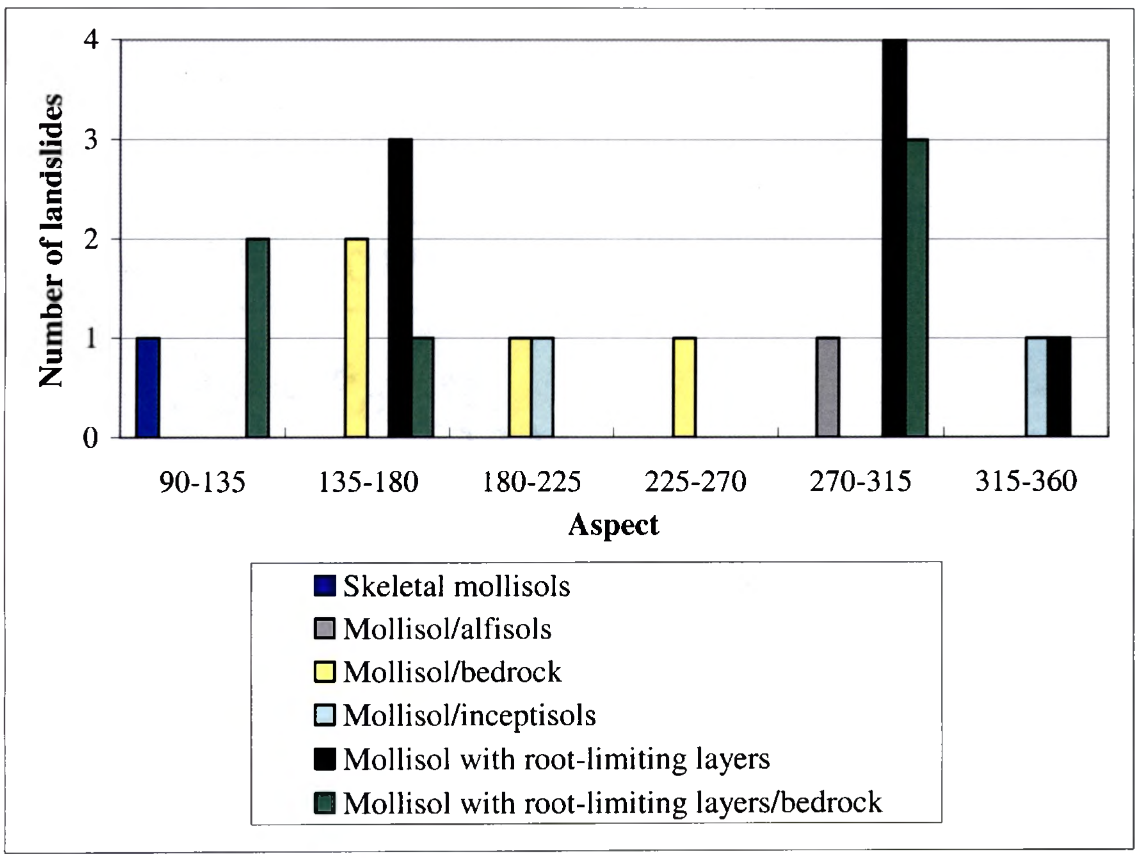

Figure 14. Histogram of the soil types, divided by aspect. Landslides did not occur from 0° - 90°.

Aspect will influence the slope's climatic conditions, which is an important factor in observing differences in soil development. Examining figure 13, a clear pattern of where the types of soils are likely to be found does not emerge. Root-limiting layers occurred multiple times within the same aspect. These soils may have contributed to slope instability. However, finding the root-limiting layers on these landslides may be insignificant. Most of the landslides also occur in these aspects (southeast and northwest), and are spatially clustered within a relatively small area where the soil may be dominant. Without measuring the amount of coverage of each type of soil within the study area, it is not possible to make any conclusions of whether root-limiting layers are a contributing factor in the landslides.

Mollisols, alfisols, and inceptisols were found in the south and northwest, which were the same aspect as a majority of the landslides. Soils on north-facing slopes may be less developed because these slopes stay colder longer in the spring and have a shorter growing season. However, no indication of less-developed soils occurring on north-facing landslides than on other aspects existed.

Mountain environments are linked to poorly developed, thin soils (Price 1981), therefore it was not surprising to find bedrock on or above the landslides. The short growing season and harsh climate associated with mountain environments limit soil development and the area may not have had time to recover from the disturbance and form new soil.

Clay in the soil horizons of mollisols and alfisols on the slopes in the study area make those slopes more prone to landslides and erosion than other slopes in YNP. The clay content within the soil horizons was not identified in the map of soils (Spatial

Analysis Center 1997), but may be present in the soils of the study area. Despain (1990) stated that YNP soils derived from andesites were more likely to be high in clay and low in sand. With the lithology of the landslides known to be andesitic and basaltic, some landslides may be high in clay. Also, alfisols will have an accumulation of clay, but inceptisols will have little accumulation of clay (Singer and Munns 1991). Soils containing high clay content will crack during droughts and swell during rain events, which effectually blocks precipitation. Runoff and erosion along the slope increases when the precipitation is unable to percolate into the lower soil layers. Soils with clay in the soil horizons can cause the slope to fail (Singer and Munns 1991). Future studies should include whether soils containing high amounts of clay are affecting the erosion and stability of the slopes in the area. Until future studies can be completed comparing the types of soils found on the landslides to the soils on all slopes in the study area, further conclusions cannot be made.

Land use and land cover

Land use was not investigated in this study as most of the area is within a national forest or national park. Temporal changes in the land cover, such as fire activity maps, were also not investigated in this study. Fire activity maps can assist in illustrating the impact of changes of the vegetation on slope stability. These maps were not utilized in this study, as the temporal occurrence of the landslides was not investigated. They are important in identifying triggering mechanisms of landslides and in the future, logging

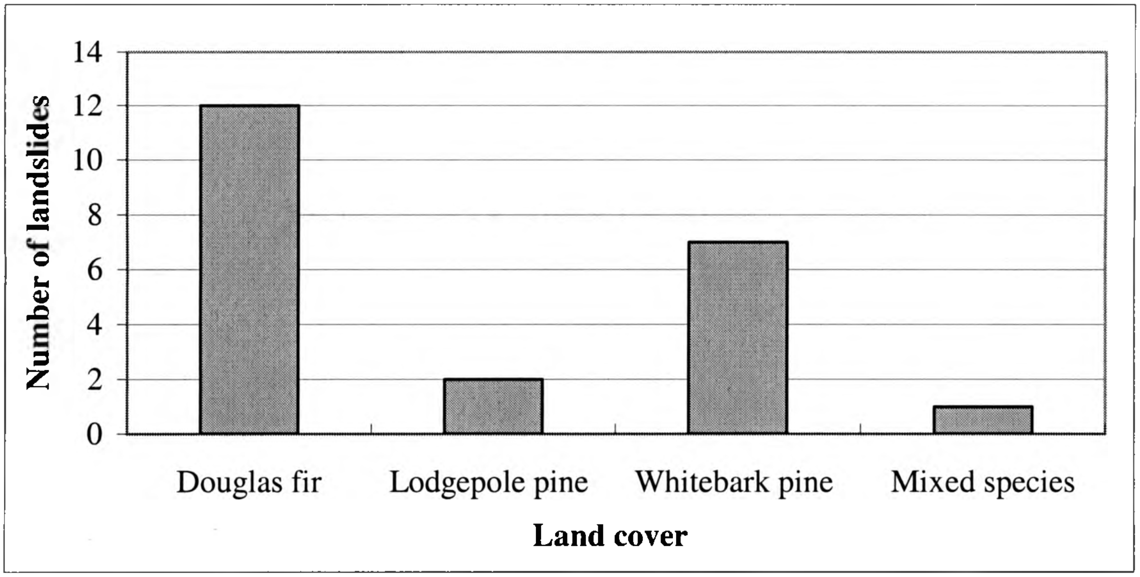

Figure 15. Land cover of the landslides by primary vegetation type.

maps and fire activity maps will be included in the temporal studies of slope stability in the study area.

The land cover on the landslides was dominated by tree species mixed with non-forested areas or other tree species (table 5). Four trees species were reported on the landslides. Understory vegetation on the landslides was not identified; however, Despain (1990) noted many shrubs and grasses are present with the tree species of the area.

Douglas fir was the most widely associated with the landslides (figure 15). Douglas firs are a medium to large tree that prefer moist, nutrient-rich soils (Benvie 2000). This species would likely anchor the soil and provide greater slope stability more than the shallow-rooted lodgepole pine. Non-forested areas listed in table 5 refer to bare rock or non-vegetated areas that are associated with scarps, cliffs, and treeline areas. Although the literature did not report on the stability of slopes related to specific tree species, Bartlett (1974) noted that trees with deep root systems have been attributed to greater slope stability than species with a shallow root system like the lodgepole pine.

Seven landslides were dominated by whitebark pine, which is a smaller tree that prefers higher elevations over 1000 meters with rocky, well-drained moist soils and deep roots (Benvie 2000). Given that all of the landslides were above 1000 meters, it is not surprising that whitebark pine was prevalent.

There are three possible reasons why tree species known for deep roots that should stabilize the slope were associated with landslides in the study area. First, Douglas fir and whitebark pine could have established themselves after the landslides occurred, given that the time scale of the landslides is unknown. Second, the soil may have been an overriding influence with the root-limiting layers preventing the trees from becoming firmly established on the slopes. Finally, looking at the general pattern of vegetation preferences in YNP, Despain (1990) noted that ryholite was more closely associated with subalpine fir and lodgepole pine than with Douglas fir or whitebark pine. Neither Douglas fir nor whitebark pine could be closely identified with any particular rock type.

Morphology

Morphology, or the slope form, was not analyzed in this study, but will be in future research analyzing a temporal study of failure rates in the study area. A digital map of slope morphology (concave, convex, or straight) has been created by the Spatial Analysis Center (1996) of the area within the national park. However, it mapped the current slope morphology, not the morphology before the landslides occurred.

Structure

The geologic structure associated with the landslides and their surrounding area was not analyzed in this study, but will be in a temporal study of failure rates in a future study. The structure of the slopes influences the landslides. The proximity to faults and volcanic intrusions are expected to influence slope failure. A few landslides had volcanic intrusions as part of their lithology (table 5). Further, Fritz (1985) noted volcanic dikes and sills in the Cooke City area. Also, several areas on the aerial photographs showed linear features that could be faults.

Comparison of attributes

Without analyzing the passive attributes within the entire study area, it is not possible to indicate the type of slope likely to fail. However, some general patterns can be seen, comparing the attributes of the landslides. Grouping landslides by aspect results in eleven landslides with a south to southeast aspect, eight landslides with a northwest aspect, two landslides with a north aspect, and one east-facing landslide. Land cover on south-facing landslides generally had Douglas fir or whitebark pine mixed with non-forested areas. One factor that contrasts with these findings is that both tree species prefer moist soil, which will be more common on the north-facing slopes. Slope angles varied between 8° and 28°. Lithology on south-facing landslides consisted of Tertiary andesites and basalts, although a majority of all the landslides were of this type. All of the landslides contained some type of soils, although south-facing landslides were primarily skeletal mollisols combined with root-limiting layers and bedrock.

Northwest-facing landslides had the greatest range of landslide deposit angles, from 6° to 30°. Landslide deposit relief was concentrated between 49 meters and 439 meters on northwest-facing landslides, whereas south-facing landslides had a deposit relief ranging from 246 meters to 671 meters. Land cover consisted of Douglas fir and one landslide with lodgepole pine mixed with non-forested areas. As with the landslide angles, lithology varied more on northern slopes, ranging from Tertiary andesites and basalts to Devonian sediments. Soils were primarily mollisols with root-limiting layers, whereas a few landslides had bedrock mixed into the area.

With only two north-facing landslides, only limited conclusions can be made. The landslide angles were 13° and 19°. The length of the landslides was 629 and 1,413 meters. The elevations of the landslides were similar with the top elevations 2,513 and 2,611 meters. Both landslides had a primary land cover of whitebark pine. These were the only landslides without any indication of tertiary volcanics, but rather had a lithology of Devonian and Mississippian sediments. The soils were dissimilar, with one landslide having a mollisol soil with root-limiting layers and the other having a mollisol and inceptisol combination.

The east-facing landslide had two attributes of note. It was the only landslide where Tertiary intrusives was the lithology, although landslide 13 had a combination of Tertiary andesites and intrusives. It was also the only landslide to have skeletal mollisols without any other distinguishing characteristics such as a root-limiting layer.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Very little research has been completed on the geomorphic effects of landslides in the Northern Rocky Mountains. Butler and Walsh (1994) and Walsh and Butler (1997) documented snow-avalanche paths and debris flows in the Livingston and Lewis Ranges of the Rocky Mountains. Meyer et al. (1995) looked at sedimentation rates relating to fire-activity and debris flows in the Absaroka Range but did not map the debris flows.

Identification and mapping of landslides in an area provides a basic map upon which further research of landslides can be completed. In the instance of temporal studies, landslide activity maps can be drawn once inventory maps are created. A key to understanding all the factors involved in slope instability includes examining precipitation, fire activity, time, and seismicity of an area. Other attributes responsible for slope instability include passive attributes that contribute to, but do not cause, slope failure. These attributes include the geologic structure, lithology, soil, and morphology. Identifying the attributes associated with landslides can assist in identifying unstable slopes and creating landslide hazard maps.

This study sought to answer two questions in the field of landslide research:

- What is the distribution of landslides in northeastern Yellowstone National Park?
- What physical attributes are associated with these landslides?

A landslide map with twenty-two landslides was presented as the answer to the first question. This map was compared to other maps of landslides in the study area, concluding that more landslides had been identified with this study than previous studies. The landslides were clustered into one watershed. As yet, no specific reason could be found to indicate why the second watershed, Cache Creek, did not have any landslides.

The second question was answered using various maps to identify the topographic and passive physical attributes of the landslides. Most of the landslides had similar attributes. It cannot yet be determined if these findings represent an association between the landslides and the attributes, or if it is because of the small data set.

The following is a summation of the factors identified with the landslides in the study area. The aspect of the landslides was dominantly southeast and northwest. The lithology was primarily Tertiary rocks, which were a mixture of volcanic rocks. These rocks tend to degrade into non-acidic soil. The soils were primarily from the mollisols order. The mollisols had varying types of development and limiting factors. The climate and aspect influences the development of soil and vegetation. The microclimates that exist on the mountain slopes varied according to the aspect, with the north-facing slopes tending to be cooler and moister and the south-facing slopes generally drier and warmer. With the root-limiting layers of the soil and otherwise lack of soil development, vegetation probably could not establish deep and slope stabilizing roots. Vegetation found on the landslides was dominated by tree species, primarily Douglas fir with some whitebark pine. Lodgepole pine, a species that has shallow roots, was identified on one landslide. Faults and volcanic intrusions, while not analyzed in this study, are known to exist in the area and can cause areas of weakness in the slopes.

A number of factors discussed in chapter five could and may have interacted to create unstable slopes resulting in landslides. Although one attribute may be the dominant cause of the landslide, it is the compilation of several passive attributes and a triggering mechanism working together that causes the slope to fail. Why the particular slopes in this research failed compared to the surrounding slopes still needs to be studied.

Landslides are a hazardous form of mass movement. The inventory map is a basic component of landslide studies in an area, and future landslides maps cannot be completed without it (Parise 2001). This landslide map is the beginning of an in-depth study of landslides in the northeastern portion of Yellowstone National Park. Fieldwork will complement this research by confirming other landslides and refining the borders of the mapped landslides. The map will then be available for temporal studies involving older aerial photographs, archival records, and topographic maps. Climatic records and earthquake activity will be included in the study to try to discover what triggering mechanisms are associated with landslides in this area. Human use and land cover change maps will also be included with the study. Further research with aerial photographs and stereo images will include mapping avalanche paths and debris flows to present a complete map of mass movements in the study area.

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