LANDSLIDE SOILS AND GEOMORPHOLOGY IN CAMP DAVIS QUADRANGLE, BRIDGER-TETON NATIONAL FOREST, WYOMING

BY

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in partial fulfillment of the requirements for the degree
Master's of Arts

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ABSTRACT

Landslide soils and geomorphology in Camp Davis Quadrangle, Bridger-Teton National Forest, Wyoming

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Active landslides are evident throughout Bridger-Teton National Forest (BTNF), and northwestern Wyoming has one of the highest landslide densities in the country (Case, 1990 and Fallon, 1996). Land use changes and increased demands for infrastructure challenge BTNF to better understand landslide processes in order to make informed land management decisions. Landscape properties related to landslide occurrence were studied via field work and laboratory analysis on 18 landslides in Camp Davis quadrangle. Landslide activity level was characterized based on geomorphic features. Landslide soil characteristics including texture, shrink-swell potential, clay mineralogy and horizonation were studied. The results show that landslides are catastrophic to soil formation. Additionally, these results support the hypothesis that landslide occurrence here is related to geology. These preliminary findings provide BTNF with a method for assessing landslide activity based on a set of field observable geomorphic and soil features, enhancing existing methods for assessing slope stability.

Keywords: landslide(s), mass movement, rotational slump(s), Bridger-Teton National Forest, soil stability, soil forming processes, geomorphology, Camp Davis, clay mineralogy

DEDICATION

This thesis is dedicated to Curt Sorenson. As one of Curt's students, I have learned to love soils and to appreciate soils for their complexities as a geographer. Curt's enthusiasm for the discipline of soils is contagious, and his direction, support and mentorship have been invaluable. I am grateful for everything Curt has taught me, and I hope to carry on his legacy of passionate dedication to the study of soil geography for many years to come. Thank you, Curt.

This work is also dedicated to my son, Mather Berg Zung. I look forward to many exciting adventures digging in the "dirt" together. I love you.

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I also wish to thank Eric Winthers and Bridger-Teton National Forest for their openness to this project. Eric provided many hours of guidance and education on soils in the field and provided excellent direction regarding the geologic hypothesis and the importance of landslide re-activation in the study area. Additionally, BTNF provided monetary support in the form of housing and field supplies, access to aerial photographs and office space while in the field. I appreciate immensely their support of the study, without which this thesis would not have been possible.

Funding was provided by Bill Johnson and a grant from the Association for Women Geoscientists (AWG) Osage Chapter for completion of X-ray diffraction (XRD) analysis. The XRD analysis was completed at the University of Nebraska-Lincoln by Denise Wally, and I appreciate Denise's time spent running samples and educating me on XRD techniques. Without generous monetary support from Bill Johnson and AWG, XRD analysis would not have happened, and the resulting understanding of soil clay mineralogy, an essential component to this study, would not have been possible.

Many friends and family members supported me emotionally and spiritually along this journey, including A.A., D.F., A.W., I.T., E.H. and C.S. I hope I am able to provide the same love and support to you that you have given to me. Additionally, I want to thank my parents, Steve and Sonya Bonner, for their encouragement in returning to school for this degree, and their time spent caring for my son, Mather. I would not have been able to complete this degree and change my career path without their help.

Finally, and most importantly, I want to thank my husband Russell for his never-ending support. When I quit my job to go back to school, cutting our income in half, you never questioned whether it was the right decision. You always support a healthier, happier, more contented me and encourage me to follow whatever path is

necessary to achieve it. I am so grateful for your encouragement and support. I couldn't have done this without a terrific soil-pit-digger and husband. I love you and couldn't imagine sharing this journey with anyone else.

A higher power has opened every door to bring me to this point. I am grateful for the grace and opportunities my higher power has extended me in this life, and exactly the way in which all of those opportunities have been delivered.

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Chapter 1: INTRODUCTION AND PROBLEM

In regions of the world where steep slopes combine with heavy moisture episodes, mass wasting and landslides are a risk. Landslides cause approximately $1-2 billion in damages and more than 25 fatalities on average each year in the United States (USGS 2007). Mapping by the Wyoming State Geologic Survey has shown that northwestern Wyoming and Bridger-Teton National Forest (BTNF) has one of the highest densities of landslides in the country (Wyoming State Geological Survey 2001).

Landslides are difficult to predict and prepare for in BTNF because a variety of factors that influence the likelihood of mass movement (the downslope movement of earthen material due to gravity) are present in this region, including oversteepened slopes due to tectonic uplift and recent stream entrenchment; montmorillonitic soils with high shrink/swell potential; heavy snowmelt in the spring; sedimentary bedrock formations alternating with rocks of varying permeability that create slip surfaces when saturated; and, earthquakes (Buma & van Asch 1996; Bailey 1971). These factors, in addition to changes humans make to land cover, can combine in any number of scenarios to trigger a landslide.

Due to dramatic population growth in northwestern Wyoming in the last decade, land development in the region has pushed into dangerous and unstable areas, placing property and people in the path of potential landslides. Consequences of this growth for BTNF include new pressure from natural gas and timber companies to increase exploration and greater demand on road building projects and infrastructure maintenance (Eric Winthers, personal communication, 2005). Unfortunately, any type of land development in this unstable, mountainous terrain has the potential for increasing the likelihood of a landslide occurring or re-occurring. This scenario challenges BTNF to better understand the complexities of landslide occurrence and reactivation in the forest in order to protect infrastructure, resources, property, and the people who live, work and recreate in BTNF.

This research aims to develop an in-depth understanding of landslides in the Camp Davis 7.5 minute Quadrangle in Bridger-Teton National Forest, Wyoming, with special attention to landslide stabilization and reactivation, in order to aid BTNF personnel in developing a quantitative measure for predicting landslide occurrence and making more informed land management decisions. More specifically, this research has two primary goals: (1) to identify landslide geomorphic characteristics that differentiate frequently re-occurring, less stable landslides (active) from stabilized ancient slides (inactive) and characterize landslides studied in the quadrangle accordingly; and, (2) to determine soil properties that are related to landslide occurrence and reactivation and that would be appropriate to consider in developing a method for predicting landslide occurrence.

While a comprehensive statistical analysis and model development to predict landslide occurrence and/or reactivation is outside of the scope of this project, this study compares slopes exhibiting evidence of instability (landslides) to stable slopes and active to inactive landslides. Both landslide occurrence or slope stability and landslide activity or re-occurrence were considered here because of interest from

BTNF personnel in the phenomenon of landslide stabilization and reactivation observed in the study area.

Figure 1 - Road damage caused by mass movement on a slope with historic landslides, Ross Plateau, Camp Davis Quadrangle, Wyoming

This study does not consider the influence that triggers may have in changing the significance of various landscape factors. Instead, it is assumed that the presence of triggers such as fire, earthquake, heavy snowmelt or precipitation and over-steepening of slopes individually or in combination increase the likelihood of landslide occurrence. This research focuses on internal slope characteristics, with special attention to soils that create an inherently unstable surface. Further studies would be necessary to determine how internal landscape factors and their significance to landslide occurrence and reactivation change with the presence of various triggers.

Chapter 2: BACKGROUND

Mass wasting, also known as mass movement, is 'the downslope movement of material due to gravity' (Montgomery 2006), and a landslide is one type of mass movement. Landslides are defined generally as the category of mass movements excluding creep and subsidence (Crozier 1986) or the downward and outward movement of slope forming materials – natural rock, soils, artificial fills, or combinations of these materials (Eckel 1958). More recently, landslides have been defined by the U.S. Transportation Research Board (Turner & Jayaprakash 1996) and Cruden (1991) for the Working Party on World Landslide Inventory as 'a movement of a mass of rock, earth or debris down a slope' (Dikau et al. 1996).

Many systems for classifying mass movements have been created in the last century (Sharpe 1938; Hutchison 1977; Varnes 1958, 1978). The most widely utilized and accepted in the U.S. is the classification system presented by Varnes (1978). The criteria used in this system to classify slope movements are type of movement primarily and type of material secondarily (Varnes 1978). Six types of movements are defined, and each type of movement is further divided based on the type of material in which the movement occurs (Table 1). Slides (landslides) are one of the six types of movements, and this category is further divided into rotational and translational slides. For the purpose of this study, rotational slides, a common form in Camp Davis Quadrangle and BTNF, were considered. Rotational slides are slides along a surface of rupture that is curved concave up, and movement is rotational

Table 1 – Classification of mass movements, adapted from Varnes, 1978

TYPE OF MOVEMENT			**TYPE OF MATERIAL**		
			Bedrock	**Soil**	
				Predominantly coarse material	Predominantly fine material
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	**Rotational**	Few units	Rock slump	Debris slump	Earth slump
	Translational		Rock block slide	Debris block slide	Earth block slide
		Many units	Rock slide	Debris slide	Earth slide
Lateral Spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow	Debris flow	Earth flow
			(deep creep)	(soil creep)	
Complex	Combination of two or more principal types of movement				

along an axis parallel to the slope (Varnes 1978, Figure 2). The classification system created by Varnes has been utilized by Case et al. (1991, 1998) and the Wyoming State Geological Survey (WSGS) to classify and map mass movements in Wyoming. For that reason, the definition of rotational slides provided by Varnes and utilized by the WSGS is the definition utilized in this study.

The likelihood of mass movement occurring is dependent on the relationship between shear stress (forces driving materials down the slope, namely gravity forces) and shear strength (forces resisting the movement of material). More specifically, stability of a soil or rock mass above a slip surface is ensured if shear stress is less than or equal to the shear strength of the slope material (Kenney 1975). When shear stress on a slope is greater than shear strength, mass movement occurs. Factors that

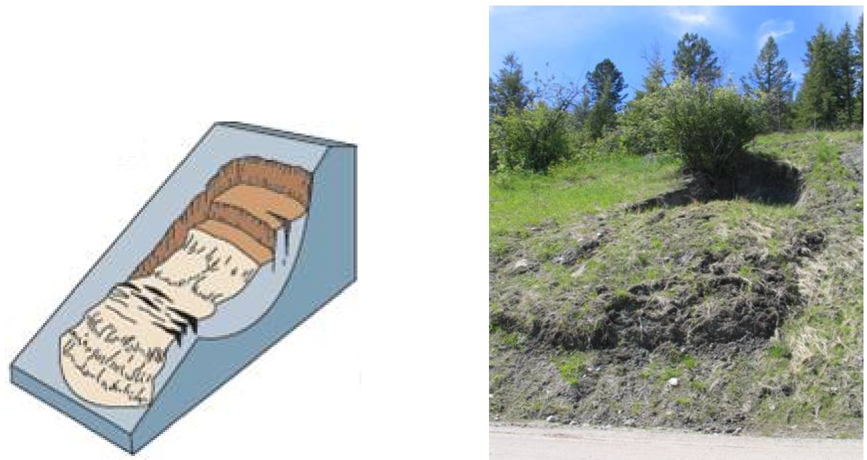


Figure 2 – Diagram of a rotational slump (Source: USGS 2007), and a slump exemplifying the concave slip surface, Ross Plateau, Camp Davis quadrangle, Wyoming

either increase shear stress or decrease shear strength, then, will increase the likelihood of a landslide occurring (Varnes 1958).

Factors that can increase shear stress include the removal of slope support or over-steepening of slopes, as can occur due to stream erosion or human activity such as road building, heavy precipitation or snowmelt events, overloading of slopes, earthquakes and increased pore-fluid pressure resulting from water freezing or from swelling within material on a slope (Varnes 1958; Keefer & Larsen 2007). Compositional, textural and structural properties of rocks and soils and the influence weathering has on these properties are considered the dominant factors determining the shear strength of a slope. Cohesionless soils, soils with high clay content, partially saturated soils, soils with low permeability, rocks composed of inherently weak materials or that become weak upon change in water content and jointed rock formations have all been noted to contribute to landslide occurrence by decreasing shear strength of slope material (Varnes 1958; Wu & Sangrey 1978).

The literature on landslide research is extensive. Fields where landslide research abounds include environmental geology, physical geography, geotechnical and civil engineering, urban planning, hazard management and mitigation, geomorphology, hydrology and ecology. Primary research themes include slope stability analysis (including geotechnical studies of shear strength and stress analysis), applied engineering practices for improving slope stability, landslide case studies, economic and social analysis of landslide hazard impacts, landslide recognition and mapping, causal studies focusing on landslide triggers, (e.g. precipitation and earthquakes) and predictive model generation for landslides based on any number of factors using statistics and/or GIS technology. Because the arena of landslide research is extremely broad and varied, it was necessary to narrow the secondary research focus to a couple of topics important to this study. Specifically, the geomorphic character of landslides, the effect of landslides on landscape features, especially soil formation and soil characteristics that contribute to decreases in shear strength and landslide occurrence are the focus of this study.

Mass wasting is a dominant geomorphic process in montane environments, contributing to landscape evolution and erosion (Keefer & Larsen 2007) and leaving an unmistakable imprint on the physical geography of a region. Common landscape features resulting from landslides include, but are not limited to, evident scarps, cracks, rounded toe slopes, well-defined benches, closed drained and undrained depressions, abrupt differences in vegetative characteristics on the landslide compared to adjacent stable slopes and irregular or hummocky topography below a scarp (Liang & Belcher 1958; Wills et al. 2004). The character of the aforementioned features depends on the type of mass movement present and the recency of activity. For example, the morphology of a mudslide typically includes a shallow concave scarp and flat lobate toe much wider than the obvious transportation path (Soeters & van Westen 1996, Figure 3). This contrasts with a rotational slide characterized by abrupt changes in slope morphology, from a concave main scarp to steplike slopes and a convex depositional toe (Soeters & van Westen 1996, Figure 4). Older slides display similar features, but not as fresh or striking (Liang & Belcher 1958). The scarp may not be as sharp, hummocky topography along the toe will be smoother and more subdued and vegetation will typically have re-established on the slope. The sharpness of features and degree to which vegetation and drainage has re-developed on a landslide can be helpful in determining the age of a landslide (Liang & Belcher 1958; McCalpin 1984; Wills et al. 2004).

Landslides make a lasting impact on drainage networks. Damming of major streams and creation of lakes near the toe of the failure is common with large-scale landslides, including Gros Vente slide (Slide Lake) in northwestern Wyoming and Slumgullion earth flow (Lake San Cristobal) in the San Juan Mountains of Colorado. Landslide dams often fail fairly soon after formation; but some, including Slumgullion Landslide Dam on the Lake Fork of the Gunnison River, become long-lasting landscape features (Schuster 1996). These dams and resulting lake formation

Figure 3 - La Valette mudslide, Barcelonette Basin, French Alps. Source: University of Caen-Basse-Normandie**.**

Figure 4 - Rotational slide, in red, south of Ashcroft, British Columbia. Source: Geological Survey of Canada

affect sediment/water transport and complimentary depositional/erosional cycles in a watershed.

Mass movements often have a dramatic affect on soil formation. Landslides strip soil from slopes, with either catastrophic effects on soil formation or at least a dramatic impact on soils in the form of mixing. When landslides remove all slope material, and transport it as colluvium downslope, any evidence of soil development is typically erased. This stops all soil forming processes and resets $time_{zero}$ for the soil. $Time_{zero}$ is the moment at which soil formation begins, when development and arrangement of soil bodies and soil profiles begins (Schaetzl 2005). Therefore, a catastrophic landslide serves to restart soil formation by providing landslide colluvium (vegetation, soil, debris and rock stripped from the slope, mixed and transported) as parent material for a new soil. When landslides are not catastrophic to soils, but simply serve to move or mix the soil, the landslide is considered a form of graviturbation. Graviturbation, a type of pedoturbation (soil mixing), is defined as soil and sediment mixing by mass movements, which are driven by gravity (Hole 1961; Schaetzel & Anderson 2005). With rotational slides, sometimes a fairly cohesive block of material moves downslope, and destruction of soil horizons may be minimal. When this occurs, the slide is a regressive process that serves to simplify the soil without completely destroying it (Johnson et al. 1987).

Whether landslides result in catastrophic destruction of soils or mixing of soil horizons, simplification of the soil profile is typically the result in landscapes affected by landslide occurrence. Bailey (1972) found that soil profile development on slump-earthflow features in BTNF was typically weakly expressed, and highly variable due to the wide continuum of ages on landslides in the forest. Soils on older landslides were typically 1-2 m thick with an A/B/C profile, while younger landslides were shallower and commonly lacked a developed B horizon (Bailey 1972). These same patterns of soil development with relation to age have been observed on the Slumgullion earth flow in southwestern Colorado. Soils developed in the oldest unit of the Slumgullion earth flow have B horizons (typically cambic B horizons) and incipient E horizons, while soils observed in the younger units lack E and B horizons (Madole 1996). Additionally, soils developed in the older landslide unit on Slumgullion earth flow were thicker than in younger units (Madole 1996). These above cited observations of patterns of soil development with regard to landslide age support an understanding of landslides as graviturbational forces or catastrophic events that reset soil formation to $time_{zero}$.

Mass movements also dramatically change vegetative communities. Landslides strip soil and existing vegetation from slopes to reveal bedrock. The harsh slope conditions created tend to increase the diversity of a forest by providing an appropriate environment for species that cannot establish in low-light conditions or that can thrive in shallow soils. These environments also tend to encourage the proliferation of early colonizers or disturbance species (Garwood 1979; Guariguata 1990; Walker et al. 1996; Myster & Walker 1997; Restrepo & Vitousek 2001). Alien species, typically herbaceous, have been shown to be likely colonizers of landslides, inhibiting the likelihood of native species to colonize (Restrepo & Vitousek 2001).

Landslides create a challenge for ecosystem management practitioners in systems where the majority of the diversity produced by landslide disturbance is represented by alien species.

Research regarding plant succession and ecosystem recovery on landslide sites has found that the early colonizer species composition strongly determines later successional stages. Replacement of species on landslides is typically slow and follows a sequence of increasing shade tolerance: high-light pioneer species on landslide sites are replaced by intermediate/low-light species (Myster & Walker 1997). The vegetation originally established on a landslide site affects the vegetation that follows (Walker et al. 1996). Climbing ferns, for example, often colonize landslides in the tropics and form thickets that inhibit light and the establishment of other species. These thickets can establish a pattern of dominance by ferns, followed by thinning or die-out, which may help facilitate the establishment of tree seedlings by providing organic matter, nutrients, shade and soil stability (Walker et al. 1996).

Several soil characteristics contribute to decreases in shear strength and increase the likelihood of a landslide occurring. Soils with high clay content tend to decrease slope strength because of two primary characteristics inherent to clay materials. One, clay particles are very small, less than 0.002 mm, and have a large specific surface area. This large external surface area, 1,000 times the surface area of the same mass of sand-sized particles, means that clays have a much greater capacity for absorbing water (Brady & Weil 2002). Surface area makes a difference to the absorption capacity of a particle because a larger surface area means far more surface(s) to which water and other materials may adhere (Figure 5). Increased water holding capacity of a soil often means eventual liquification of the soil and movement of soil material downslope.

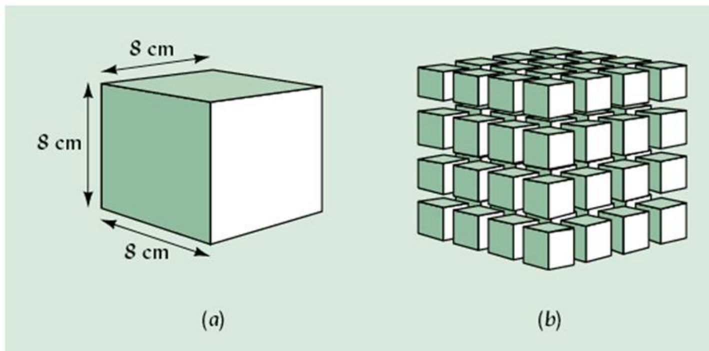


Figure 5 – Illustration showing surface(s) available for adherence for particles with a small surface area (a) vs. large surface area (b). Source: Brady & Weil 2005: pp. 125

Two, some clays have extensive internal surface area in the interlayers between crystal units to which water can adhere (Brady & Weil 2005). The 2:1 silicate clay minerals are characterized by one octahedral sheet between two tetrahedral sheets (Brady & Weil 2005). Water is greatly attracted to the spaces between layers (interlayer spaces), and adsorption of water between the crystal layers can cause layers to move apart and create extensive internal surface areas (Brady & Weil 2005, Figure 6). 2:1 expandable clays with interlayer spaces, including smectite (included in the smectite group is montmorillonite) and vermiculite, have

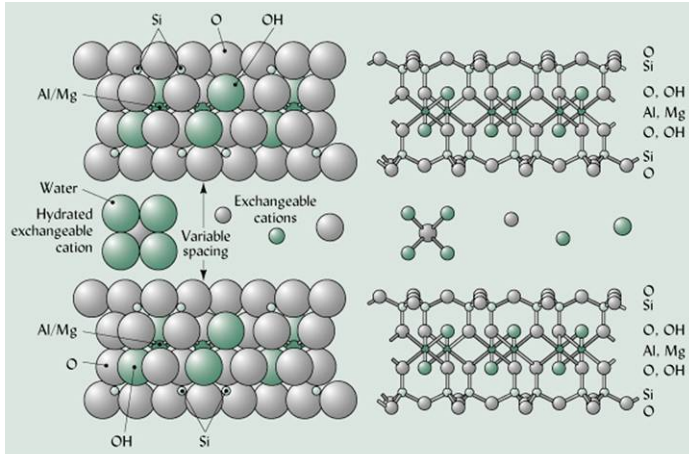


Figure 6 – Crystalline structure of montmorillonite, a 2:1 layer silicate clay. Source: Brady & Weil 2005: pp. 327

incredibly extensive internal surface areas in addition to a large external surface area (Table 2). The phenomenon of adsorption of interlayer water leads to high degrees of shrinking and swelling, plasticity, sitckiness and soil movement, as occurs with landslides. Additionally, 1:1 silicate clay minerals, such as kaolinite, have been shown experimentally to exhibit much greater strength than the 2:1 layer silicates illite and montmorillonite (Olson 1974, Figure 7).

Clay mineralogy of landslide soils is commonly studied in geotechnical investigations, and the presence of expandable 2:1 silicate clays in soils on landslides is well documented (Matsukura & Mizuno 1986; Chleborad et al. 1996; Teoman et al. 2004; Bhandary et al. 2005; Fall & Sarr 2007). The presence of these clays has been linked to decreases in soil strength. Shear strength values have been experimentally shown to decrease for slope materials with a high percentage (60%+) of smectite

Table 2 – Physical properties of major silicate clays. Source: Brady and Weil 2005

Clay mineral	Type	Size, µm	Surface area, m^2/g	
			External	Internal
Smectite	2:1 silicate	0.01-1.0	80-150	550-650
Vermiculite	2:1 silicate	0.1-0.5	70-120	600-700
Fine mica	2:1 silicate	0.2-2.0	70-175	-
Chlorite	2:1 silicate	0.1-2.0	70-100	-
Kaolinite	1:1 silicate	0.1-5.0	5-30	-

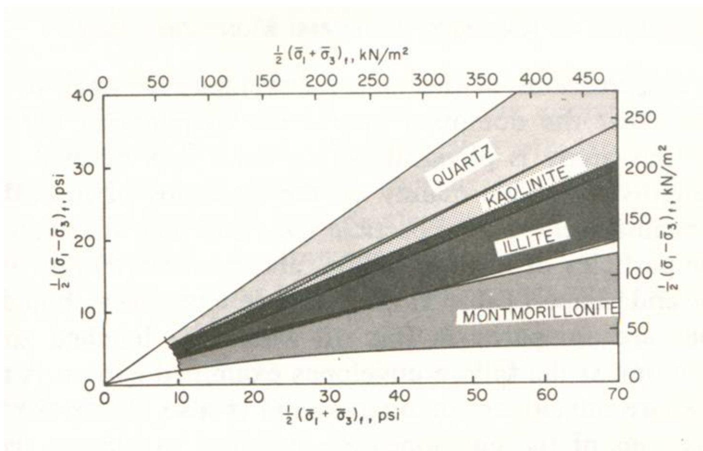


Figure 7 – Range in failure envelopes for soils composed of pure clay minerals or quartz.

Source: Olson 1974

clays (Chleborad et al. 1996; Fall & Sarr 2007). The angle of shearing resistance, also referred to as the angle of repose, has been shown to decrease as well with increases in percent smectite in soils (Matsukura & Mizuno 1986, Bhandary et al. 2005). Several studies have additionally linked the presence of 2:1 expandable clays in soils on landslides to the degree of geologic weathering that has occurred in a place (Matsukura & Mizuno 1986; Teoman et al. 2004; Meisina 2006; Borrelli et al. 2007).

Most references in the literature to landslides in northwestern Wyoming have come in geologic mapping work over the last 60 years (Swenson 1949; Love et al. 1951; Love 1956; Albee 1968; Rohrer 1968, 1969; Schroeder 1969; Case et al. 1991). The most extensive geologic mapping that addresses landslides in the study area is that of Case et al. (1991). This work by the WSGS maps landslides on a large scale (1:24,000, 7.5 minute quadrangles are mapped) and classifies mass movements based on a scheme developed by Case et al. (1991) specifically for landslide phenomenon in Wyoming.

In addition to geologic mapping, several in-depth studies of the Gros Ventre slide and surrounding area northeast of Jackson have been written (Blackwelder 1912; Alden 1928; Hayden 1956; Keefer & Love 1956; Love 1956; Palmquist et al. 1985), as well as a few studies on the relationship of earthquakes to landslide occurrence in northwestern Wyoming (Smith et al. 1976; Palmquist et al. 1985). The only extensive characterization and field study of landslide phenomenon in BTNF is Robert G. Bailey's 1971 work, *Landslide Hazards Related to Land Use Planning in Teton National Forest, Northwest Wyoming*. Bailey's publication thoroughly examines the climatic, geologic and biogeographic setting of BTNF, how these regional characteristics contribute to landslide occurrence, landscape evidence of mass movements in the forest and the impact of forest land use on landslide activity. This publication has been invaluable to the research presented here.

Chapter 3: STUDY AREA

3.1 Geographical Setting

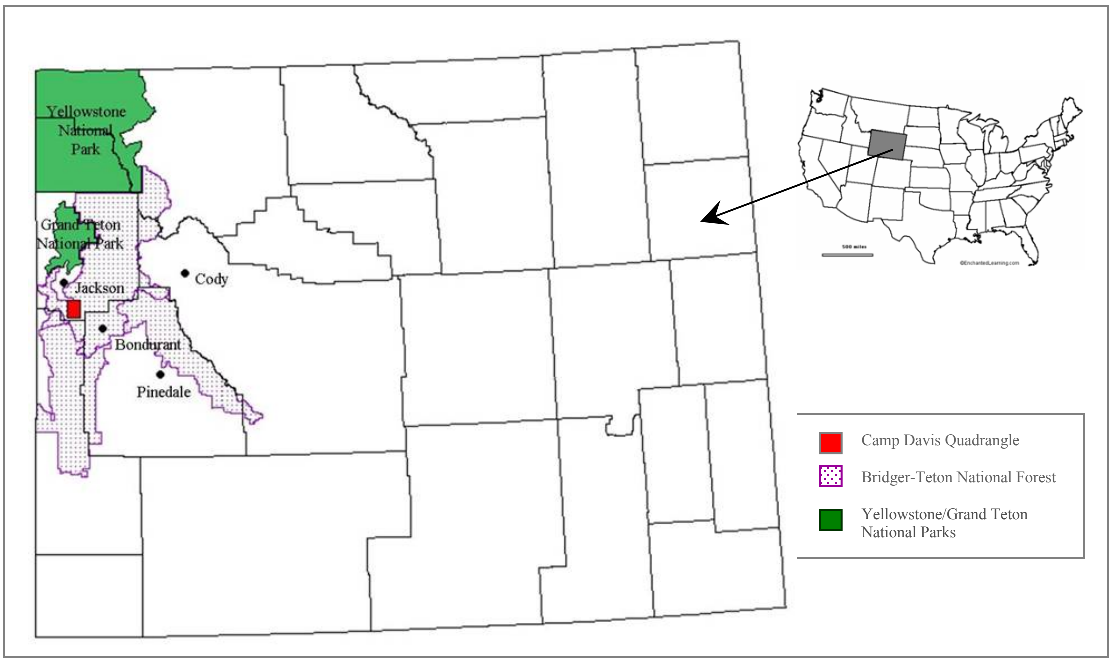


Figure 8 – Location of study area, Camp Davis Quadrangle, BTNF, Wyoming

Bridger-Teton National Forest (BTNF) covers 3.4 million acres of wildland in northwestern Wyoming. The forest is a part of the Greater Yellowstone Ecosystem, the largest intact ecosystem in the lower 48 states (USDA 2007). BTNF acreage includes three main trunks of forest south of Yellowstone National Park, stretching east of Grand Teton National Park toward Dubois, southeast of Jackson Hole across the Wind River mountain range and directly south of Jackson along the Salt River, Hoback and Wyoming ranges. Camp Davis Quadrangle, so named because it is home to the University of Michigan Rocky Mountain Geological Field Station Camp Davis, is centrally located in the forest - 12 miles south of Jackson, 15 miles northwest of Bondurant and 57 miles northwest of Pinedale, WY (Figure 8).

3.2 Physical Geography and Geomorphology

Camp Davis Quadrangle is a mountainous locality with many steep slopes and valleys. This region of Wyoming is located in the Middle Rocky Mountain geomorphic province, a province characterized by a variety of types of mountain ranges trending in many directions. Some of these ranges trend directly north-south (Teton Range), others trend northwest-southeast (Wind River Range) and still others east-west (Uinita Mountains). Additionally, these ranges can be contrasted in their formation, some a result of volcanic activity, others block faulting, and still other mountains formed from anticlinal uplift (Henry & Mossa 1995). The north-south trending Hoback Range intersects the Camp Davis study area. The northwest-southeast trending Gros Ventre Range and north-south oriented Wyoming Range, also closely surround Camp Davis quadrangle.

The quadrangle is divided by two major rivers: Snake River and Hoback River. The Snake River flows from north to southwest on the western end of the quadrangle, while the Hoback River, a tributary to the Snake, flows into the Snake River at Hoback Junction from the south. Typically, streams are consequent or subsequent in nature, following the topography and resistance of geologic structures to find the path of least resistance to lower elevations. However, both the Snake and

Hoback Rivers in Camp Davis Quadrangle are antecedent streams. The paths of antecedent streams were established millions of years ago, prior to tectonic uplift, and the stream paths were not dramatically changed by tectonic events. Antecedent streams, therefore, remain in their channel with no course change as uplift occurs, cutting their channel bed deeply to form canyons in the newly uplifted rocks. In Camp Davis Quadrangle, the antecedent Hoback River has formed Hoback Canyon, a narrow canyon winding through the Hoback Range across the center of the quadrangle. In addition to the obvious influence of the Hoback River on the physiography of the quadrangle, smaller tributaries to the Snake and Hoback Rivers, such as Willow Creek and Palmer Creek, have incised the landscape to form steep valleys (Figure 9).

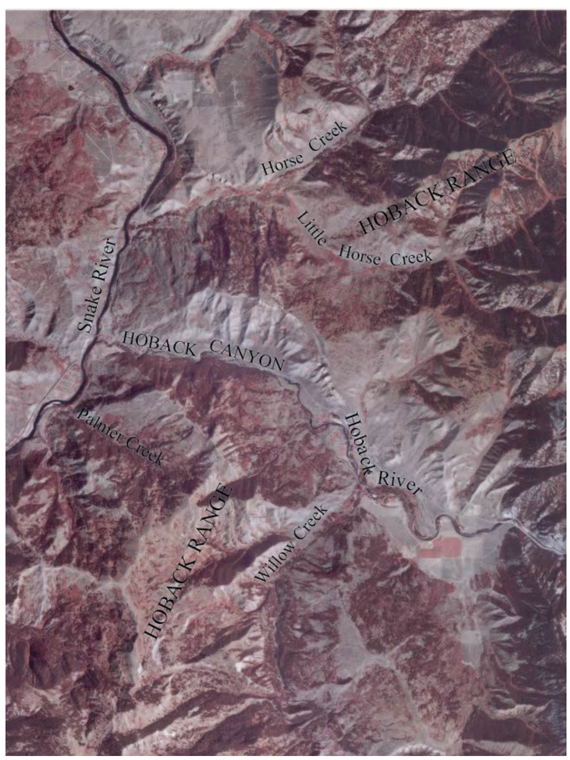


Figure 9 – Digital elevation model, Camp Davis quadrangle. Source: USGS 1998

3.3 Geologic Setting

The Hoback and Wyoming Ranges, both intersecting or near Camp Davis quadrangle, formed by a combination of folding and thrust faulting occurring during the Laramide Orogeny. The Laramide Orogeny was a period of active and wide-spread mountain-building 55 to 150 million years ago responsible for most of the Rocky Mountain chains we know today. The Hoback and Wyoming Ranges belong to the Idaho-Wyoming Overthrust Belt. The overthrust belt is a series of large sheets of rock that have been thrust over other sheets of rock to create a formation that resembles shingles on a roof (Lageson & Spearing 1988). More specifically, a series of 5 thrust faults spanning from early Cretaceous to early Tertiary periods repeatedly slapped layer upon layer of sedimentary rocks on top of one another, building the over-thrust belt from the west eastward (Lageson & Spearing 1988). Camp Davis quadrangle lies on the northeastern most section of the overthrust belt. These overthrust sections of rock have created great relief and varying topography in the Forest and the Camp Davis quadrangle.

A second major period of tectonic activity followed the Laramide Orogeny during the Miocene and was characterized by widespread normal faulting. The Hoback Fault (a normal fault) that transects the eastern edge of the quadrangle from north to south and nearby Teton Fault, both resulted from this stage of tectonic activity. This fault is one of a series of Cenozoic faults that extend from northwestern Arizona to British Columbia, representing a second and very different time of structural deformation in the thrust belt (Dorr et al. 1977). The close association of the Pliocene Camp Davis formation to the Hoback Fault (see Camp Davis Geologic Map, Figure 10) dates fault motion from the late Miocene to early Pliocene time period.

The tectonic history of the region is reflected in the geologic structure of the Camp Davis Quadrangle (Figure 10). Formations in the quadrangle are overwhelmingly sedimentary. The western part of the quadrangle is dominated by early Cretaceous shales and mudstones typical of the Idaho-Wyoming overthrust belt that rise and fall along the Willow Creek anticline and syncline (Schroeder 1974).

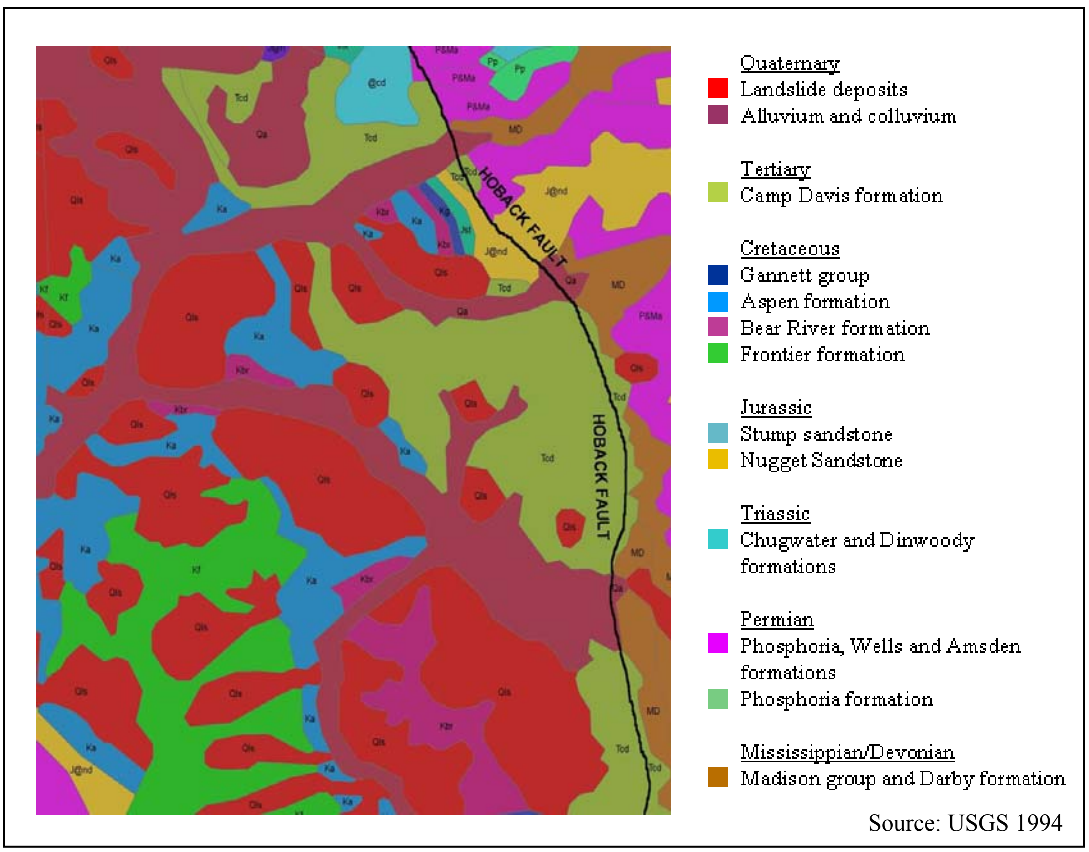


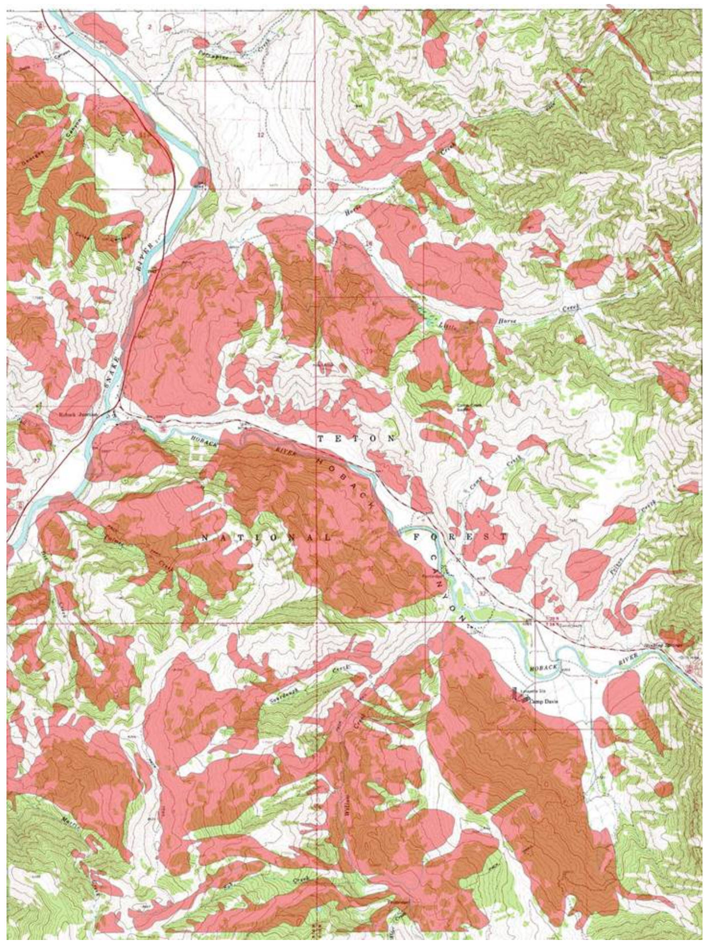
Figure 10 - Bedrock Geology, Camp Davis Quadrangle, Teton County, WY

Sections just west of Hoback fault are dominated by Camp Davis formation, a Tertiary conglomerate that formed as a result of erosion of Mesozoic and Upper Paleozoic strata following activity along the fault (Dorr et al. 1977). To the east of Hoback fault and the northeast corner of the quadrangle, upthrown Paleozoic and Mesozoic rocks dominate (Dorr et al. 1977; Schroeder 1974).

Alluvium and colluvium deposits are evident on the map surrounding Snake River, Hoback River, Willow Creek, Horse Creek and Little Horse Creek. Also of note are the numerous areas classified as landslide deposits. This is an especially active quadrangle for mass wasting compared to the total Forest, where approximately 17% of the area has been affected by landslides (Fallon 1996). Figure 11 provides a detailed inventory of landslides in the quadrangle as recorded by the Wyoming State Geological Survey. Note this map includes only soil related mass movements. Therefore, rock falls, topples and slides are not shown.

3.4 Soils

Soils in Camp Davis Quadrangle (Figure 12) can be grouped into three primary categories based on geomorphic associations: alluvial soils, landslide soils and steep mountain-side slope soils. Alluvial soils form in alluvium adjacent to major streams in the quadrangle, especially along Snake River, Hoback River, Horse Creek and Little Horse Creek. Willow and cottonwood communities are supported by these soils. Two of the primary alluvial BTNF map units in the quadrangle (soil map units 100, 101) are composed of soils somewhat excessively drained and sandy with many



Source: WSGS 2001

Figure 11 - Landslides, Camp Davis Quadrangle, Teton County, WY

rock fragments (Nordin & Blackwell 1985). These are classified as Typic Cryofluvents and Typic Cryoborolls (Nordin & Blackwell 1985). A third alluvial map unit in the quadrangle (soil map unit 102), classified as Aquic Cryoborolls and Typic Cryaquents, includes soils formed in clayey alluvium, described as poorly to moderately well drained clay loams (Nordin & Blackwell 1985).

Five map units in the quadrangle (soil map units 606, 610, 618, 646, 654) represent soils found on slump/earthflow features, and the locations of these map units correspond to large slump blocks mapped by both the WSGS and the USGS. Hummocky topography, slump/seep ponds and poorly defined drainage is noted on all of these soils, as well as a patchy vegetation mosaic including aspen, sagebrush and forbs (Nordin & Blackwell 1985). Soils included in these map units are classified as Typic/Argic Cryoborolls or Cryoboralfs. These are fine soils with loamy surface layers and clay loam subsoils (Nordin & Blackwell 1985). Many of these soils are also montmorillonitic.

Five map units found in the quadrangle (soil map units 451, 455, 456, 483, 484) have formed in Cretaceous sedimentary formations including the Frontier Formation, Bear River Formation and Aspen Shale found at higher elevations along mountain ridges and side slopes of the Hoback Range. Slopes here are extremely steep, averaging 40 to 80 percent, and rock outcrops are a noticeable feature among these map units. Soils included in these map units are well drained gravelly or cobbly loams or clay loams, with rock fragments scattered throughout the profile and content typically increasing with depth (Nordin & Blackwell 1985). These map units typically support a variety of vegetative communities, including sagebrush, forb communities and coniferous forest (Nordin & Blackwell 1985).

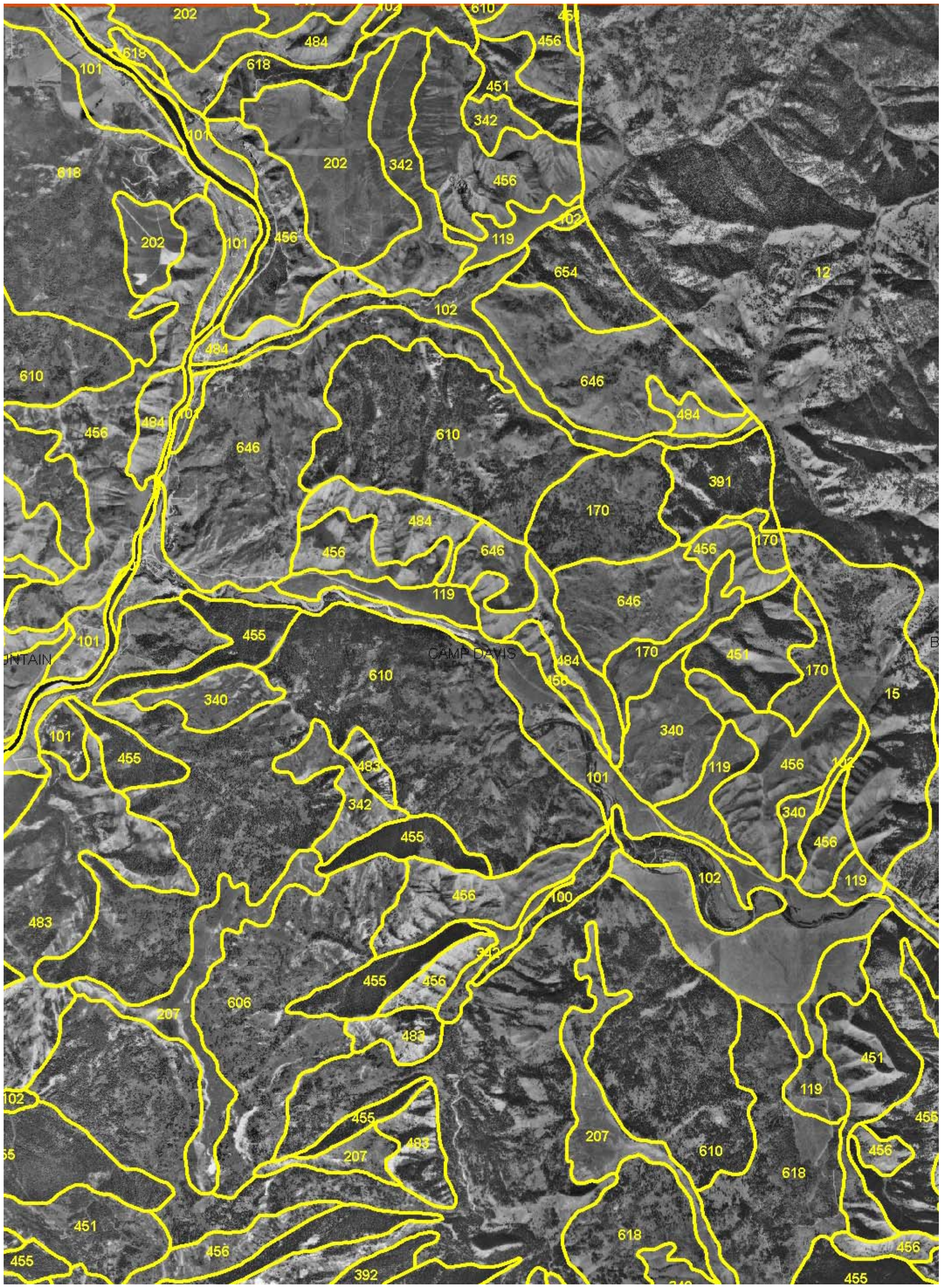


Figure 12 – Soil map units, Camp Davis Quadrangle, Teton County, WY. Source : Nordin & Blackwell 1985

3.5 Climate

Climate records for stations in BTNF and surrounding Camp Davis Quadrangle illustrate the wide seasonal and daily variations of temperature and moisture conditions in the area. This variability is due to the mid-latitude location of the study area and the topographical variation inherent to this mountainous region. Table 3 shows monthly minimum and maximum temperature averages, Table 4 gives monthly precipitation totals on average, and Table 5 provides average monthly snowfall totals for Bondurant and Jackson, WY, the two closest weather stations to Camp Davis Quadrangle.

Temperature varies most greatly at both stations when maximum temperatures are at their highest, namely during July and August where ranges top 40˚F. Lowest minimum temperatures occur in January when temperatures drop to -4.8˚F at Bondurant and 5.4˚F in Jackson. Highest maximum temperatures for both locations occur in July with 78.7˚F in Bondurant and 81.9˚F in Jackson. Throughout the year, temperatures at higher elevations are about five to fifteen degrees cooler than in the valley, in general. However, very cold air can be trapped in the valleys during winter creating a temperature inversion when compared to air temperatures in the mountains (Nordin & Blackwell 1985).

Precipitation is essentially a daily occurrence somewhere in BTNF throughout the year (Nordin & Blackwell 1985). Rain during the late spring and summer and, more importantly, snowfall from late fall through mid-spring and snowmelt in late spring, fuels the many rivers and creeks throughout the forest. Total annual

Table 3 – Average temperatures, monthly, Jackson and Bondurant, WY

Monthly Average Temperatures (F) – 1948-2005

Bondurant - 6,620 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Min	-4.8	-3.3	5.1	18.3	27.7	32.0	34.7	32.9	25.8	17.5	8.2	-3.8	15.9
Max	23.0	28.4	37.1	48.0	61.5	70.4	78.7	77.4	68.1	56.0	36.6	23.7	50.7

Jackson - 6,230 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Min	5.4	8.0	16.1	24.7	30.8	36.8	40.6	38.7	31.5	23.5	15.9	6.5	23.2
Max	27.5	32.6	41.1	52.5	62.9	72.4	81.9	80.5	71.1	58.6	39.6	28.2	54.1

Source: WRCC 2007.

Table 4 – Average precipitation, monthly, Jackson and Bondurant, WY

Monthly Average Precipitation* (inches) – 1948-2005

Bondurant - 6,620 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Total	2.67	1.97	1.98	1.23	1.71	1.58	1.20	1.27	1.45	1.32	2.10	2.65	21.14

Jackson - 6,230 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Total	1.48	1.00	1.16	1.12	1.88	1.63	1.05	1.15	1.29	1.14	1.44	1.54	15.90

* Precipitation totals include rain and the liquid equivalent of frozen and/or freezing precipitation.

Source: WRCC 2007.

Table 5 – Average snowfall, monthly, Jackson and Bondurant, WY

Monthly Average Snowfall (inches) – 1948-2005

Bondurant - 6,520 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Annual
Total	33.4	22.3	17.4	5.3	1.5	0.2	0.0	0.0	0.4	3.6	20.2	34.0	138.5

Jackson - 6,230 feet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Annual
Total	20.2	12.5	9.1	3.9	0.8	0.1	0.0	0.0	0.1	0.9	9.4	17.7	74.7

Source: WRCC 2007.

precipitation is quite variable in the forest due to the rainshadow effect and varying elevations. For these two locations, Bondurant receives about 21 inches precipitation annually, while Jackson expects closer to 15 inches of precipitation each year. Greatest precipitation occurs in May at Jackson (1.88 inches) and January at Bondurant (2.67 inches). This difference points to the contrast in snowfall totals for the two locations, where Bondurant receives one-and-three-quarters the annual snowfall total that Jackson receives (Table 5). Highest snowfalls occur in December at Bondurant and January at Jackson.

3.6 Vegetation

Based on work done by Bailey (1971), and considering elevation, two primary ecological zones are found in Camp Davis Quadrangle: a transition zone between sagebrush/grassland and forest and a montane zone consisting primarily of evergreen forest. Areas in the transition zone (6,500 to 7,000 feet) include basins in the forest and could include south-facing mountain slopes where moisture is less available compared to north-facing slopes. This zone consists of brush species including *Artemisia tridentate* (sagebrush), *Purshia tridentate* (antelope bitterbrush) and *Chrysothamnus nauseosus* (rubber rabbitbrush). Grass species include *Agropyron* spp. and *Festuca idahoensis* (Bailey 1971). Willows (*Salix* spp.) and cottonwood trees (*Populus augustifolia*) are found along streams where moisture is more readily available (Bailey1971).

The Montane ecological zone is found primarily in mountainous regions with elevations ranging anywhere from 7,000 to 9,000 feet. According to Bailey (1971), this zone receives more moisture due to higher elevations and can therefore support vegetation requiring consistent precipitation. Common vegetative species for this zone include *Pseudotsuga menziesii* (Douglas fir), *Picea engelmannii (*Engelmann spruce), *Pinus contorta* (lodgepole pine) and *Populus tremuloides* (aspen) (Bailey 1971). Each of these species satisfies a niche for the ecosystem, the spruce more suited for moist microtopographies and the fir for more arid locations. The pine and aspen are especially adapted to thrive with disturbance, namely fire and mass wasting episodes, respectively.

3.7 Landslide Geomorphology

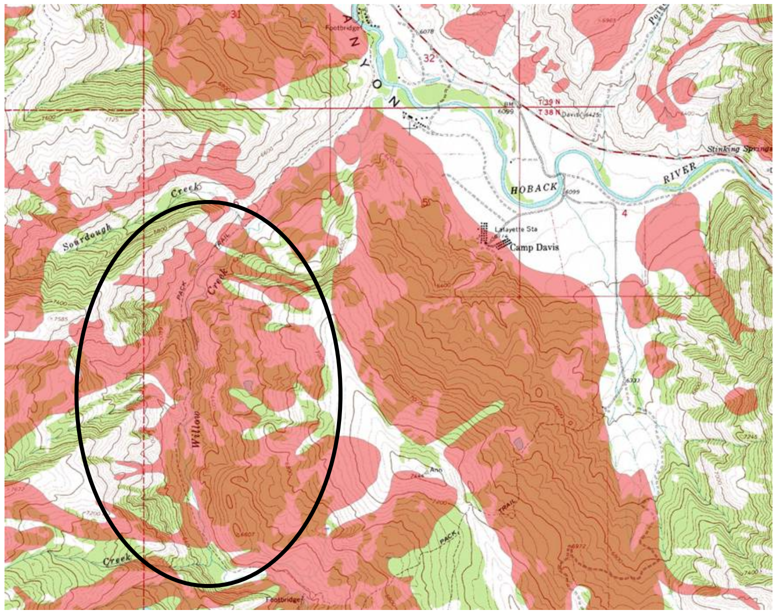
On June 23, 1925, a one-mile-wide section of earth northeast of Jackson collapsed, damming the Gros Ventre River and creating Lower Slide Lake (Figure 14, USDA 2007). Two years later the dam failed and destroyed the town of Kelly, WY. This event, known as the Gros Ventre slide, is the largest natural landslide in the recorded history of the United States (American Geological Institute 2007). While this landslide is known worldwide for its size and dramatic impact on the surrounding community, it is by no means the only mass movement that has occurred in BTNF. In fact, in few parts of the U.S. is landsliding so prominent a geomorphic process as in Bridger-Teton National Forest (Bailey 1971).

Figure 13 - Scarp of Gros Ventre slide (left); Lower Slide Lake (right), formed by daming of slide debris (Dutch 2003)

This active landsliding is due to a number of characteristics common in BTNF and especially inherent to the geology and geography of Camp Davis. A primary regional cause of landsliding is evident in the Camp Davis Quadrangle – the presence over extensive areas of soft, incompetent shales exposed on fairly steep slopes and oriented in the downslope direction (Bailey 1971). The Aspen, Bear River and Frontier Formations, all found exposed on steep slopes in Camp Davis Quadrangle, are three of thirteen formations listed by Bailey (1971) as stratigraphic units most susceptible to landsliding in BTNF. These formations are soft, plastic shales and siltstones interbedded with sandstones (Bailey 1971, Schroeder 1974). Rocks including shales, siltstones, mudstones and claystones are made of very fine to fine-sized particles that take on the properties of clay when weathered. More specifically, these formations tend to act plastically when saturated, absorbing water, increasing pore pressure and becoming prone to sliding.

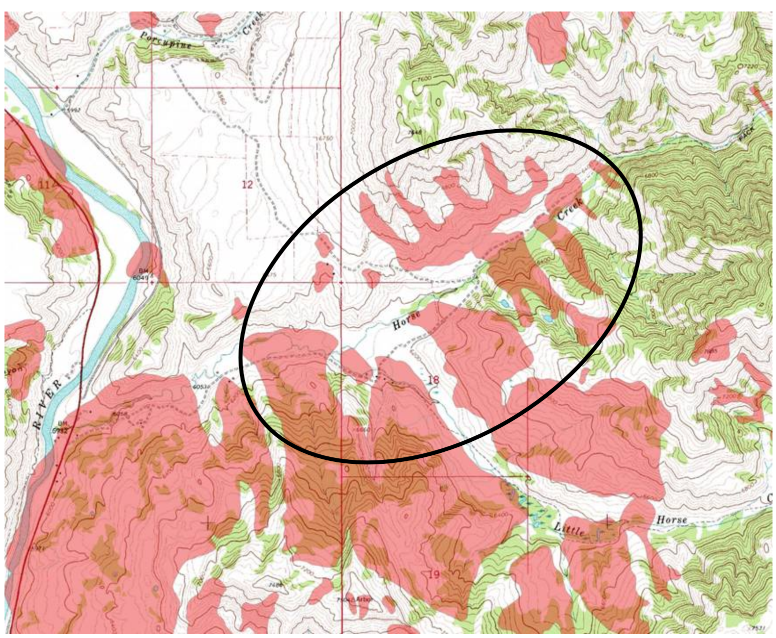
The plasticity of these formations is aided by the presence of bentonite and porcellanite, clay minerals often of volcanic origin that swell considerably when exposed to water (Bailey 1971; Wanless et. al. 1955; Schroeder 1974). The presence of these minerals, often the result of deposition of volcanic ash, could be the result of nearby active volcanism in the Idaho Batholith and Yellowstone National Park. While these formations are found in many other ranges of the Rocky Mountains, including the Wind River Range and ranges in the Southern Rocky Mountains, they have often been eroded and deposited in the lowlands, rather than remaining on the steep slopes as in the Teton region (Bailey 1971). Bailey (1971) writes that these shales are easily weathered, and shallow slides, even on fairly gentle slopes in the region, take place within the zone where the shale has been effectively eroded through weathering.

In addition to the presence of geologic formations inherently susceptible to sliding, slopes in the region have been severely steepened by antecedent streams. In the Camp Davis Quadrangle, the Snake and Hoback Rivers and many of their tributaries have cut deep canyons in the uplifted rock. As is evident in Figure 11, many landslides in the quadrangle occur on over-steepened slopes along streams and deposit sediment and debris in stream channels. These tongues of earthflow debris extending down valley are especially evident along Willow Creek and Horse Creek (Figure 14, Figure 15).



Willow Creek section is circled. Source: WSGS 2001

Figure 14 - Willow Creek Landslides, Camp Davis Quadrangle, WY



Horse Creek section is circled. Source: WSGS 2001

Figure 15 - Horse Creek Landslides, Camp Davis Quadrangle, WY

While factors that increase shear stress on a slope are not a consideration for this study, it should be noted that there are a number of external factors present in the region that act as triggers to aggravate conditions and increase the potential for landslide occurrence. Precipitation and rainfall on slopes in the region can be almost constant and fairly heavy. During the early summer, thunderstorms combine with constant flow of water from melting snow to saturate hillslopes (Bailey 1971). This moisture acting on clayey shales often induces flow. In fact, many of the most substantial landslides that have occurred in the region, including the famed Gros Ventre Slide, have occurred in late spring triggered by extensive rainfall and snowmelt.

Earthquakes are an additional trigger, as they can jar loose sediment and initiate sliding. Earthquakes are especially common in northwestern Wyoming due to numerous normal faults in the crust of the region and a volcanic hot spot located beneath Yellowstone (Figure 16). In fact, 444 earthquakes have been recorded in Wyoming between 1897 and 2001 and 283 in just the last 20 years of observation (University of Wyoming Department of Geography 2002). An earthquake is the agreed trigger for the Madison Slide in the region and is often also discussed as a possible factor triggering the Gros Ventre Slide (Smith et al. 1976). Road building and other types of development that lead to oversteepened slopes can be another landslide trigger. Bailey specifically refers to the Hoback Junction area in Camp Davis Quadrangle as a region where road building has impacted slope stability. Here, Highway 187-189 cuts across the toe of the slope and upbulge of the pavement is evident as well as numerous slides that have crossed the road.

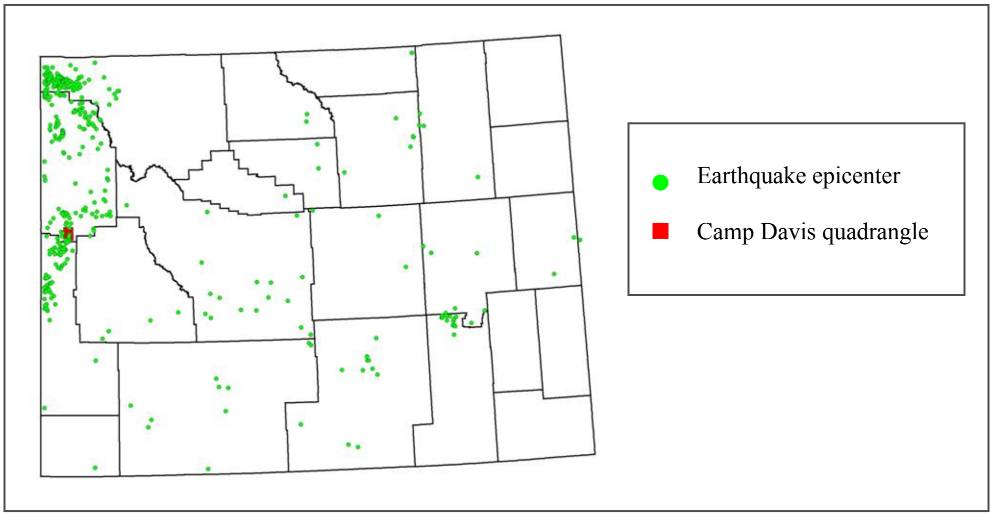


Figure 16 – Earthquakes in Wyoming, 1897 – 2001. Source: University of Wyoming, Department of Geography 2002

The prevalence of landslides in Camp Davis Quadrangle leaves an unmistakable impression on the landscape. Hummocky topography, visible as lumpy, bumpy hillslopes, is evident throughout the quadrangle. This type of topography is created as repeated failures impact a hillslope, leaving concave depressions above and mounds of deposited debris below repeatedly on slopes. The soil survey for this region describes surfaces with benches and bench-like features, as well, and points to these as evidence of prior mass failure (Nordin &Blackwell 1985). Bare scarps and displaced or broken bedrock, other consequences of frequent landsliding, are observed throughout the quadrangle (Figure 17).

Figure 17 - Visible scarps indicate locations of past landslides. Camp Davis Quadrangle, Wyoming.

Vegetation and drainage patterns in the quadrangle are often dictated by mass wasting processes, as well. Surfaces impacted by landslides often display unconsolidated drainages with slump ponds and seeps covering the surface. At locations in the quadrangle where repeated failures have occurred at various scales, such as the Hoback Junction area, unconsolidated drainage, hummocky topography, and slump/seep pools – "a jumble of knolls and undrained depressions" are observed (Bailey 1971, Figure 18).

Small groves of Aspen surrounded by mature conifer forest and trees with "pistol-butted" trunk growth are useful indicators of unstable ground or historical mass movements. Aspen are a common pioneer species on landslide sites because they are fast growing (soil movement doesn't support slow-growing conifers), require wet conditions common in clayey soils, and they reproduce by root suckers. Some scientists hypothesize that disturbance stimulates root sprouting by the Aspen, and therefore reproduction (Bailey 1971). Additionally, trees on unstable ground

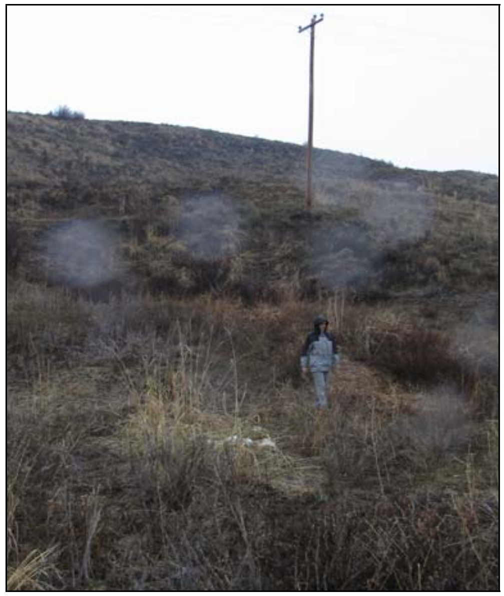


Figure 18 - Hummocky topography, seep pools, knolls and depressions at Hoback Junction, Camp Davis Quadrangle, Wyoming.

sometimes develop bent trunks as they re-grow their trunks straight after being tilted downslope by instability (Bailey 1971). These two vegetation characteristics are commonly observed in Camp Davis Quadrangle (Figure 19, 20).

Figure 19 - Pistol-butted trees observed on Ross Plateau, Camp Davis Quadrangle, Wyoming

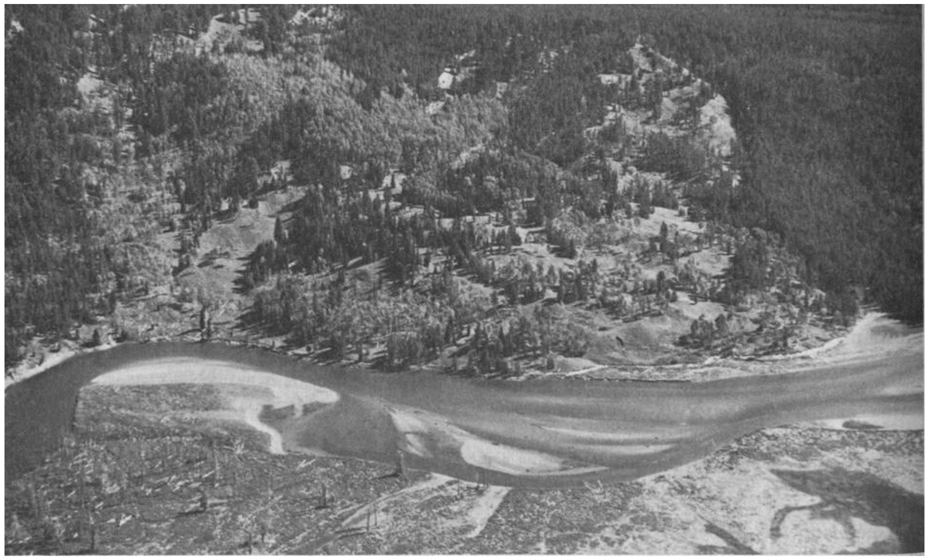


Figure 20 - Contrasting vegetation on slump/debris flow (Aspen, bare ground) and surrounding stable area (mature conifer forest), Snake River, BTNF. Source: Bailey 1971

Chapter 4: METHODOLOGY

4.1 Secondary Research Methodology

The first step in better understanding the intricacies of landslide occurrence and the geomorphic expression of mass movement in Camp Davis Quadrangle was to research four primary subject areas pertinent to the problem: (1) the physical landslide mechanism and how/why landslides happen; (2) the impact of mass movements on slope geomorphology; and how these slope characteristics could be indicative of landslide activity or frequency; (3) landscape factors, especially those related to soils, generally agreed upon to contribute to landslide occurrence regardless of location; and, (4) the soil geography, slope geomorphology and geology of Camp Davis, specifically with regard to landscape components that could be indicative of landslide occurrence or a cause of instability in the quadrangle. Literature on landslide occurrence, landslide geomorphology, soil characteristics on landslides and model creation for estimating slope stability was reviewed. Factors that researchers generally consider to be historically important variables affecting slope stability regardless of study area, such as slope steepness, slope aspect, hillslope material and bedrock geology, were noted for inclusion in this study. Additionally, less apparent soil and geomorphological characteristics that have been found to correlate with landslide occurrence, such as soil mineralogy, clay content and the presence of hummocky topography, were considered.

Once a general secondary literature review was completed on how and why landslides are believed to occur regardless of locality and the expression of mass movement on slope morphology, literature specific to soils, geology, geomorphology and mass wasting in BTNF and Camp Davis Quadrangle was reviewed. Data from this review were used to narrow the landscape properties that could be contributing factors to landslide occurrence in any environment to include only those most relevant to this study area. Geologic maps, topographic maps, soil surveys, literature on the geologic history of the region and geomorphic processes at work in the study area were reviewed in order to tailor the research focus to the quadrangle.

4.2 Pilot Statistical Analysis

After determining the landscape factors that could contribute to landslide occurrence and reactivation in Camp Davis quadrangle, a preliminary statistical analysis was performed to help guide work in the field. Specifically, a multivariate logistic regression focusing on soil properties was performed to determine whether interdependency of soil characteristics existed and the relation of the factors to the presence of landslide activity. Soil factors (independent variables) considered in this preliminary statistical analysis included: permeability, presence of montmorillonitic clays, AASHTO stability rating, texture, liquid limit, plasticity, shrink/swell potential and erosion k-factor [all of the preceding data were available from the Teton National Forest Soil Survey, (Nordin & Blackwell 1985)]. Elevation was included as an independent variable in the analysis, as well. The dependent variable for this exercise was landslide occurrence (yes or no) as ascertained by the WSGS and recorded in their landslide database (2001).

Chi-square and t-tests were performed to determine whether a relationship existed between landslide occurrence and the various independent variables. The null hypothesis (there is no relationship between landslide occurrence and each independent variable) was accepted for soil series, soil texture, presence of montmorillonitic clays, AASHTO rating, elevation, soil permeability and erosion K-factor. The null hypothesis was rejected for shrink-swell potential (sig=.004, alpha=.025 adjusted from .15 since six chi-square tests were run), and clay content (sig=.007, alpha=.0375 adjusted from .15 considering four t-tests were run). Additionally, erosion K-factor and bedrock geology were nearly significant with sig values of 0.048 and 0.101, respectively. It is important to note that a variable not significant in preliminary tests could be included in a model created through the logistic regression analysis because of relationships to other variables in the equation and resulting impacts on predictability of the model.

While the data provided by the soil survey is fairly generalized, these results did confirm the importance of thoroughly understanding clay content, clay mineralogy and shrink-swell potential for soils as they relate to landslide occurrence in the study area. These factors were determined to be emphasized in both the field and laboratory investigations for this study.

4.3 WSGS Landslide Database Interpretation

Next, a preliminary understanding of landslide activity in the quadrangle was developed. James C. Case, head of the Geologic Hazards section at the WSGS, created a Wyoming Landslide Classification Scheme in 1991 based on the widely accepted work of Varnes (1978) and Campbell (1985). The system considers five types of mass movements (falls, topples, slides, lateral spreads and flows) that can occur in three types of material (bedrock, debris and earth). Additionally, flows are further divided based on whether it occurs in cohesive or non-cohesive material. Many landslides found in Wyoming are considered complex by the WSGS and are assigned designations accordingly, such as slump/earthflow complex or block slide/rock slide/flow complex. Complex slides are defined by the WSGS as slides that begin as one type of mass movement and grade into another type(s) farther downslope. Therefore, the slump/earthflow is composed of a slump at its head changing to an earthflow farther down the body of the slide, and a block slide/rock slide/flow is a block slide that grades into a rock slide and finally a flow toward the toe (Case 1991).

For the purpose of this investigation, landslides mapped and classified by WSGS in Camp Davis Quadrangle were reviewed, and a revised landslide map for the quadrangle was created to include only the types of mass movements of importance to this research. This study focuses primarily on factors such as soil and geology as they affect shear strength of slope material. Therefore, mass movements more likely to occur due to decreases in shear strength needed to be considered, while those occurring primarily due to increases in shear stress were disregarded. Landslides classified as falls and/or topples, which occur due to an increase in shear stress brought about by an increase in the angle of inclination, were removed from the dataset. All flows, slumps and blockslides that were not composed only of bedrock or debris were kept in the data set because these types of failures typically occur due to inherent weaknesses in hillslope material. A revised landslide map was produced for the quadrangle (Figure 11). The edited quadrangle map showed the locations, according to the WSGS, of all landslide types pertinent to this study and served as the set of potential landslides for aerial photograph analysis and field investigation.

4.4 Aerial Photograph Analysis

Aerial photographs (1:15,840 or 4 inches:1 mile) of Camp Davis were provided by the United States Forest Service in approximately 10-year intervals from 1970 to 2000. Photographs were organized by year, scale and geography and were studied using a stereoscope. In conjunction with the modified WSGS landslide database, the photographs were used to establish a more detailed characterization of landslides in the quadrangle. Five important things were accomplished through this analysis. First, landslide locations mapped by the WSGS were confirmed. Second, landslides not included on the WSGS map were discovered by examining aerial photos for topographic indicators of mass movement, such as a sharp line or break at a scarp, hummocky topography below a scarp, undrained depressions on an earthen mass, slanted trees on a slope and abrupt changes in vegetation and/or soil tones between a landslide and adjoining stable area (Liang and Belcher 1958). New landslides observed were noted and drawn over a DEM. Third, specifics of landslide form and direction were studied. Landscape position/orientation was confirmed for each landslide, and evidence of multiple displacements, lateral and head scarps, direction of movement and landslide form were noted. Fourth, the affect of landslides on the surrounding area was observed, with special attention to vegetation on the slide area compared to surrounding vegetation, noticeable damage to roads, structures, etc. and slope morphology. Fifth, activity level/frequency for landslides in the quadrangle was speculated based on landscape evidence. Landscape characteristics outlined by James McCalpin (1984) as useful for age classification of landslides in BTNF, including head scarp observations, drainage patterns, slope and toe morphology and vegetation characteristics, were used to speculate activity level for landslides in Camp Davis. Landslides in the quadrangle were assigned to one of two categories: active or inactive.

Individual landslides identified in the quadrangle as possibilities for study were numbered, and a landslide/landscape observation worksheet was completed for each slide based primarily on observations from the aerial photograph analysis. Information from the BTNF soil survey (Nordin & Blackwell 1985) and geologic map for Camp Davis (Schroeder 1974) were used to fill-in information on soils and bedrock geology for each landslide. Landslide/landscape worksheets completed for each slide studied in this investigation are included as Appendix 1.

4.5 Field Methodology

To make the field, lab and statistical analysis manageable for a project of this scope, data for the analysis were taken primarily from an approximately three square mile area representative of the Camp Davis study area, located in the southeast corner of the quadrangle, surrounding the junction of Willow Creek and Hoback River. This three square mile area contained all the requisite predictors for landslide occurrence and re-occurrence in BTNF, and served as the real world basis for an in-depth analysis. Additionally, landslides outside of this three square mile area, but of special interest to BTNF personnel because of their impact on roads and infrastructure maintenance or known activity, were included in the sample.

A sampling strategy for the area was developed based on the understanding of landslide activity gained from aerial photograph analysis and study of the WSGS landslide inventory, Camp Davis Geologic Map and the BTNF soil survey. Since it was essential that a variety of landscape arrangements and factors be addressed in the sample, a stratified random sampling technique was employed. Stratification of the sample was based on bedrock geology, slope, aspect and preliminary estimates of landslide activity level and form. Considering much of the quadrangle is road-less, accessibility also influenced sampling. The basis for the stratification was largely determined by the results of the preliminary statistical analysis, initial aerial photograph interpretation and conditions in the field. I attempted to collect samples from at least 20 slides for each activity level in order to obtain a sample size (n) that is generally acceptable for statistical analysis (two categories of activity/frequency level * 20 samples each totals n=40 observations). Additionally, samples from adjacent stable slopes at each landslide were collected in order to study not only differences in landslides of various activity levels, but also differences in landslide sites compared to stable sites.

The first objective for work in the field was to validate aerial photograph interpretation of landslide activity via ground truthing. While aerial photos provided an excellent preliminary understanding of patterns of mass movement in the study area, field observations were necessary to confirm landslide locations identified in the photographs, record geographic coordinates for each location, make more detailed observations of landslide characteristics such as form, direction, scarp arrangement and vegetative patterns and confirm the activity categorization of each landslide. Conclusions drawn from the aerial photographic analysis were confirmed or adjusted based on closer field observations of vegetation, drainage patterns, slope morphology and soil patterns visible at the surface. Any changes or additions to landslide characterizations due to observations in the field were noted on the landslide/landscape observation worksheet (Appendix 1).

Once location, site characteristics and activity level for each landslide was determined, sample sites were chosen. Two sites were sampled for each landslide location: (1) near the center of the material displaced by the landslide, between the scarp and toe; and, (2) on an adjacent/nearby stable slope of earth with similar slope, aspect and parent material. The site of each profile was observed for landscape and soil properties. More detailed data on the topography, landforms, drainage patterns, vegetation and geologic structure for each site were noted. Additionally, soil characteristics at the landslide and adjacent stable site were of particular interest. At each sample site, soil pits were dug and a general profile description was completed. Those observations routinely recorded in soil field investigations, as outlined in Field Book for Describing and Sampling Soils (Version 2.0 USDA, NRCS 2002) were included. Table 6 lists all soil and landscape observations recorded in the field.

Three-pound samples of soil from all horizons in the profile were collected and returned to Lawrence for further analysis in the lab. When new landslide sites were identified in the field for study, these new sites were noted and data were collected in the same manner in which other sites were studied. Due to inclement weather and available time in the field, fewer than the targeted 40 slides were studied. 19 landslides were inventoried in the field for this project, for a total of 38 sample sites and profile descriptions (one landslide profile and one adjacent stable profile for each landslide inventoried).

Table 6 – Soil and hillslope factors observed in the field

Elevation
Slope aspect
Slope angle
Slope shape and complexity
Hillslope profile position
Soil observations
• Horizonation – presence, depth, boundary, nomenclature
• Color
• Rock fragments – kind and percentage
• Texture
• Structure – grade, size, type
• Consistence – moist
• Stickiness
• Plasticity
• Roots – quantity, size, location
• Effervesence
Vegetation – species and percent cover

4.6 Laboratory Analysis of Soil Samples

Laboratory testing was guided by knowledge obtained from the pilot statistical analysis and work in the field. Tests specifically considering soil texture, organic matter content, shrink-swell potential and clay mineralogy were conducted following standard procedures as specified by Burt (2004).

4.6.1 Soil Texture - Hydrometer Method for Particle Size Analysis

Clay content was one of two variables in the pilot statistical analysis determined to be related to landslide occurrence in Camp Davis Quadrangle (sig = 0.007). Because of this finding and secondary research findings regarding the impact of clay content on slope stability, it was important to obtain an accurate estimate of soil texture for each soil sample in this study. Therefore, a particle size analysis was performed using the Bouyoucos hydrometer method (Bouyoucos 1951, 1962) to estimate the percent sand (0.05-2mm), silt (0.002-0.05 mm) and clay (<0.002 mm) components of soil samples from every horizon for the 38 sample sites. This method is based on the principle that particles of different sizes and diameters will settle at different rates in the same fluid, as described by Stokes' Law (Bouyoucos 1929). The hydrometer method is widely accepted for determining soil texture and was chosen for this project because of its acceptance by the discipline, simplicity, time-effectiveness and availability of laboratory equipment in the KU Geography Department Soils Laboratory. A total of 105 samples were analyzed. This laboratory analysis provided weight estimates of percent sand, silt and clay for all horizon soil samples collected in the field excluding O horizon samples.

4.6.2 Soil Organic Matter Content – Loss-on-Ignition

In the loss-on-ignition technique for determining soil organic matter (SOM) content, SOM in an oven-dry soil sample is oxidized at a moderately high temperature, and weight loss from the sample is assumed to be proportional to the amount of SOM in the sample (Konen et al. 2002). Loss-on-ignition (LOI) was chosen as the method for determining SOM for this project because of its accuracy, time-effectiveness and availability of equipment in the KU Geography Department Soils Laboratory.

Several sample characteristics that can affect LOI results were considered when determining LOI methodology appropriate for this project. First, samples used in determining SOM via LOI must be free of all hygroscopic water. This insures that weight loss measured following ignition is the result of loss of organic matter and not loss of moisture from the soil sample. Second, clay content was a consideration because weight loss related to water loss from the structure of clays can affect LOI results. Structural water is lost from clays at temperatures 500˚C or greater (Schulte & Kaufmann 1991) and this variation is eliminated when soils are fired at 375˚C (Ball 1964). Because most of the samples tested for this project were determined to have a high clay content, this was an important consideration. Third, loss of CO_2 from carbonates in soils can occur when samples are fired at high temperatures, contributing to measured weight loss from the sample and creating error in the data. Davies (1974) found that the presence of calcium carbonate in soils made no difference to LOI results at 430˚C, and he recommended furnace temperatures for both calcareous and non-calcareous soils be controlled between 375˚C and 450˚C when performing LOI experiments. Because several of the samples for this project reacted to hydrochloric acid (HCl) in field tests, indicating the presence of calcium carbonate ($CaCO_3$), possible errors due to carbon dioxide (CO_2) loss and recommendations regarding firing temperatures for calcareous soils were considered here.

Based on the above considerations, time required for various LOI techniques and safety regulations for the KU Geography Department Soils Laboratory, two LOI methods were tested on a set of 29 samples. This set included samples from O, A, B and C horizons formed in a variety of parent materials, found under a variety of vegetative covers and on both landslide and stable sites. First, a method proposed by

Konen et al. (2002) for soils in the north central U.S. plains was tested. This method involved five steps: (1) samples were oven dried overnight at 105˚ C; (2) five to ten grams of dried soil was placed in a crucible and the weight of the crucible before adding the soil (crucible wt.) and with addition of the soil (crucible + soil wt.) was noted; (3) the crucibles were placed in a muffle furnace and fired at 360˚ C for two hours; (4) the crucibles with soil were re-weighed following combustion (crucible + soil wt. post combustion); and, (5) LOI was calculated using the following formula considering the crucible weight, crucible + soil weight and crucible + soil weight post combustion:

$$\text{SOM \%} = \frac{\text{(crucible + soil wt.)} - \text{(crucible + soil wt. post combustion)}}{\text{(crucible + soil wt.)} - \text{(crucible wt.)}}$$

Second, the technique proposed by Ben-Dor and Banin (1989), developed from work with 91 arid-zone samples, was tested. This method followed the same five step process as the first test, with variations in muffle furnace temperature and time of firing. Here, samples were fired at 400˚ C for eight hours. The same three weights were noted as in the first method (crucible weight, crucible + soil weight and crucible + soil weight post combustion), and LOI was calculated using the formula given above. These two tests provided almost identical SOM estimates for the 29 samples. Therefore, the method proposed by Konen et al. (2002) was used for this project considering time constraints in the laboratory. LOI was run on 118 total samples providing percent SOM estimates for all horizon soil samples collected in the field.

4.6.3 Shrink-swell Potential – Coefficient of Linear Extensibility

Shrink-swell potential of soils was the second variable included in the pilot statistical analysis determined to be significantly related to landslide occurrence in the quadrangle (sig = 0.004). The shrink-swell potential of soils is the potential for volume change in a soil with a loss or gain in moisture, and volume changes typically occur because of the interaction of clay minerals with water in the soils (Nordin & Blackwell 1985). The expansion and contraction of soils with high shrink-swell potential can destabilize a slope, increasing the likelihood of mass movement. For these reasons, it was important to obtain estimates of shrink-swell for all horizon soil samples collected in the field.

To accomplish this, a test to measure coefficient of linear extensibility (COLE) was run on 105 soil samples. Because the original method developed by Grossman (1968) ($COLE_{std}$) requires intact soil clods at specific moisture contents (these were not collected in the field for this project), an alternate method for estimating shrink-swell, the $COLE_{rod}$ method (Schafer & Singer 1976), was utilized. Comparison of $COLE_{rod}$ and $COLE_{std}$ by Simon et al. (1987) found that $COLE_{rod}$ agreed well with $COLE_{std}$, making it an acceptable measure for shrink-swell. Shrink-swell potential was determined for 105 total samples.

$COLE_{rod}$ involved several steps. First, 100 g of oven-dry soil, ground to pass through a 2mm sieve, was placed in a 250 mL beaker and mixed with water until a paste that glistened slightly, but did not flow when tilted, was obtained (Schafer & Singer 1976). The soil paste was then left to sit overnight (20-24 hours) in order for the moisture to equilibriate through the sample. The next day, moisture content of the soil was readjusted, if necessary, to achieve the desired consistency (just drier than saturated), and the soil paste was loaded into an Air-Tite Norm-Ject syringe with a 1 cm opening at the end using a spatula. Next, three rods per sample, each six to ten cm long, were extruded from the syringe onto a glass plate (the drying surface), and the ends were trimmed perpendicular to the drying surface. The length of all rods was measured and recorded, and the rods were left in a safe location to air dry 24 hours. Following the 24 hour air-drying, rods were transferred to an oven set at 100° C for additional drying overnight (Simon et al. 1987). Last, rods were removed from the oven and lengths were re-measured and recorded for comparison to wet lengths. Additionally, rods were observed for cracking.

COLE is the measure of linear extensibility, or the length change of a soil body between two moisture contents (Schafer & Singer 1976). Therefore, COLE was calculated using the following formula:

$$COLE = (\text{wet length} - \text{dry length})/\text{dry length}$$

4.6.4 Soil Clay Mineralogy – X-Ray Diffraction Analysis

Because the types of clays dominantly found in a soil affect the ability of that soil to take on and hold water, in was important to understand qualitatively the clay minerals found on sites in my study area. A total of 51 soil samples were sent to the Soil Geomorphology Laboratory at the University of Nebraska-Lincoln (UNL) for X-ray diffraction analysis (XRD). These included samples from the C horizon for every study site, B horizons where present, and horizons overlying the C horizon where clay content was comparable to or greater than that of the C horizon. The procedures employed at UNL are standard methodologies commonly practiced at XRD laboratories (Wally 2007).

4.7 Statistical Analysis

Data generated in the laboratory analysis, in addition to observations from the field, were recorded in an excel spreadsheet and reviewed for consistency of coding and missing information. After reviewing the spreadsheet, four cases (two landslide sites, two stable sites) were removed from the data set because several observations were missing from field records, and it was not feasible to return to the field site to complete the record. The remaining 35 cases were classified as landslide or stable (17 landslide, 17 stable). Landslide cases were further divided based on classification of the landslide activity as active (11 total) or inactive (7 total). One landslide was included in the active versus inactive analysis that is not included in the group of 17 landslides compared to stable slopes. This landslide was not included in the landslide versus stable slope analysis because there was insufficient data from the adjacent stable slope to be included. However, since sufficient data was available for the landslide case, it was included in the comparison of active versus inactive landslides.

Therefore, the two dependent variables considered in this study are landslide occurrence (landslide or stable, n=34) and landslide activity (active or inactive, n=18)

A total of 32 variables, based on observations recorded during field work and/or laboratory analysis, served as independent variables (IVs) for the study. These variables were included because secondary research findings, results of the pilot statistical analysis and/or observations in the field showed them to have a possible relationship to landslide occurrence in Camp Davis Quadrangle. The 32 variables considered in this research, and level of measurement for each, are listed in Table 7.

It is important to note that field observations and lab analysis of soil characteristics were conducted by soil horizon for each profile. This means that all IVs describing soil characteristics considered included data points by horizon, with no value for the total profile recorded. Because the problem studied here involves comparing landslide sites to stable sites and active to inactive landslides, with a profile described at each site, soil data collected by horizon needed to somehow be

Table 7 – Independent variables considered in data analysis

Independent Variable Name	Measurement Type
Presence of O horizon	Nominal – yes/no
Presence of B horizon	Nominal - yes/no
Depth to C horizon	Interval/Ratio – inches
Stickiness – profile average	Nominal – SO, SS, S
Stickiness – C horizon	Nominal – SO, SS, S
Stickiness – C:A horizon ratio	Nominal
Plasticity – profile average	Nominal – PO, PS, P, VP

Table 7 (cont.) - Independent Variables considered in data analysis

Plasticity – C horizon	Nominal – PO, PS, P, VP
Plasticity – C:A horizon ratio	Nominal
Most abundant clay mineral – C horizon	Nominal – Kaolinite (K), Illite (I), Interstratified Illite/Montmorillonite (I/M), Montmorillonite (M)
Most abundant clay mineral pairs – C horizon	Nominal – various pairs of K, I, I/M, M
Presence of montmorillonite – any horizon	Nominal – yes/no
Presence of montmorillonite – C horizon	Nominal – yes/no
Presence of illite or illite/mont – C horizon	Nominal – yes/no
Presence of kaolinite – C horizon	Nominal – yes/no
% rock fragments – profile average	Interval/Ratio - %
% rock fragments – C:A horizon ratio	Interval/Ratio - ratio
Slope	Interval/Ratio - %
Elevation	Interval/Ratio – feet
Aspect	Interval/Ratio – degrees
% clay – profile average	Interval/Ratio - %
% clay – C horizon	
% clay – C:A horizon ratio	Interval/Ratio - ratio
% sand – profile average	Interval/Ratio - %
% sand – C horizon	Interval/Ratio - %
% sand – C:A horizon ratio	Interval/Ratio - ratio
COLE – profile average	Interval/Ratio - %
COLE – C horizon	Interval/Ratio - %
COLE – C:A horizon	Interval/Ratio - ratio
Presence of cracks upon drying – any horizon	Nominal – yes/no
Presence of cracks upon drying – C horizon	Nominal – yes/no

Table 7 (cont.) - Independent Variables considered in data analysis

% SOM – A:underlying horizon ratio	Interval/Ratio - ratio
% SOM – A horizon	Interval/Ratio - %

collapsed to describe the total profile. For example, clay content was measured by hydrometer method for each soil horizon in a profile. Therefore, a landslide site with an A/C profile would have two different clay content estimates: one for the A horizon and one for the C horizon. In order to collapse these two data points into one value that accurately described the profile with a minimal loss of detail, three separate clay content variables, (average clay content weighted by horizon depth, clay content of the C horizon, ratio of C horizon clay content to A horizon clay content), were calculated and included for consideration in the data analysis. This type of data collapse was necessary for eight variables: percent rock fragments, stickiness, plasticity, sand percentage, clay percentage, COLE and soil organic matter (SOM). Table 8 shows the above mentioned variables as recorded in the field and the revised variables included for consideration in the data analysis.

A comparison of soil and landscape characteristics on landslide versus stable and active versus inactive cases was first performed using descriptive statistics. Mean, median, mode and range values for the 32 independent variables were calculated by landslide occurrence and activity level. Relationships between the independent variables and the dependent variables were noted where they occurred and considered in tests for statistical significance.

Table 8 - Soil horizon data as estimated for profile

Variable Name	Original data recorded	Revised data format
Clay percentage	% clay by horizon	weighted AVG* % clay, % clay C horizon, % clay C horizon: % clay A horizon
Sand percentage	% sand by horizon	weighted AVG* % sand, % sand C horizon, % sand C horizon: % sand A horizon
Percent rock fragments	% rock fragment, by type, by horizon	weighted AVG* % GR**, % GR** C horizon: % GR** A horizon
Stickiness	capacity of soil to adhere to an object; measured in the field by working moistened soil between fingers	weighted AVG* stickiness, stickiness C horizon, stickiness C horizon: stickiness A horizon
Plasticity	Degree to which reworked soil can be deformed without rupturing; measured in the field by making a 4cm roll of soil	weighted AVG* plasticity, plasticity C horizon, plasticity C horizon: plasticity A horizon
COLE	COLErod by horizon	weighted AVG* COLE, COLE C horizon
Percentage SOM	% SOM by horizon	weighted AVG* % SOM A horizon: % SOM A horizon: underlying horizon

* - weighted AVG is a weighted average calculated for the profile. Weighting was based on horizon depth as a percentage of total profile depth.
** - only gravel (GR) was considered. GR was the most abundant and common rock fragment type

Differences between groups detected via descriptive statistics were tested for statistical significance using three different non-parametric statistical tests. Non-parametric tests were chosen because there are not stringent assumptions regarding normality and sample size, both of which are concerns with this data set. Chi-square, Mann-Whitney U and Wilcoxon signed-rank tests were used to determine whether a significant relationship existed between any of the independent variables and the dependent variables landslide occurrence and landslide activity. The chi-square test was utilized to determine the relationships between categorical independent variables and landslide occurrence and/or landslide activity. The Mann-Whitney U was used to analyze the relationship between the numerical independent variables and landslide activity, and the Wilcoxon signed-rank test was performed to identify differences between numerical variables measured on landslide versus stable sites.

Wilcoxon signed-rank was used rather than Mann-Whitney U to test for statistically significant differences between landslide cases and stable cases because the method utilized for sampling landslides and adjacent stable sites purposefully created sample pairs with similar slopes, aspects, vegetation and geology. The Wilcoxon signed-rank test is the non-parametric test equivalent to the matched pairs t-test (Burt & Barber 1996).

Chapter 5: RESULTS

5.1 Landslide Morphology – Field Observations

A total of 18 landslides were examined in the field for this study. Plates showing the landslide form and soil profiles observed on the landslide and an adjacent stable slope can be found in Appendix 2. Elevation on the 18 slides ranged from 6,068 feet to 7,379 feet, with a mean elevation of 6,664 feet, and slope angles ranged from 11% to 67%, with a mean slope of 27%. Slope aspect widely ranged, with five landslides on north-facing slopes, four on east-facing slopes, six on south-facing slopes and three on west facing slopes. Landslides sampled in the quadrangle were on three geologic formations - Camp Davis, Aspen Shale and Bear River.

A variety of geomorphic features common to landslide occurrence were observed on the 18 landslides studied. Appendix 1 includes detailed landslide geomorphologic observations made for each slide. Geomorphic observations at each slide focused in three main areas: scarp morphology, general landslide and drainage morphology and sub-surface features. Scarp morphology was considered with special attention to the visibility and sharpness of the scarp, and vegetation patterns on the lateral and head scarps. Head scarps were not evident on four landslides (nos. 12, 13, 22, 23), vague on two landslides (nos. 1 & 7), smooth on six landslides (nos. 14, 17, 18, 19, 20, 21) and sharp on six landslides (nos. 2, 3, 5, 9, 15, 16, Figure 21). Head scarps on nine landslides were vegetated (nos. 1, 12, 13, 17, 18, 19, 20, 22, 23), on four were partially vegetated (nos. 2, 7, 14, 21) and unvegetated on five landslides (nos. 3, 5, 9, 15, 16). Lateral scarps were not evident on eight landslides (nos. 1, 12, 13, 17, 19, 20, 22, 23), vague on one landslide (no. 7), smooth on three landslides (nos. 14, 18, 21) and sharp on six landslides (nos. 2, 3, 5, 9, 15, 16). Lateral scarps on eight landslides were vegetated (nos. 12, 13, 17, 18, 19, 20, 22, 23), on four landslides were partially vegetated (nos. 1, 7, 14, 21) and unvegetated on six landslides (nos. 2, 3, 5, 9, 15, 16).

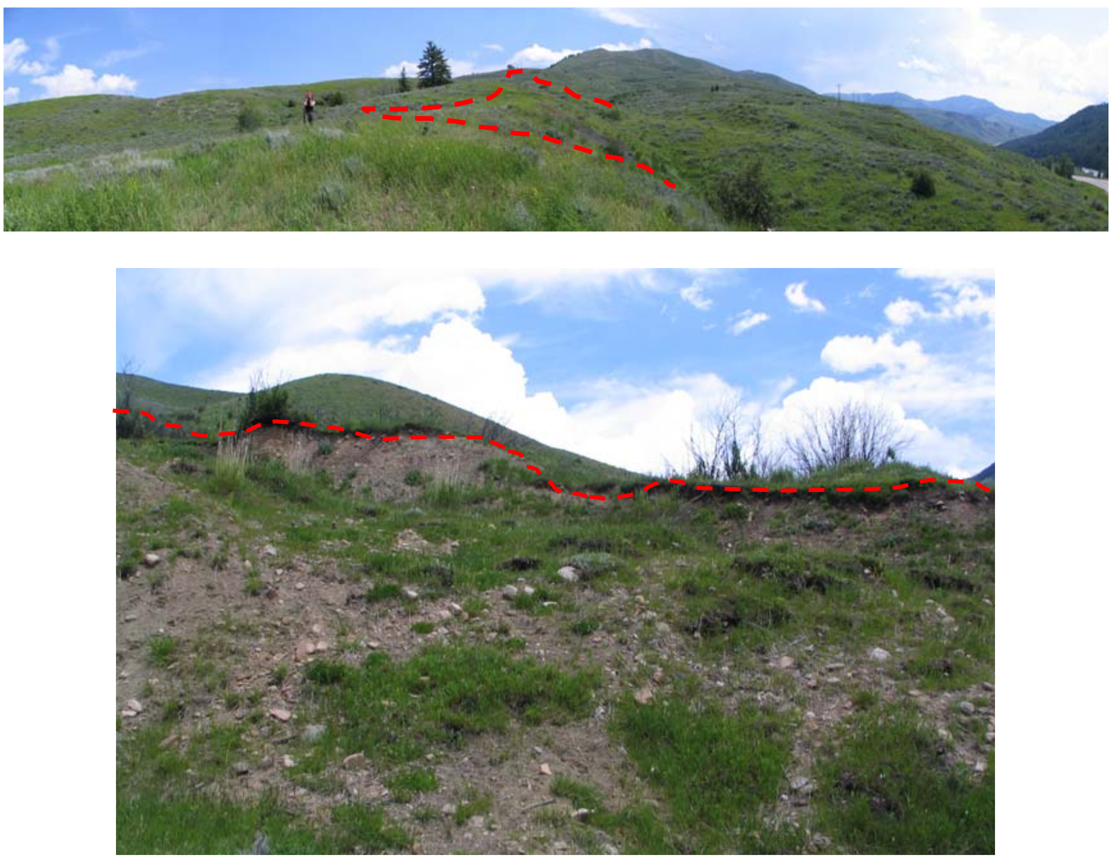


Figure 21 – Smooth, vegetated scarp observed at landslide no. 14 (top photo), and sharp, partially vegetated scarp observed at landslide no. 2 (bottom photo). Scarps are traced in red.

Landslide morphologies in this study were characterized by the presence or absence of five primary features: unvegetated cracks, hummocky topography, slide planes/detachments, ponds or marshes and drained and undrained depressions. Unvegetated cracks on the soil surface of the landslide body were observed on 11 landslides (nos. 2, 3, 5, 7, 9, 12, 14, 15, 16, 21, 23, Figure 22) and were not seen on the seven other slides. Hummocky topography was observed on all but four slides, where the landslide topography was described as smooth and rolling (nos. 1, 16, 17, 18). Slide planes and/or detachments were detectible at nine slides (nos. 2, 3, 5, 7, 9, 12, 15, 16, 21, Figure 23), but not at the nine other slides. An extensive marshy area was present at the toe of landslide no. 3, along Little Horse Creek, and a large, intact pond was present at the toe of landslide no. 13 (Figure 24). Drained and/or undrained depressions were observed at nine of the eighteen landslides studied (nos. 2, 3, 5, 7, 9, 12, 13, 15, 22).

Figure 22 – An unvegetated crack, (traced in red), observed on landslide no. 2.

Figure 23 – A plane of displacement (slide plane) observed on landslide no. 9. The shiny appearance of the slide surface is noticable in the center of the photo (red arrow).

Figure 24 – A stable pond, indicated by beaver activity and well-established vegetation, observed at the toe of landslide no. 13.

The two primary sub-surface features investigated on landslides for this study were the presence of slickensides and/or buried soils. Slickensides, shrink-swell features expressed as grooves and striations on a glossy pedo-structure surface (USDA NRCS 2002) were observed only at landslide no. 9. Buried soils were observed at landslides nos. 2, 5, 7, 9, 16 and 19 (Figure 25).

Based on the above outlined observations of landslide morphology, the eighteen slides were categorized as active or inactive utilizing a decision tree created by the author (Figure 26). Definitions of active (slides that have moved in the last 100-125 years) and inactive (no movement in the last 100-125 years and displaying more subdued geomorphic features) landslides are from McCalpin (1984) and factors considered in the decision tree are based on works by McCalpin (1984) and Liang and Belcher (1958) that address assessing landslide age based on geomorphology. The order in which these factors are included in the decision tree is based on landslide

Figure 25 – Buried soils observed at landslides no. 5 (left) and no. 9 (right).

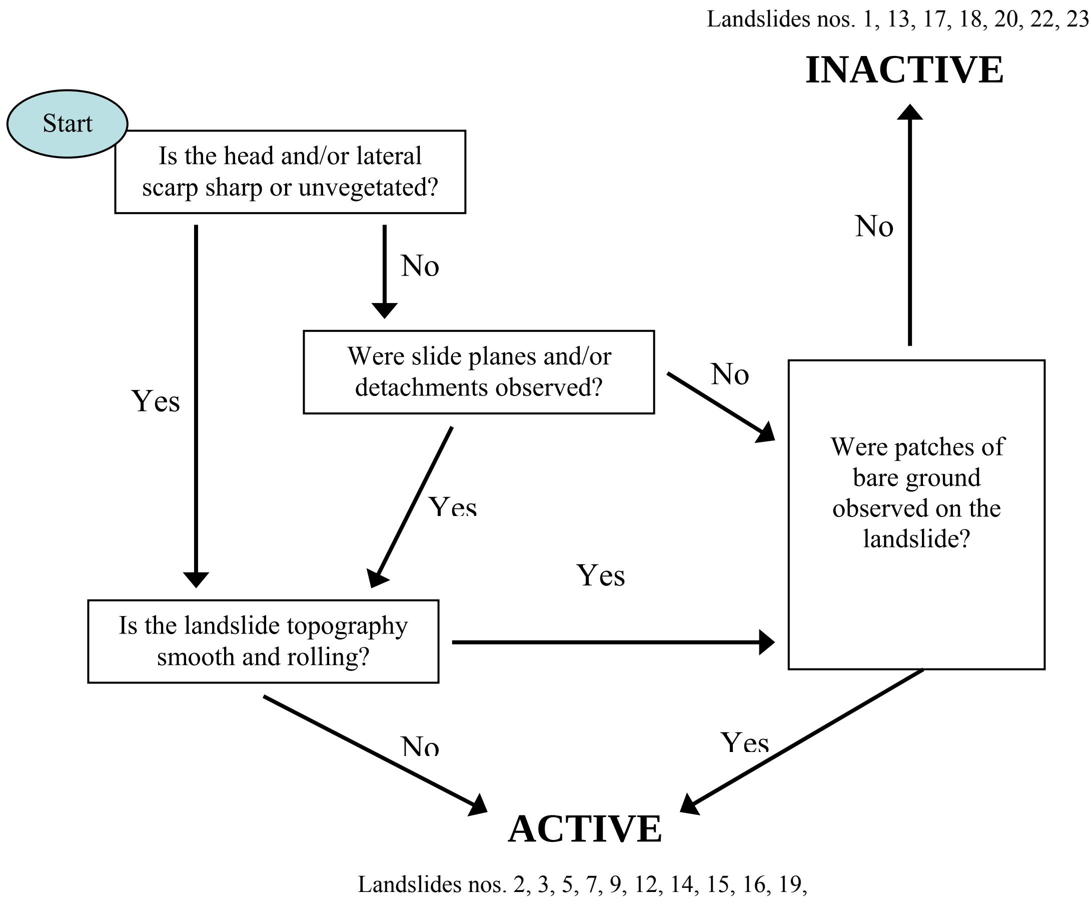


Figure 26 – Decision tree for classification of landslides as active or inactive

observations made in the field for this study. The process utilized here progressively defines the sampled landslides as either recently active or relatively stable, inactive slides based upon the geomorphicl characteristics observed at each landslide. For example, utilizing the decision tree shown in Figure 26, landslide no. 3 was categorized as active. This categorization resulted because sharp and unvegetated head and lateral scarps were observed, and topography on landslide no. 3 was hummocky, not smooth and rolling. Conversely, using the decision tree, landslide no.

17 was assigned to the inactive category. The head scarp of landslide no. 17 was smooth and vague, and the lateral scarp was not evident. Additionally, no slide planes, detachments or bare ground was observed on landslide no. 17.

When categorizing the landslides studied as inactive or active, confusion arose regarding landslides no. 16 and no. 19 because characteristics of both active and inactive slides were observed. The head and lateral scarps of landslide no.16 were both sharp and unvegetated, but the topography was smooth and rolling, not hummocky. Because a slide plane, unvegetated cracks, pistol butted trees and a buried soil were observed on landslide no. 16, (factors more characteristic of recent landslide activity), landslide no. 16 was classified as active. Landslide no. 19 did not display sharp or even visible scarps, slide planes were observed and topography was smooth and rolling. However, because bare ground was present throughout the landslide body and a buried soil and unvegetated cracks were also noted, this landslide was also categorized as active. Utilizing this method, 11 landslides were categorized as active (nos. 2, 3, 5, 7, 9, 12, 14, 15, 16, 19, 21), and seven landslides were categorized as inactive (nos. 1, 13, 17, 18, 20, 22, 23).

5.2 Soils - Field Observations

Numerous soil observations were recorded for profiles studied at each landslide, as well as on an adjacent stable slope. Appendix 3 summarizes soil findings recorded in the field by horizon for each landslide site (sample b) and adjacent stable slope (sample a). Depth to the C horizon on landslide sites ranged from three inches (nos. 2, 5, 9, 16) to 30 inches (no. 12), with a mean depth to the C horizon of 13.2 inches, while depth to the C horizon on adjacent stable slopes ranged from 10 inches to 40 inches, with a mean depth of 22.2 inches. On active landslides, depth to the C horizon ranged from three inches to thirty inches, with a mean depth of 11.7 inches. On inactive landslides, depth to the C horizon ranged from 11 inches to 28 inches, with a mean depth of 16.6 inches.

A/C profiles were most commonly observed for landslide soils, (nos. 2, 5, 9, 14, 16, 19, 20, 21, 22, 23), followed by A/AC/C profiles (landslides nos. 1, 3, 13, 17). A/B/C profiles were observed on adjacent stable slopes for 14 landslides, A/AC/C horizonation was observed on two others, and an A/C profile on the remaining stable section. B horizons were present on one landslide soil compared to 14 soils studied on adjacent stable slopes, and an O horizon was noted on four landslide soils versus 10 stable soils. There was no notable difference in the presence of O horizons or B horizons on active compared to inactive landslides.

Gravel was the most commonly noted rock fragment on both landslide soils and stable slope soils. Gravel was observed in at least one horizon of the profile on 16 landslide soils and 16 stable soils. Cobbles and/or stones were additionally observed on eight landslide soils and eight soils on adjacent stable slopes. Only landslide and stable profiles on landslide no. 7, and landslide soils on landslide no. 9 did not display rock fragments of some kind. Profile average percent gravel, calculated as weighted percent gravel based on percent gravel by horizon, ranged from 0.0% to 50.0% on stable soils, with a mean percent gravel of 24.6% across all stable soils. Percent gravel for the profile on landslide soils ranged from 0.0% (nos. 7 & 9) to 58.0% (no. 17) and averaged 25.9% for all landslide soils. The ratio of percent gravel in the C horizon to percent gravel in the A horizon on landslide soils ranged from 0.3 (no. 21) to 15.0 (landslide no. 22), averaging 3.6. The ratio of percent gravel in the C horizon to percent gravel in the A horizon on stable soils ranged from 0.0 to 50.0 and averaged 5.4.

Profile average percent gravel was between 0.0% (nos. 7 & 9) and 44.0% (no. 21) on active landslide soils, with a mean of 21.0%. Percent gravel for the profile on inactive landslide soils ranged from 16.0% (no. 18) to 58.0% (no. 17) and averaged 33.0% for inactive landslide soils. The ratio of percent gravel in the C horizon to percent gravel in the A horizon on active landslide soils ranged from 0.3 (no. 21) to 4.0 (no. 5), with a mean ratio of 2.2, and on inactive slides from 1.3 (no. 23) to 15.0 (no. 22) with a mean of 5.7.

Stickiness and plasticity were estimated in the field for each soil horizon on landslide and stable slope soils. An estimate of average profile stickiness and plasticity was made by weighting the contribution of stickiness from each horizon based on depth. Average profile stickiness was categorized as ‘non-sticky’ for one landslide soil (no. 9) and two stable soils. ‘Slightly sticky was the most common designation for both landslide soils (eight slide soils were classified as ‘slightly sticky’) and stable soils (10 stable soils were classified as ‘slightly sticky’). Five stable soils and eight landslide soils were assigned the stickiness designation ‘sticky.’ C horizon stickiness was most commonly designated as ‘sticky’ or ‘slightly sticky’ for both landslide soils (seven slide soil C horizons were categorized as 'sticky' and six as 'slightly sticky') and stable soils (eight stable soil C horizons were categorized as 'sticky' and five as 'slightly sticky'). One stable soil C horizon and two landslide soil C horizons (nos. 13 & 17) were classified as 'very sticky,' while three stable soil C horizons and two landslide soil C horizons (nos. 7 & 9) were classified as 'non-sticky.'

Average profile stickiness on active landslides was dominantly 'sticky' or 'slightly sticky' (10 slides), and one active landslide was categorized as 'non-sticky' (no. 9). This pattern was true for inactive landslides as well, where four landslides were categorized as 'sticky', and the remaining three were 'slightly sticky.' C horizon stickiness differed more substantially on active versus inactive landslide soils. C horizons on five active landslides were classified as 'slightly sticky,' four were classified as 'sticky' and two were classified as 'non-sticky.' Stickiness assignments for C horizons on inactive landslide soils were dominantly 'very sticky' (nos. 13, 17, 18) and 'sticky' (nos. 1, 20, 23), and one inactive landslide soil C horizon was classified as 'slightly sticky.'

Average profile plasticity was calculated in the same fashion in which average profile stickiness was determined. On landslide soils, average plasticity was classified as 'non-plastic' for two landslides (nos. 13 & 17), 'slightly plastic' for four slides (nos. 1, 3, 20, 21), 'plastic' for six landslides (nos. 2, 12, 14, 19, 22, 23) and 'very plastic' for five slides (nos. 5, 7, 9, 15, 16). Plasticity of the C horizon of landslide soils was similar to the profile average, where two landslide C horizons were categorized as ‘non-plastic’, two as ‘slightly plastic,’ six as ‘plastic’ and seven as ‘very plastic.’ Average plasticity for soil profiles on stable slopes was dominantly ‘slightly plastic’ (five profiles) and ‘plastic’ (10 profiles). One stable soil profile had an average plasticity of ‘non-plastic,’ and only one was ‘very plastic.’ C horizon plasticity on stable soils was most commonly classified as ‘very plastic’ (six soil C horizons) and ‘plastic’ (six soil C horizons), and four soil C horizons were classified as ‘slightly plastic.’ Only one stable soil C horizon was considered ‘non-plastic.’

Average profile plasticity on active landslides was dominantly ‘plastic’ (four slides) and ‘very plastic’ (five slides), and soils on two active landslides were classified as ‘slightly plastic.’ On inactive landslides, average profile plasticity was ‘non-plastic’ on three slides, ‘slightly plastic’ on two slides and ‘plastic’ on two slides. C horizon plasticity on active landslides was also dominantly ‘very plastic’ (five slides) and ‘plastic’ (five slides), with one slide’s C horizon classified as ‘slightly plastic.’ C horizon plasticity on inactive slides was ‘non-plastic’ on three landslides, ‘slightly plastic’ on one slide, ‘plastic’ on one slide and ‘very plastic’ on the final two slides.

Several additional soil observations were made in the field, including color, structure (type, grade and size), texture (estimated by hand), percent clay (estimated from hand texturing), dry and moist consistence, quantity, location and size of roots and reaction to 10% hydrochloric acid. However, these observations are not specifically noted here because either they are not particularly relevant to the research problem or a better estimate for the parameter was made utilizing laboratory methods. Field notes on the above-mentioned soil observations are included in Appendix 3.

5.3 Soils - Laboratory Results

Soil samples collected in the field were examined in the laboratory for the purpose of obtaining more precise data on four important soil properties: particle size/soil texture, soil organic matter content, shrink-swell potential and clay mineralogy. Clay, silt and sand percentages were obtained for soil samples by horizon and then a weighted profile average was calculated considering horizon depth. Profile average percent clay ranged from 14% (no. 17) to 58% (no. 9) for landslide soils (mean = 35.1%) and was between 21% and 54% on stable soils (mean = 31.4%). Percent clay in the C horizon on landslide soils was between 14% (no. 17) and 66% (no. 12), and clay percent in the C horizon of soils on six landslides (nos. 2, 5, 7, 9, 12, 23) was greater than 50%. C horizon clay content averaged 39.2% for landslide soils. Percent clay in the C horizon of soils on adjacent stable slopes ranged from 18% to 52% and averaged 33.3%. Clay content of the C horizon was greater than 50% for two stable slope soils. Clay content generally increased with depth for both landslide soils and stable slope soils, with the exception of soil on landslide no. 21 (percent clay C:A horizon = 0.58) and the stable slopes adjacent to landslides no. 22 (percent clay C:A horizon = 0.85) and no. 14 (percent clay C:A horizon = 0.75). Average ratio of clay content in the C horizon to A horizon clay content was 1.45 for landslide soils and 1.42 on stable slope soils.

On active landslides, percent clay for the profile averaged 38.1%, ranging from 21% (no. 21) to 58% (no. 9). C horizon clay content was between 15% (no. 21) and 66% (no. 12) for active landslide soils, averaging 42.6%. Average clay content for soil profiles on inactive landslides ranged from 14% (no. 17) to 42% (no. 23), averaging 28.5%. C horizon clay content was between 14% (no. 17) and 51% (no. 23), with a mean clay percentage in the C horizon across all inactive landslide soils of 31.2%. The ratio of clay content in the C horizon to clay content in the A horizon averaged 1.39 for active landslide soils and 1.42 for inactive landslide soils.

Silt content for the profile averaged 35% on stable slopes and ranged from 18% (no. 21) to 57% (no. 22). On landslides, silt percentage averaged 31% and ranged from 18% (no. 15) to 42% (no. 18). C horizon silt content ranged from 18% (no. 21) to 61% (no. 22) for soils on stable slopes, averaging 37%, and ranged from 15% (no. 17) to 45% (no. 18) for soils formed on landslides, averaging 29%. On average, silt content did not change with depth, with the ratio of C horizon silt content compared to A horizon silt content averaging 0.98 on stable slopes and 1.01 on landslides. The ratio of C horizon silt to A horizon silt ranged from 0.68 (no. 20) to 1.45 (no. 14) for stable soils and 0.53 (no. 23) to 3.14 (no. 15) for landslide soils.

Active landslide silt content averaged 28% for the profile and ranged from 18% (no. 15) to 41% (no. 3). On inactive landslides, silt content averaged 35% and ranged from 22% (no. 17) to 42% (no. 18). C horizon silt content was higher on inactive slides on average (32%) compared to active landslides (27%) and ranged more widely on inactive landslides, from 15% (no. 17) to 45% (no. 18), compared to active landslides (ranged from 17% to 39%). The ratio of silt content in the C horizon compared to the A horizon averaged 1.14 on active landslides and ranged from 0.46 (no. 12) to 3.14 (no. 15). On inactive slides, the ratio of C horizon silt to A horizon silt averaged 0.80 and ranged from 0.53 (no. 23) to 1.22 (no. 18).

Average sand content for landslide profiles ranged from 17% (no. 9) to 54% (no. 15) and averaged 35% across all landslide soils. For stable soil profiles, percent sand for the profile was between 7% and 53%, averaging 33%. Sand content in the C horizon of landslide soils ranged from 10% (no. 2) to 59% (mean = 33%), and on stable soils between 6% and 49% (mean = 30%). Percent sand slightly decreased with depth for both soils on landslides and adjacent stable slopes. The ratio of percent sand in the C horizon compared to the A horizon averaged 0.82 for stable soils and was above 1.00 for only one profile (1.36, slope adjacent to landslide no. 7). The ratio comparing C horizon sand to A horizon sand averaged 0.87 for soils on landslides, and was 1.0 or greater for soils on five landslides (nos. 13, 17, 19, 20, 22).

On active landslides, percent sand ranged from 17% (no. 9) to 54% (no. 15) (mean = 34%), and on inactive slides was between 21% (no. 22) and 64% (no. 17) (mean = 37%). Percent sand in the C horizon of active landslide soils averaged 30% and ranged from 10% (no. 2) to 59% (no. 21). On inactive landslides, C horizon sand content was between 22% (no. 22) and 71% (no. 17), averaging 37%. Percent sand in the soils decreased with depth by an average of 21% on active landslides (mean C horizon percent sand: A horizon percent sand = 0.79), and increased with depth for only one active landslide soils (no.19, 1.17). Soil sand content increased with depth for four inactive landslide soil (no. 13, 17, 20, 22), and decreased on three inactive landslides (no. 1, 18, 23), with an average ratio of percent sand in the C horizon to percent sand in the A horizon of 0.99 on inactive landslide soils.

Soil organic matter content (SOM) in the A horizon on landslide soils averaged 7.7% and ranged from 4.1% (no. 7) to 18.8% (no. 23). On stable slope soils, SOM was between 4.1% and 20.9%, averaging 8.2%. SOM decreased with depth for both landslide soils and soils on adjacent stable soils, where the ratio of A horizon SOM to SOM in the underlying horizon averaged 1.52 on landslides and 1.80 on stable slopes. A horizon SOM on active landslides ranged from 4.1% (no. 7) to 9.4% (no. 19) (mean = 5.6%) and from 7.7% (no. 18) to 18.8% (no. 23) on inactive landslides (mean = 11.1%). The ratio of A horizon SOM compared to SOM in the horizon underlying the A on active landslides averaged 1.28, ranging from 0.73 (no. 9) to 2.01 (no. 1). On inactive landslides, this ratio averaged 1.87 and ranged from 1.06 (no. 13) to 2.59 (no. 17).

Averages for coefficient of linear extensibility (COLE) estimated for landslide soil profiles ranged from 0.024 (no. 17) to 0.149 (no. 9), with a mean value of 0.063. COLE profile averages for soils on adjacent stable slopes averaged 0.049, ranging from 0.015 to 0.121. C horizon COLE for landslide soils was between 0.016 (no. 17) and 0.157 (no. 9, mean = 0.070) and between 0.011 and 0.097 on stable soils (mean = 0.049). Cracks after drying were observed on nine of the seventeen landslide C horizon samples and on six of the seventeen stable slope C horizon soil samples. COLE for active landslide soil profiles averaged 0.069 and ranged from 0.036 (no.

15) to 0.149 (no. 9). C horizon COLE on active landslides was between 0.036 (nos. 15 & 21) and 0.157 (no. 9), averaging 0.813. On inactive landslide soils, COLE for the soil profile ranged from 0.012 (no. 18) to 0.084 (no. 22), with a mean COLE of 0.045. C horizon COLE for inactive landslide soils averaged 0.042 and ranged from 0.000 (no. 18) to 0.085 (no. 22). Cracks from drying were noted on eight of eleven active landslide samples and one of seven inactive landslide samples.

Soil samples from the C horizons on all landslide and stable soil profiles were submitted to x-ray diffraction (XRD) analysis, and four clay minerals were identified: kaolinite, illite, illite interstratified with montmorillonite and montmorillonite. Appendix 5 provides XRD patterns for C horizon samples from landslide and accompanying adjacent stable slope soils on all 18 landslides studied here. Kaolinite was the most abundant mineral in the C horizons of one of the landslide soils (no. 20) and three of the stable slope soils. Illite was the most abundant clay mineral for C horizons in six landslide soils (nos. 3, 12, 13, 14, 15, 22) and six stable soils, and illite stratified with montmorillonite was most abundant for three landslide soil C horizons (nos. 1, 5, 7) and three soils on adjacent stable slopes. Montmorillonite was the most abundant mineral identified in the C horizon of six landslide soils (nos. 2, 9, 16, 19, 21, 23) and five stable slope soils. Montmorillonite was detected, regardless of abundance, in the C horizon of ten landslides soils (nos. 2, 3, 9, 12, 16, 19, 20, 21, 22, 23) and nine stable slope soils.

The most abundant clay mineral in the C horizon on active landslides was most commonly montmorillonite (five slides, nos. 2, 9, 16, 19, 21), followed by illite (four slides) and illite interstratified with montmorillonite (two slides). No active landslide soils were dominated by the clay mineral kaolinite. The presence of montmorillonite, regardless of abundance was detected in seven of the eleven active landslide soil C horizons. Illite was the most abundant clay mineral detected in soil C horizons on three inactive landslides, and two inactive landslide soil C horizons were dominantly kaolinite (nos. 17 & 20). On one inactive landslide, illite interstratified with montmorillonite was the most common clay mineral, and montmorillonite was most abundant on one inactive slide, as well. Montmorillonite was detected in the C horizon of three of the seven inactive landslide soils (nos. 20, 22, 23).

5.4 Statistical Analysis

Three statistical methods (chi-square, Mann-Whitney U and Wilcoxon signed-rank) were utilized to determine whether significant differences existed between soil properties on landslides and soil properties on adjacent stable slopes, and to test for significant differences in soil and slope properties on active landslides compared to inactive landslides. The chi-square test is appropriate to determine the relationships between categorical soil variables and landslide occurrence. A chi-square was performed to test ten null hypotheses comparing landslides to stable slopes: that there is no relationship between landslide occurrence and (1) presence of an O horizon; (2) presence of a B horizon; (3) stickiness – profile average; (4) C horizon stickiness: A horizon stickiness; (5) C horizon stickiness; (6) plasticity – profile average; (7) C horizon plasticity: A horizon plasticity; (8) C horizon plasticity; (9) presence of cracks in any horizon with drying; and, (10) presence of cracks in the C horizon with drying. Categorical variables that did not appear different on landslide soils versus stable slope soils following initial review of the field and laboratory data collected (e.g. clay mineralogy) were not included in the statistical analysis.

The top portion of Table 9 provides the results of the chi-square test, and only presence of the B horizon is significant (sig=0.000 using an alpha level of 0.015, adjusted from an alpha of 0.15 because 10 tests were run). This means that there is a significant relationship between the presence of a B horizon on slopes and landslide occurrence. The next nearly significant relationship is presence of an O horizon with sig=0.037.

There were 12 null hypotheses comparing active landslides to inactive landslides tested utilizing a chi-square: that there is no relationship between landslide activity and (1) presence of montmorillonite in any horizon; (2) presence of montmorillonite in the C horizon; (3) most abundant clay mineral in the C horizon; (4) most abundant pair of clay minerals in the C horizon; (5) stickiness – profile average; (6) C horizon stickiness: A horizon stickiness; (7) C horizon stickiness; (8) plasticity – profile average; (9) C horizon plasticity: A horizon plasticity; (10) C horizon plasticity; (11) presence of cracks in any horizons with drying; and, (12) presence of cracks in the C horizon with drying. The bottom portion of Table 9 shows results of the chi-square for the dependent variable landslide activity. The null

Table 9 – Chi-square Results

Dependent Variable	Independent Variable	Chi-Square Sig. (2-sided)
Landslide Occurrence (landslide vs. stable)	Presence of O horizon	0.037
	Presence of B horizon	0.000
	Stickiness – profile AVG	0.290
	Stickiness – C:A	0.183
	Stickiness – C horizon	1.000
	Plasticity – profile AVG	0.160
	Plasticity – C:A	0.429
	Plasticity – C horizon	0.910
	Presence of cracks any horizon	0.169
	Presence of cracks C horizon	0.300
Landslide Activity (active vs. inactive)	Presence of montmorillonite any horizon	0.387
	Presence of montmorillonite C horizon*	0.387
	Most abundant clay mineral C horizon*	0.215
	Most abundant clay pair C horizon*	0.093
	Stickiness – profile AVG	0.629
	Stickiness – C:A*	0.019
	Stickiness – C horizon*	0.040
	Plasticity – profile AVG*	0.024
	Plasticity – C:A	0.629
	Plasticity – C horizon*	0.026
	Presence of cracks any horizon*	0.066
	Presence of cracks C horizon	0.016

* >50% of cells with expected count < 5 or any cells with expected count < 2

hypothesis was not rejected for any of the 12 hypotheses tested at an alpha of 0.0125 (adjusted from 0.15 for the 12 tests). The variables most nearly significantly related to landslide activity were presence of cracks in the C horizon (sig=0.016), the ratio of C horizon stickiness to A horizon stickiness (sig=0.019), average plasticity for the profile (sig=0.024) and C horizon plasticity (sig=0.026).

The Wilcoxon signed-rank and Mann-Whitney U tests were used to determine if there were significant differences between landslide and stable sites and active and inactive landslides, respectively, for numerical independent variables. Six null hypotheses were tested on landslide sites compared to stable slopes using a Wilcoxon signed-rank test: there is no relationship between landslide occurrence and (1) depth to the C horizon; (2) percent gravel in the C horizon: percent gravel in the A horizon; (3) percent clay – profile average; (4) COLE – profile average; (5) percent clay in the C horizon; and, (6) COLE for the C horizon. The null hypothesis was accepted for all six tests at an alpha = 0.025 (adjusted for the six tests from an alpha of 0.15). Results of the Wilcoxon signed-rank test are shown in Table 10. None of the results were significant and the lowest sig generated via this test was 0.055 when comparing depth to the C horizon on landslide versus stable soils.

Table 10 – Wilcoxon signed-rank Results

Dependent Variable	**Independent Variable**	**Sum of Positive Ranks**	**Sun of Negative Ranks**	**Sig**
Landslide Occurrence (landslide vs. stable)	Depth to C horizon	36.0	117.0	0.055
	% gravel C:A	70.0	66.0	0.918
	% clay – profile AVG	105.0	48.0	0.177
	COLE – profile AVG	108.5	44.5	0.130
	% clay – C horizon	99.5	53.5	0.276
	COLE – C horizon	107.5	45.5	0.142

The Mann-Whitney U test was used to examine differences between active and inactive landslides when considering various numerical independent variables. Specifically, 14 null hypothesis were tested: there is no relationship between landslide activity and (1) elevation; (2) aspect; (3) slope; (4) depth to the C horizon; (5) percent gravel – profile average; (6) percent gravel in C horizon: percent gravel in A horizon;

(7) percent clay – profile average; (8) percent clay – C horizon; (9) percent clay in C horizon: percent clay in A horizon; (10) percent sand - profile average; (11) percent sand – C horizon; (12) percent sand in C horizon: percent sand in A horizon; (13) COLE – profile average; and, (14) COLE – C horizon. As Table 11 shows, the null hypothesis was accepted for all 14 tests at an alpha = 0.011 (adjusted from an alpha of 0.15 because 14 tests were run). The most nearly significant sig value was for the ratio of gravel in the C horizon versus the A horizon on active compared to inactive landslides (sig = 0.045). The next two most nearly significant results were for C horizon COLE (sig = 0.070) and elevation (sig = 0.094) on active versus inactive landslides.

Table 11 – Mann-Whitney U Results

Dependent Variable	Independent Variable	Sig
Landslides Activity (active vs. inactive)	Elevation	0.094
	Aspect	0.298
	Slope	0.188
	Depth to C horizon	0.157
	Percent gravel – profile AVG	0.221
	Percent gravel – C:A	0.045
	Percent clay – profile AVG	0.135
	Percent clay – C horizon	0.147
	Percent clay – C:A	0.821
	Percent sand – profile AVG	0.497
	Percent sand – C horizon	0.341
	Percent sand – C:A	0.189
	COLE – profile AVG	0.135
	COLE – C horizon	0.070

Chapter 6: DISCUSSION & CONCLUSION

6.1 Discussion

Several important conclusions are evident from the results of this study. First, soil profiles studied in Camp Davis Quadrangle show that landslides are catastrophic events for soil formation in the study area, dramatically mixing slope material, destroying soil profiles and transporting the disturbed material downslope as colluvium. Upon deposition and stabilization of the colluvium, soil forming processes begin, setting $time_{zero}$ for a new soil forming in landslide-created colluvium. Soils that have recently begun forming on landslides typically exhibit characteristics of a young soil, similar to Entisols or Inceptisols, as less time has been provided for soil forming processes to act on the deposited colluvium. Therefore, soils formed on active landslides have characteristics more closely related to the colluvial material in which they form than soils formed on stable slopes where differentiated soil profiles are observed.

Several important landslide soil characteristics were observed that provide a testament that landslides are catastrophic events and serve to reset $time_{zero}$ for soils in the study area. Depth to the C horizon was less on landslide soils compared to soils on adjacent stable slopes (averaging 13.6 inches vs. 22.2 inches, respectively) despite sampling on hillslopes with purposefully similar slope angles (slope averaged 27% on landslides and 25% on stable slopes). Shallower soils on landslides are a result of surfce and subsoils being removed from the slope upon landslide occurrence, leaving little material over bedrock on the back slope of the landslide, where samples for this study were taken. Additionally, because less time has elapsed since $time_{zero}$ for soils formed on landslides than on adjacent stable slopes, differences in soil depth, a soil characteristic which is in part a function of time, reflect differences in time since inception of soil formation.

Additionally, profile horizonation differed in two primary ways when comparing landslide soils to soils on adjacent stable slopes. Landslide soils were far less likely to have B horizons and O horizons than soils on stable slopes. In fact, a B horizon was observed on only one of the 17 landslide soil profiles studied, compared to 14 of the 17 stable soil profiles examined. O horizons were present on four of the 17 landslide soils and 10 of the 17 stable slopes. Statistical testing found these differences to be important, as well. The chi-square test that was executed to examine differences in landslide and stable slope soil characteristics found presence of a B horizon to be the only soil characteristic significantly related to landslide occurrence (sig = 0.000), while presence of an O horizon had the next lowest sig value (sig = 0.037). Well-developed soils require time and slope stability, and these differences in horizonation on landslide compared to stable slope soils indicate differences in time during which soil forming processes have been at work.

Differences in soil organic matter content (SOM) in the A horizon were also observed when comparing landslide soils to stable slope soils. A horizon SOM averaged 8.2% for soils on stable slopes and 7.7% on landslide soils. Based on qualitative observations in the field, this difference, as well as O horizons being less commonly observed on landslides, is at least in part due to differences in vegetation on landslide and stable slopes. Specifically, coniferous species such as Douglas Fir and Engelmann Spruce, were more commonly observed on stable slopes than on landslides. Therefore, both the presence of an O horizon and SOM content in the A horizon seem to be due to differences in vegetation and the time required to establish a mature tree stand and accumulate organic matter in soil.

By examining differences in soil characteristics on active landslides versus inactive landslides studied here, it is clear that soils can also provide clues as to the recency of landslide failure. Deep soils with differentiated profiles require time and stability to develop. Depth to the C horizon for soils on active landslides averaged 11.7 inches compared to 16.6 inches on inactive landslides. While this difference could partly be due to slope (mean = 31% for active landslides and mean = 27% for inactive landslides), it also is an indication of the relationship of soil development to time since the last failure. Note that the mean depth to the C horizon was least for soils formed on active landslides and greatest for soils on stable slope soils (Table 12). This arrangement shows that depth to the C horizon is a soil characteristic related to time since slope failure, and it provides information helpful in assessing landslide activity and recency of the last failure.

An interesting pattern was observed in gravel and SOM distribution through the soil profile on active landslides compared to inactive slides, as well. The ratio of gravel in the C horizon to gravel in the A horizon for soils formed on inactive

Table 12 – Depth to the C horizon and landslide occurrence

	Mean depth to C horizon (inches)
Active Landslides	11.7
All Landslides	13.2
Inactive Landslides	16.6
Stable Slopes	22.2

landslides was almost three times the ratio for soils on active landslides (5.7 vs. 2.2). This difference may be partly due to differences in geologic parent material for inactive and active landslides, as will be discussed in more detail in a later section. At the same time, differences in gravel content with depth may be exacerbated by differences in degree of soil development due to a more recent $time_{zero}$ for active landslides.

The ratio of A horizon SOM to SOM in the horizon underlying the A horizon was also greater for inactive landslide soils (1.9) versus active landslide soils (1.3). Note that the distribution of SOM and gravel through the soil profile show a sequence similar to that of depth to the C horizon when considering active landslides, inactive landslides, all landslides and stable slopes together (Table 13). However, ratios of SOM and gravel are very similar on inactive and stable slopes, illustrating the differences between these two groups are fairly minimal. The degree to which differentiation in SOM and gravel content has occurred between horizons in a soil profile provides an additional clue regarding the recency of landslide occurrence and the time during which soil forming processes have been active. Adding soil properties strongly related to time since soil formation began, such as horizonation, depth to the C horizon and changes in gravel and SOM with depth, to the landslide activity categorization system could improve understanding of landslide phenomenon in the quadrangle.

Table 13 – SOM and percent gravel by landslide occurrence

	SOM A horizon : SOM underlying horizon	% gravel C horizon : % gravel A horizon
Active Landslides	1.3	2.2
All Landslides	1.5	3.6
Inactive Landslides	1.9	5.7
Stable Slopes	1.8	5.4

There were no noticeable differences in soil characteristics related to shear strength and soil stability when comparing landslides to stable slopes. Only differences resulting from variations in soils genetic pathways, as outlined above, due to the resetting of $time_{zero}$ by landslide occurrence were found. This was not the case when comparing soil properties on active landslides to inactive landslide soil properties. Several differences in soil characteristics on active and inactive soils, especially related to clay type and behavior, were identified in this research. The lowest sig values generated when statistically comparing active to inactive landslide soils were for the independent variables strongly determined by clay type and behavior. Specifically, stickiness in the C horizon (sig = 0.040), ratio of stickiness for the C horizon versus stickiness for the A horizon (sig = 0.019), profile average plasticity (sig = 0.024), C horizon plasticity (sig = 0.026) and cracks in the C horizon (sig = 0.016) generated the lowest sig values, illustrating the importance of clay properties when considering slope stability in this region.

Clay content for the profile averaged 38% for soils on active landslides compared to 29% on inactive landslides. More importantly, clay mineralogy was different on active and inactive landslides. Montmorillonite was more frequently the most abundant clay mineral on active landslides, while illite and kaolinite were often the most abundant clay mineral on inactive landslides (Table 14). It would be expected, considering the known specific surface area and cation exchange capacity of montmorillonite, that slopes with soils dominated by montmorillonite would be less stable. The results shown here, where active landslide soils were more dominantly montmorillonitic than inactive landslide soils, illustrate that the relationship between abundance of montmorillonite in soils and degree of slope stability is observable in Camp Davis Quadrangle.

Table 14 - Most abundant clay mineral - active vs. inactive landslides

	Kaolinite	Illite	Illite/Mont	Montmorillonite
Active Landslides	0	4	2	5
Inactive Landslides	2	3	1	1

Plasticity and stickiness also varied for active and inactive landslide soils. Analysis of C horizon plasticity and stickiness on active versus inactive landslide soils showed an interesting pattern: active landslide C horizons were dominantly 'plastic' or 'very plastic', and less sticky, while inactive landslide C horizons were most likely to be 'sticky' or 'very sticky' and less plastic (Figures 27, 28). Note also that chi-square testing generated fairly low sig values for independent variables involving C horizon stickiness and C horizon plasticity (Table 9), exposing the potential of a relationship between C horizon stickiness and plasticity and landslide activity.

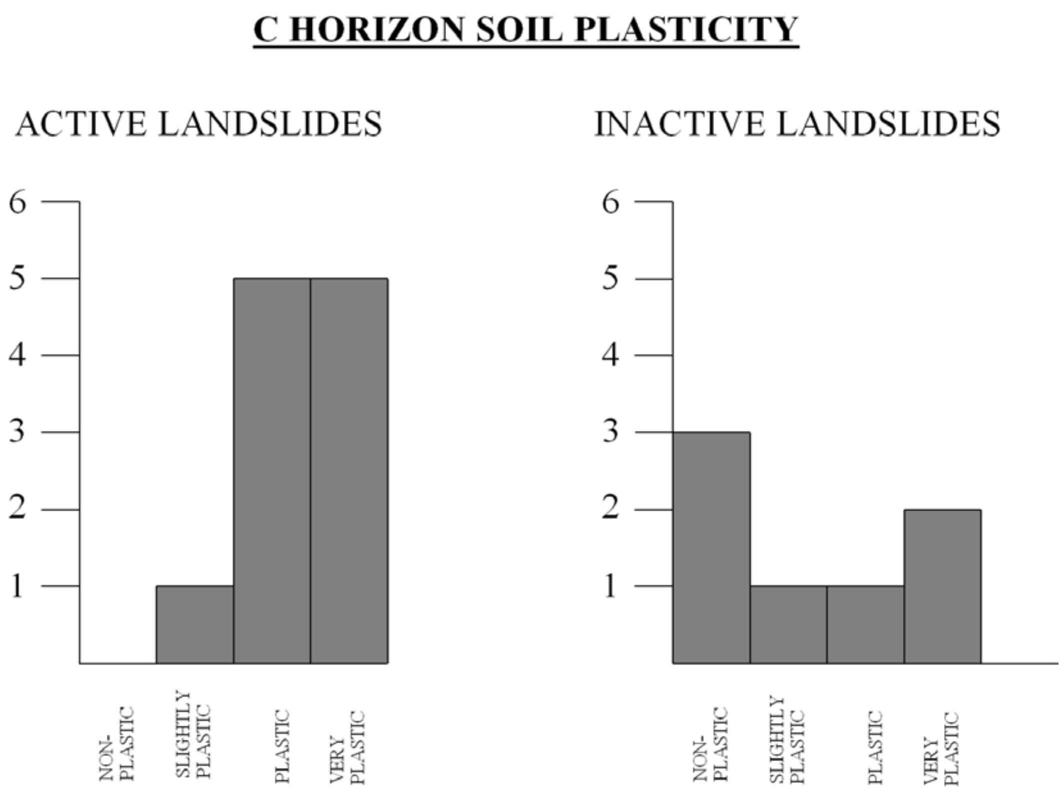


Figure 27 – Soil plasticity in the C horizon on active compared to inactive landslides

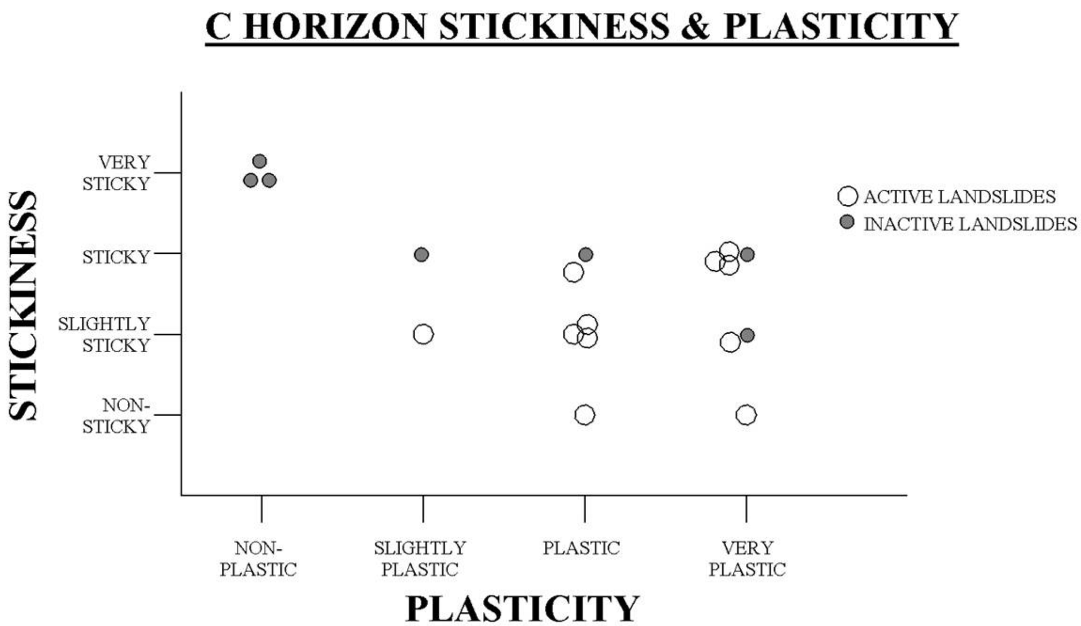


Figure 28 – Soil plasticity and stickiness in the C horizon of active and inactive landslides

COLE values were higher and the presence of cracks with wetting and drying were more prevalent for soils on active landslides than on inactive landslides. COLE averaged 0.069 for active landslide profiles and 0.045 on inactive landslide soils. Cracks that developed upon drying of soil were observed in any horizon on eight of eleven active landslide soils compared to two of seven inactive landslide soils. COLE and cracking are additional metrics for understanding the types of clays present in a soil and how a soil will behave with the addition and removal of water. These soil properties, as well as stickiness, plasticity and clay mineralogy, give clues regarding the behavior of clays in a soil, a crucial factor in determining soil stability on slopes.

While important differences were noted between active and inactive landslide soils when considering the profile, many of these differences were expressed to a greater degree when comparing C horizons alone. The difference in clay content on active compared to inactive landslides was far greater in the C horizon than the profile average (Table 15): 38% for soils on active landslides compared to 29% on inactive landslides. C horizon clay percentage also differed for active versus inactive landslide soils, at 43% versus 31%, respectively. Additionally, COLE differed more substantially when comparing C horizon samples versus an examination of the total soil profile. Average COLE for the soil profile on active landslides was 0.069 and on inactive landslides was 0.045. This compares to C horizon COLE values on active landslides of 0.081 and on inactive landslides of 0.042 (Table 16). Cracks with drying, another indication of high content of shrink-swell clays in a soil, were observed more frequently in C horizon samples from active landslides than in C horizon samples from inactive landslide soils (Figure 29).

Table 15 – Clay content - active vs. inactive landslides

	Profile AVG	**C horizon**
Active Landslides Mean	38%	43%
Inactive Landslides Mean	29%	31%

Table 16 – COLE - active vs. inactive landslides

	Profile AVG	C horizon
Active Landslides Mean	0.069	0.081
Inactive Landslides Mean	0.045	0.042

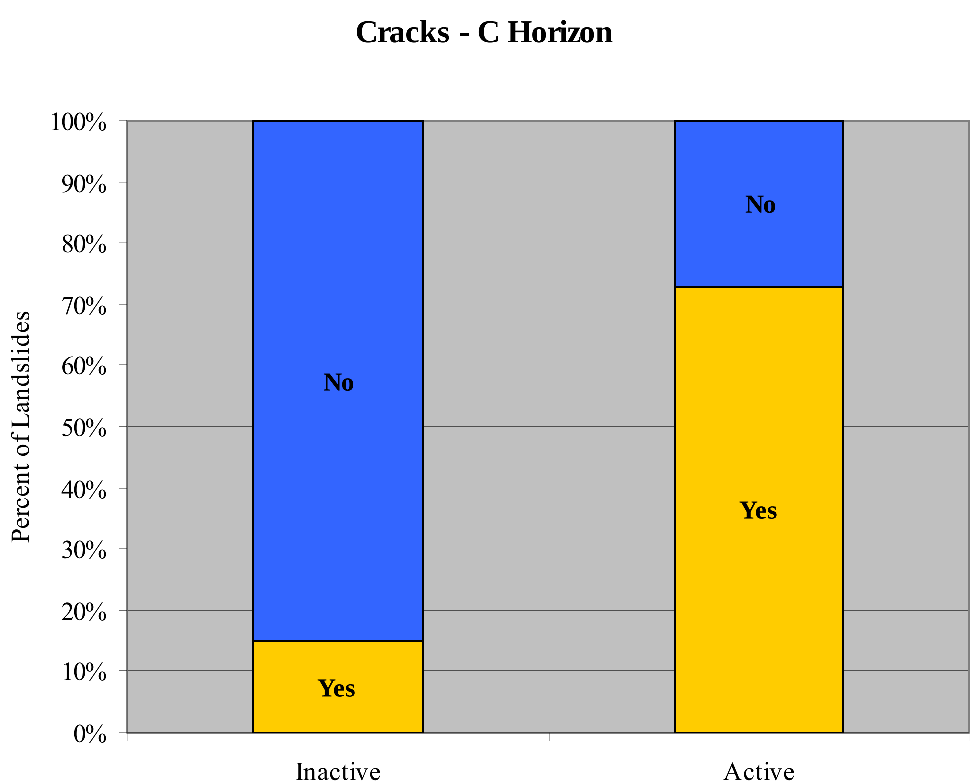


Figure 29 – Number of active and inactive landslides where cracks were observed in C horizon samples with drying

Notable differences in clay behavior were observed on active landslide soils compared to inactive landslide soils, and the greatest differences in soil characteristics including percent clay, stickiness, plasticity and COLE were observed in the C horizon. Additionally, mineralogical results presented here for active versus inactive landslide soils are for samples from the C horizon of the soil. These results support the hypothesis that variations in landslide activity in the quadrangle are due to differences in soil properties inherited from the geologic parent material in which the soils form. It appears, that differences in soil characteristics strongly related to the behavior of clays in soil and slope stability, are more apparent with depth in the soil profile, providing evidence that these characteristics are inherited from the parent material.

In addition to differences in soil properties relating to clay behavior, active and inactive landslides studied here differed in two additional ways related to differences in parent material. Elevation was noticeably different, averaging 6,528 feet on active landslides versus 6,877 feet for inactive landslides. Additionally, while not statistically significant considering the number of tests performed and the overall alpha of 0.15, one of the lowest sig values generated by the Mann-Whitney U test for differences in active and inactive slide characteristics was for elevation (sig = 0.094). While it is difficult to ascertain the relationship between elevation and geologic formation in a region as tectonically active as the Middle Rocky Mountains, these differences in elevation on active versus inactive slide could reflect changes in geology moving up the stratigraphic section.

Differences in the amount of coarse grained rock fragments observed throughout the profile and at depth on active and inactive landslides also seem to point to differences in geologic parent material for the two landslide classes. Percent gravel for the soil profile averaged 21% on active landslides and 33% on inactive landslides, and was 19% for the C horizon of active landslide soils compared to 41% for the C horizon of inactive landslide soils. Sand content in the C horizon corroborated this pattern. On active landslides, sand percent averaged 30% in the C horizon, compared to sand percent averaging 37% for C horizon samples on inactive landslides. Additionally, sand content was maintained with depth on inactive slide soils, but decreased with depth in soils on active landslides (Figure 30).

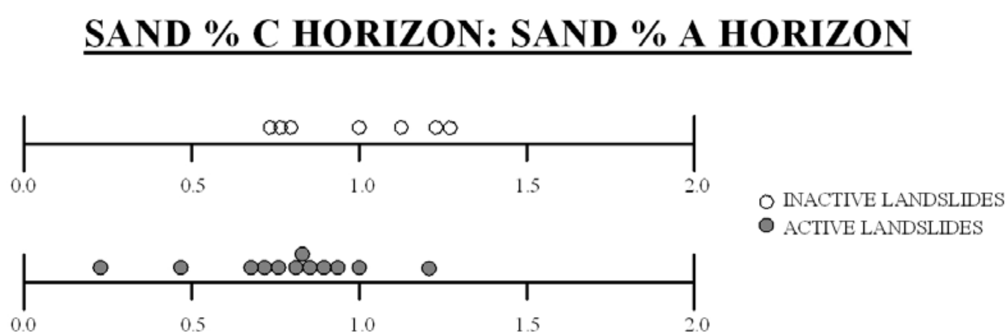


Figure 30 – Ratio of sand in the C horizon to sand in the A horizon (a measure of change in sand content with depth) on active and inactive landslides.

This pattern of differing coarse grained rock fragment content is surprising because I would expect more rock fragments on active landslides, and possibly an increase with depth, as rock located at the slide plane breaks up and is transported with failure. The fact that the reverse of this expected pattern was observed, as well as more dramatic differences in C horizon rock fragments and sand content, lend credence to the idea that this is an additional soil property inherited from the geologic parent material. Additionally, soils forming in residual rock at slightly higher elevations, as noted by the Teton National Forest Soil Survey and described in Chapter 3, display increases in rock fragments with depth. This compares to fine, montmorillonitic soils formed on landslide and slump features at lower elevations. Differences observed on inactive and active landslide soils are similar to those described by the forest soil survey as occurring in soils formed in two very different parent materials: bedrock residual compared to landslide colluvium. These similarities further coroborate the hypothesis that differences in soil characteristics on active and inactive landslides are the result of differences in geologic parent material.

Another important conclusion from this research is that prediction of landslide occurrence may be less important for this region than an assessment of landslide frequency and re-occurrence potential. Differences in soil characteristics, especially related to soil stability, were most evident when comparing active to inactive slides, and little difference existed between inactive landslide soils and soils on stable slopes. Only clay content and COLE, especially in the C horizon, were noticeably different on landslide soils versus stable soils. Both COLE and clay content was higher for C horizons on landslides than on adjacent stable slopes, but these differences were more dramatic when comparing active and inactive landslides (Table 17). Additionally, some soil characteristics that contribute to slope instability were more commonly observed on stable slopes than on inactive landslides (e.g. COLE in the C horizon = 0.049 on stable slopes compared to 0.042 on inactive landslides, Table 17). Also, several soil characteristics that were noticeably different on landslide slopes compared to stable slopes and active landslides versus inactive landslides, including C horizon clay content, COLE for the C horizon and presence of buried soils, did not exhibit the same pattern when comparing inactive landslides to stable slopes.

Table 17 – Clay content and COLE - landslides and stable slopes

	Clay % - C horizon	**COLE – C horizon**
Landslide soils	34%	0.066
Stable slope soils	31%	0.049
Difference	**3%**	**0.017**
Active landslide soils	43%	0.081
Inactive landslide soils	37%	0.042
Difference	**7%**	**0.039**

The evidence presented here shows little difference in soil characteristics related to slope stability on landslides versus stable slopes, with soils on some inactive landslides having characteristics related to slope stability more strongly expressed than comparable stable slopes. This finding suggests that stable slopes in the quadrangle may be just as or more prone to landsliding than inactive, stabilized landslides are prone to a re-occurring failure, meaning that any location in the quadrangle may be subject to slope failure. Therefore, the challenge in the study area may not be determining whether a landslide will occur or where, as all regions seems equally prone to landslide occurrence, but rather the degree of landslide activity, frequency and/or likelihood of re-occurrence for specific localities in the region.

This research has led to the generation of several interesting hypotheses that necessitate further testing. First, any additional research regarding mechanisms of slope failure in the study area should focus on clay mineralogy and its relationship to parent material. Conclusions from this research show that soil charcteristics on active landslides, especially those related to clay type and behavior, may be the result of the geologic parent material in which the soil forms. Therefore, a more detailed study on the relationship between landslide activity and geology is in order. In order to test this hypothesis, a stratified sampling strategy based on geology and landslide activity (active or inactive) could be employed to obtain an adequate sample size and a representative sample considering geology. Both rock and soil samples would be collected for each landslide sampled, and XRD analysis of the samples could help determine if clay characteristics of soils on landslides are inherited from the geologic parent material. Additionally, soil and rock mineralogical analysis would provide an understanding of weathering pathways for landslide soils and the relationship of weathering processes to landslide re-occurrence in the study area.

Additionally, a better understanding of weathering processes at work on these landslides and how these processes affect slope stability would be beneficial. The presence of illite interstratified with montmorillonite indicates that many of the soils on landslides in Camp Davis Quadrangle are in an intermediary state in the weathering process. Additionally, the dominance of illite interstratified with montmorillonite and montmorillonite on active landslides compared to abundant illite and kaolinite on inactive landslides indicate that the place of clay minerals in the weathering cycle may be related to slope stability in the study area (Matsukura & Mizuno 1986). The differences in clay mineralogy on active landslides compared to inactive landslides could be indicative of differences in geologic parent material and the affect of weathering on geology in the study area, where active landslides occur on slopes composed primarily of severely weathered landslide colluvium compared to inactive landslides occurring in residual rock material. Additional XRD analysis of landslides in the quadrangle and quantification of the abundance of clay minerals identified in active versus inactive landslide soils would provide the data necessary to better understand the weathering processes at work on soils in Camp Davis Quadrangle and their relation to slope stability and geology.

A second interesting extension of this study involves improving the system presented here for categorizing landslide activity via the addition of quantitative metrics of landslide frequency to the decision tree. The generation of several additional data sets would be necessary for this improvement. Dendrochronology of pistol-butted trees, radiocarbon dating of buried soils and/or optically stimulated luminescence dating of sediments could be used to quantify the timing and frequency of landslide occurrence in the quadrangle. These data could then be utilized to quantify the time required for soil forming processes to work in order to create various soil morphological features. For example, if the date of landslide occurrence for a set of active landslides based on radiocarbon dates and dendrochronological work ranged from 300 to 500 years, and B horizons were not observed on any of these active landslide soil profiles, we could deduce that B horizons require greater than 500 years of stability for development in this region. This quantitative knowledge could be added to the categorization system presented here to provide additional detail and understanding of the active landslide category. This type of data could additionally allow further division of the active landslide category into recently and historically active landslides based on an understanding of what various soil morphological characteristics reveal about landslide age/frequency.

Third, vegetation on landslides was not considered in this study. Based on qualitative observations in the field, this is an area ripe for additional study. It was evident that vegetational patterns existed when comparing landslides to adjacent stable slopes and active landslides to inactive landslides. A quantitative study of vegetational communities on landslides in Camp Davis Quadrangle could be combined with the above-mentioned techniques for dating landslide occurrence to develop an appreciation for vegetation successional patterns on landslides in this region. These data could also provide yet another metric of landslide activity and further improve the categorization system presented here.

Fourth, more sophisticated statistical analysis, especially development of a quantitative method for predicting landslide re-occurrence, is desirable. Personnel at the U.S. Forest Service expressed an interest in a quantitative measure for landslide re-occurrence based on soil data. The original intent of this study was to develop such a model based on soil data collected in the field. However, an inadequate sample size was obtained for this sort of predictive analysis. Therefore, the focus of the study changed to developing a more intimate understanding of the specifics of landslide activity in Camp Davis Quadrangle, especially related to soils. This research has shown that landslide re-occurrence is probably more important for this study area than prediction of landslide occurrence, and has additionally provided an initial understanding of the soil characteristics most likely related to landslide activity and re-occurrence. While statistical tests did not find any soil properties to be significantly related to landslide activity, the results of the statistical analysis did provide a better understanding of the soil properties more probably related to landslide activity in the quadrangle. Patterns only evident as trends here may prove to be significantly related to landslide activity with consideration of a larger sample size.

The most important improvement that could be made to this study and a necessary step for any future research is the generation of a larger sample. In this study, I aimed to obtain a sample size of 40 landslides (20 active and 20 inactive slides); however, this was not achieved due to limited time in the field, weather conditions and underestimating the time needed to travel to each slide and dig soil pits. In order to easily utilize parametric statistical methods and obtain a more representative picture of landslide occurrence in the quadrangle, a sample of at least

60 landslides (approximately 30 active and 30 inactive slides) and 60 adjacent stable slopes would be appropriate. In order to develop a model for predicting landslide re-occurrence utilizing a method such as logistic regression, an even larger sample size (80-120 landslides) would be necessary (Harrell 2001). While the time required to study the additional landslides necessary to obtain this sample size would be sizeable (approximately six to eight weeks assuming fair weather and a full-time, two-person team in the field), the improvements to data quality and flexibility in data analysis would be worth the added effort.

6.2 Conclusion

Internal and external factors related to slope stability and present in the region of BTNF and Camp Davis Quadrangle work together to create unstable slopes. Additionally, buried soils, hummocky topography, visible vegetated and unvegetated scarp scars and recent slides occurring where past landslides occurred are evidence that mass wasting in this region has occurred throughout recent geologic time. In the Camp Davis Quadrangle, mass wasting is one of the most important geomorphic processes affecting the landscape. As population, development and economic demands continue to increase in this region, a better understanding of the factors that cause slope instability will be necessary to be sure that human impact does not trigger dangerous and sometimes life-threatening mass movements.

Understanding landslides and their impact on operations and infrastructure in BTNF is an important challenge. The Teton National Forest Soil Survey includes stability ratings for soil map units in consideration of the impact slope stability has on timber management and road building and development. These ratings are qualitative assessments of stability based on observed soil characteristics and evidence of known mass movement. The only information provided by the stability rating is a qualitative classification of soil stability for each map unit as stable, marginally stable, marginally unstable or unstable.

The agency currently performs only qualitative assessments of possible instability by observing sites for the presence of landslide indicators and utilizing qualitative stability ratings from the 1985 soil survey. This research provides BTNF with a more detailed understanding of landslide occurrence in Camp Davis Quadrangle and an extensive set of soil properties and landscape features observable in the field indicative of active landsliding. More specifically, soil stickiness, plasticity, COLE, clay content and percent gravel in the C horizon have been shown to be strongly related to active landsliding. Field investigations of potentially hazardous hillslopes this include these metrics would improve existing methods for assessing slope stability. While the generation of a quantitative measure of landslide potential was not possible for this study, several suggestions have been provided on which to focus future landslide research in order to achieve that ultimate goal.

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APPENDIX 1

Landslide/Landscape observation worksheets

Landslide #1

AREA 455 LANDSLIDE 1

GENERAL LANDSCAPE OBSERVATIONS

General Description
mbsl per WSGS landslide database. A complex of multiple slides/slumps off slope toward Poisoncreek

Bedrock Geology Camp Davis Formation
_X_ consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits _X_ landslide deposits

Drainage and Erosion
___ widely spaced drainage _X_ closely spaced drainage
_X_ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
_X_ long, smooth gullies (clay) _X_ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 456 or 340
___ distinct boundaries _X_ fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
___ sharp ___ smooth _X_ vague ___ not evident
___ unvegetated ___ partly vegetated _X_ vegetated

Lateral Scarp
___ sharp ___ smooth ___ vague _X_ not evident
___ unvegetated _X_ partly vegetated ___ vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide _X_ no lateral drainage

Morphology and Drainage
___ undrained depressions ___ drained and undrained depressions _X_ no undrained depressions
___ hummocky topography ___ unvegetated cracks ___ ponds/marshes _X_ smooth, rolling topography
_X_ deranged drainage network ___ integrated drainage

Vegetation
___ absent/sparse ___ younger than adjacent ___ different type than adjacent ___ same age as adjacent
_X_ same type as adjacent

Toe
___ dammed drainage _X_ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
_X_ gradiational ___ abrupt

Landslide #2

AREA 44N LANDSLIDE 2

GENERAL LANDSCAPE OBSERVATIONS

General Description
A large slump block w/repeated slumping from scarp to toe. Not mapped by WSGS.

Bedrock Geology Qls, Camp Davis
____ consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage X closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage X disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 646
X distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
X sharp ____ smooth ____ vague ____ not evident
____ unvegetated X partly vegetated ____ vegetated

Lateral Scarp
X sharp ____ smooth ____ vague ____ not evident
X unvegetated ____ partly vegetated ____ vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography X unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
____ deranged drainage network ____ integrated drainage

Vegetation
X absent/sparse ____ younger than adjacent X different type than adjacent ____ same age as adjacent
____ same type as adjacent

Toe
____ dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
____ gradiational X abrupt

Landslide #3

AREA 44N LANDSLIDE 3

GENERAL LANDSCAPE OBSERVATIONS

General Description
Large slide w/ multiple slumps off of steep slopes to Little Horse Creek

Bedrock Geology Qls and Underlying Kb, Kal, Kg
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage X closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage X disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 646
X distinct boundaries ____ fuzzy boundaries

Vegetation
Description____

LANDSLIDE DESCRIPTION

Head Scarp
X sharp ____ smooth ____ vague ____ not evident
X unvegetated ____ partly vegetated ____ vegetated

Lateral Scarp
X sharp ____ smooth ____ vague ____ not evident
X unvegetated ____ partly vegetated ____ vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography X unvegetated cracks X ponds/marshes ____ smooth, rolling topography
X deranged drainage network ____ integrated drainage

Vegetation
____ absent/sparse X younger than adjacent X different type than adjacent ____ same age as adjacent
X same type as adjacent

Toe
X dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
____ gradiational X abrupt

Landslide #5

AREA 42S/43S LANDSLIDE 5

GENERAL LANDSCAPE OBSERVATIONS

General Description
Slump block in heavily forested area. Slopes and toes to Palmer Creek which has steeply incised and down cut geologic formations. Classified as part of [illegible] by WSGS.

Bedrock Geology Qls over Kal, Kf
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage X closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage X disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 610
X distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
X sharp ____ smooth ____ vague ____ not evident
X unvegetated ____ partly vegetated ____ vegetated

Lateral Scarp
X sharp ____ smooth ____ vague ____ not evident
X unvegetated ____ partly vegetated ____ vegetated
X streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography X unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
X deranged drainage network ____ integrated drainage

Vegetation
____ absent/sparse X younger than adjacent X different type than adjacent ____ same age as adjacent
____ same type as adjacent

Toe
X dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
____ gradiational X abrupt

Landslide #7

AREA 42N/43N   LANDSLIDE 7

GENERAL LANDSCAPE OBSERVATIONS

General Description
mblsl @ Hoback Jct. - section along road

Bedrock Geology Qls over Kbr
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage X closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage X disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 646
____ distinct boundaries ____ fuzzy boundaries

Vegetation
Description____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp ____ smooth X vague ____ not evident
____ unvegetated X partly vegetated ____ vegetated

Lateral Scarp
____ sharp ____ smooth X vague ____ not evident
____ unvegetated X partly vegetated ____ vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography X unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
X deranged drainage network ____ integrated drainage

Vegetation
X absent/sparse X younger than adjacent X different type than adjacent ____ same age as adjacent
____ same type as adjacent

Toe
X dammed drainage X modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation DISRUPTS ROAD STABILITY

Soil Tones
X gradiational ____ abrupt

Landslide #9

AREA 455 LANDSLIDE 9

GENERAL LANDSCAPE OBSERVATIONS

General Description
Part of mb/sl/mf/ms classification by WSGS? New slide! Off of ridge toward drainage

Bedrock Geology Qls / Kbr / Kg
_X_ consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits _X_ landslide deposits

Drainage and Erosion
___ widely spaced drainage _X_ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage _X_ disordered drainage
_X_ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BINF 207 + 618
_X_ distinct boundaries ___ fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
_X_ sharp ___ smooth ___ vague ___ not evident
_X_ unvegetated ___ partly vegetated ___ vegetated

Lateral Scarp
_X_ sharp ___ smooth ___ vague ___ not evident
_X_ unvegetated ___ partly vegetated ___ vegetated
_X_ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions _X_ drained and undrained depressions ___ no undrained depressions
_X_ hummocky topography _X_ unvegetated cracks _X_ ponds/marshes ___ smooth, rolling topography
_X_ deranged drainage network ___ integrated drainage

Vegetation
_X_ absent/sparse ___ younger than adjacent ___ different type than adjacent ___ same age as adjacent
___ same type as adjacent INTACT VEG. THAT SLID?

Toe
_X_ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
___ gradiational _X_ abrupt

Landslide #12

AREA 42N LANDSLIDE 12

GENERAL LANDSCAPE OBSERVATIONS

General Description Hoback to Jackson slide. Described as mb/sl by WSGS. Locality "Ross Plateau" locally

Bedrock Geology Ql and Qt over Kal

X consolidated sedimentary X glacial deposits ___ unconsolidated sedimentary
X alluvial deposits X landslide deposits

Drainage and Erosion

___ widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones

Description BTNF 618
X distinct boundaries ___ fuzzy boundaries

Vegetation

Description ___

LANDSLIDE DESCRIPTION

Head Scarp

___ sharp ___ smooth ___ vague X not evident
___ unvegetated ___ partly vegetated ___ vegetated

Lateral Scarp

___ sharp ___ smooth ___ vague X not evident
___ unvegetated ___ partly vegetated ___ vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage

___ undrained depressions X drained and undrained depressions ___ no undrained depressions
X hummocky topography X unvegetated cracks ___ ponds/marshes ___ smooth, rolling topography
X deranged drainage network ___ integrated drainage ROAD AFFECTED

Vegetation

___ absent/sparse X younger than adjacent X different type than adjacent ___ same age as adjacent
___ same type as adjacent pistol-butted aspen, downed trees

Toe

X dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Landslide #13

AREA 45S LANDSLIDE 13

GENERAL LANDSCAPE OBSERVATIONS

General Description
Classified as part of the large blsl/ms/mf by WSGS

Bedrock Geology Qls
____ consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage ____ closely spaced drainage
X tree-like drainage ____ parallel drainage ____ trellis drainage X disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 610
X distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated

Lateral Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide X no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography ____ unvegetated cracks X ponds/marshes ____ smooth, rolling topography
X deranged drainage network ____ integrated drainage

Vegetation
____ absent/sparse X younger than adjacent X different type than adjacent X same age as adjacent
X same type as adjacent MATURE CONIFERS ON B UNTOUCHED? NOT SLID?

Toe
X dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
X gradiational ____ abrupt

Landslide #14

AREA 42N LANDSLIDE 14

GENERAL LANDSCAPE OBSERVATIONS

General Description
mapped as mb/sl/ms/mf by WSGS. Large slump block with multiple displacements at Hoback Junction

Bedrock Geology Qls, Kb
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage ____ closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage ____ disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 646
____ distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp X smooth ____ vague ____ not evident Difficult to discern, multiple?
____ unvegetated X partly vegetated ____ vegetated

Lateral Scarp
____ sharp X smooth ____ vague ____ not evident
____ unvegetated X partly vegetated ____ vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions ____ drained and undrained depressions X no undrained depressions
X hummocky topography X unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
____ deranged drainage network ____ integrated drainage

Vegetation
X absent/sparse ____ younger than adjacent X different type than adjacent ____ same age as adjacent
X same type as adjacent

Toe
____ dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
X gradiational ____ abrupt

Landslide #15

AREA 43N LANDSLIDE 15

GENERAL LANDSCAPE OBSERVATIONS

General Description
Small slump in steep, rocky soil just past Hoback Jct. mblsl. Not mapped by USGS.

Bedrock Geology Qls, Kbr
X consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits X landslide deposits

Drainage and Erosion
___ widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 456
X distinct boundaries ___ fuzzy boundaries

Vegetation
Description sage 15% indian grass 45% balsalm root 25% bare ground/rock 15% - A
indian grass - 45% balsalm root 20% bare ground/rock - 35% - B

LANDSLIDE DESCRIPTION

Head Scarp
X sharp ___ smooth ___ vague ___ not evident
X unvegetated ___ partly vegetated ___ vegetated

Lateral Scarp
X sharp ___ smooth ___ vague ___ not evident
X unvegetated ___ partly vegetated ___ vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions X drained and undrained depressions ___ no undrained depressions
X hummocky topography X unvegetated cracks ___ ponds/marshes ___ smooth, rolling topography
___ deranged drainage network ___ integrated drainage

Vegetation
X absent/sparse ___ younger than adjacent X different type than adjacent ___ same age as adjacent
X same type as adjacent

Toe
___ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
___ gradiational X abrupt

Landslide #16

AREA 44N LANDSLIDE 16

GENERAL LANDSCAPE OBSERVATIONS

General Description small slump to west of trail across Camp creek saddle. classified as mrs/mf by WSGS, but individual slump not classified.

Bedrock Geology Camp Davis

X consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits ___ landslide deposits

Drainage and Erosion

X widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones

Description BTNF 646
X distinct boundaries ___ fuzzy boundaries

Vegetation

Description ___

LANDSLIDE DESCRIPTION

Head Scarp

X sharp ___ smooth ___ vague ___ not evident
X unvegetated ___ partly vegetated ___ vegetated

Lateral Scarp

X sharp ___ smooth ___ vague ___ not evident
X unvegetated ___ partly vegetated ___ vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide X no lateral drainage

Morphology and Drainage

___ undrained depressions ___ drained and undrained depressions X no undrained depressions
___ hummocky topography X unvegetated cracks ___ ponds/marshes X smooth, rolling topography
X deranged drainage network ___ integrated drainage

Vegetation

X absent/sparse X younger than adjacent X different type than adjacent ___ same age as adjacent
X same type as adjacent

Toe

___ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones

___ gradiational X abrupt

Landslide #17

AREA 445 LANDSLIDE 17

GENERAL LANDSCAPE OBSERVATIONS

General Description
Large slide with multiple slumps off ridge. Classified as mblsl/ms/mf by WSGS.

Bedrock Geology Qls over Kbr
___ consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits _X_ landslide deposits

Drainage and Erosion
_X_ widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 610
___ distinct boundaries _X_ fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
___ sharp _X_ smooth ___ vague ___ not evident
___ unvegetated ___ partly vegetated _X_ vegetated

Lateral Scarp
___ sharp ___ smooth ___ vague _X_ not evident
___ unvegetated ___ partly vegetated _X_ vegetated
_X_ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions ___ drained and undrained depressions _X_ no undrained depressions
___ hummocky topography ___ unvegetated cracks ___ ponds/marshes _X_ smooth, rolling topography
_X_ deranged drainage network ___ integrated drainage

Vegetation
___ absent/sparse _X_ younger than adjacent _X_ different type than adjacent ___ same age as adjacent
___ same type as adjacent

Toe
___ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
_X_ gradiational ___ abrupt

Landslide #18

AREA 445 LANDSLIDE 18

GENERAL LANDSCAPE OBSERVATIONS

General Description
Large landslide with benches, multiple slumps. Classified as mb/sl/ms/mF by WSGS.

Bedrock Geology Qls over Kbr
X consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits X landslide deposits

Drainage and Erosion
___ widely spaced drainage X closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) X u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 610 on slide
___ distinct boundaries X fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
___ sharp X smooth ___ vague ___ not evident
___ unvegetated ___ partly vegetated X vegetated

Lateral Scarp
___ sharp X smooth ___ vague ___ not evident
___ unvegetated ___ partly vegetated X vegetated
___ streams at edge X small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions ___ drained and undrained depressions X no undrained depressions
___ hummocky topography ___ unvegetated cracks ___ ponds/marshes X smooth, rolling topography
___ deranged drainage network ___ integrated drainage

Vegetation
___ absent/sparse X younger than adjacent X different type than adjacent ___ same age as adjacent
___ same type as adjacent

Toe
___ dammed drainage X modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
X gradiational ___ abrupt

Landslide #19

AREA 44S LANDSLIDE 19

GENERAL LANDSCAPE OBSERVATIONS

General Description
Small slump near landslide #9. Classified as part of mblsl/ms/mf by WSGS.
Young aspen growth in slump, mature conifers above scarp.

Bedrock Geology Qls, Kbr
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage X closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage ____ disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 618
____ distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp X smooth X vague ____ not evident
____ unvegetated ____ partly vegetated X vegetated

Lateral Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions ____ drained and undrained depressions X no undrained depressions
X hummocky topography ____ unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
____ deranged drainage network ____ integrated drainage

Vegetation
____ absent/sparse X younger than adjacent X different type than adjacent ____ same age as adjacent
____ same type as adjacent pistol-butted trees

Toe
____ dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
X gradiational ____ abrupt

Landslide #20

AREA 44S LANDSLIDE 20

GENERAL LANDSCAPE OBSERVATIONS

General Description
part of large mblsl/ms/af from Mt. Ann Ridge to ranger station

Bedrock Geology Qls/Kbr
X consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits X landslide deposits

Drainage and Erosion
___ widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 618
___ distinct boundaries ___ fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
___ sharp X smooth X vague ___ not evident
___ unvegetated ___ partly vegetated X vegetated

Lateral Scarp
___ sharp ___ smooth ___ vague X not evident
___ unvegetated ___ partly vegetated X vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions ___ drained and undrained depressions X no undrained depressions
X hummocky topography ___ unvegetated cracks ___ ponds/marshes ___ smooth, rolling topography
___ deranged drainage network ___ integrated drainage

Vegetation
___ absent/sparse ___ younger than adjacent X different type than adjacent (ASPEN + SAGE) ___ same age as adjacent
X same type as adjacent

Toe
___ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
___ gradiational ___ abrupt

Landslide #21

AREA 44N LANDSLIDE 21

GENERAL LANDSCAPE OBSERVATIONS

General Description
Small, slump w/ well-defined scarp on Camp Davis (?); mapped as bls/mf by WSGS

Bedrock Geology Qls/Tcd/Kal
X consolidated sedimentary ___ glacial deposits ___ unconsolidated sedimentary
___ alluvial deposits X landslide deposits

Drainage and Erosion
___ widely spaced drainage ___ closely spaced drainage
___ tree-like drainage ___ parallel drainage ___ trellis drainage ___ disordered drainage
___ long, smooth gullies (clay) ___ u-shaped gullies (silt) ___ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 456 & 484
___ distinct boundaries ___ fuzzy boundaries

Vegetation
Description ___

LANDSLIDE DESCRIPTION

Head Scarp
___ sharp X smooth ___ vague ___ not evident
___ unvegetated X partly vegetated ___ vegetated

Lateral Scarp
___ sharp X smooth ___ vague ___ not evident
___ unvegetated X partly vegetated ___ vegetated
___ streams at edge ___ small tributaries to lateral streams ___ tributaries on slide ___ no lateral drainage

Morphology and Drainage
___ undrained depressions ___ drained and undrained depressions X no undrained depressions
X hummocky topography X unvegetated cracks ___ ponds/marshes ___ smooth, rolling topography
___ deranged drainage network ___ integrated drainage

Vegetation
___ absent/sparse X younger than adjacent ___ different type than adjacent ___ same age as adjacent
X same type as adjacent

Toe
___ dammed drainage ___ modified by stream ___ not modified by stream
___ overlapped by modern floodplain ___ overlapped by evidence of glaciation

Soil Tones
___ gradiational ___ abrupt

Landslide #22

AREA 44S LANDSLIDE 22

GENERAL LANDSCAPE OBSERVATIONS

General Description
part of large mlbls/nf/ms mapped by WSGS from ridge to ranger station

Bedrock Geology Kbr/Qls
X consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage ____ closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage ____ disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 610
____ distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated

Lateral Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions X drained and undrained depressions ____ no undrained depressions
X hummocky topography ____ unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
____ deranged drainage network ____ integrated drainage water hit @ 2ft. in soil pit

Vegetation
____ absent/sparse X younger than adjacent X different type than adjacent ____ same age as adjacent
____ same type as adjacent

Toe
____ dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
____ gradiational ____ abrupt

Landslide #23

AREA 445 LANDSLIDE 23

GENERAL LANDSCAPE OBSERVATIONS

General Description
Part of large mblsl/ms/mf from ridge of Mt. Anne to ranger station

Bedrock Geology Qls/Kbr
____ consolidated sedimentary ____ glacial deposits ____ unconsolidated sedimentary
____ alluvial deposits X landslide deposits

Drainage and Erosion
____ widely spaced drainage ____ closely spaced drainage
____ tree-like drainage ____ parallel drainage ____ trellis drainage ____ disordered drainage
____ long, smooth gullies (clay) ____ u-shaped gullies (silt) ____ short, v-shaped gullies (sand)

Soil Tones
Description BTNF 618
____ distinct boundaries ____ fuzzy boundaries

Vegetation
Description ____

LANDSLIDE DESCRIPTION

Head Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated

Lateral Scarp
____ sharp ____ smooth ____ vague X not evident
____ unvegetated ____ partly vegetated X vegetated
____ streams at edge ____ small tributaries to lateral streams ____ tributaries on slide ____ no lateral drainage

Morphology and Drainage
____ undrained depressions ____ drained and undrained depressions X no undrained depressions
X hummocky topography X unvegetated cracks ____ ponds/marshes ____ smooth, rolling topography
____ deranged drainage network ____ integrated drainage

Vegetation
____ absent/sparse ____ younger than adjacent X different type than adjacent ____ same age as adjacent
X same type as adjacent

Toe
____ dammed drainage ____ modified by stream ____ not modified by stream
____ overlapped by modern floodplain ____ overlapped by evidence of glaciation

Soil Tones
____ gradiational ____ abrupt

APPENDIX 2 - Landslide Plates

Landslide #1 - Hoback Canyon

Stable site soil profile

Landslide site soil profile

Landslide #2 - Camp Creek

Stable site

Landslide site soil profile

Stable site soil profile

Landslide #3 - Little Horse Creek

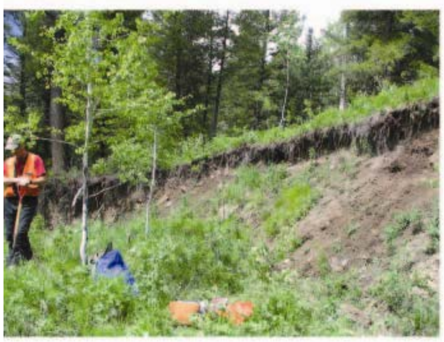
Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #5 - Palmer Creek



Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #7 - Hoback Junction #1

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #9 - Willow Creek Trail/Rim Rock Road

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #12 - Ross Plateau

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #13 - Willow Creek/Ranger Station

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #14 - Hoback Junction #2

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #15 - Hoback Junction/Hoback Canyon

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #16 - Camp Creek Saddle

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #17 - Camp Davis/Willow Creek #1

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #18 - Camp Davis/Willow Creek #2

Landslide site

Landslide site soil profile

Landslide #19 - Rim Rock Road

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #20 - Willow Creek/Mt. Ann

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #21 - Hoback Canyon/Camp Creek

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #22 - Willow Creek Ridge

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

Landslide #23 - Willow Creek Trail/Ridge

Stable site

Landslide site

Stable site soil profile

Landslide site soil profile

APPENDIX 3 - Soil Field Observations

			Horizonation		Color	Texture		Rock Fragments		Structure			Consistence		Roots			
Local Area	Slide #	Sample	Horizon	Depth (in)	Moist	Texture	Clay Content	Kind	Percent	Grade	Size	Type	Stickiness	Plasticity	Quantity	Size	Location	Effervesence
Hoback Canyon	1	a	A	0-15	10YR 4/3	GR SL	10%	G	20%	2	F	GR	SS	PS	2	VF-F	T	mildly
															1	M	T	
			AC	15-20	10YR 4/4	VGR SL	10%	G	50%	2	M	GR	SS	PS	2	VF-F	T	moderately
															2	M	T	
			C	20-30+	10YR 5/4	XGR SL	15%	G	80%	2	M	GR	S	PS	1	M	T	violently
Hoback Canyon	1	b	O	0-1														
			A	1-8	10YR 2/2	GR SL	10%	G	25%	2	F-M	GR	SO	PS	3	VF-F	T	na
															2	M	T	
			AC	8-28	10YR 2/2	VGR SCL	20%	G	50%	2	CO	GR	SS	PS	2	VF-F	T	na
			C	28-30+	7.5YR 3/2	XGR CL	30%	G	65%	1	Vf-f	SBK	S	PS	1	VF-f	T	na
															1	M	T	
Camp Creek	2	a	O	0-2	10YR 2/2										3	VF	T	
			A	2-12	10YR 2/2	SIL	<10%	G	10%	2	mis-	GR	SO	P	3	VF	T	mildly
			Bt	12-22	7.5YR 4/3	VGR SCL	25%	G	60%	1	sing	SBK	S	P	2	VF-f	T	mildly
			BC	22-40	7.5YR 4/4	XGR SCL	<20%	G	60%+	1	dat	SBK	SO	P	1	VF-F	R	mildly
			C	40-44+	7.5YR 4/4	SCL	15%	G	60%+			M	SS	P				violently
Camp Creek	2	b	A	0-3	10YR 2/2	SCL	22%	G	20%	2	F	GR	SS	PS	3	F	T	mildly
			C1	3+	10YR 4/6	SICL	35%	G	35%	3	M	SBK	S	P	1	F	P	violently
			C2	0+	5Y 5/3	SIC	50%	G	15%	3	F	SBK	S	VP	1	VF	P	mildly
Little Horse Creek	3	a	A	0-4	10YR 3/2	L	20%	G	25%	3	VF	SBK	SO	PS	3	VF-F	T	na
			Bt	4-10	10YR 4/2	SIC	50%	G	10%	3	F	SBK	S	P	2	F	T	mildly
			C	10-36+	5Y 5/3	C	>50%	CB	10%			M	SO	P	1	VF	T	violently
															1	M	T	
Little Horse Creek	3	b	A	0-4	10YR 4/3	L	15%	G	20%	2	F	GR	SS	PO	2	F	C	mildly
			AC	4-18	10YR 5/3	CL	35%	G	40%	3	F	SBK	VS	PS	2	F	P	moderately
			C	18-30+	10YR 5/4	C	60%	G	50%			M	SS	P	1	F	T	moderately
Palmer Creek	5	a	Oi	0-2	needles and duff													
			Oe	2-4	mud, decomposing Oi													
			A	4-8	10YR 4/1	CB L	18%	CB	15%	2	M	GR	S	PS	3	VF-F	T	na
								G	5%						1	M	T	
			Bw	8-15	10YR 5/3	GR SIL	18%	CB	5%	3	M	GR	VS	P	3	VF-F	T	na
								G	50%						1	M	T	
			C	15-50+	10YR 5/3	VCB SIC	50%	CB	25%	2	M	SBK	S	P	1	VF-F	T	na
								G	15%						1	M	T	
Palmer Creek	5	b	A	0-3	10YR 4/2	SCL	24%	G	5%	1	M	GR	SS	PS	2	VF-F	T	mildly
			C	3-20+	10 YR 5/3	GR SIC	55%	G	20%			M	SS	VP	1	M	MAT	na
Hoback Junction #1	7	a	O	0-2	7.5 YR 2.5/3													
			A	2-5	7.5YR 2.5/2	L	15%	na	na	2	F	GR	SO	PO	3	VF-F	T	na
															3	M	T	
			AB	5-12	7.5YR 2.5/2	SIC	38%	na	na	2	F	SBK	SS	PS	3	VF-F	P	na
															1	M	T	
			Bt	12-18	10YR 3/2	C	>60%	na	na	2	F	SBK	SS	P	3	VF-F	P	na
															1	M	T	
			C	18-30+	10YR 4/2	C	>60%	na	na	2	F	SBK	SS	P	1	M	T	na
Hoback Junction #1	7	b	A	0-12	10YR 4/1	SICL	40%	na	na	3	M	SBK	SS	VP	3	VF-F	T	mildly
															2	M	T	
			AC	12-26	10YR 4/1	SIC	50%	na	na	3	CO	SBK	SS	VP	1	VF-F	T	mildly
			C	25-30+	10YR 4/1	SIC	50%	na	na	3	M	SBK	SO	P	1	VF-F	P	mildly
Willow Creek Trail/Rim Rock Rd.	9	a	O	0-1	not always present													na
			A	1-5	10YR 5/1	C	50%	G	5%	2	M	GR	SO	VP	3	VF-F	T	na
															2	M	T	
			Bt	5-20	10YR 5/2	SC	65%	na	na	3	M	SBK	SS	VP	2	F	P	na
															1	M	P	
			C	20+	10YR 6/2	SIC	60%	na	na			M	SS	VP	na	na	na	moderately
Willow Creek Trail/Rim Rock Rd.	9	b	A	0-3	10YR 4/2	SICL	40%	na	na	2	F	GR	SO	VP	2	F	T	na
			C	3-26+	10YR 5/2	C	65%	na	na			M	SO	VP	1	F	T	na
Ross Plateau	12	a	O	0-2														
			A	2-6	10YR 2/2	L	10%	na	na	3	M	GR	SS	PO	3	F	T	na
															1	M	C,T	
			Bw	6-16	10YR 3/2	VGR L	25%	G	35%	2	F	SBK	SO	PS	1	F	T	na
															3	M	T	
															2	C	T	
			C	16-30+	10YR 4/2	XGR CL	38%	G	50%	2	M	SBK	SO	P	1	M	C	na
								ST	20%						1	C	C	
Ross Plateau	12	b	Oi	0-1														
			A	1-16	10YR 4/1	CL	32%	G	15%	2	M	GR	SS	PS	1	C	T	na
															3	M	T	
															1	VF-F	T	
			Bw	16-30	10YR 4/2	CL	32%	CB	10%	1	M	SBK	S	PS		na		na
			2C	30+	10YR 5/2	VCB C	65%	G	15%			M	S	VP		na		na
								CB	35%									
Willow Creek/Ranger Station	13	a	O	0-4	10YR 3/2													
			A	4-12	10YR 3/2	SL	18%	G	5%	2	M	SBK	S	PS	3	VF-F	T	na
															2	M	T	
			AB	12-20	10YR 3/2	SIL	20%	G	5%	2	CO	SBK	S	P	2	VF-F	T	na
															2	C	P	
			Bt	20-30+	10YR 4/3	VCB SIC	45%	G	40%	2	CO	SBK	VS	VP	1	F	T	na
															1	M	T	
Willow Creek/Ranger Station	13	b	A	0-8	10YR 2/2	SL	12%	G	5%	2	M	GR	SO	PO	3	VF-F	T	na
			AC	8-14	10YR 2/2	VCB SL	15%	CB	60%	2	M	GR	SS	PO	2	M	T	na
			C	14-24+	10YR 4/2	XGR SL	15%	G	65%	2	F	SBK	VS	PO		na		na

APPENDIX 3 (continued) - Soil Field Observations

			Horizonation		Color	Texture		Rock Fragments		Structure			Consistence		Roots			
Local Area	Slide #	Sample	Horizon	Depth (in)	Moist	Texture	Clay Content	Kind	Percent	Grade	Size	Type	Stickiness	Plasticity	Quantity	Size	Location	Effervesence
Hoback Jct	14	a	A1	0-14	10YR 4/1	SCL	33%	G	10%	3	F	GR	SS	PS	2	VF-F	T	moderately
			A2	14-20	10YR 4/1	SCL	35%	G	25%	1	F	SBK	SS	PS	1	F	C	moderately
															1	M	C	
			AC	20-36	10YR 5/1	SCL	30%	G	30%	3	F	GR	SS	PO	1	F	C	violently
															1	M	C	
			C	36-40+	10YR 5/2	CL	30%	G	35%	3	M	GR	S	PO	1	F	C	violently
															1	M	C	
Hoback Jct	14	b	A	0-8	10YR 4/1	CL	35%	G	10%	2	F	GR	SS	P	1	M	C	mildly
			C	8-16+	10YR 4/1	C	45%	G	30%			M	S	P	na	na	na	moderately
Hoback Jct/Hoback Canyon	15	a	A	0-6	10YR 4/1	SL	20%	G	35%	2	F	GR	SS	PS	3	F	T	mildly
															1	C	C	
			Bt	6-22	10YR 3/2	SCL	35%	G	15%	2	M	SBK	SS	P	1	C	C	mildly
								CB	35%						1	F	P	
			C	22-26+	10YR 4/1	SC	45%	G	35%			M	S	VP	1	C	C	mildly
Hoback Jct/Hoback Canyon	15	b	A	0-8	10YR 4/2	CL	40%	G	40%	3	CO	GR	SS	VP	3	VF-F	C	moderately
			C	8-25+	10YR 4/1	C	50%	CB	20%	2	M	SBK	SS	VP	1	C	P	moderately
								G	30%						1	F	P	
Camp Creek Saddle	16	a	A	0-2	10YR 2/1	L	20%	G	10%	1	VF	GR	SO	PS	3	VF-F	T	na
			Bt	2-24	10YR 3/2	C	50%	G	15%	3	F	SBK	SS	P	3	VF-F	P	na
															2	M	T	
			C	24-36+	10YR 4/3	C	65%	G	40%	2	F	SBK	SS	VP	1	F	C	na
Camp Creek Saddle	16	b	A	0-3	10YR 2/2	CL	35%	G	5%	1	F	GR	SS	P	3	VF-F	T	na
			C	3-30+	10YR 5/3	C	65%	G	5%			M	S	VP	na	na	na	na
Camp Davis/Willow Creek #1	17	a	O	0-1														
			A	1-4	10YR 2/1	SL	15%	G	10%	2	F	GR	SO	PO	3	V-F	F, T	na
															3	M	C	
			Bt	4-12	10YR 4/2	CL	30%	G	35%	2	F	SBK	S	PO	1	F	P	na
								CB	25%						1	C	T	
			C	12-30+	10YR 5/3	SCL	35%	G	40%			M	S	PS	na	na	na	na
								CB	35%									
Camp Davis/Willow Creek #1	17	b	A	0-8	10YR 2/1	SL	10%	G	20%	2	F	GR	SO	PO	3	VF-F	F, T	na
															1	M	T	
			AC	8-14	10YR 4/2	SL	15%	G	65%	1	F	SBK	SS	PO	2	F	T	na
															2	M	C, T	
			C	14-24+	10YR 4/1	SL	15%	G	75%			M	VS	PO	1	M	C, T	na
Camp Davis/Willow Creek #2	18	b	A	0-8	10YR 3/2	CL	30%	G	10%	3	F	GR	SO	PO	3	VF-F	T	na
			Bt	8-20	10YR 2/1	SICL	30%	G	5%	2	M	SBK	SS	PO	1	C	P	na
															1	F	P	
			C	20-32+	10YR 3/3	SIC	45%	G	25%			M	VS	PO	1	F	T	na
															1	M	T	
Rim Rock Rd.	19	a	O	0-2														
			A	2-16	10YR 3/1	SC	40%	na	na	2	F	GR	SO	P	3	VF-F	T	mild
															1	M	T	
			Bw	16-24	10YR 4/2	C	50%	G	5%	1	F	SBK	SS	VP	1	F	P	na
															1	M	T	
			BC	24-36	10YR 4/2	SIC	40%	G	10%	2	M	GR	S	P	1	F	T	na
			C	36-40+	5Y 5/6	C	65%	na	na			M	SO	VP	1	F	C	moderately
Rim Rock Rd.	19	b	O	0-1														na
			A	1-10	10YR 2/2	L	25%	G	5%	2	F	GR	SO	PS	3	VF-F	T	na
															1	M	T	
			C	10-24+	10YR 4/3	SIC	50%	G	40%			M	SS	P	na	na	na	na
								CB	20%									
Willow Creek/Mt. Ann	20	a	A	0-4	10YR 3/3	SL	10%	G	10%	2	F	GR	SO	PO	3	VF-F	T	na
															2	M	C	
			Bt	4-16	10YR 5/4	CL	35%	G	45%	2	F	SBK	SS	P	1	F	P	na
			C	16-24+	10YR 5/4	C	55%	G	5%			M	SS	VP	na	na	na	na
								CB	15%									
Willow Creek/Mt. Ann	20	b	A	0-14	10YR 2/2	SL	10%	G	10%	2	F	GR	SS	PS	2	F	T	na
			C	14-24+	10YR 5/3	SIC	50%	G	20%			M	S	P	1	M	C	na
								CB	40%									
Hoback Canyon/Camp Creek	21	a	O	0-1														
			A	1-6	10YR 2/2	SL	15%	G	50%	2	F	GR	SS	PS	3	VF-F	T	violently
															2	M	T	
															1	C	C	
			Bw	6-15	10YR 4/2	SCL	35%	G	40%	1	M	SBK	SS	P	2	VF-F	C	violently
								CB	20%						1	C	C	
			C	15-28+	10YR 5/3	CL	35%	G	40%	2	M	GR	S	P	1	F	C	moderately
								CB	30%									
Hoback Canyon/Camp Creek	21	b	A	0-18	10YR 5/1	CL	30%	G	65%	3	F	GR	SS	PS	3	VF-F	T	violently
			C	18-28+	10YR 6/2	SCL	30%	G	20%	3	M	GR	SS	PS	1	F	C	moderately
								CB	15%									
Willow Creek Ridge	22	a	O	0-2														na
			A	2-12	10YR 4/2	L	20%	G	5%	3	F	GR	SO	PS	1	F	T	na
															2	M	T	
			Bt	12-30	10YR 3/3	CL	35%	G	20%	2	M	SBK	SS	PS	1	F	P	na
															3	M	C	
			C	30-40+	10YR 4/3	C	40%	na	na	2	M	SBK	S	PS	1	C	P	na
Willow Creek Ridge	22	b	A	0-11	10YR 2/2	L	25%	na	na	3	M	GR	SO	PS	3	VF-F	T	na
															1	C	T	
			C	11-24+	10YR 6/2	C	50%	G	15%	2	M	SBK	SS	VP	1	M	T	na
								CB	40%						1	C	T	
								ST	20%									
Willow Creek Trail/Ridge	23	a	A	0-12	10YR 3/2	L	10%	G	10%	3	M	GR	SS	PO	2	VF-F	T	na
															2	M	T	
															1	C	T	
			C	12-24+	10YR 4/2	L	20%	G	40%	2	F	SBK	S	PS	2	M	T	na
								CB	25%						2	C	T	
Willow Creek Trail/Ridge	23	b	O	0-5														na
			A	5-15	10YR 3/2	CL	32%	G	15%	3	M	GR	SS	PS	3	VF-F	T	na
															3	M	T	
															1	C	T	
			C	15-30+	10YR 4/1	C	50%	G	20%	2	F	SBK	S	VP	1	C	T	na
								CB	30%									

APPENDIX 4 – Soil Laboratory Data

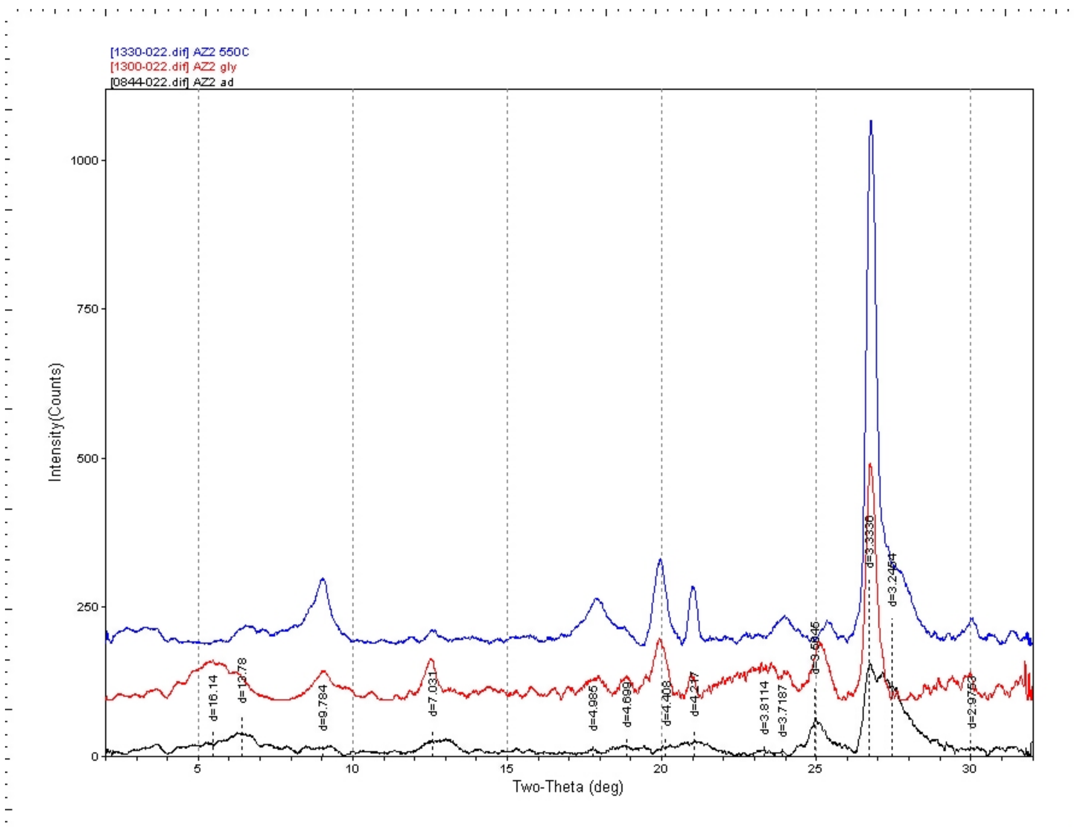
					Particle Size Analysis			Organic Matter	COLE		Mineralogy
Local Area	#	Sample	Horizon	(in)	% Clay	% Silt	% Sand	% SOM	$COLE_{rod}$	Cracks Yes/No	Clay minerals, listed in order of abundance
Hoback Canyon	1	a	A	0-15	20.2	36	43.8	5.2%	0.031	yes	
			AC	15-20	27.2	35	37.8	4.6%	0.038	no	illite, montmorillonite, kaolinite
			C	20-30+	24.2	36.5	39.3	3.9%	0.035	no	illite, montmorillonite, kaolinite
Hoback Canyon	1	b	O	0-1				no data			
			A	1-8	16.2	38	45.8	9.5%	0.046	yes	
			AC	8-28	26.2	37	36.8	6.1%	0.057	yes	
			C	28-30+	28.2	36	35.8	4.9%	0.054	no	interstratified illite/montmorillonite, illite, kaolinite
Camp Creek	2	a	O	0-2				15.5%			
			A	2-12	22.4	37	40.6	7.0%	0.034	yes	
			Bt	12-22	21.8	22	56.2	3.5%	0.025	no	
			BC	22-40	23.8	27	49.2	3.2%	0.027	yes	
			C	40-44+	25.2	46	28.8	3.1%	0.025	no	montmorillonite, illite, kaolinite
Camp Creek	2	b	A	0-3	24.8	33	42.2	6.9%	0.035	yes	
			C1	3+	33.8	28	38.2	3.5%	0.052	yes	montmorillonite, illite, kaolinite
			C2	0+	61.8	28	10.2	4.7%	0.151	yes	montmorillonite, illite, kaolinite
Little Horse Creek	3	a	A	0-4	30.8	37	32.2	7.4%	0.062	no	
			Bt	4-10	40.8	34	25.2	5.8%	0.080	no	
			C	10-36+	45.8	30	24.2	4.6%	0.072	yes	interstratified illite/montmorillonite, illite, kaolinite
Little Horse Creek	3	b	A	0-4	23.6	42	34.4	4.9%	0.045		
			AC	4-18	26.4	43	30.6	4.2%	0.049	no data	
			C	18-30+	31.6	39	29.4	3.0%	0.051		illite, interstratified illite/montmorillonite, montmorillonite, kaolinite
Palmer Creek	5	a	Oi	0-2				68.3%			
			Oe	2-4				21.2%			
			A	4-8	44.2	29	26.8	6.8%	0.056	yes	
			Bw	8-15	50.2	28	21.8	6.0%	0.061	yes	interstratified illite/montmorillonite, kaolinite
			C	15-50+	46.2	30	23.8	4.3%	0.070	yes	interstratified illite/montmorillonite, illite, kaolinite
Palmer Creek	5	b	A	0-3	39.2	33	27.8	5.0%	0.021	yes	
			C	3-20+	50.2	30	19.8	4.9%	0.074	yes	interstratified illite/montmorillonite, illite, kaolinite
Hoback Junction #1	7	a	O	0-2				22.7%			
			A	2-5	29.2	43	27.8	8.9%	0.052	yes	
			AB	5-12	35.2	41	23.8	6.0%	0.050	yes	illite, interstratified illite/montmorillonite, kaolinite
			Bt	12-18	34.2	36	29.8	4.5%	0.040	yes	Illite, kaolinite, interstratified illite/montmorillonite
			C	18-30+	30.2	32	37.8	4.1%	0.051	yes	illite, kaolinite, interstratified illite/montmorillonite
Hoback Junction #1	7	b	A	0-12	53.2	19	27.8	4.1%	0.075	yes	
			AC	12-26	59.2	19	21.8	4.6%	0.085	yes	interstratified illite/montmorillonite, illite, kaolinite
			C	25-30+	55.2	22	22.8	3.6%	0.072	yes	interstratified illite/montmorillonite, illite, kaolinite
Willow Creek Trail/Rim Rock Rd.	9	a	O	0-1				18.0%			
			A	1-5	45.2	39	15.8	11.0%	0.099	yes	
			Bt	5-20	60.2	34	5.8	7.4%	0.151	yes	interstratified illite/montmorillonite, montmorillonite, illite, kaolinite
			C	20+	50.2	44	5.8	5.0%	0.097	yes	montmorillonite, interstratified illite/montmorillonite, illite, kaolinite
Willow Creek Trail/Rim Rock Rd.	9	b	A	0-3	49.2	31	19.8	5.2%	0.085	yes	
			C	3-26+	59.2	24	16.8	7.1%	0.157	yes	montmorillonite, interstratified illite/montmorillonite, kaolinite
Ross Plateau	12	a	O	0-2				25.7%			
			A	2-6	9.2	50	40.8	11.5%	0.020	no	
			Bw	6-16	16.2	44	39.8	4.0%	0.032	no	
			C	16-30+	25.2	37	37.8	3.3%	0.030	no	montmorillonite, illite, interstratified illite/montmorillonite, kaolinite
Ross Plateau	12	b	Oi	0-1				27.8%			
			A	1-16	27.2	37	35.8	5.4%	0.061	no	
			Bw	16-30	29.2	33	37.8	4.0%	0.044	no	
			2C	30+	66.2	17	16.8	5.5%	0.106	yes	illite, interstratified illite/montmorillonite, montmorillonite, kaolinite
Willow Creek/Ranger Station	13	a	O	0-4				no data			
			A	4-12	16.7	42	41.3	6.9%	0.026	no	
			AB	12-20	21.2	37	41.8	3.9%	0.024	no	
			Bt	20-30+	30.2	31	38.8	4.0%	0.039	yes	interstratified illite/montmorillonite, illite, kaolinite
Willow Creek/Ranger Station	13	b	A	0-8	18.2	43	38.8	8.7%	0.035	no	
			AC	8-14	20.2	37	42.8	8.2%	0.036	no	
			C	14-24+	25.2	31	43.8	3.2%	0.026	no	illite, kaolinite, interstratified illite/montmorillonite

APPENDIX 4 (continued) – Soil Laboratory Data

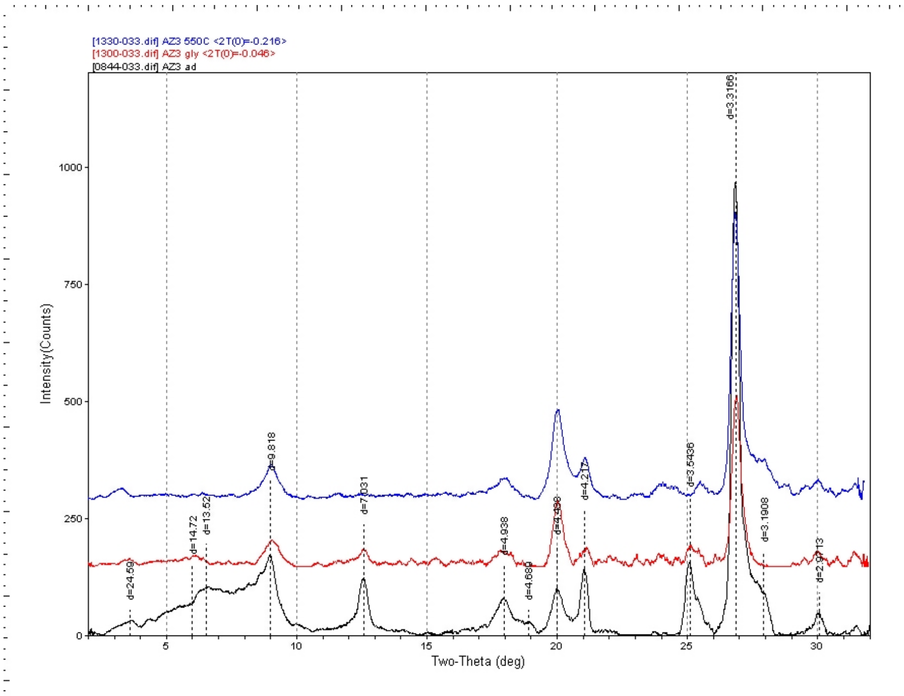
					Particle Size Analysis			Organic Matter	COLE		Mineralogy
Local Area	Slide #	Sample	Horizon	Depth (in)	% Clay	% Silt	% Sand	% SOM	$COLE_{rod}$	Cracks Yes/No	Clay minerals, listed in order of abundance
Hoback Jct #2	14	a	A1	0-14	24.2	33	42.8	4.2%	0.033	no	
			A2	14-20	24.2	35	40.8	4.0%	0.157	no	
			AC	20-36	24.2	43	32.8	3.4%	0.038	no	illite, kaolinite, interstratified illite/montmorillonite
			C	36-40+	18.2	48	33.8	2.6%	0.023	no	kaolinite, illite, interstratified illite/montmorillonite
Hoback Jct #2	14	b	A	0-8	22.2	31	46.8	4.3%	0.043	no	
			C	8-16+	27.2	30	42.8	5.2%	0.056	yes	illite, kaolinite, interstratified illite/montmorillonite
Hoback Jct/Hoback Canyon	15	a	A	0-6	19.8	19	61.2	4.7%	0.036	no	
			Bt	6-22	28.6	16	55.4	4.4%	0.054	no	
			C	22-26+	30.2	27	42.8	4.6%	0.060	no	illite, interstratified illite/montmorillonite, kaolinite
Hoback Jct/Hoback Canyon	15	b	A	0-8	27.2	7	65.8	4.6%	0.034	no	
			C	8-25+	28.2	22	49.8	4.0%	0.036	yes	illite, interstratified illite/montmorillonite, kaolinite
Camp Creek Saddle	16	a	A	0-2	21.8	43	35.2	10.7%	0.033	no	
			Bt	2-24	29.2	33	37.8	3.9%	0.039	no	
			C	24-36+	35.8	33	31.2	4.1%	0.077	no	montmorillonite, interstratified illite/montmorillonite, illite, kaolinite
Camp Creek Saddle	16	b	A	0-3	24.4	43	32.6	6.5%	0.034	no	
			C	3-30+	37.8	33	29.2	4.7%	0.080	yes	montmorillonite, interstratified illite/montmorillonite, kaolinite, illite
Camp Davis/Willow Creek #1	17	a	O	0-1				64.6%			
			A	1-4	15.2	46	38.8	20.9%	0.027	no	
			Bt	4-12	28.2	42	29.8	4.3%	0.035	no	
			C	12-30+	31.2	48	20.8	2.8%	0.034	no	illite, kaolinite, interstratified illite/montmorillonite
Camp Davis/Willow Creek #1	17	b	A	0-8	12.2	32	55.8	11.3%	no data		
			AC	8-14	15.2	26	58.8	4.4%	0.014	no	illite, kaolinite, interstratified illite/montmorillonite
			C	14-24+	14.2	15	70.8	5.7%	0.016	no	kaolinite, illite, interstratified illite/montmorillonite
Camp Davis/Willow Creek #2	18	b	A	0-8	17.8	37	45.2	7.7%	0.013	no	
			Bt	8-20	24.8	42	33.2	5.5%	0.029	no	illite, kaolinite
			C	20-32+	20.4	45	34.6	3.1%	0.000	no	illite, kaolinite, interstratified illite/montmorillonite
Rim Rock Rd.	19	a	O	0-2				55.5%			
			A	2-16	34.2	38	27.8	8.2%	0.073	no	
			Bw	16-24	32.2	39	28.8	5.2%	0.067	no	illite, montmorillonite, kaolinite, interstratified illite/montmorillonite
			BC	24-36	30.2	36	33.8	4.5%	0.067	no	illite, kaolinite, interstratified illite/montmorillonite
			C	36-40+	40.2	38	21.8	4.8%	0.064	yes	illite, kaolinite, interstratified illite/montmorillonite, montmorillonite
Rim Rock Rd.	19	b	O	0-1				17.1%			
			A	1-10	31.2	39	29.8	9.4%	0.044	yes	
			C	10-24+	36.2	29	34.8	5.8%	0.074	no	montmorillonite, illite, kaolinite, interstratified illite/montmorillonite
Willow Creek/Mt. Ann	20	a	A	0-4	19.6	40	40.4	6.9%	0.012	no	
			Bt	4-16	33.6	37	29.4	4.2%	0.040	no	
			C	16-24+	51.6	27	21.4	6.0%	0.083	no	kaolinite, montmorillonite, illite, interstratified illite/montmorillonite
Willow Creek/Mt. Ann	20	b	A	0-14	36.6	38	25.4	8.5%	0.052	no	
			C	14-24+	36.6	38	25.4	4.2%	0.036	yes	kaolinite, montmorillonite, illite, interstratified illite/montmorillonite
Hoback Canyon/Camp Creek	21	a	O	0-1				no data			
			A	1-6	24.4	23	52.6	6.2%	0.043	no	
			Bw	6-15	24.6	16	59.4	6.2%	0.056	no	
			C	15-28+	33.4	18	48.6	4.9%	0.049	no	montmorillonite, illite, kaolinite, interstratified illite/montmorillonite
Hoback Canyon/Camp Creek	21	b	A	0-18	26.2	14	59.8	5.0%	0.039	yes	
			C	18-28+	15.2	26	58.8	2.6%	0.036	no	montmorillonite, illite, kaolinite, interstratified illite/montmorillonite
Willow Creek Ridge	22	a	O	0-2				37.5%			
			A	2-12	26.6	54	19.4	7.0%	0.037	no	
			Bt	12-30	29.6	54	16.4	3.7%	0.033	no	illite, kaolinite, montmorillonite
			C	30-40+	22.6	61	16.4	2.3%	0.009	no	kaolinite, illite, montmorillonite, interstratified illite/montmorillonite
Willow Creek Ridge	22	b	A	0-11	32.6	49	18.4	13.5%	0.081	no	
			C	11-24+	42.6	35	22.4	6.3%	0.085	no	illite, kaolinite, montmorillonite, interstratified illite/montmorillonite
Willow Creek Trail/Ridge	23	a	A	0-12	24.2	39	36.8	6.7%	0.021	no	
			C	12-24+	26.2	34	39.8	4.0%	0.011	no	illite, kaolinite, interstratified illite/montmorillonite
Willow Creek Trail/Ridge	23	b	O	0-5				46.9%			
			A	5-15	23.2	40	36.8	18.8%	0.047	no	
			C	15-30+	51.2	21	27.8	8.1%	0.078	no	montmorillonite, illite, kaolinite, interstratified illite/kaolinite

APPENDIX 5 – C Horizon XRD patterns

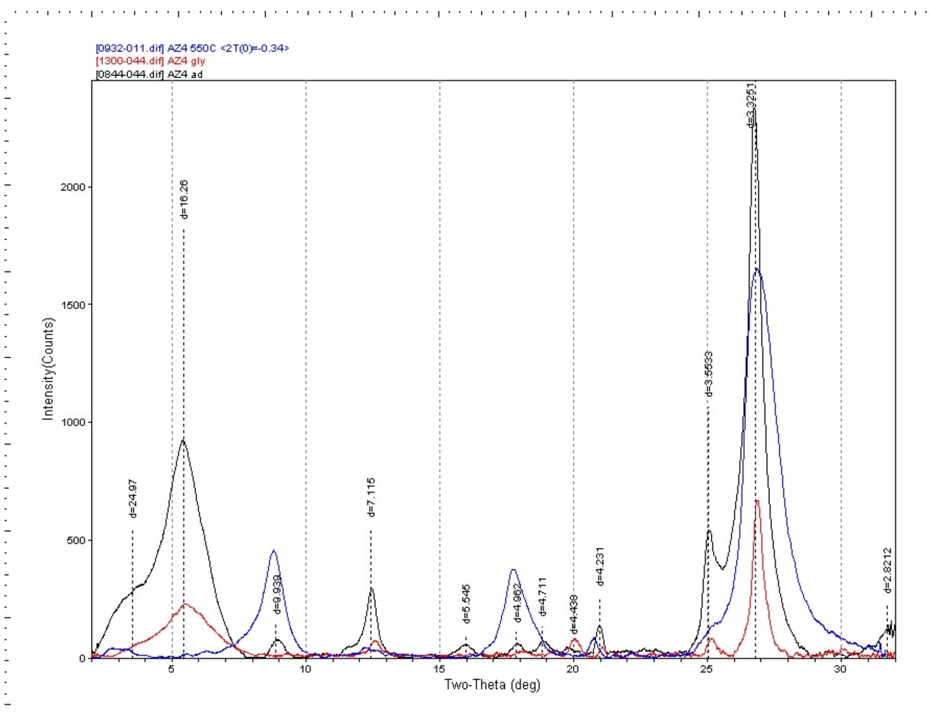
Landslide 1a – C horizon, 20-30+ inches



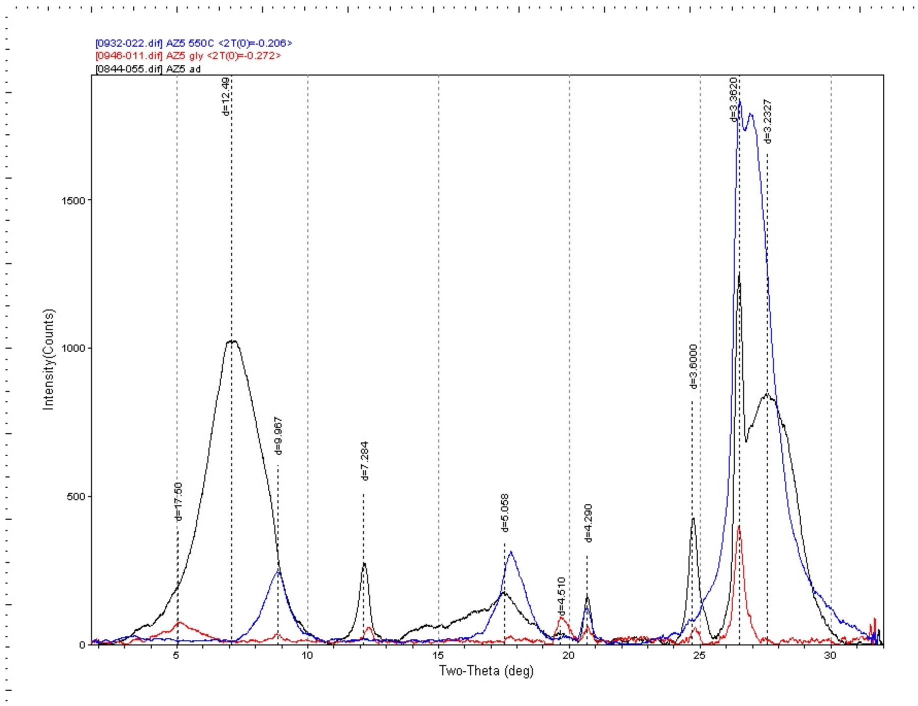
Landslide 1b – C horizon, 20-22+ inches



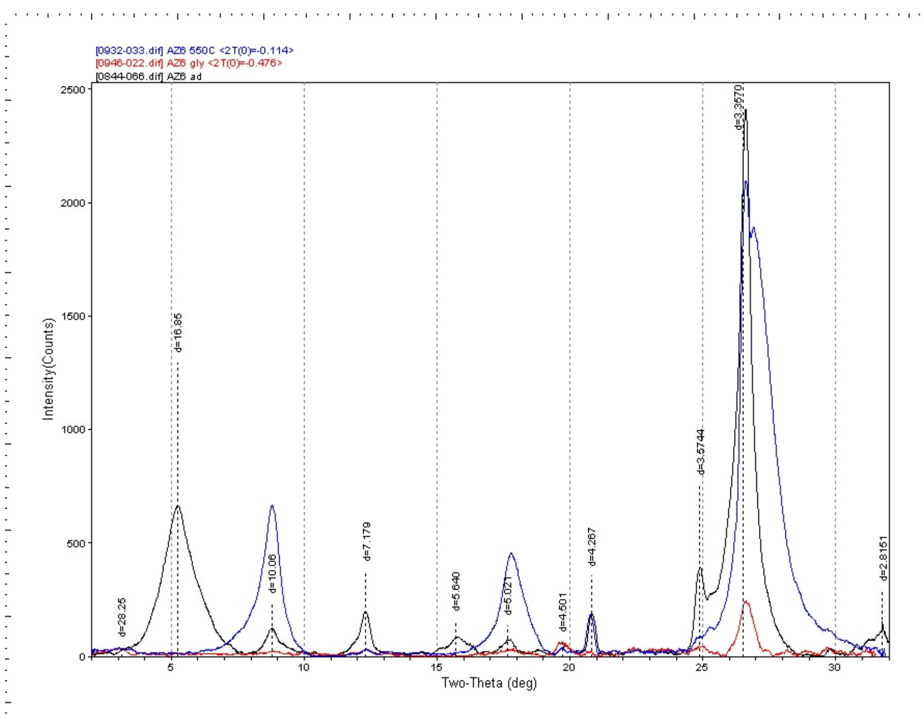
Landslide 2a – C horizon, 40-44+ inches



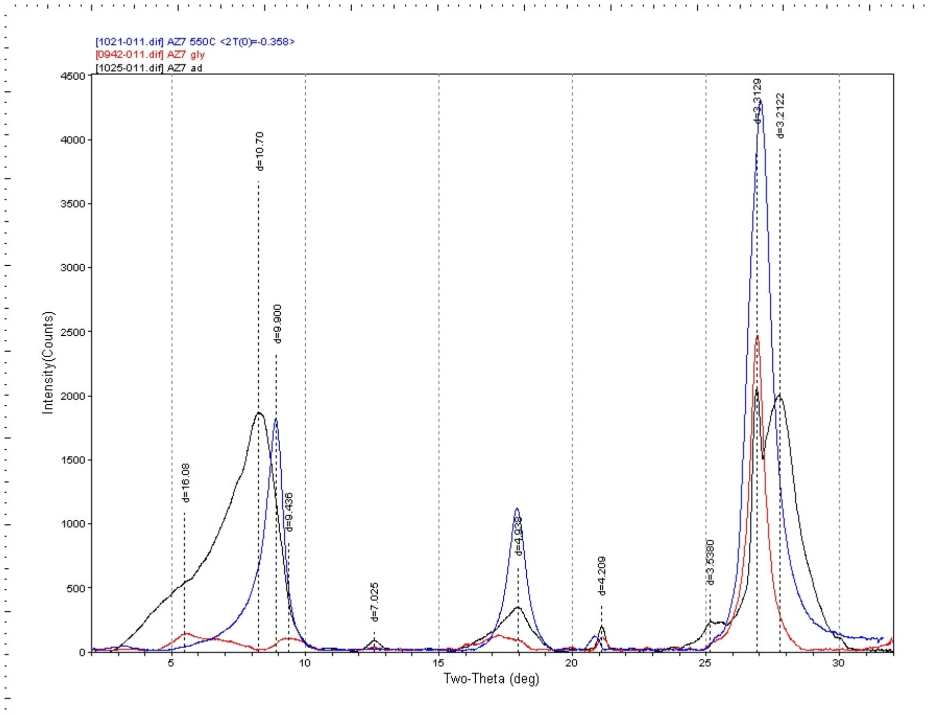
Landslide 2b – C1 horizon, 3+ inches



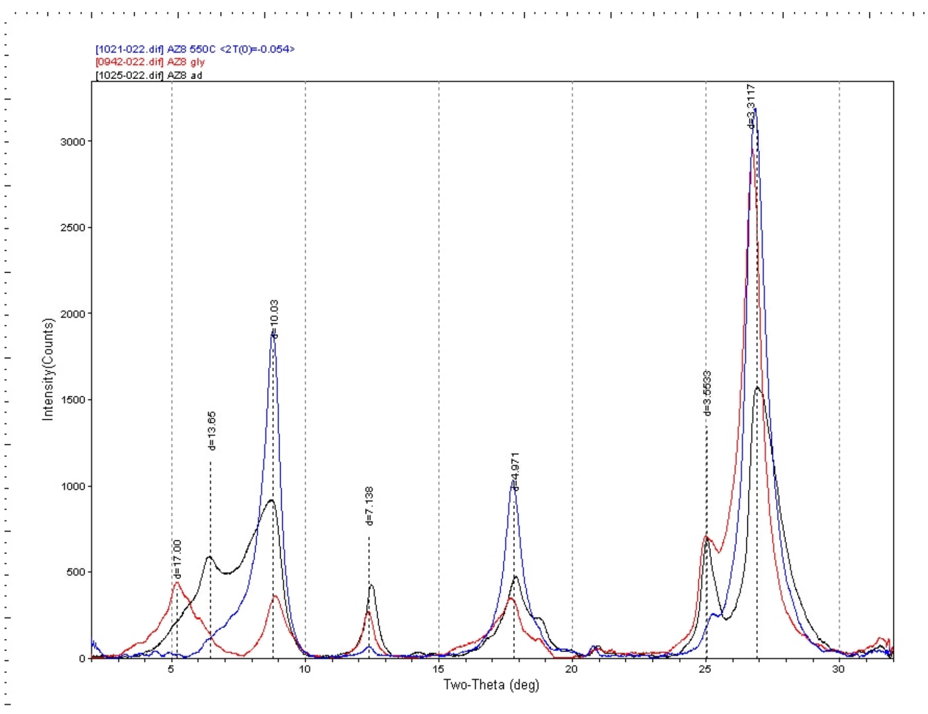
Landslide 2b – C2 horizon, 0+ inches



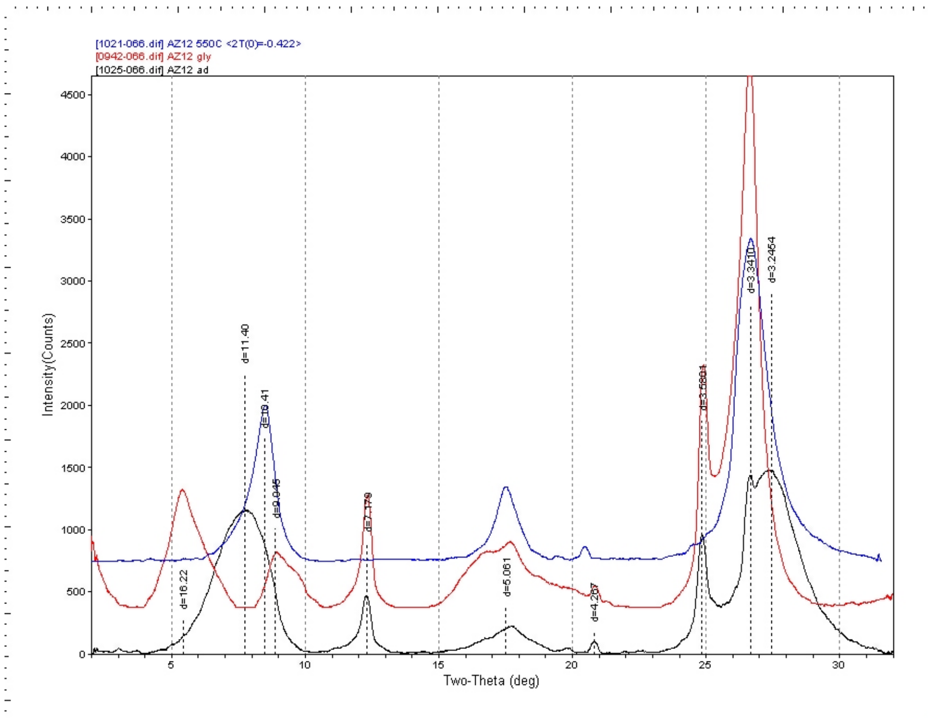
Landslide 3a – C horizon, 10-36+ inches



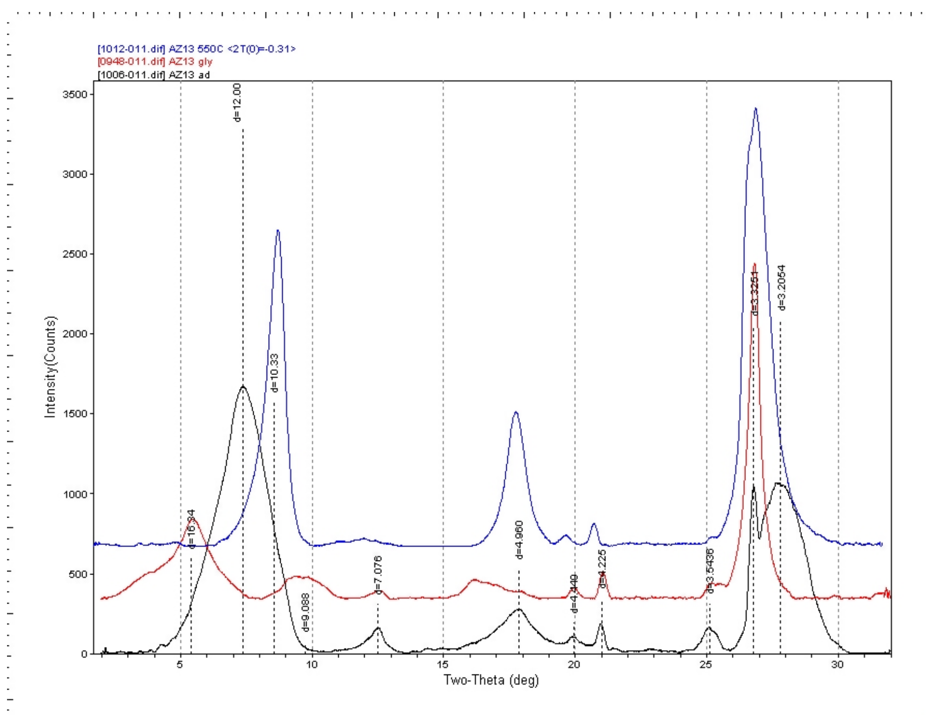
Landslide 3b – C horizon, 18-30+ inches



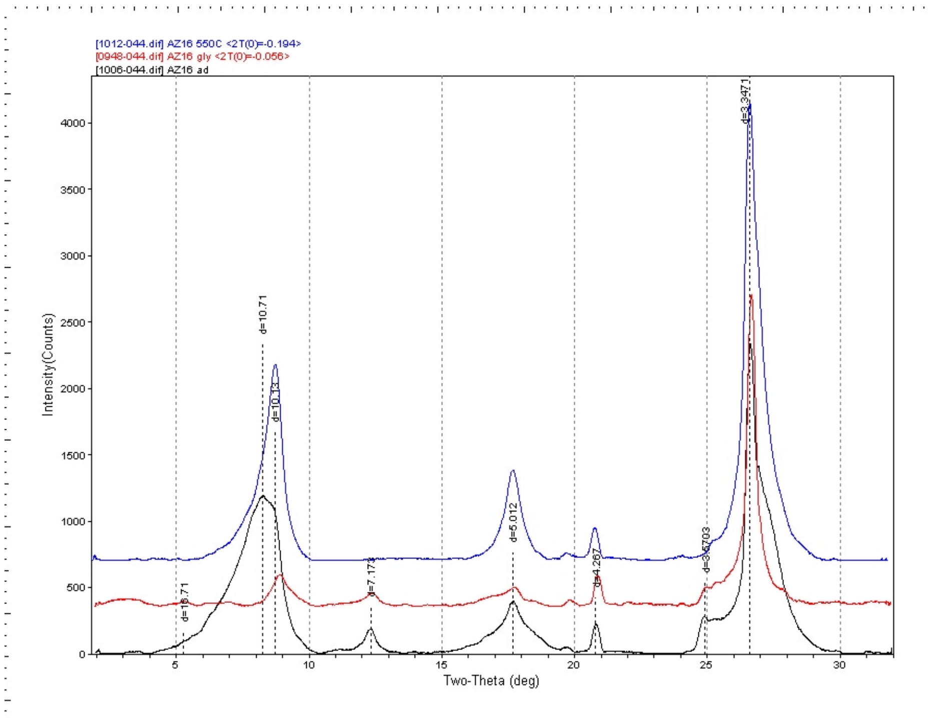
Landslide 5a – C horizon, 15-50+ inches



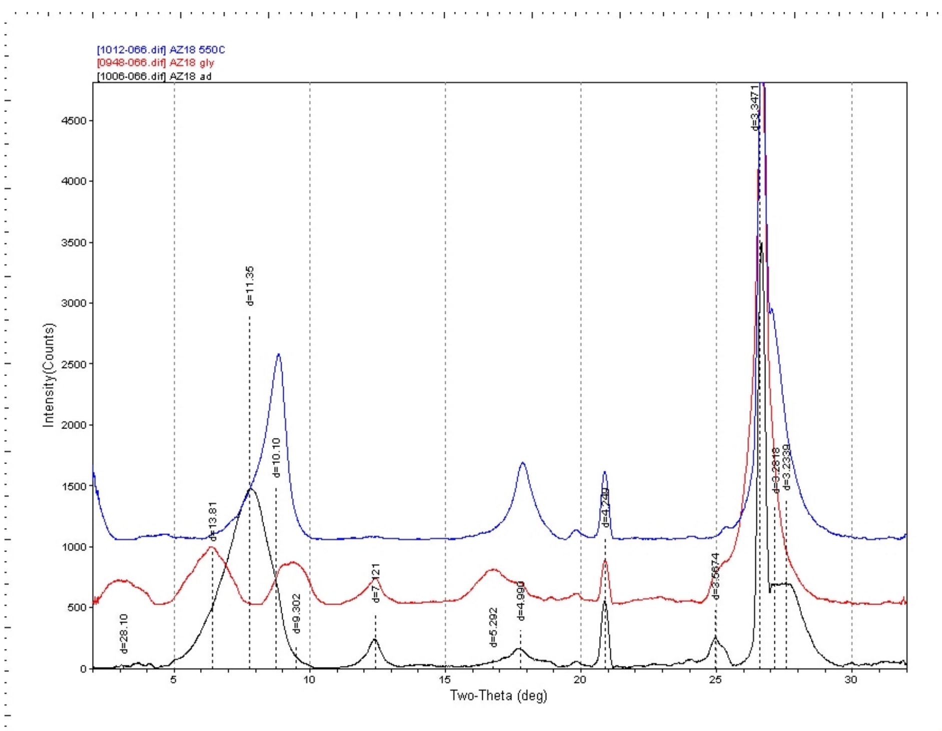
Landslide 5b – C horizon, 3-20+ inches



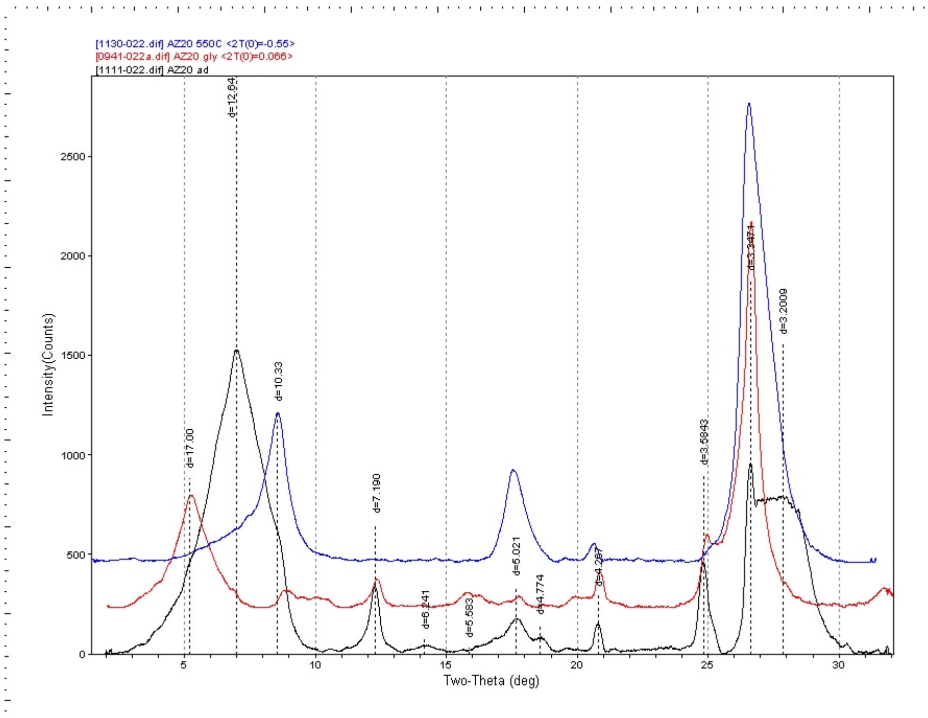
Landslide 7a – C horizon, 18-30+ inches



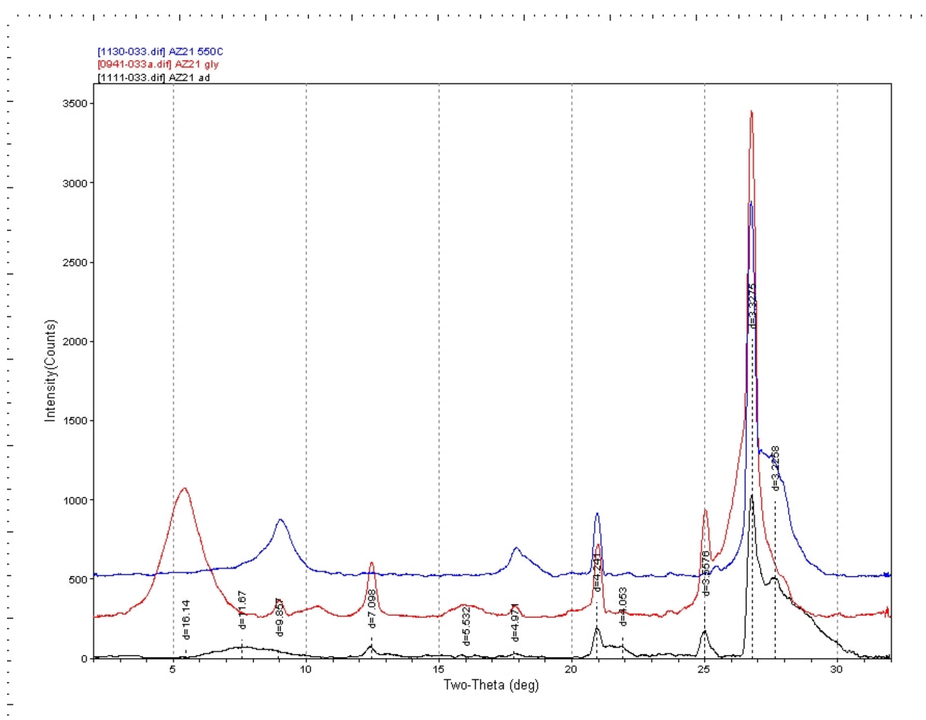
Landslide 7b – C horizon, 25-30+ inches



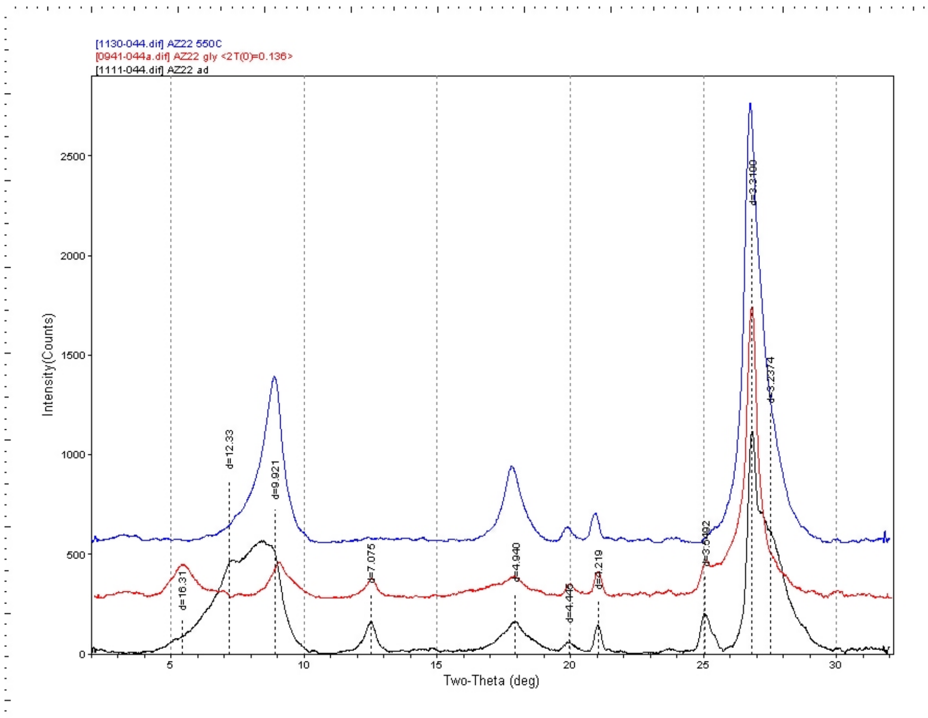
Landslide 9a – C horizon, 20+ inches



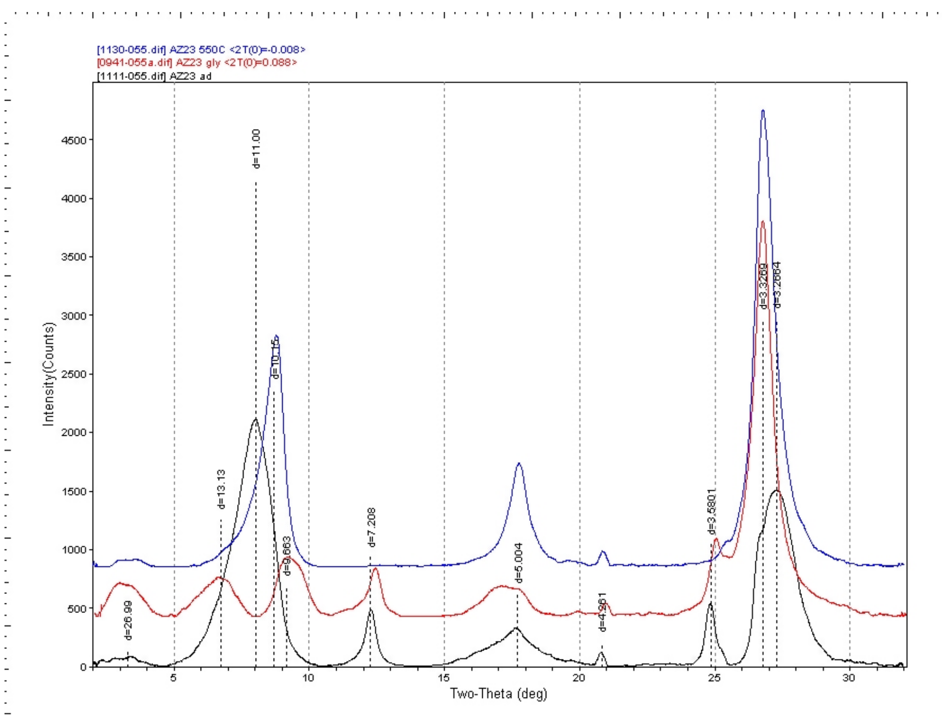
Landslide 9b – C horizon, 3-26+ inches



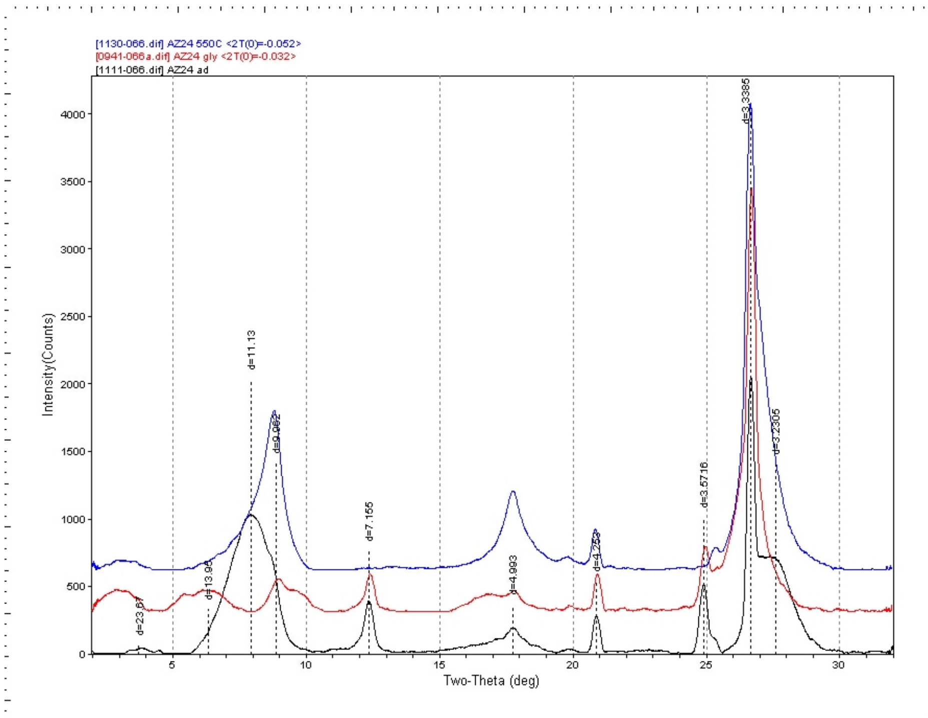
Landslide 12a – C horizon, 16-30+ inches



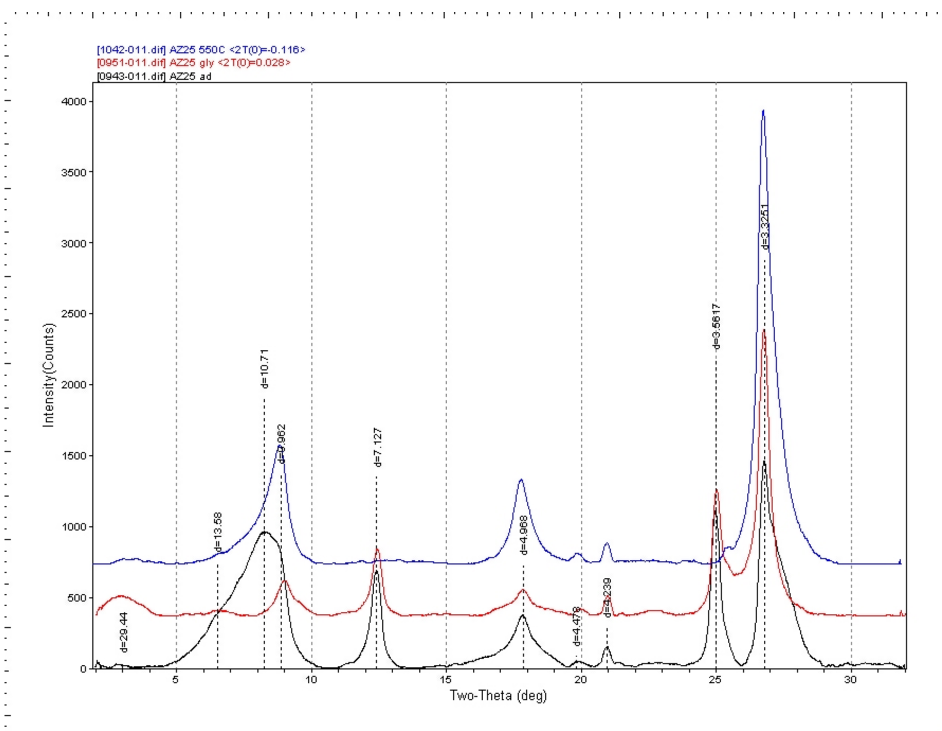
Landslide 12b – 2C horizon, 30+ inches



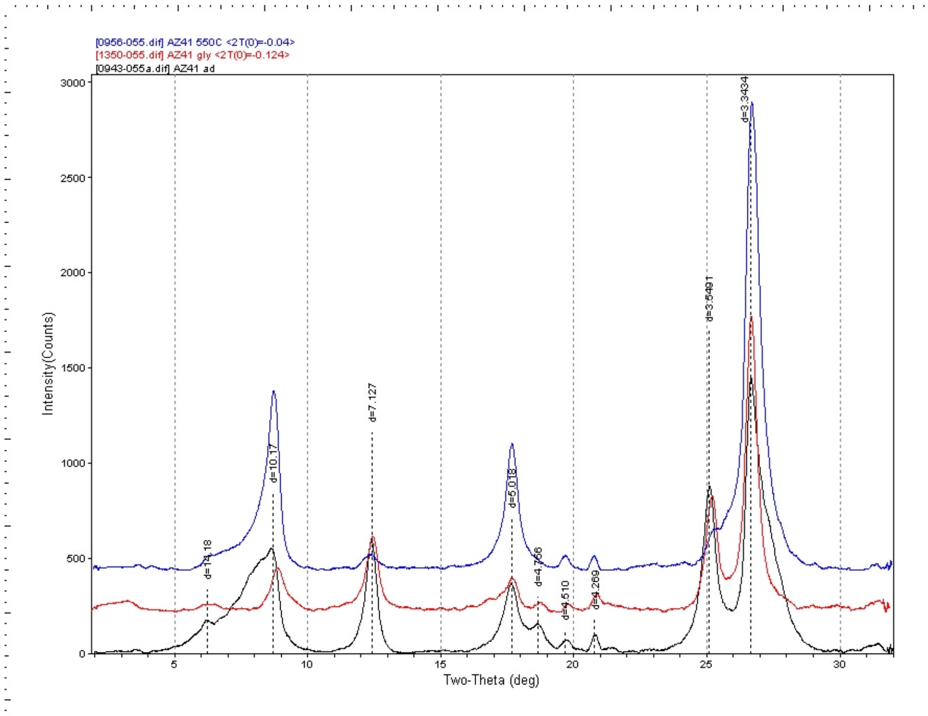
Landslide 13a – Bt horizon, 20-30+ inches



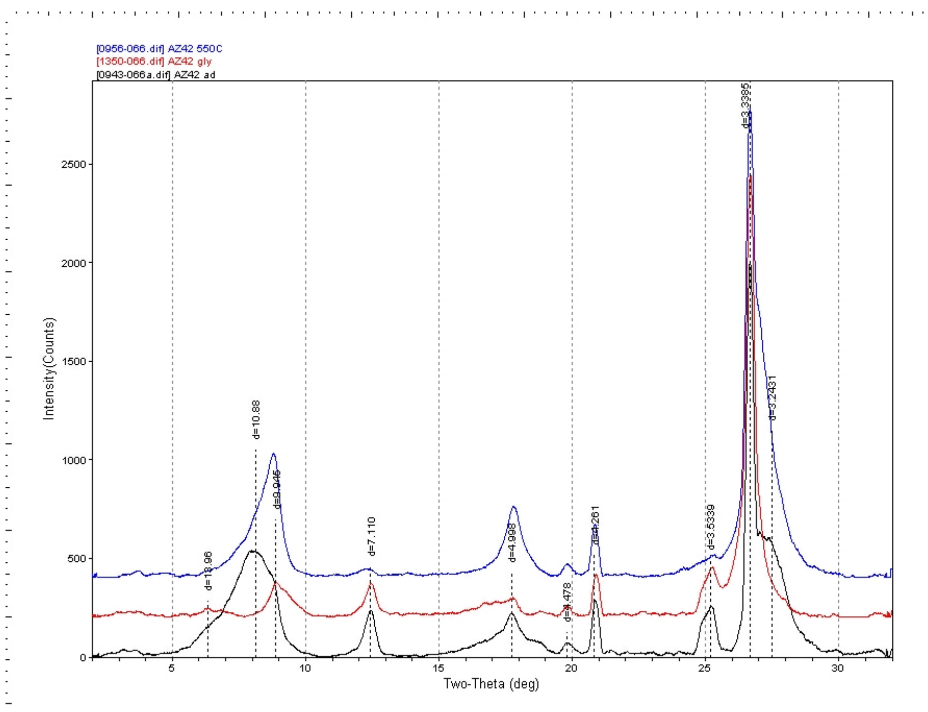
Landslide 13b – C horizon, 14-24+ inches



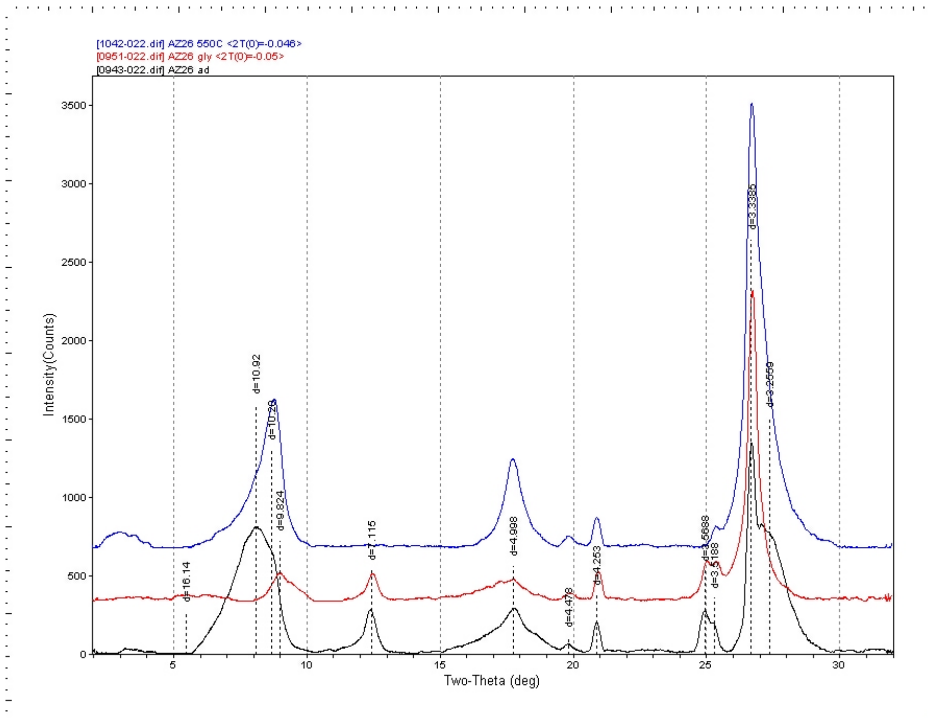
Landslide 14a – C horizon, 36-40+ inches



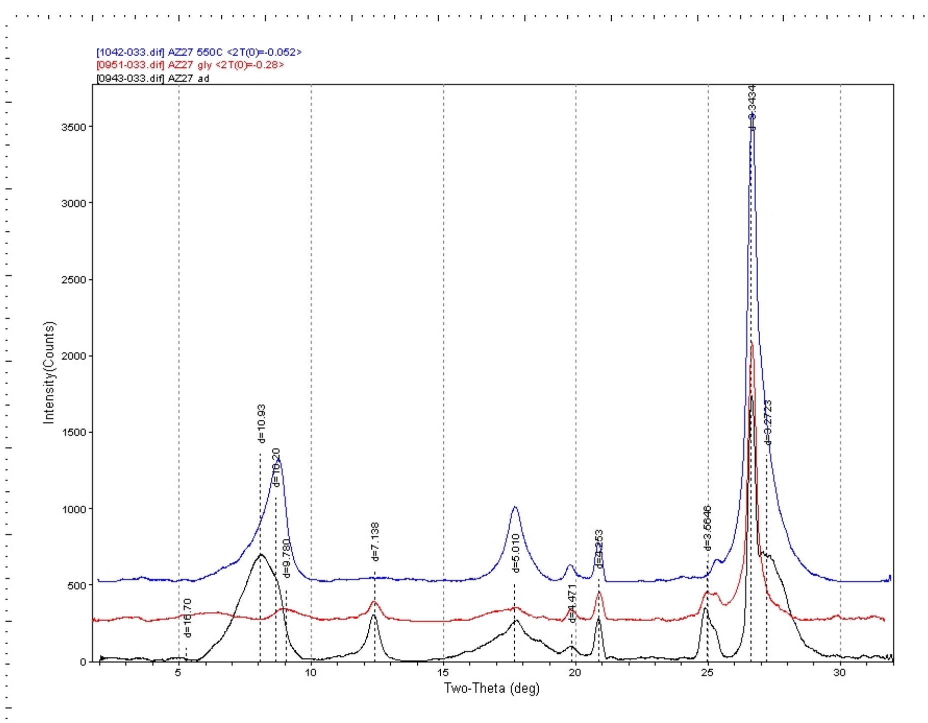
Landslide 14b – C horizon, 8-16+ inches



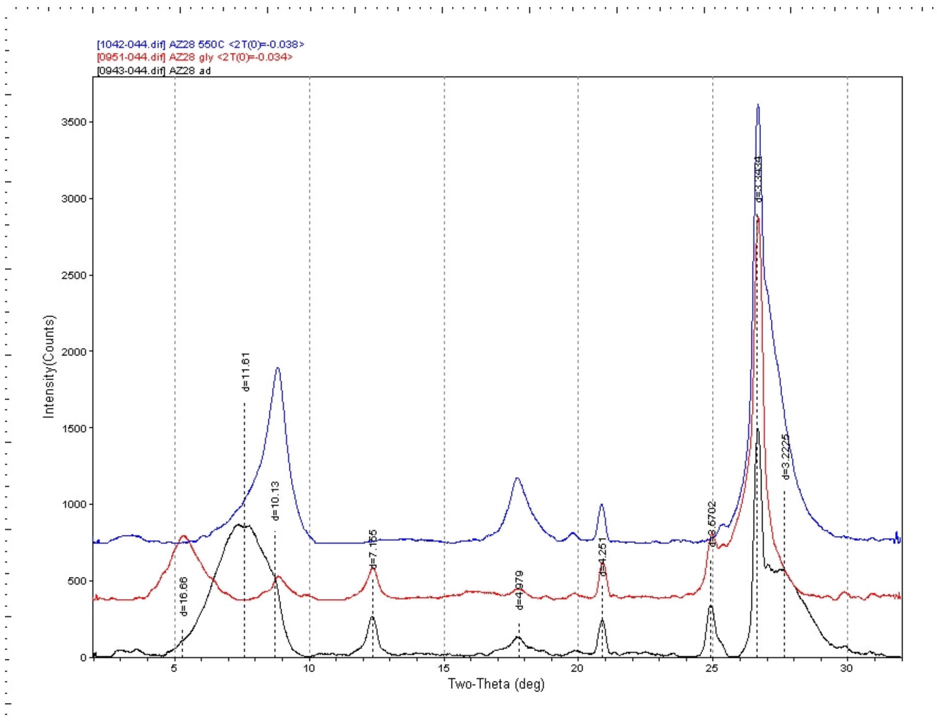
Landslide 15a – C horizon, 22-26+ inches



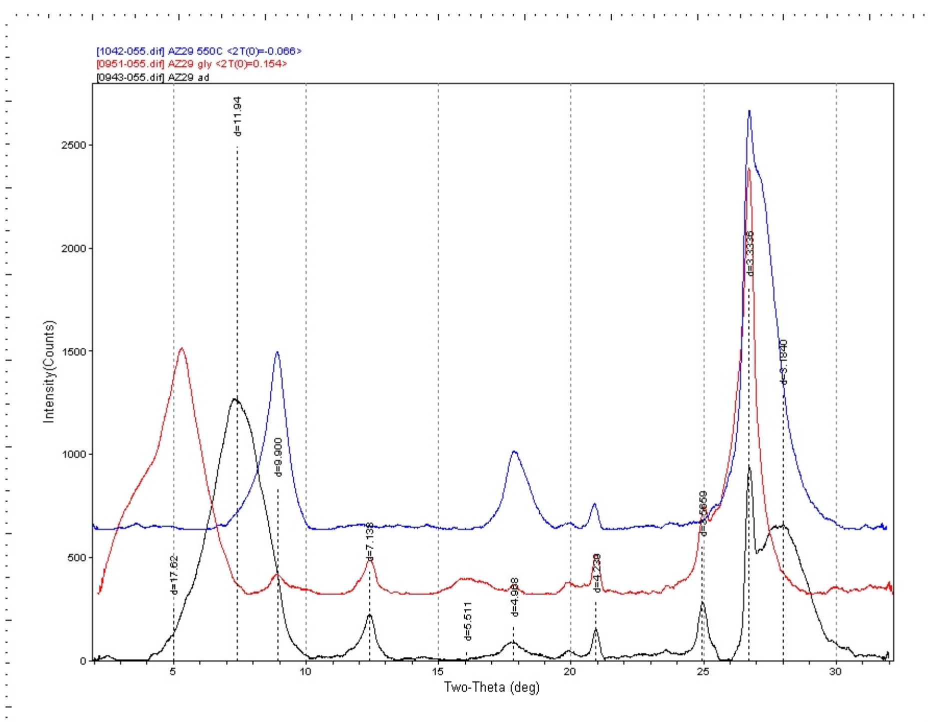
Landslide 15b – C horizon, 8-25+ inches



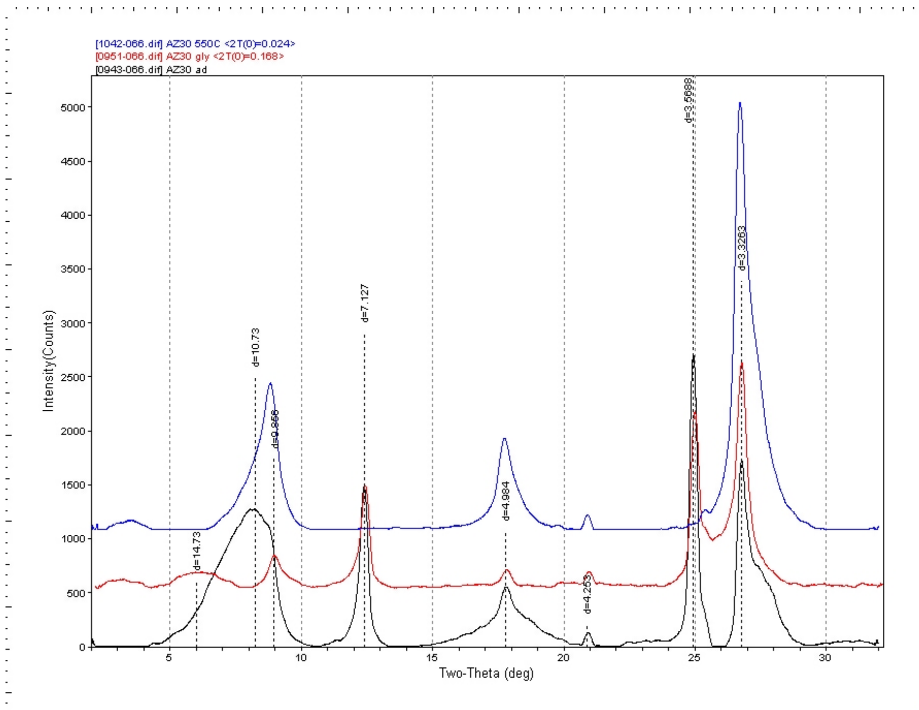
Landslide 16a – C horizon, 24-36+ inches



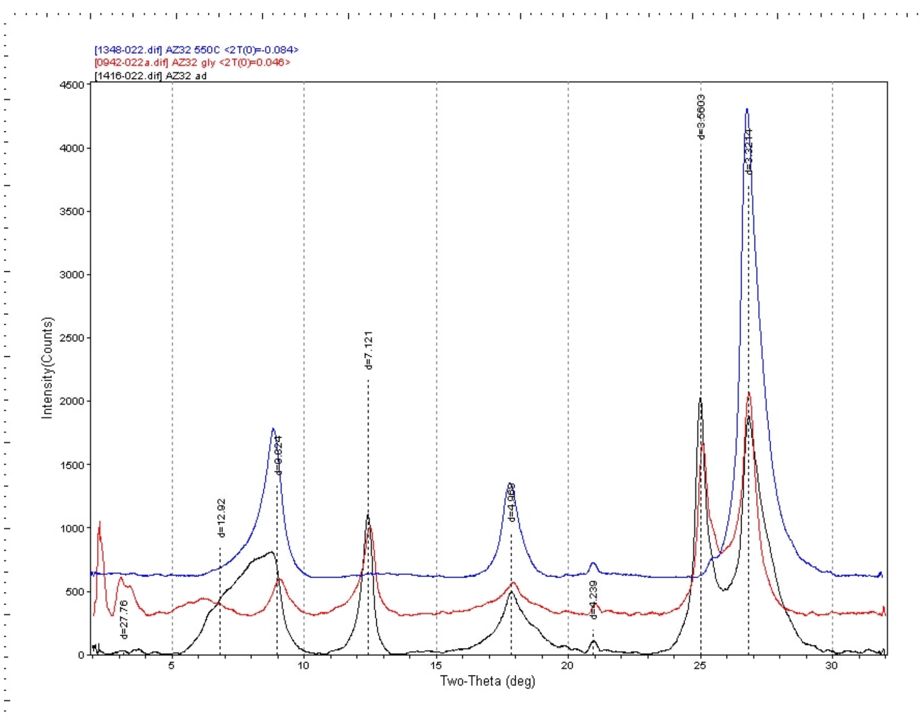
Landslide 16b – C horizon, 3-30+ inches



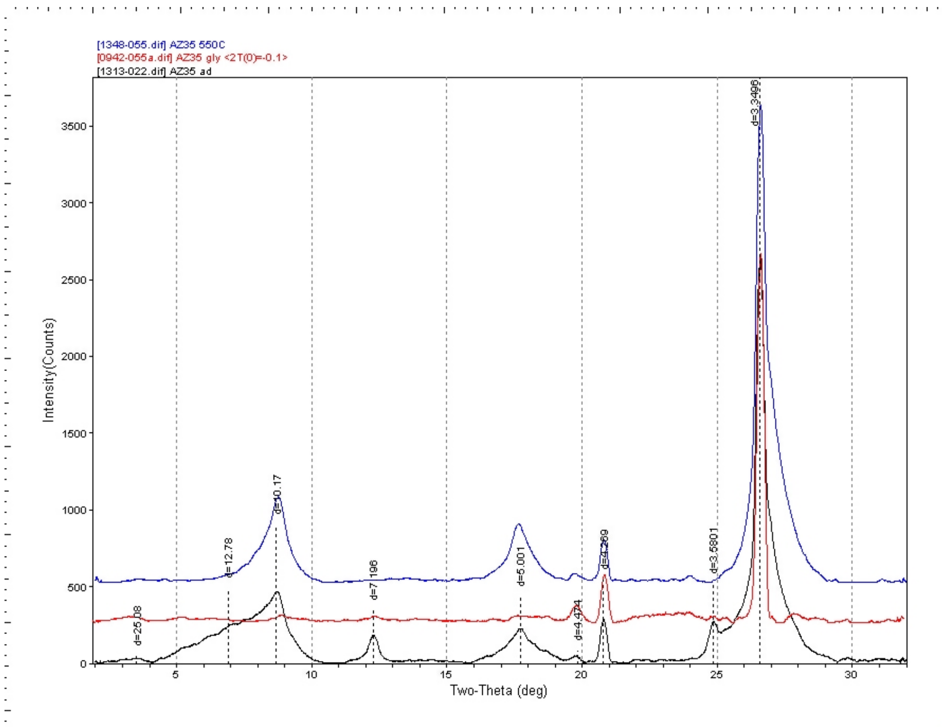
Landslide 17a – C horizon, 12-30+ inches



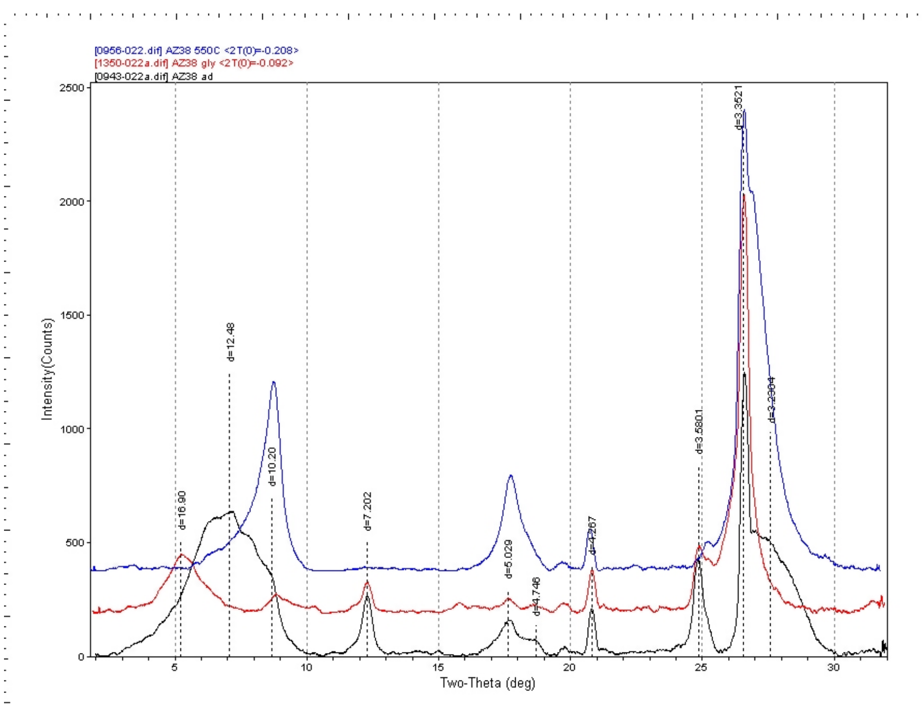
Landslide 17b – C horizon, 14-24+ inches



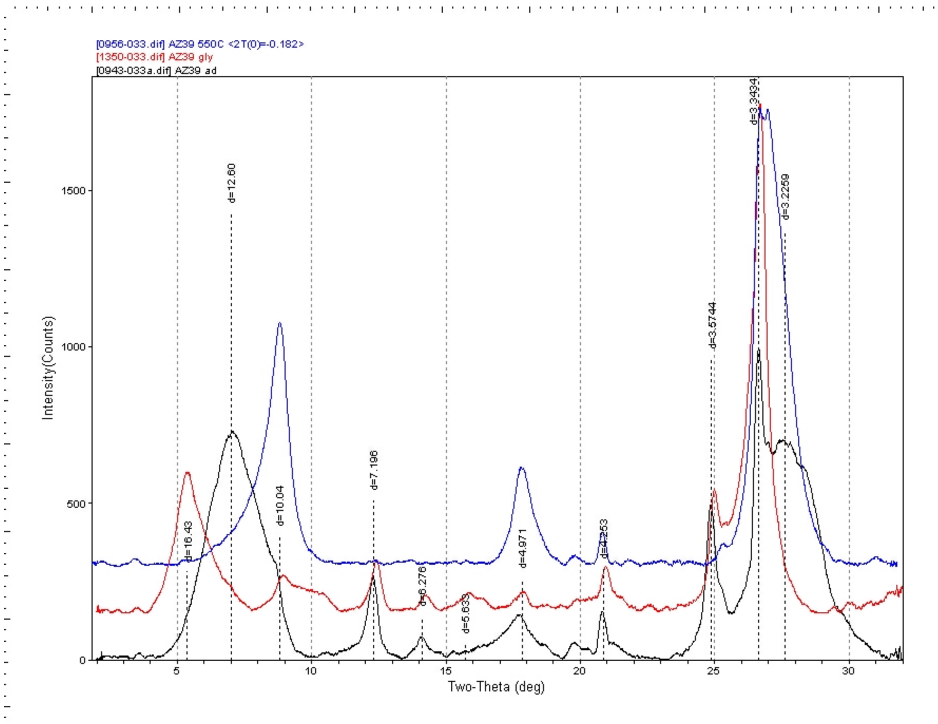
Landslide 18b – C horizon, 20-32+ inches



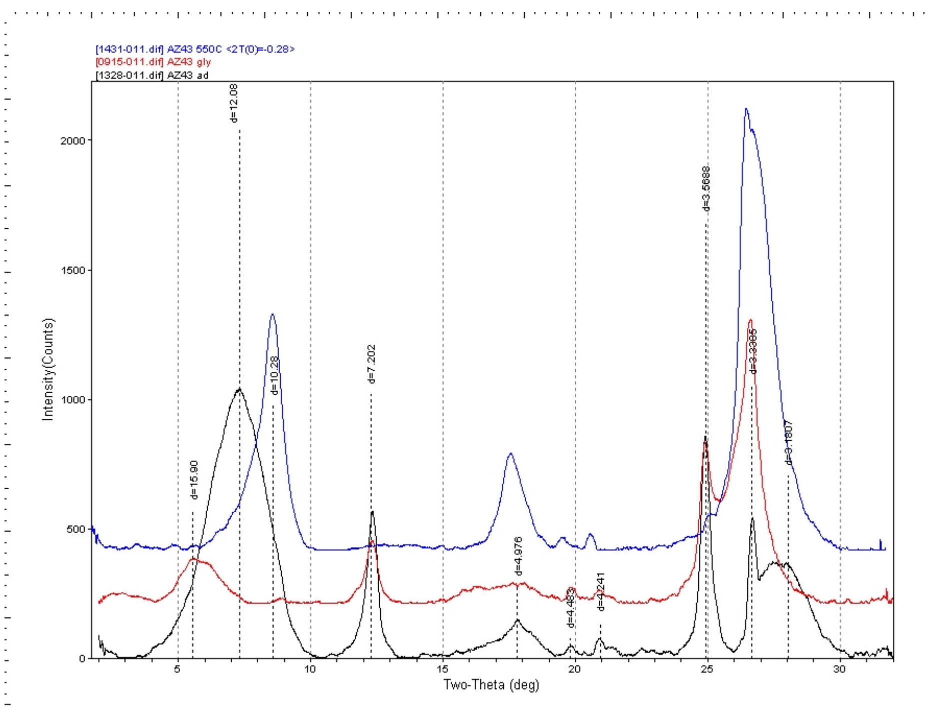
Landslide 19a – C horizon, 36-40+ inches



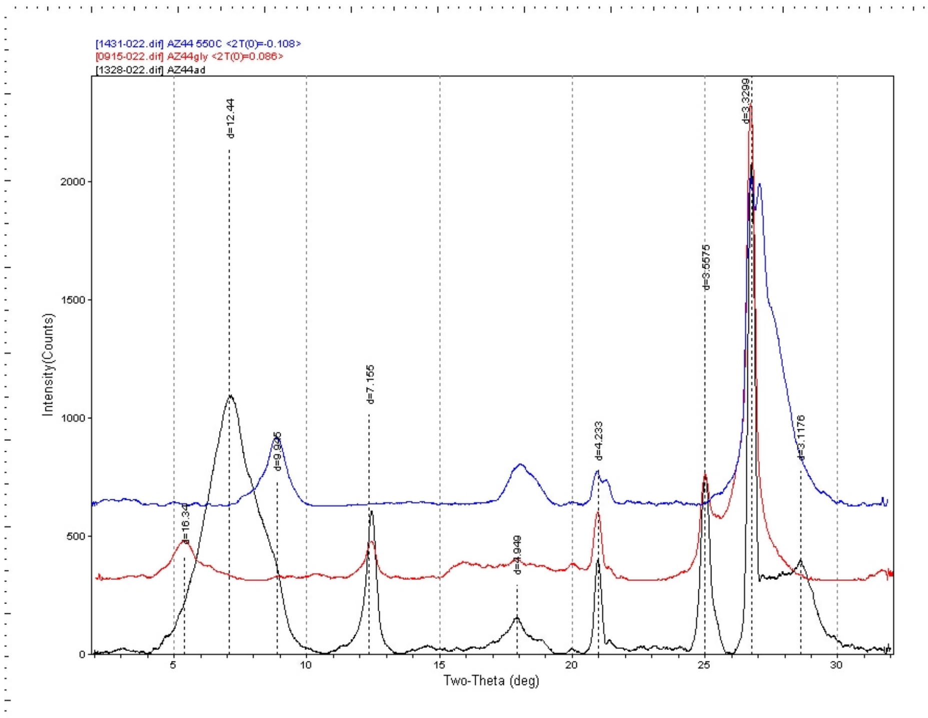
Landslide 19b – C horizon, 10-24+ inches



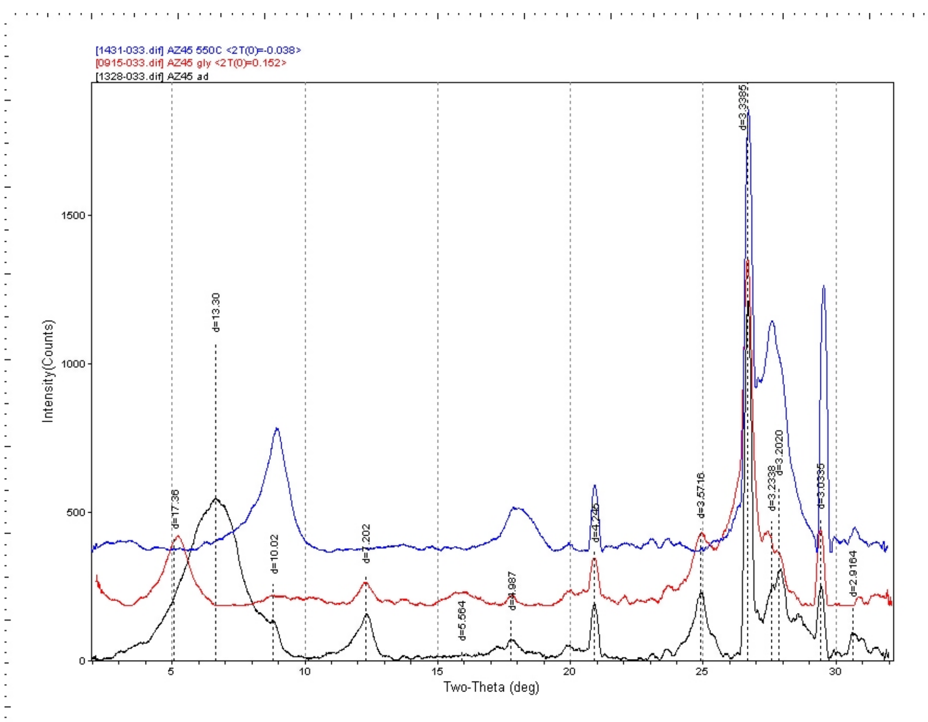
Landslide 20a – C horizon, 16-24+ inches



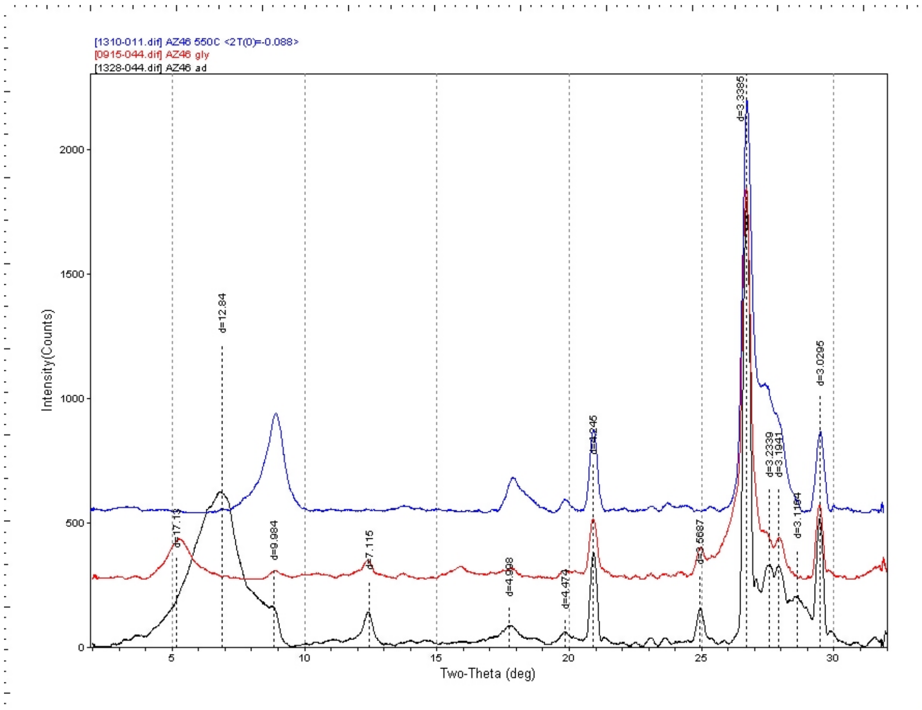
Landslide 20b – C horizon, 14-24+ inches



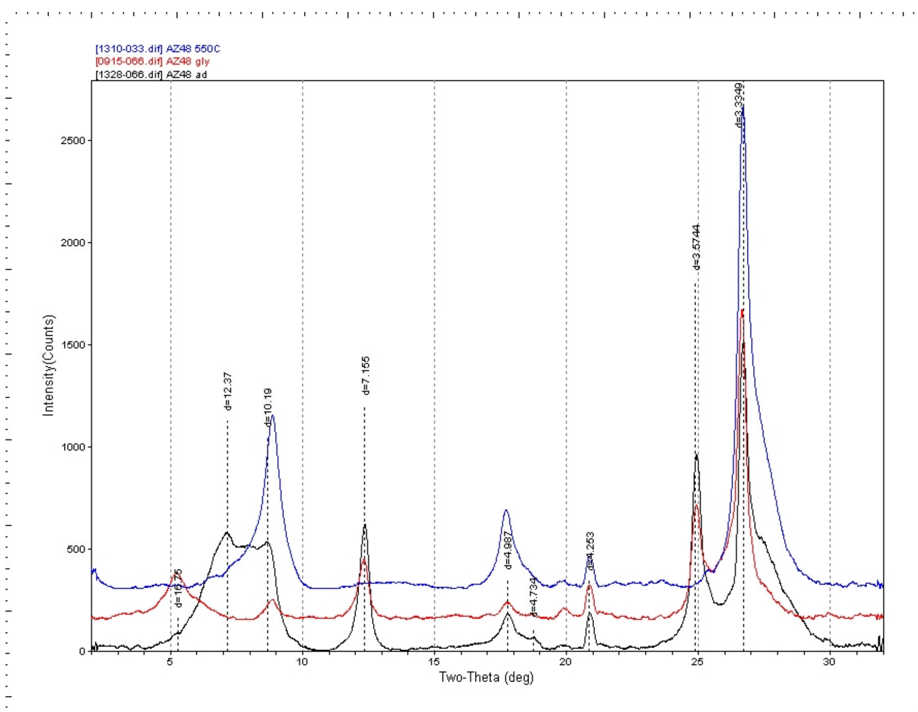
Landslide 21a – C horizon, 15-28+ inches



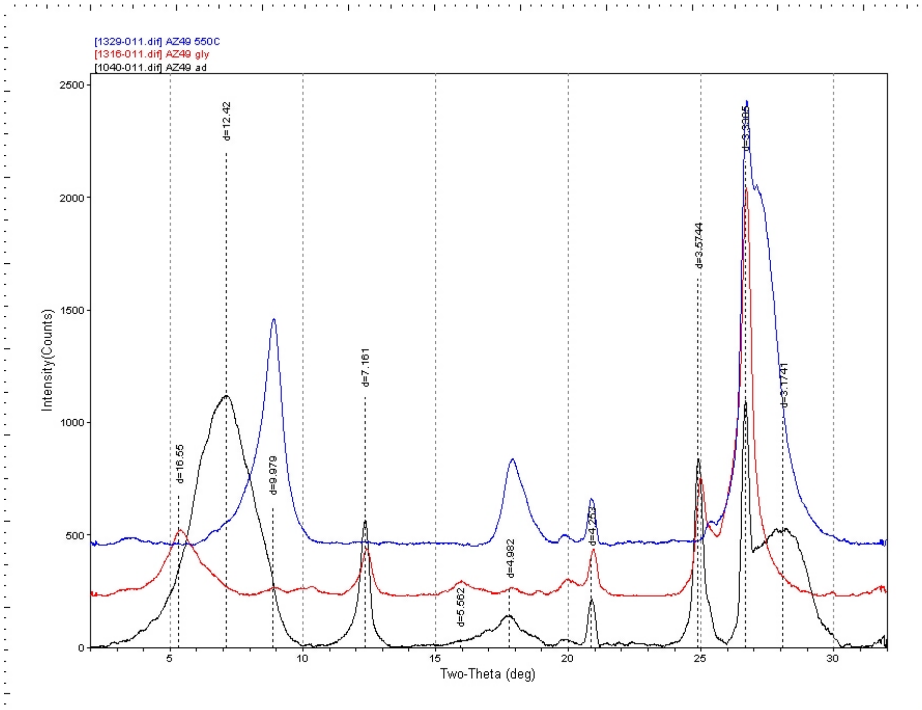
Landslide 21b – C horizon, 18-28+ inches



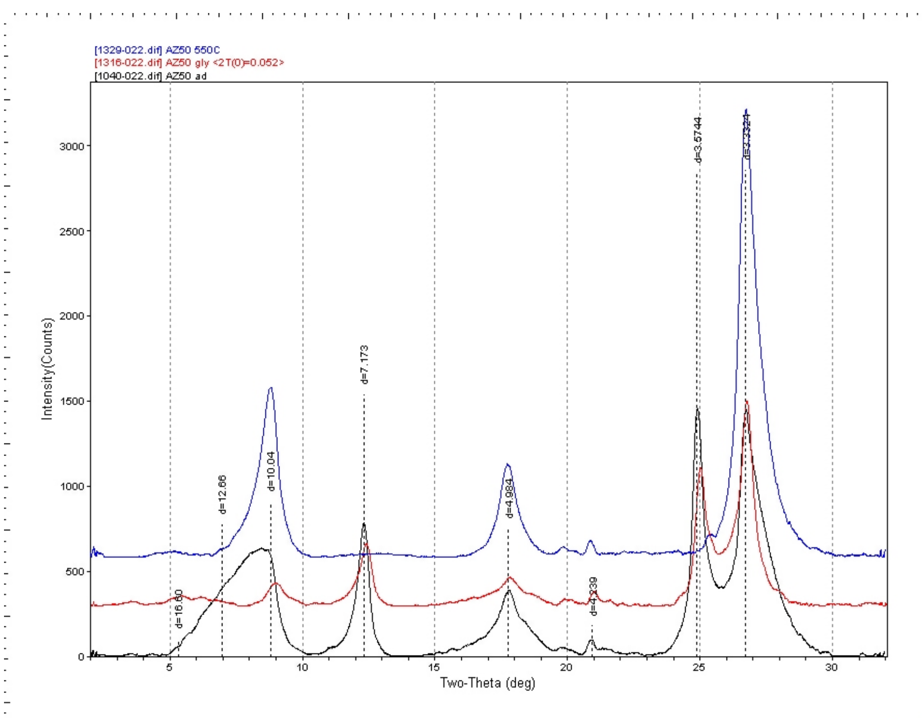
Landslide 22a – C horizon, 30-40+ inches



Landslide 22b – C horizon, 11-24+ inches



Landslide 23a – C horizon, 12-24+ inches



Landslide 23b – C horizon, 15-30+ inches