A DENROGEOMORPHOLOGICAL ASSESSMENT OF THE DONALD DUCK LANDSLIDE COMPLEX, GRAND MESA, COLORADO

A Thesis

by

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ABSTRACT

Grand Mesa, Colorado exhibits numerous dynamic geomorphologic phenomena, including ancient and currently active features of mass movement. The dense, basaltic mesa top that makes up Grand Mesa is underlain by weak Tertiary strata that is highly susceptible to slope failure. Together, these formations have historically produced slump-block failures along the flanks of the mesa. This thesis investigates the landslide complex on the north flank of Grand Mesa along Highway 65, where periodic landslides block and damage the roadway. The United States Forest Service has inquired as to why these events are occurring and if it is possible that the landslide will stabilize.

Geomorphic mapping in conjunction with dendrochronological methods were used to determine the frequency, direction, and magnitude of mass movements associated with the landslide complex. Weather data were collected from local stations and compared with the dendrogeomorphological data to pinpoint the threshold amount of precipitation that could initiate movement on the landslide complex.

The Donald Duck landslide complex is 150m x 100m and situated on the eastern flank of an ancient landslide that originated at a toreva block along the top of the mesa. The ancient landslide originated south of the DDLC, 1km above, and terminates north at the valley floor 1.4km below. Three distinct lobes of movement were identified in the landslide complex, and eighty-eight cross-sections were taken from trees that are situated on and adjacent to the landslide complex. Tree ages on the complex indicate that the landslide was activated in the early 1960s. This time-frame corresponds to when Highway

65 was re-routed to its current location, which would have resulted in the stabilizing soil at the base of the slope being removed. Subsequent movement of the complex appears to occur after above-average precipitation events (+1 Std. Dev.) and results in material flow that impacts the highway. The three distinct lobes on the complex then pulse and creep in tandem approaching re-stabilization.

The Donald Duck Landslide complex was first activated in its entirety in the early 1960s and moved toward the northwest. Subsequent movement has occurred in the same general direction after periods of extreme rainfall followed by extreme drought, resulting in only surficial creep movement.

DEDICATION

To my dad, James Sexton; thank you for leading me up the mountains, down the rivers, and through the canyons to experience the vastness, and to ask “how” and “why.” Thanks, Pops.

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With warm and deep appreciation, thank you to the late Linda Bledsoe of the USFS, for introducing me to the Grand Mesa Uncompahgre and Gunnison National Forests, and for sharing with me your insights and enthusiasm for this beautiful land.

NOMENCLATURE

DDLC	Donald Duck Landslide Complex
EBE	External Bum East
EBS	External Banana South
EBW	External Bum West
EDS	External Duck Scarp
EHW	External Highway West
ENSO	El Nino Southern Oscillation
IBB	Internal Bum Bungalow
IBD	Internal Banana Dance
IDS	Internal Duck Scarp
IDT	Internal Duck Toe
INF	Internal North Flank
MIS	Marine Oxygen-Isotope Stage
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
SNOTEL	Snow Telemetry
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
WRCC	Western Regional Climate Center

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1. INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

The area of Grand Mesa is highly susceptible to mass movement (Regmi et al., 2010a). This movement influences rates of slope development and location of urban infrastructure including roads, buildings and mining activities. Mass movement is especially active along the flanks of Grand Mesa, and one specific location has been selected for this study in conjunction with the United States Forest Service (USFS). This research involves the landslide complex known as the Donald Duck Landslide. Located along the northwest slope of Grand mesa, Colorado, reconnaissance field work suggests this landslide appears to have been active over several decades and occasionally transports debris downslope blocking Colorado State Highway 65 (SH-65). Thus far, the management strategy for the landslide on SH-65 has been reactive in that debris is removed from the road once it accumulates and blocks the road.

1.2 Problem Statement

Scientists have understood that a primary correlation exists between the occurrence of landslides and large amounts of precipitation (Lang, et al. 1999). Unfortunately, the threshold between the volume or intensity of rainfall and resulting movement of the landslide is unknown for the Donald Duck landslide complex. This research will determine the dynamics of the landslide in an attempt to minimize the impact of the landslide on human infrastructure. This thesis is based on answering the question: why is this complex moving?

Several working hypotheses have been formulated for this thesis. The working hypotheses are:

- Excessive precipitation is the cause of landslide movement;
- Slope aspect is the cause of landslide movement;
- Steep slope angle is the cause of landslide movement; and
- Lack of vegetation cover is the cause of landslide movement.

2. OBJECTIVES OF STUDY

The goal of this study is to establish a rate of movement and assess the general mechanics within this complex that provide an explanation of current stability. Understanding the history of the slide indicates the probability of future activity, which can provide background information to Forest Service personnel in regard to hazard planning and prevention of future mass movement in this area.

To achieve the goal of this study, three research objectives have been established:

1) identify and analyze the bounds, movement and morphology of the slide;

2) explain the temporal movement of the slide; and

3) determine the threshold conditions for movement.

3. STUDY AREA DESCRIPTION

3.1 Site Location

The Donald Duck landslide complex is located on the northern slope of Grand Mesa, Colorado on the east side of State Highway 65 along a prominent switchback between the old Mesa Creek Ski Resort and Mesa Lake (N39°04’17”, W108°05’35”, N39°04’15”, W108°05’30”, Figure 1). The elevation at the head of the complex is 2,841m and at the base is 2,813m. The aspect of the complex is northwest and is situated on the edge of a valley that drains to Coon Creek and then to Mesa Creek.

The modern climate of Grand Mesa is semi-arid to desert with varying amounts of precipitation, which results in varying types of vegetative cover and soils (USDA, 2010). Vegetation consists mostly of grasslands, quaking aspen (*populus tremuloides*), Engelmann spruce (*picea engelmannii*) and subalpine fir (*abies lasiocarpa*) (USDA, 2015). Soils consist of

Precipitation occurs mostly as localized summer-convection thunderstorms and large winter snowfalls (Regmi et al., 2010a) with an average annual rainfall of 75 to 90cm. Snow cover usually begins in lateSeptember and persists to June; high summer temperatures average ~19.8°C during July (NOAA, 2015).

3.2 General Geology

Grand Mesa is composed of flat-lying Tertiary sediments that are capped by multiple Miocene - Pliocene basalt flows (Cole, 2010). The Tertiary sediments, including undifferentiated claystone of the Green River, Uinta and Wasatch formations,

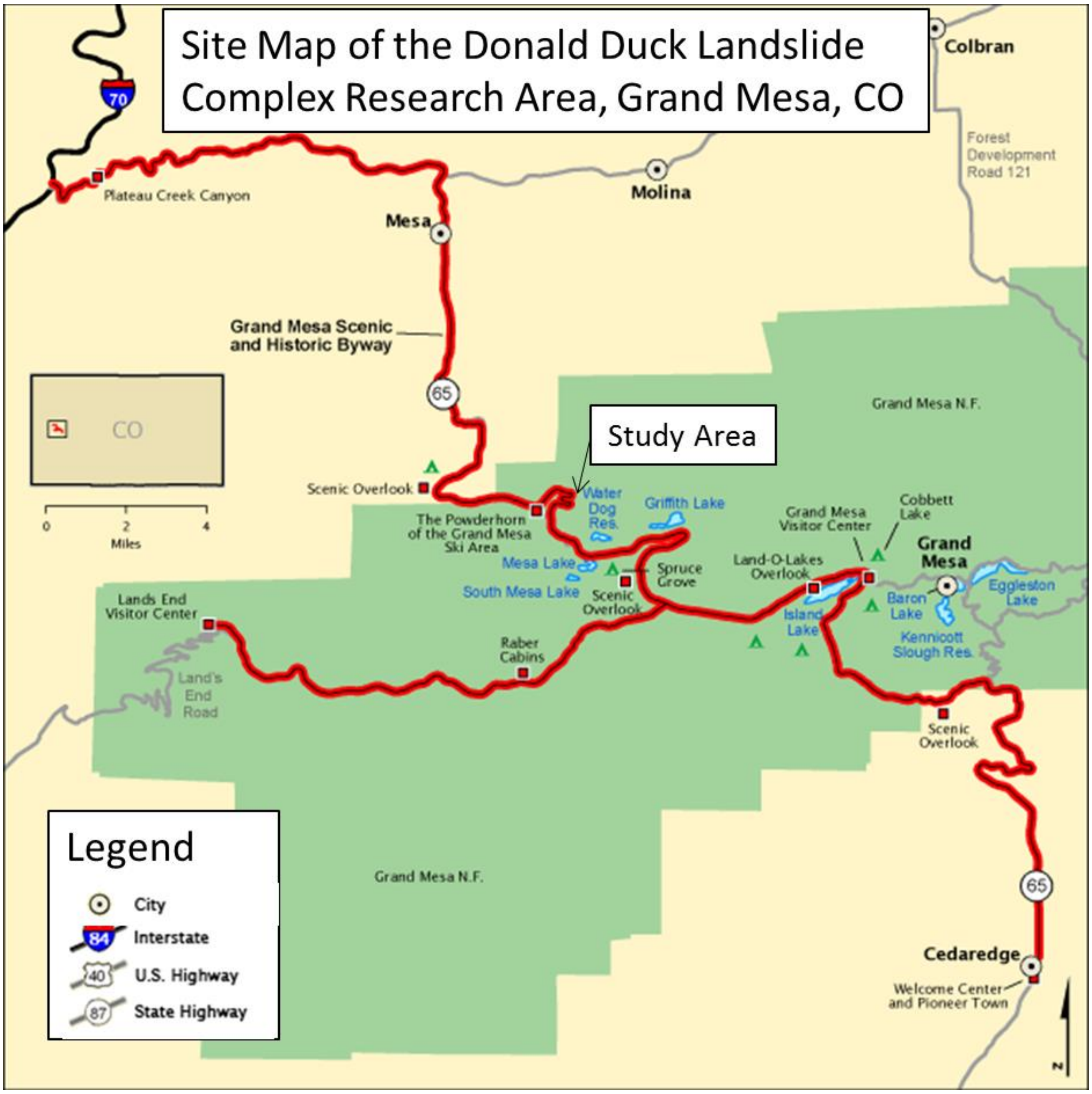


Figure 1. Site map. Location of the Donald Duck Landslide on Grand Mesa, Central West Colorado.

are moderately to highly susceptible to slope failure or have moderate to high incidences of failure (Baum, 1996). Slopes of the Mesa are generally draped with Pleistocene sediments of glacial, fluvial, or colluvial origin (Cole, 1981). A generalized geology map of Grand Mesa is shown in Figure 3. The area of the Donald Duck landslide complex is located within the Pinedale glacial limits of Grand Mesa on Quaternary surficial deposits, defined as glacial/colluvial/alluvial undifferentiated. Grand Mesa is drained by the Gunnison River to the south and west and the Colorado River to the north.

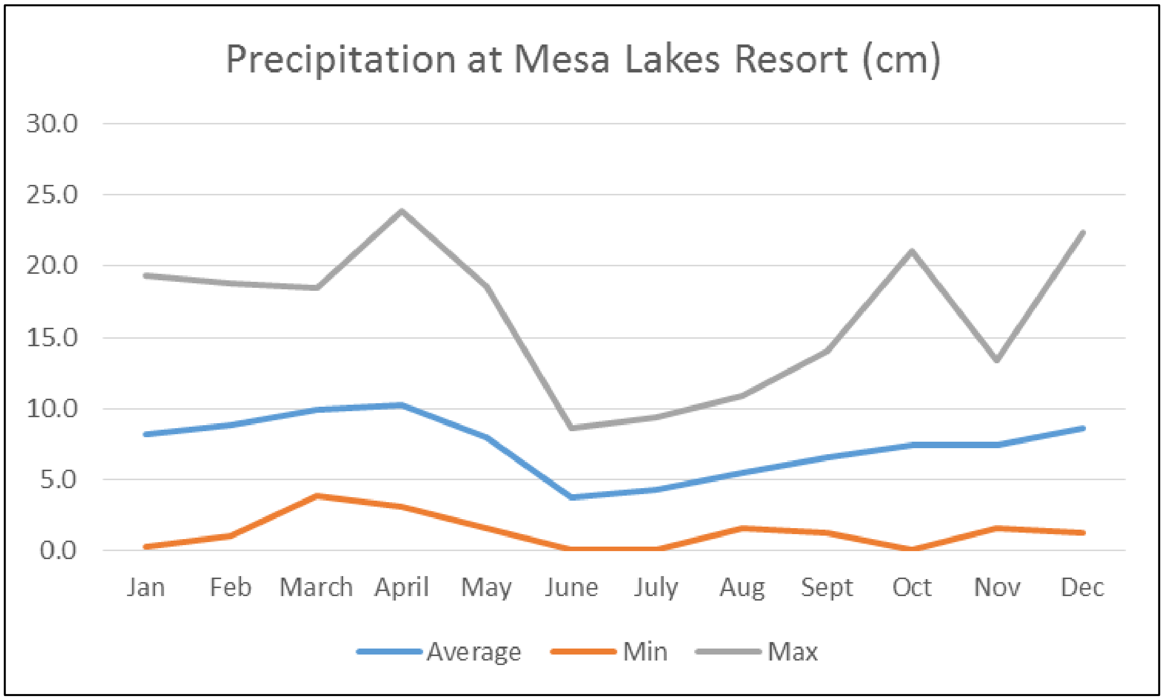


Figure 2. Climate graph. Average monthly precipitation at the Donald Duck Landslide as recorded at Mesa Lakes Resort.

3.3 Geomorphology

The top of the Mesa has been sculpted by multiple stages of glaciation that range from pre-Bull Lake (pre-MIS 6) to Pinedale (MIS 2) (Pierce, 2003). Grand Mesa was covered by an ice cap that extended 15 to 25 kilometers east-west in length and 4.5 to 6.5 kilometers north-side wide and extruded from the mesa into the valleys ~3 to 5 kilometers below. The ice cap was composed mainly of drifted snow that formed small

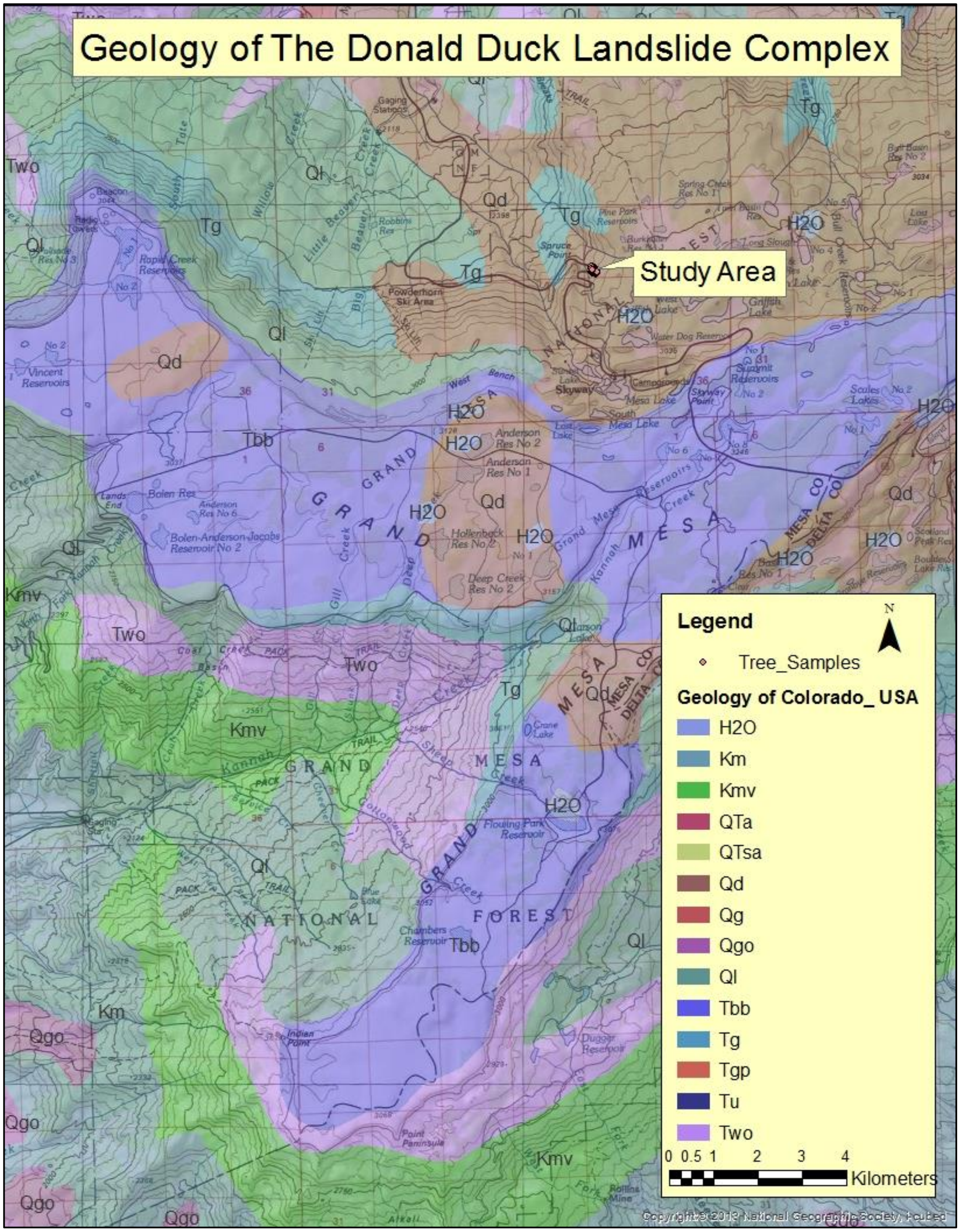


Figure 3. Geology on Grand Mesa. Geology as defined by the USGS.

glaciers on top of the mesa (Henderson, 1923). As a result of glaciation, many depressions were formed that today retain water. Most lakes on the surface are small depressions that have been engineered into reservoirs. These bodies of water now comprise the largest concentration of lakes in the western U.S. (Baum, 2007).

3.4 Mass Movement

Past mass-movement, which consists of land slumps and slides, is evident along the north and south slopes of the Mesa. Most obvious along the slopes are steep cliff edges at the heads of parabolic features that extend downslope. These steep cliffs are head scarps of ancient landslides. Below the steep cliff edges and above the landslides are detached and back-rotated blocks of basalt called toreva blocks (Yeend, 1973)(Fig 4.). The toreva blocks are recognizable as the crowns of extensive ancient landslides and

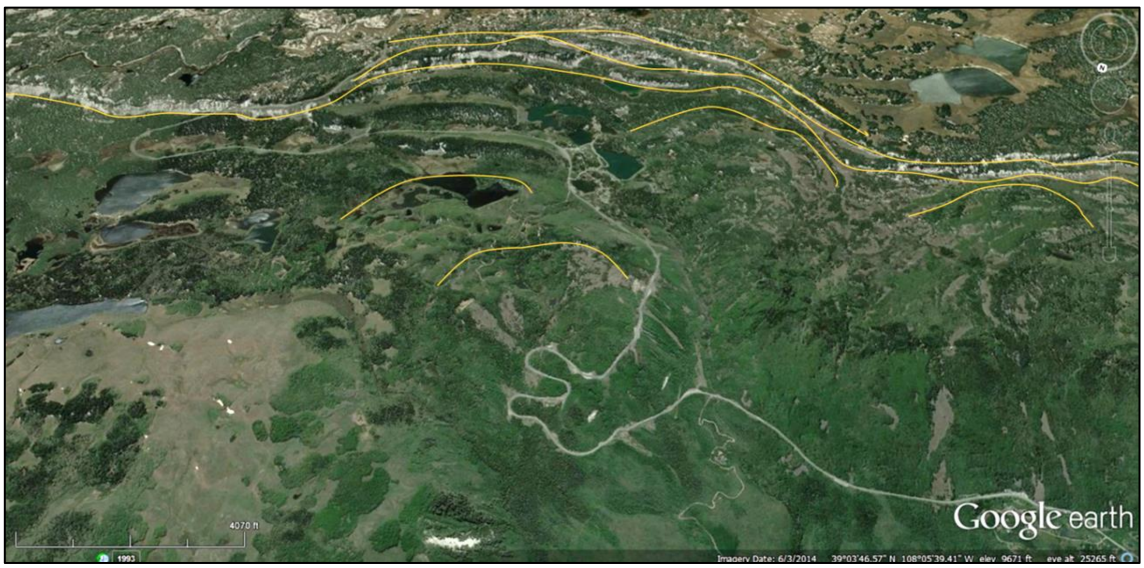


Figure 4. Geomorphology of Grand Mesa. Ancient landslides are evident below the outlined scarps and toreva blocks. Google Earth, June, 2014.

are evident in aerial photographs as well as from the valleys below (Baker, 2002). Recent landslides can sometimes be identified solely on the abundant distribution of aspen trees that concentrate in areas on the slide surfaces because aspen re-establish much more quickly than do conifers (USDA). Figure 4 shows the head scarps, toreva blocks, and ancient rotational landslides.

The geomorphology of the north flank on Grand Mesa is complex and interrelated. Within two kilometers of the study site is the Mesa Creek drainage head. It is the site of another modern landslide that is also causing road damage along SH-65 (CDOT, 2015). The Mesa Creek drainage has a general north-northwest aspect, as does the Donald Duck Landslide Complex. The Colorado Department of Transportation (CDOT) is currently monitoring and mitigating the damage caused to SH-65 at the head of the Mesa Creek drainage. Evidence exists for multiple landslides along the drainage from the currently CDOT monitored site to the valley below.

East of the study area is the West Salt Creek debris slide that moved in 2014. This slide is ~1.5km^2, extending from the Mesa top to the valley above Collbran. The slump block failed as a rock fall and a rockslide/debris avalanche, according to White et al. (2015), and created a sag pond below the head scarp. The structure is a characteristic toreva, and its aspect is to the north-northwest. A secondary creek formed at the top of the landslide during the summer of 2015 and is now causing a safety concern to the city of Collbran. This creek could possibly re-saturate portions of the landslide and, thus, activate movement in susceptible areas inside the debris scar. The evolution of this massive slide is a replication of the larger landslides that occurred in the Holocene.

Extensive work has been conducted and data compiled for generations that investigate the Grand Mesa in breadth and detail. According to Baum (2007), the majority of these slump blocks were probably mobile during the late Holocene and the Pleistocene. Yeend (1973) attributed the cause for such slumping to frost-wedging of the basalt, which allows percolation of rain and snowmelt into the underlying claystone. The weight of thick basalts atop saturated low shear-strength claystone is the driving force for failure of the slump blocks on Grand Mesa.

A highly generalized regional-scale study was conducted by Regmi, et.al., (2010a, 2010b) in Western Colorado where active mass movement is well known. According to Regmi et al. (2010a), hillslope evolution is the result of Pleistocene glaciation and mass movement induced by precipitation and fluvial erosion. Here, shallow translational landslides dominate the mass movement processes, in concert with deep-seated rotational slides and rock falls. This regional study area overlaps the southeastern face of Grand Mesa and establishes a framework of landslide susceptibility for the area based on analysis of 735 shallow movement landslides with 78% predicted accuracy (p. 186). Parameters considered in their study were topography, hydrology, geology, land cover, and human influences. Most landslides on Grand Mesa occur on steep slopes of 40-50° in interbedded sandstone, shale and mudstone or in unconsolidated colluvial, alluvial, and/or glacial deposits at elevations between 1800-2000m. Most susceptible areas are located along stream banks, or road cuts on steep slopes with a western aspect and vegetative cover of shrubland and woodland on low plasticity to non-plastic soils. Regmi et al. (2010b) state that the role of rainfall and snowmelt relative to hillslope movement still needs to be evaluated in this region. According to Brunsden (1993) and Processes (2010), to understand the evolutionary conditions of a landslide, one must, to some extent, investigate the seasonal weather patterns along with the geological and geomorphological environments.

Establishing a chronology of events in place is essential to understanding the initiating event in fundamental geomorphologic research. In a study conducted by Lang et al., (1999), they considered dendrochronology as the most precise and accurate dating method for assessing landslide stability. This method has been widely utilized and with great success in studies of relatively recent events (Degraff and Agard, 1984; Fantucci and Sorriso-Valvo, 1999; Giardino et al., 1984; Lang et al., 1999; Shroder, 1978; Stoffel and Perret, 2006; Stoffel and Bollschweiler, 2009; Stoffel, 2010). Because this direct method can be used on recent movements (within decades of the event), it is ideal for reconstructing the chronology, frequency, causation, and magnitude of landslides and addressing the influence of seasonal weather patterns on landscape evolution (Lang et al., 1999). Lang et al. challenged researchers to further determine the factors that initiate landslides once the chronology and cause are established.

3.5 The Donald Duck Landslide Complex

The Donald Duck landslide complex is noticeable from Highway 65 between mile markers 38 and 39 between Mesa Lakes Lodge and Powderhorn Resort (Figure 1). The complex stands in contrast to the surrounding densely forested hillside by a lack of mature trees and a presence of thick cover of native grasses. Aspen is the dominant tree species present on the complex with young fir trees growing in sparse patches. The complex and the geomorphic features that define the landslide can be seen in Figure 5.

This landslide complex is a logistical and financial problem for the US Forest Service because of frequent movement across and blockage of Highway 65. Material

Figure 5. Aerial image of the Donald Duck Landslide Complex. Landslide scarps are drawn as well as modern surface drainage. Aug. 2011.

removed from the roadway after landslide activity is stockpiled to the north of the complex along the roadside. Road damage is evident above and below the landslide where fissures appear in the highway pavement. Concrete barriers have been erected at the base of the complex along the roadside and boulders have been added by the road

Figure 6. CDOT management of the DDLC. Debris is removed from the road and stockpiled (6a) while concrete barriers and boulder rip-rap are used to stabilize the toe. July 2011.

department in an apparent attempt to weigh down the toe of the slide and potentially stabilize the complex. The stockpile and concrete barriers can be seen in Figures 6a and 6b.

Upslope from the Donald Duck landslide complex are two ephemeral streams that converge just below the crown of the slide. Both of these streams drain periodically from the ridge above, including the torevas and the reservoirs. Because these streams only flow when high precipitation occurs, the complex surface receives increased direct precipitation during peak events, and also from the watershed above that includes the reservoirs and hillslopes that are situated along the flank of the Mesa.

This thesis provides a timescale of mass-movement utilizing dendrochronological methods to analyze landslide evolution on Donald Duck as paralleled with historic precipitation. Lithology, landscape evolution, climate, biota, and human impact are each considered as influences on the movement of the Donald Duck landslide complex.

The Donald Duck landslide complex is part of a much larger geomorphic system on the northern flank of the Grand Mesa, Colorado. The surface material of the slide is characterized by basalt boulders, gravel, and glacial till of MIS2 Pinedale-age glacial epic. Yet, at the same elevation on the opposite side of Spruce Point, as well as further north on the same ridge face, is the white claystone of the Eocene Uinta Formation. Below the complex, fluvial gravels are evident in the braided and intermittent creeks that flow along the short valley floor. In field traversing and in topographic map and aerial photography review, the complex is readily identifiable as being part of an ancient landslide (Figure 7). This ancient landslide originated at the toreva slump blocks parallel to the top of Grand

Mesa; it is flanked by the ridge at Spruce Point to the west; an unnamed ridge, and Coon Creek to the east; and it extends north to where the toe terminates just before reaching Old Grand Mesa Road. The ancient landslide fills the valley floor and State Highway 65 meanders across the landslide. It is poorly drained by an unnamed creek that flows into Coon Creek to the north.

Figure 7. Outline of the ancient landslide. The gold line outlines the ancient landslide. The landslide underlies the entire valley occupied by the SH 65 switchbacks. Google Earth, Jan. 2014.

4. METHODS

4.1 Summary of Objectives

The first objective of this study is to identify and analyze the bounds, movement and physiographic features of the Donald Duck landslide complex. This objective will be satisfied though geomorphic mapping within and surrounding the landslide complex via field mapping, utilization of aerial photography and topographic maps.

The second objective of this study is to provide an explanation of the temporal movement of the landslide complex. This objective will be satisfied through dendrochronological sampling of trees on and around the complex and analyzing the tree cores for age and growth of reaction wood. These data will then be used to construct a temporal map that represents periods of movement on the complex.

The third objective of this study is to determine the threshold conditions between stability and movement of the landslide complex. This objective will be satisfied through collecting historic precipitation data, comparing these data to dendrochronological data, and identifing of simultaneous events in these records.

4.2 Geomorphic Mapping

An assessment of the surface of the landslide includes recognition of typical features, measuring the primary characteristics, and conducting detailed mapping of all features (Brunsden, 1993; Degraff and Agard, 1984; Parise, 2003; Shroder, 1978; Stoffel and Bollschweiler, 2009), which are internal and bound the slide. Parise (2003) found in studying the Slumgullion slide in the San Juan Mountains of western Colorado that employing these observations proved critical as indicators of deformation in structure and in sequence. The complexity of the Donald Duck site is illustrated in Figure 8. The head scarp, three lobes, the main body, neck, toe and tension cracks are visible from a vantage point southwest of the complex along State Highway 65.

Figure 8. Panoramic view of the DDLC from the north flank. The main scarp, body and toe are visible in the near field view. The smaller two contributing slides are in the far field view. Personal photos, June 2011.

Recent aerial photographs (2011) and topographic maps of the research area were acquired to construct a base map. The perimeter and surface of the complex were traversed to map slide boundaries, locations of tension cracks, impacted trees, internal lobes, and direction of movement of the lobes, as well as the general topography above and adjacent to the slide area (Parise, 2003). Parameters identified are: scarps, fractures, basins, ridges, types of vegetation/distribution/density/change and surface drainage. The aerial extent and aspect of the slide are recorded, also.

4.3 Dendrochronology Survey

The dominant tree species available for sampling are quaking aspen (populous tremuloides) and subalpine fir (albies lasiocarpa). On the more barren surfaces of the slide, aspen are the dominant species with few fir present.

Trees identified for sampling were initially selected from robust trees outside of the perimeter of the landslide and from trees on the complex that showed impact scars and geotropic growth (Figure 9). Whereas mapping the dendrochronology of the multiple-lobe landslide, clusters of trees in close proximity to one another were documented and cored

Figure 9. A tree cluster on the DDLC. These five mature trees were each cored then grouped as part of the 'scarp' unit. Personal photo, June 2011.

individually and then grouped in units according to the geomorphic location on the landslide. One such grouping of trees is shown in Figure 9.

Typically, a minimum of four cores were taken from each tree cluster, either through the bend of geotropic growth on the tree through visible scars or at breast height (Figure 10a and 10b) to capture age (Giardino et al., 1984). Geotropic growth was determined to be related to mass movement by identifying downed trees or remnant scars that may indicate restricted growth and for the presence of a landslide lobe crest. If downed trees or associated scars were not present and the tree presenting geotropic growth was at the edge of a lobe crest, it was sampled as an indicator of mass movement (Stoffel, 2010). Visible scars were noted for height, depth, and direction toward the landslide complex (Stoffel and Perret, 2006). Bites, rubs, and scratches from local wildlife were also identified and noted as not related to mass movement. Because of the general difficulty of dating and analyzing Aspen, each tree in a cluster was sampled individually and some were sampled more than once. Each core extended through the entire width of the tree to aid in precision dating to the initiation of reaction wood (Fantucci and Sorriso-Valvo, 1999). Each sample was documented with its latitude, longitude and elevation by GPS, labeled and photographed (Giardino et al., 1984) for georeferencing purposes. To ensure field relationships were accurately recreated in the lab, a relative location of the sampled trees were recorded, orientation of the lean of the tree, the orientation of cores, the tree circumference and crown width, and the density of the tree cluster were recorded and mapped.

In the lab, the tree cores and one tree cookie were prepared, measured, recorded and dated. Preparation included mounting, drying, sanding, and staining the cores to enhance tree-ring appearance (per Giardino, in discussion, 2010). Once prepared, the width of individual rings were measured and recorded by digital ring counter with the aid of a microscope. For cores that were too short to reach the tree pith, a maximum date

Figure 10. Coring trees. Coring through geotropic growth (10a) of impacted trees and at breast height of age referenced trees (10b). Personal photos, Aug. 2010.

is recorded and noted in the results. Where cores passed through the pith, a pith meter was fitted to the core to estimate age (Lafon, in discussion, 2011). The years 1983 and 2000 were reliable marker years and were used for cross-dating across the core samples.

The year 1983 experienced exceedingly high winter and spring precipitation for the region and exhibited quite significant tree-ring growth. The year 2000 was a year of large contrast in nearly all of the tree cores and was a very thin tree-ring growth year. Tree-ring growth and scars of reaction wood and suppression wood were identified in the cores, and the date of initiation as well as length of time was determined (Shroder, 1978; Giardino et al., 1984; Stoffel, 2010).

4.4 Determining Threshold Conditions for Stability

Historical precipitation records reflecting the Donald Duck landslide complex were collected from two nearby weather stations that are currently managed by the National Oceanic and Atmospheric Administration (NOAA) and reported by the National Centers for Environmental Information (NCEI). The Mesa Lakes and Mesa Lakes Resort weather stations are on the northern flank of Grand Mesa (39.04968, -108.09030), 2.4km south of and 152m elevation above the Donald Duck landslide complex. Precipitation data were collected at the Mesa Lakes Resort weather station through the Western Regional Climate Center (WRCC) from 1972 to 1977. Precipitation, snowfall, and temperature data were collected at the Mesa Lakes weather station by NOAA from 1987 to 2015. Data retrieved from Mesa Lakes during 1987 to 2015 are monthly summaries of temperature and of precipitation, which includes daily snowfall amounts. Annual, seasonal, and monthly precipitation averages were generated from these monthly summaries.

Monthly precipitation data that were collected at Bonham Reservoir between 1963 and 2015 were used in in conjunction with Mesa Lakes Resort data from 1972 to 1977 to retrodict precipitation at the landslide complex from 1963 to 1986. A regression, which was collected from statistic (Figure 11) was fitted to the data that also illustrates a slow increase in precipitation over the last half century. The Bonham Reservoir weather station is on top of Grand Mesa (39.10217, -107.89888), 17km east of and 515m elevation above the Donald Duck landslide complex.

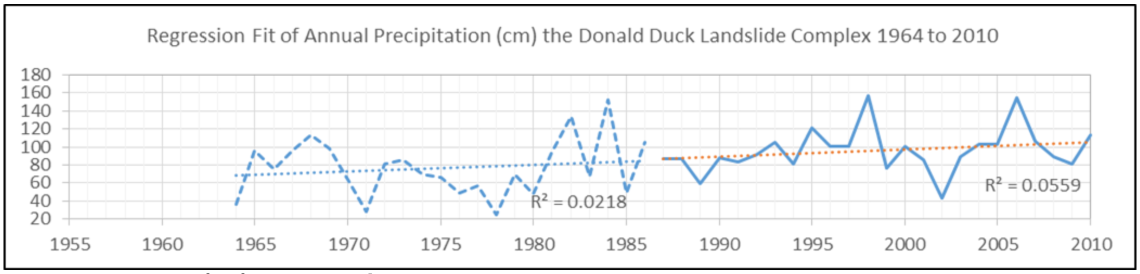


Figure 11. Regression fit of precipitation data.

Historical precipitation data were compared and cross-referenced with tree-ring data to evaluate simultaneous high-precipitation dates and reaction-wood growth of the trees on the landslide complex. Simultaneous dates are used as indicators of mass movement. Based on these events, critical precipitation events were identified to establish a critical precipitation level to base a recurrence interval.

5. DATA ANALYSIS

5.1 Geomorphic Setting

The Donald Duck landslide complex (DDLC) consists of multiple terraces and three, distinct landslide lobes. The main body of the movement is identified as the Donald Duck (DD) landslide and has a distinct toe, neck and scarp. To the right (south) of Donald Duck is the Banana Dance (BD) lobe, which is located less than one meter higher in elevation. A deep transverse fissure and subsequent drainage divides the two landslide bodies. Above BD and to the southeast is the Bum Bungalow (BB) lobe. BB is long and narrow and is separated from the rest of the complex by a high ridges. The terraced toe of BB flows into the DD just above the toe at the neck and flows into the BD lobe at its head scarp. A plan view and surficial geomorphic features of the complex is shown in Figure 12.

Field work in the study area revealed DDLC to be concave (15°) in the neck in relation to the abrupt steepness in slope at the head scarp (40°) and toe (50°), respecively. Minor scarps within the toe approached a 60° slope. Elevation rises 31 m along a length of 137 m. The width at the crown of the landslide is 55 m; the landslide is 41m wide at the narrowest section of the neck and is 82 m wide at the toe. Based on a seismic refraction survey conducted in the field, calculation (Rahn, 1996) of the depth of loose landslide material and till at the head scarp is 5.95m thick, in the main body it is 6.68m thick, and at the foot it is 3.79m thick. The material within the Bum Bungalow lobe is 2.35m thick and within the Banana Dance lobe, the material is 4.51m thick. The volume of the slide material is ~37,870m^3.

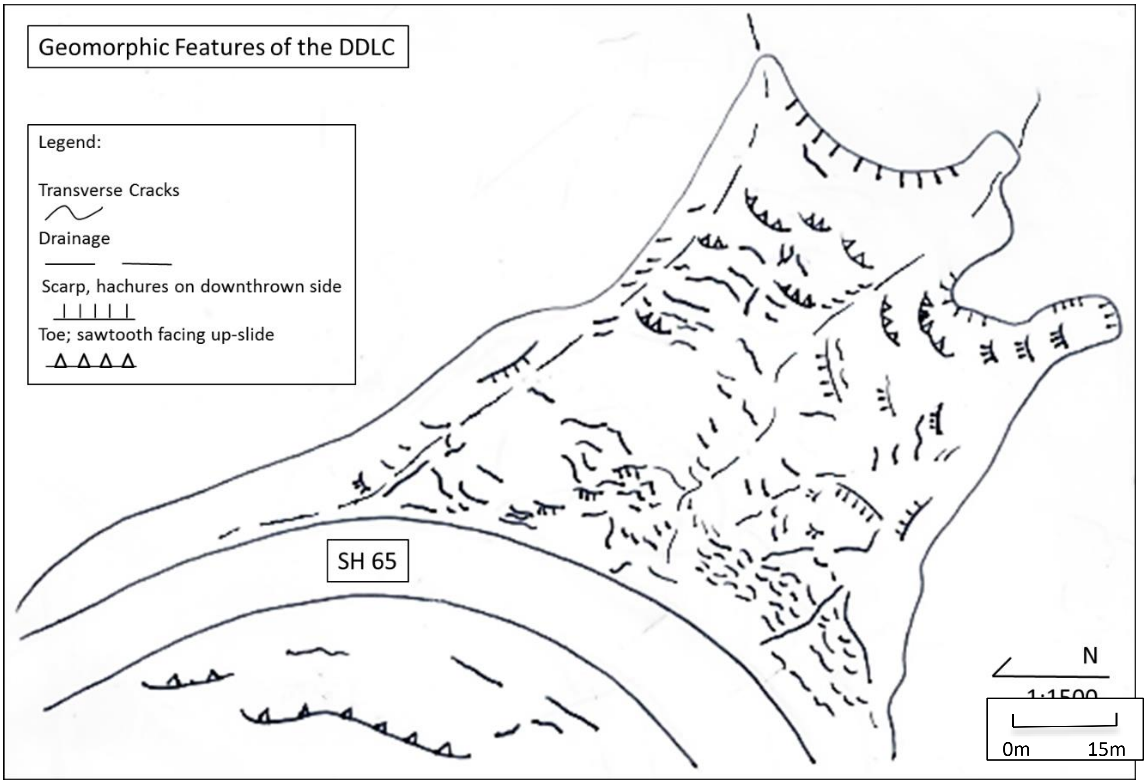


Figure 12. Geomorphology as mapped on the DDLC. The scarps, shear zones and toes of the three slides are visible.

The material in the DDLC ranges from 1m² basalt boulders to orange and red mottled sandy clays with interspersed gravels. These sediments have been identified as Quaternary glacial till (Cole, 1981) of the MIS 2 (Pinedale) isotope-age stage glaciation epic within the Grand Mesa Formation. Two intermittent streams, located on either side of the slide, drain the area from the eastern ridge above the landslide. Transverse and radial tension fissures are present on the surface and along the perimeter of the slide complex, as can also be seen in Fig 12.

5.2 Dendrochronological Indicators

Eighty-eight tree-cores and one tree-cookie were collected and processed using standard dendrochronological methods. Of these 88 cores, 72 were from aspen trees and

16 were from fir trees. Dendrochronology is typically applied to conifers, which differ greatly from Aspen in how data are recorded in the tree-rings. Conifers are gymnosperm, which exhibit very clear compression wood with wide, dark red rings on the downslope-side of the tree in response to geotropic growth. Aspen are angiosperm, which exhibit indistinct tension wood with wide ring-growth of various ambiguous textures on the upslope side of the tree in response to geotropic growth (DeGraff and Agard, 1984). Because the rings are indistinct, the cores were measured from the downslope side to establish tree ages and examined from the upslope side under low angle, dim light conditions for reaction-wood growth. Photos of the cores are shown in

Figure 13. Cores and cookie. Examples of aspen and conifer in core. The conifer cookie demonstrates the complexity of movement at the junction of the three slides. Personal photos, March, 2015.

Appendix A and graphs of the tree-rings are shown in Appendix B.

The cores from trees were grouped by species and were labelled by species', location in regard to being inside, outside, or on the perimeter of the landslide, and whether or not they were used to indicate age or length of record of reaction wood. Each tree-ring width was measured three times to minimize error and ensure repeatability. Examples of the tree-ring mounts and tree-cookie can be seen in Figure 13. Measurements of samples that had tree-ring widths that could not be repeated were rejected based on lack of confidence in the measurements. Cores that were questionable as to the original state or did not appear intact were also rejected. The samples that were rejected were not used in the analysis. The sixty remaining tree-cores and one tree-cookie were grouped based on the location on the DDLC.

The tree-cores used in analysis are grouped into one of ten tree clusters on and around the Donald Duck landslide complex. The clusters are classified based on the location relative to the morphometric characteristics of the landslide complex. Photographs of the tree-cores in the tree clusters are shown in Appendix A. Clusters were assigned maximum ages of tree establishment dependent on the age of the oldest trees within the group. Tree clusters that are located externally above and beside the complex have maximum measured ages of establishment in 1887, 1901, 1907 and 1932, respectively. The tree cluster below the landslide, External Highway West (EHW), has a maximum established age of 1965. One tree cluster on the flank of the complex has a maximum established age of 1959. Tree clusters that are internal to the complex have maximum measured ages of establishment in 1964, 1965, and 1966, respectively. The tree-cluster ages and the locations on the DDLC are shown in Figure 14.

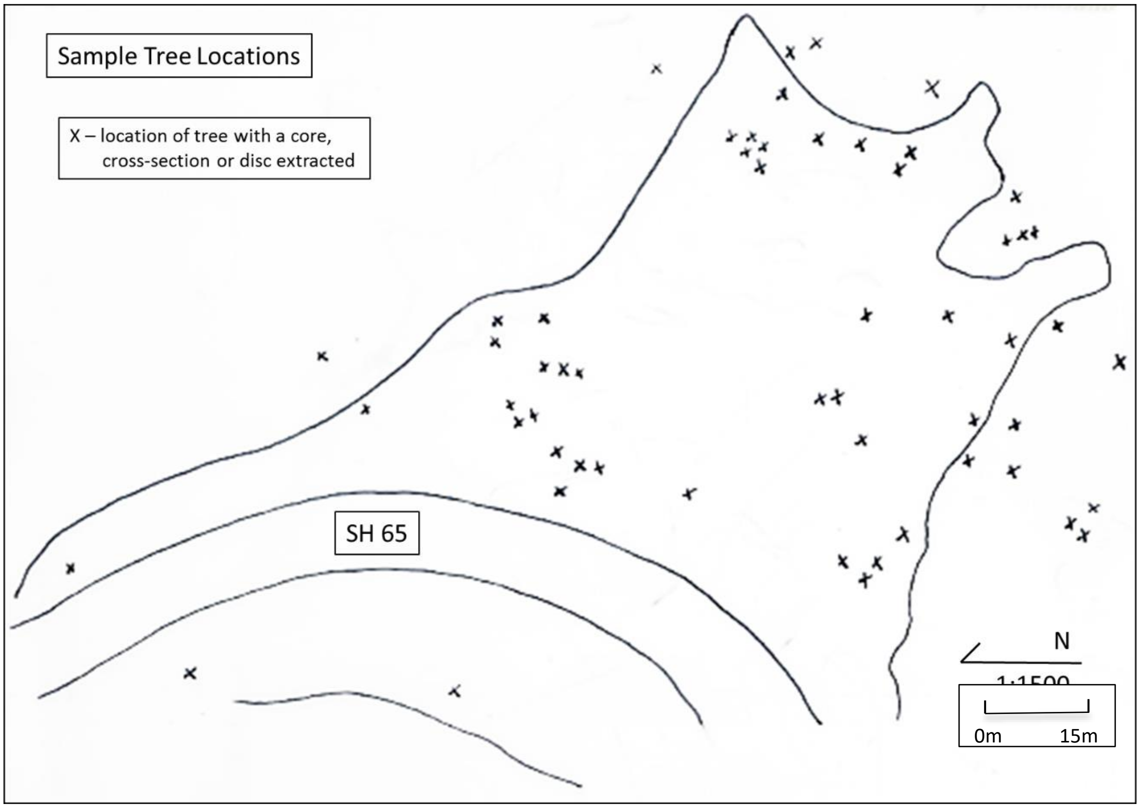


Figure 14. Tree Locations. Placement of the cored tree across the landslide complex.

The EHW appears to be situated on disturbed ground and is either the extended toe of the landslide complex or is the by-product of construction activities of the highway. Given the rapid re-establishing abilities of clonic aspen after disturbance (Shepperd, 1986), it appears that the tree record on the landslide complex was reset before the early 1960s.

When the years of tree-ring reaction wood are placed in a cross-plot, reaction wood in the aspen and fir align during years of active landslide movement. Most tree-cores indicate multiple years of continual impact and adjustment (Figure 15). In the graph of (Figure 15), the tree age as well as isolated event responses and continually occurring event responses can be observed in most cores. The groupings, Internal Duck

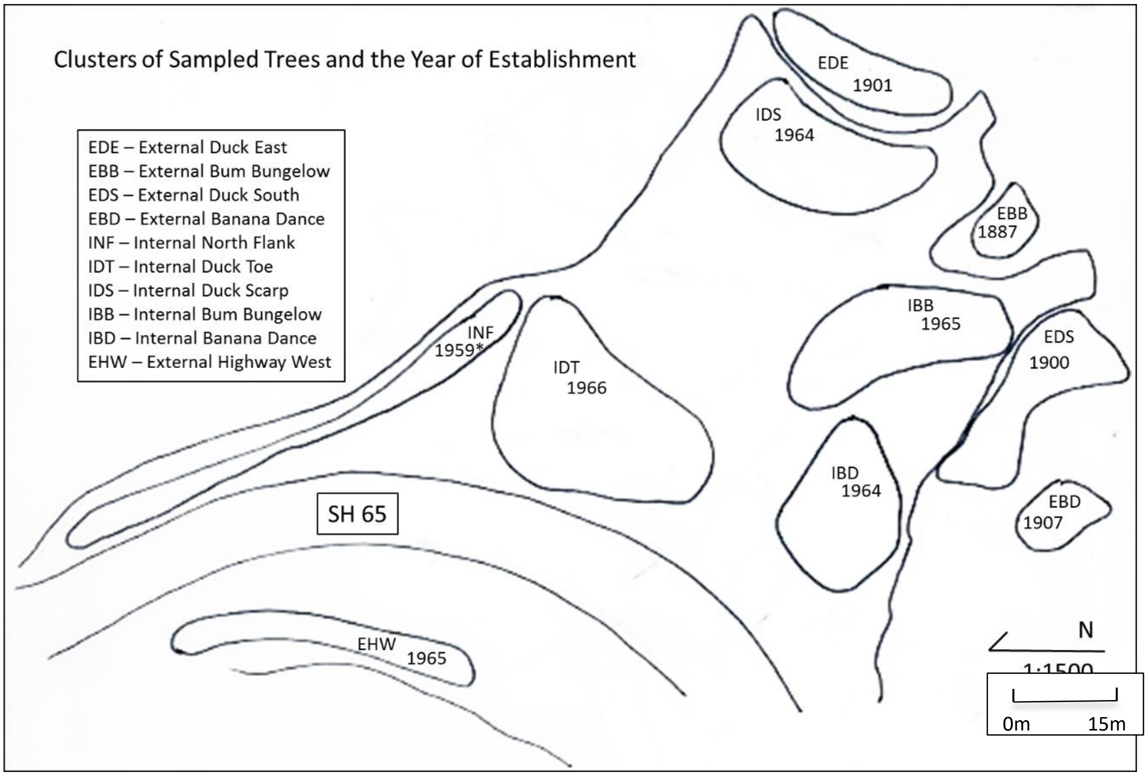


Figure 15. Tree group ages. Ages are based on the oldest tree in the group and are used as an indicator of earliest surface stability and tree repopulation.

Scarp (IDS), Internal Duck Toe (IDT), Internal Bum Bungalow (IBB), Internal Banana Dance (IBD), and Internal North Flank (INF), show reaction-wood in tandem to the surrounding groupings.

INF appears to have the most large events that occurred in the early 1960s and in the early 1980s (1981, 1984, and 1987). Situated on the perimeter of the complex and with response limited to high-magnitude events that involve the primary slide, it is an indicator of the most significant events.

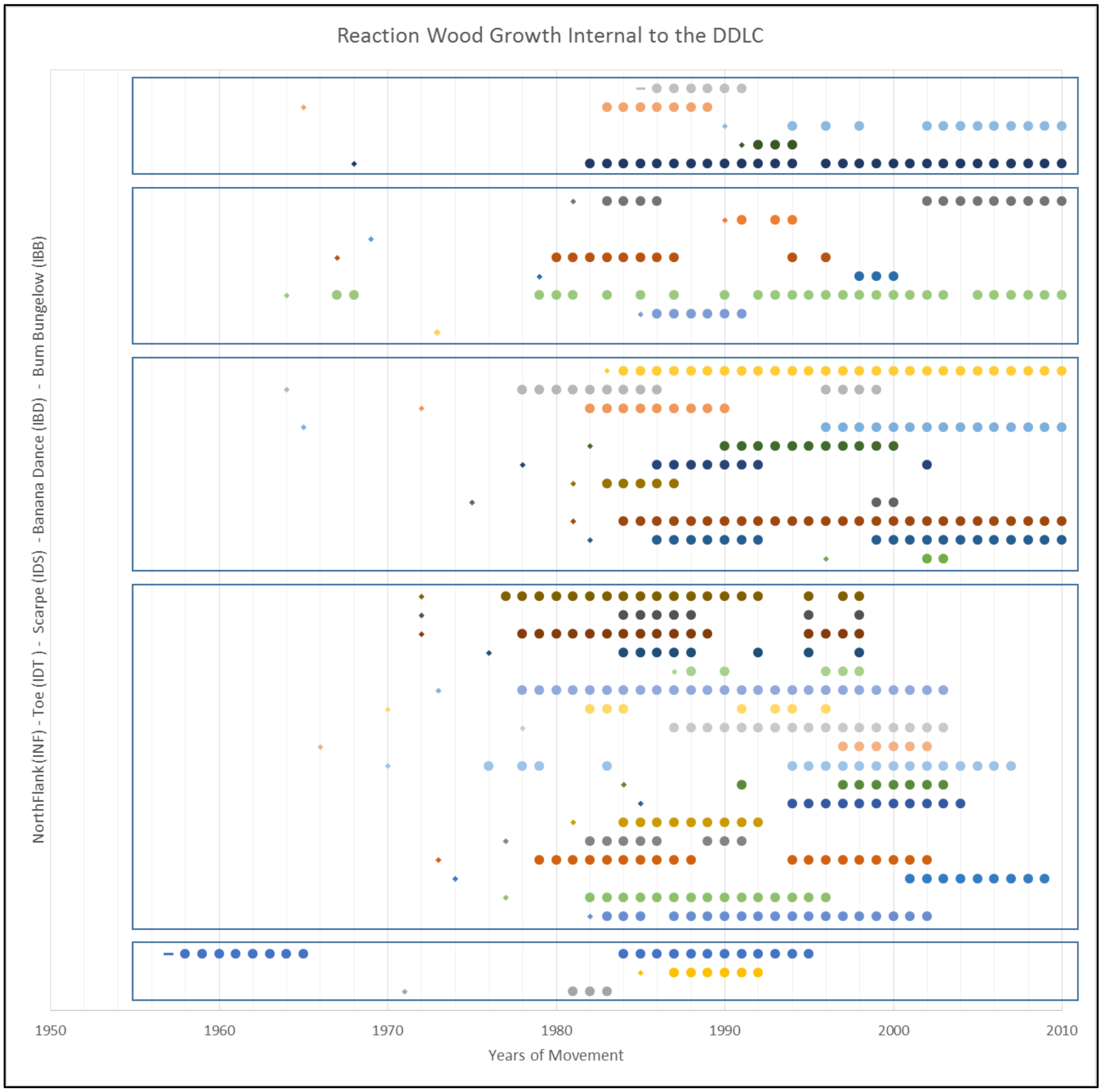


Figure 16. Graph of tree ages and response growth. The groupings are tree clusters as they occur on the complex. (X) indicates the age of the tree, the dots are tree ring years were reaction wood growth was observed in the individual tree within the tree cluster.

IDT records the earliest movement responses that are recorded in reaction wood in trees that are internal to the complex. Reaction wood is prevalent in the late 1970s (1976-

1979) and early 1980s (1982-1984). IDS, however, contains tree-cores with reaction wood that begin later in 1978 and then in 1982-84. IBD tree-cores begin recording reaction wood shortly thereafter (1979, 1980, 1983, and 1985). Years of movement recorded in IBB show response much later in 1982, 1983, and 1986, respectively. Years of subsequent adjustment appear to occur infrequently and sporadically in IDT throughout the late 1980s and into the early 1990s with occasional adjustments again in the surrounding lobes. IDT appears to have increase movement again in 1994 and 1995 with the same pattern of response: Tree-cores record movement for IDS in 1996, for IBD in 1997, and minor adjustments throughout for IBB.

In Figure 16, the first response years of landslide movement as recorded in tree-ring cores are plotted by tree groupings. Years of activity that show response in only one of the groupings or directly following the response pattern of movement that follows

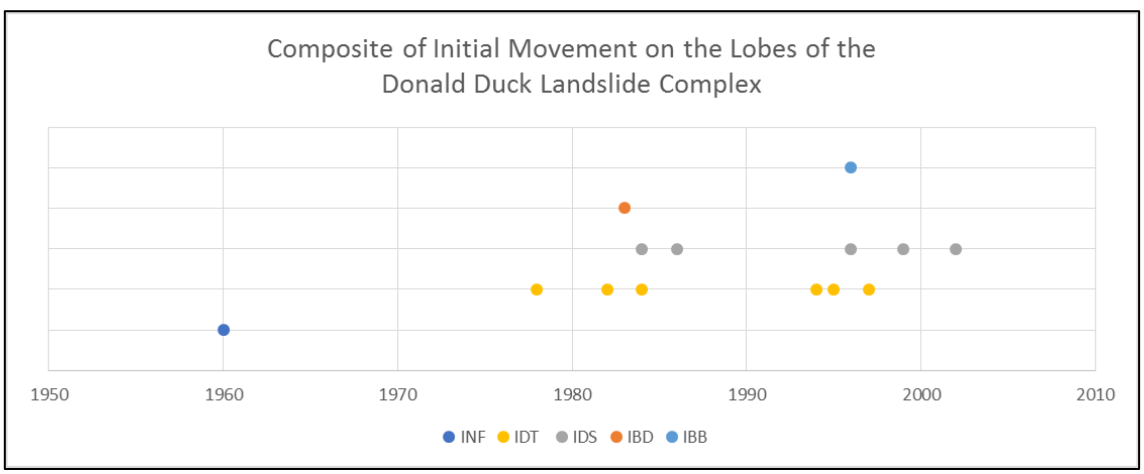


Figure 17. Composite graph of movement as indicated by statistically significant initiating movement as recorded in the reaction wood of the tree rings. The complex will have regained quasi-stability after internally adjusting from the initiating event before it will record the next initiating event.

IDT, IDS, IBD and IBB, are attributed to adjustments within the landslide for stability and reaction-wood growth occurring closely after these dates will be part of a continually adjusting response movement, which can sometimes extend from one year to twenty-five years. Thus, it is crucial to identify statistically significant, initiating occurrences as opposed to response movement. Graphs of response frequency within the clustered groups are shown in Appendix B. The composite graph (Figure 17) illustrates the initiating movements that occurred in a minimum of 20% of the entire group population. The significant initiating years of movement are pre-1960, 1998, 1982, 1983, 1984, 1994, 1995, 1996, 1997, 1999, and 2002, respectively. Movements in 1984 and 1996 were significant across more than one lobe, suggesting high magnitude events. Individual maps of lobe movement are shown in Appendix C.

5.3 Analysis of Precipitation Data

Monthly weather data from 1987 to 2010 were acquired from NOAA for the Mesa Lakes weather stations and calculated for monthly, seasonal, and annual averages, as well as totals for precipitation, including snowfall, and temperatures.

At the Mesa Lakes weather station, winter (~26.66cm) and spring (~28.55cm) are seasons of higher precipitation, ranging in average from 8.22cm in May to 10.3cm in April. The dryer seasons occur in summer (13.45cm) and fall (25.54cm), ranging in average from 3.76cm in June to 9.52 in September. Annual precipitation at the Mesa Lakes weather station between 1987 and 2010 averages 96.16cm per year. The precipitation data from 1987 to 2010 show anomalies months, seasons, years, and groupings of successional years stand out.

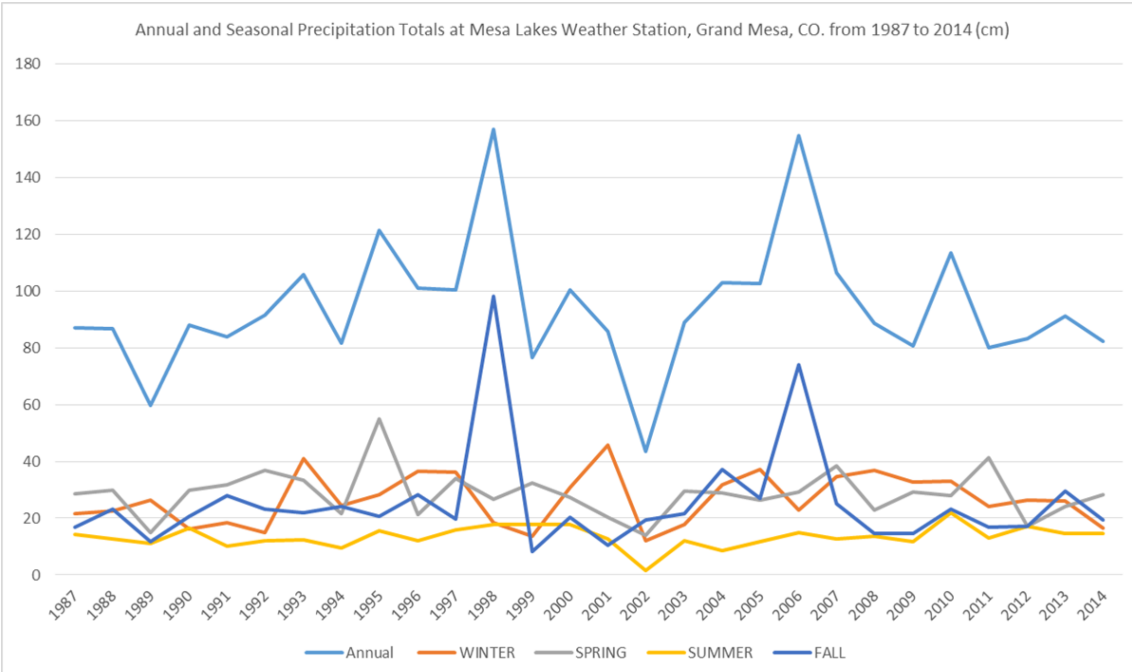


Figure 18. Annual and seasonal precipitation fluctuations at the Mesa Lakes weather station.

Four months within the data range have precipitation totals that exceed 300% of the respective monthly average: May of 1995 (26.64cm), September of 1998 (88.64cm), February of 2001 (29.96), and November of 2006 (42.39cm). Five seasons within the data range have precipitation totals that exceed 150% of the respective seasonal average (Figure 17): winter of 1993 (41.12cm) and 2001 (45.63cm), spring of 1995 (54.78cm), and fall of 1998 (98.04cm) and 2006 (74.10cm). Three years within the data range have precipitation totals that exceed 120% of the annual average. The years 1998 and 2006 are particularly wet with 157.00cm and 154.63cm, respectively, and 1995 (121.20cm) is also a remarkably high precipitation year. The years 1995 through 1998 and 2004 through 2007 are successive years of high precipitation. In the 1964-1986 precipitation data set, two more groupings of high precipitation years stand out: 1965 through 1969 and 1981 through1984, respectively (Figure 18).

Six months within the data range have precipitation totals that are less than 10% of the respective monthly average: October of 1988 (0.25cm), July of 1994 (0.25cm), October of 1997 (0.0cm), January, June and July of 2002 (0.28, 0.0, 0.0cm), respectively. Five seasons within the data range have precipitation totals that are less than 50% of the respective seasonal average (Figure 17): fall of 1999 (8.32cm) and of 2001 (10.63cm), winter, spring and summer of 2002 (11.92, 13.92, and 1.52cm) respectively. Three years within the data range have precipitation totals that are less than 80% of the annual average: 1989 (59.55cm), 1999 (76.68) and 2002 (43.36). The years 1987 through 1991 and 1999 through 2003 are years of low precipitation. Among the retrodicted data, the year 1971 is of exceptionally low precipitation as are the years between 1976 to 1981 and 1985, respectively (Figure 18).

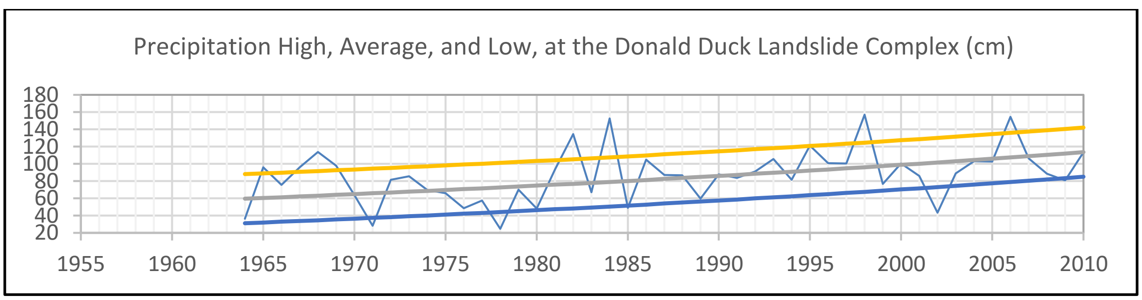


Figure 18. Recorded and retrodicted precipitation at the DDLC, 1964 to 2010. Yellow bar is above average annual precipitation, grey is average, and blue is below average annual precipitation.

The emerging pattern of groupings of high precipitation and periods of low precipitation suggested a look into the occurrence of the El Nino/Southern Oscillation (ENSO), fluctuating oceanic temperatures of the Pacific Ocean that affect air temperatures and, thus, precipitation rates across the United States. El Nino is the term typically given to abnormally warm and wet years whereas La Nina is the term for cooler temperatures and, thus, often lower precipitation (Barnston, 2016). According to NOAA (NOAA, 2015), the strongest El Nino years to date were in 1997 to 1998. The second strongest El Nino years to date were in 1982 to 1983. The third strongest El Nino years to date were in 1972 to 1973. In the precipitation data available for the DDLC, 1972 to 1973 were not remarkable years of high annual precipitation. The years of 2006 to 2007 are also El Nino years but are considered a weak season by NOAA but are years of high precipitation in the study area. Most weather coverage is related to El Nino years because of the highly predictable increase in precipitation. La Nina years are often more variable in impact and occurrence. La Nina years at the study site are evident around the years of 1964, 1971, 1974-1976, 1985, 1989, 1999, and 2008. The La Nina years are often not classified and ranked as are the El Nino years.

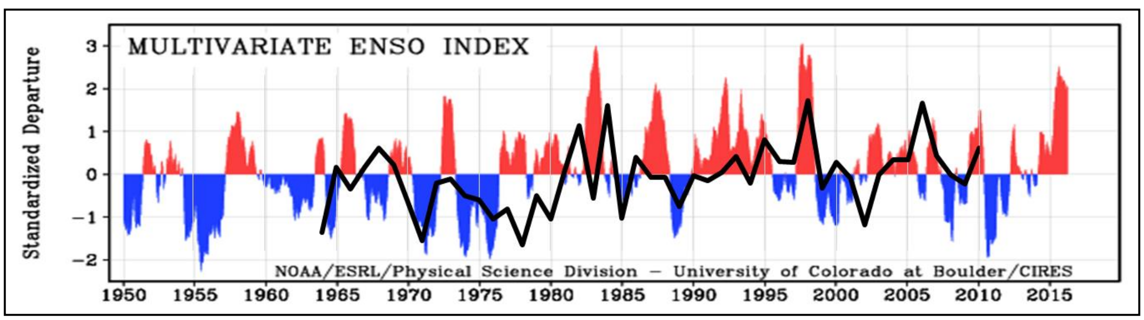


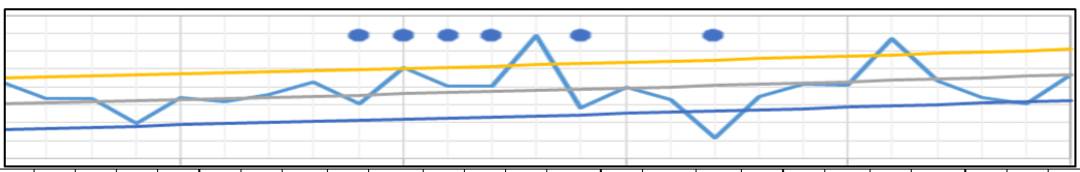
Figure 19. Multivariate ENSO Index and DDLC precipitation (modified from Wolter, 2016). Localized precipitation overlays recorded ENSO El Nino years.

5.4 Thresholds of Movement

Possible thresholds of movement were determined by cross-referencing annual precipitation anomalies with years of significant initial movement on the DDLC. The data set containing detailed precipitation data were assessed, including annual, seasonal and monthly precipitation anomalies to surmise if these quantities appreciably contributed to the overall movement patterns on the complex. For the rest of the precipitation records and tree-growth records, a generalization is accessed across annual records.

The trees that were sampled will record response growth to landslide movement only during the growing year for a tree, which is most active during spring and summer and dormant during fall and winter. Precipitation that occurs during fall and winter and, thus, movements that may occur during fall and winter will then be recorded in the following spring and summer growth period of the trees. For the purpose of aligning growth years with the events that would be recorded in the reaction wood, precipitation data have been adjusted to reflect the events that would be recorded in the growing year. Thus, the fall and winter anomalies of 1999 are evident in the growth patterns of 2000, as well as the spring and summer anomolies of 2000.

During the years of detailed precipitation records of 1987-2010, six initial periods of movement are recorded on the DDLC; 1994-1997, 1999, and 2002. The year 1994 was a year of exceptionally low precipitation during the summer month of July, 10%- the monthly average. The year 1994 also followed a year with a record high winter precipitation, 150%+ seasonal average. The year1995 was a very wet growing year, 120%+ of the annual average, with a very wet spring 150%+ of the seasonal average, and a very wet May, 120%+ of the monthly average. The movement in 1996 was in the complex scarp, and is likely an adjustment response to the toe movement in 1995. The movement during 1997 is in the complex toe, but with no greater or lesser precipitation averages across the annual, seasonal, and monthly spectrum than any other year. This movement is likely an adjustment response to the scarp movement and subsequent material loading of the toe. The year 1999 is a record dry year, 80%- the annual average, that with an exceptionally wet preceding September, 300%+ the monthly average. The year 2002 is the driest year during the 1987-2010 record, 80%-, with the driest four seasons, 50%- the seasonal averages, and the driest January, June, and July, 10%- the monthly records. This dry year followed a year with a record high winter season, as well as a record high February in 2001. It appears that movement begins in years of low precipitation that follow a year of high precipitation. Following the initiation, movement continues in the lobes as the mass attempts to adjust to the landslide to attain re-stabilization.



	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
AN			596						1212			1570	767			434				1546				1135
F														83.2		106.3			370.6		417.1			
W							411.2								456.3	119.2								
S									547.8							139.2								
S																15.2								219.9
S													*886.4											
O			*2.5									*0												
N																					*423.9			
D																								
J																*2.8								
F															*299.6									
M																								
A																								
M									*266.4															
J																*0								
J								*2.5								*0								
A																								

Figure 20. Cross-referencing detailed precipitation data with precipitation averages and years that movement was initiated on the DDLC. Abrupt changes in precipitation from above average to below average appear to initiate movement during the 1987-2010 years of record. High precipitation events that immediately follow drought appear to perpetuate movement.

Between 1978 and 1986, movement of the DDLC was recorded in the aspen and fir during five years, 1978, 1982-1984, and 1986. Of these years, 1978 was a year of severe drought on the complex, followed by increasingly high, annual precipitation averages, centered around the second strongest El Nino year on record as of yet, 1982-1983.

According to the results of this study, high-volume months, seasons and years of precipitation, such as occur during strong El Nino years that follow low volume months, seasons or years of precipitation such as occur in strong La Nina years, create a recognizable pattern that is reflected in the ENSO record. This pattern predicts a cycle

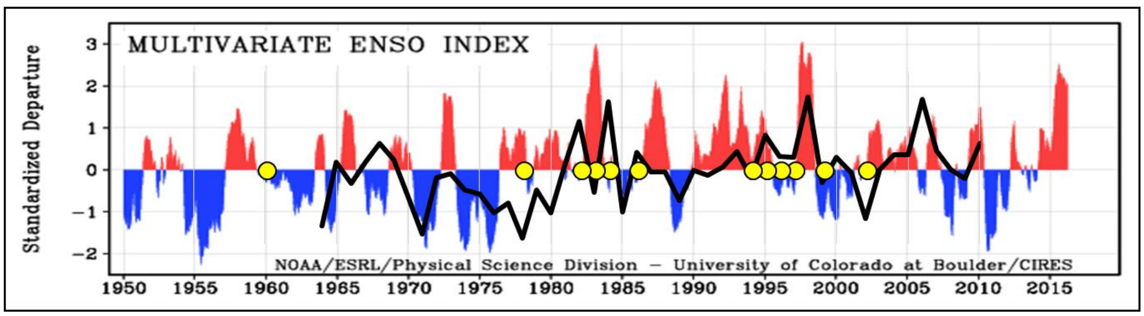


Figure 21. Cross-referencing the years of significant landslide activity, localized precipitation records, and the ENSO index (modified from Wolter, 2016).

of fissures opening on the DDLC during drought years that are then infiltrated during high-precipitation events that then de-stabilizes the complex and initiates episodes of activation and adjustment on the DDLC. The individual ranges of precipitation that fall on the complex are critical to movement and just as critical is this cycle of extensive drought before long-duration wet periods, which is considered the threshold series of events that may activate movement on the DDLC.

5.5 Discussion

The goal of this study is to be able to establish a rate-of-movement by assessing the general mechanics within this complex and to provide an explanation of current stability. Understanding the history of the slide indicates the probability of future activity, which can provide awareness to Forest Service personnel in regard to hazard planning and prevention in this area. To achieve the goal of this study, three research objectives have been established: identify and analyze the bounds, movement and geomorphology of the slide; explain the temporal movement of the slide; and determine the threshold conditions for movement.

Geomorphic mapping within and surrounding the landslide complex was conducted via field mapping, utilization of aerial photography and topographic maps. The DDLC is a northwest aspect-facing shallow landslide with a volume of approximately 37,870m^3 dispersed through three active lobes consisting of Holocene-aged glacial till and basalt boulders. The area is part of the eastern flank of a much larger ancient slide that originates at the Grand Mesa flank above and terminates in the Mesa Valley below.

Dendrochronological sampling of trees on and around the complex and analyzing the tree-cores for age, growth, and occurrence of reaction wood provided data from 62 samples from aspen and fir trees. These data provide the time construct of activation in the landslide, as well as the adjustment periods while the landslide approached a return to stability. Significant episodes of activity on the DDLC were in the late 1950s to early 1960s when the tree record on the slide was destroyed and tree growth began anew; again in 1978 into the mid-1980s; in the mid-1990s, and again in 2002.

Analysis of historic precipitation data across months, seasons and years that are compared to dendrochronological results reveal a pattern that begins with a drought year (80%- annual average), which is followed by simultaneous peak events on record that center around strong El Nino years with exceptionally wet months (300%+ monthly average), and exceptionally wet annual accumulations (120%+ annual average). This pattern, or intense dry-wet cycle, occurs in the period 1978 to 1986 and again in 1994 to 1999. Record of DDLC initiating movements began in 1978, a very dry year locally, and in 1982-1983, an El Nino season, and in 1984, very high precipitation, and in 1985, an above average precipitation year following a locally very dry year. The second dry-wet cycle began in 1994, of locally below-average precipitation, followed by a locally very high precipitation year (120%+ annual average) that is also a weak El Nino year in 1995. Years of above average rain and internal lobe adjustment occurred on the DDLC in 1996, 1997, and a strong El Nino year in 1998 with very high precipitation (120%+ annual average). Movement recorded in 1999 is attributed to the below average annual precipitation (80%-) and the extremely wet September at the end of the 1998 growing season. Precipitation in this month was more than 13 times the monthly average for September during the 1987-2010 period.

Reviewing historic ENSO cycles shows the moderate La Nina period of 1955-1956 occurred concurrently with road construction of SH 65, and in concert with a strong El Nino period following in 1957-1958 was the initial cycle responsible for the initial Donald Duck Landslide. Activity recorded in core 5B of INF is datable back to 1959 and records occurance of reaction wood. Older rings of the core sample and the center were damaged beyond recoverability. This sample is outside of the active DDLC but is along a narrow northern flank that is the location of much older, more established trees and undisturbed ground. An El Nino activation of the DDLC in 1957-1958 would have followed the road construction of 1954 that would have destabilized the ancient landslide flank. Therefore, the historic series of events for the DDLC activation would be destabilization by road construction that began in 1954, activation during a possibly dry La Nina year of 1955-1956 and following wet El Nino years of 1957-1958, and restabilization of the tree population by 1964.

A record dry year in 2002, at 37% the annual average precicpitation, corresponded with movement on the DDLC, but no subsequent initiating movement was recorded during the above-average, seasonal precipitations of fall 2005 and 2007 nor the very wet year of 2006 (120%+ annual average). It is possible that the responses to precipitation events in 2006 may have been hidden in the continuing growth adjustments between lobes that followed the larger events. Yet, only 9 of the 55 samples were in continual movement during the 2005-2007 time period, and only 1 tree shows initial movement in 2005. It is possible also that the landslide complex is reaching stabilization during this period.

The dendrochronology of the aspen trees between the years of 2002 and 2010 were often highly suppressed and difficult to distinguish. Aspen, in themselves, are difficult to date because of the cellular structure and because they are also subject to Sudden Aspen Decline (SAD). SAD was first identified in the Grand Mesa, Uncompaghre, and Gunnison National Forests (GMUG) in the southwestern San Juan Mountains of Colorado in 2004 and by 2008 where 45% of the aspen groves in Colorado were considered to be in severe condition, having over 50% mortality (Shepperd, 2013). Yet by 2009, new cases of SAD had rapidly diminished. Young stands of aspen that are less than 40years old, such as on the DDLC, are shown to be more resilient than the older counterparts but are certainly susceptible to the effects of climate change, in particular drought as well as wetter and warmer conditions (Shepperd, 2013). Increasing precipitation and warm days at greater elevations, like on the DDLC, may have caused increased stress on the aspen populations in the 2000s.

Aspen are already difficult angiosperms to interpret because of the soft, wet, fiber and rapid growth. This complexity is because they are a diffuse-porous wood, meaning that the cell structure across the growth year is soft, course and largely homogeneous with indistinct heartwood and latewood growth; dense end-of-season growth that distinguishes the end of one growth year from the beginning of the next. The rapid growth allows for minimal scaring and very faint ring boundaries. Scaring can show as either a faint, thin scar or as a slight color change in the rings. This color change is sometimes difficult to distinguish from heartwood. Some scars and discolorations may be attributed to other stresses such as blight, insect invasion, defoliation, drought, and root exposure, to all of which aspen are highly susceptible (Shepperd, 1986). The aspen also tend to mold easily, even with proper field handling and laboratory preparation, making individual ring color difficult to document. With the majority of the cores being aspen samples, many of the cores were difficult to measure under a microscope because of the ambiguity of the annual rings, of the indistinct reaction wood and the cores gnarled because of being extremely wet or rotten. Tree-ring cores that were in good condition and could be measured were measured from the downslope side, not where reaction wood is recorded in angiosperm. The downslope side does not show the reaction tension wood that is desired in recording geotropic growth, but the tree ring growth is still restricted under great stress, again restricting the ability to distinguish individual tree-rings.

Though useful data were obtained after many creative efforts and multiple measurements, future studies involving the use of aspen to evaluate reaction wood in geomorphic research would benefit from taking two or more samples from each aspen tree. One core, taken at breast height, as is standard in dendrochronology for aging, and a second through the center of geotropic growth for the geomorphic investigation is suggested. A skeleton plot, which is usually used in cross-dating trees to ensure correlation and accuracy across a sample group, can be built from more reliable width measurements of the tree-rings from undisturbed cores. The second core should be prepared by cross-abrasion instead of sanding and assessed under a dim, low-angle light (yellow seems to be the most helpful) for reaction wood and the resulting data then plotted for cross-plot.

6. CONCLUSIONS

The objective of this study is to define why the Donald Duck landslide complex is moving. Field investigation and review of aerial photography indicate that the DDLC is a secondary and shallow landslide that is part of the eastern flank of an ancient slump-block failure along Grand Mesa. Cross-plotted dendrochronology and historic record of highway construction activities indicate that the destabilization of this portion of an ancient landslide occurred prior to 1964 and possibly during the re-routing of Old Grand Mesa Road during 1952 to 1954 to its current location as Colorado Scenic Highway 65. The construction activities would have effectively cut off the stabilizing base of the Donald Duck landslide complex. Archived precipitation data indicate that particularly dry years such as 80%- of the annual average precipitation are associated with moderate to strong La Nina years, when the DDLC initially mobilizes. Particularly wet years that exceed 120% of the annual precipitation average or strong to very strong El Nino year or years continually re-activate movement on the DDLC until stability is reached. The threshold of movement determined for the DDLC and rapid aspen colony re-establishment in the early-1960s indicate that previous significant La Nina drought of 1954-1955 followed by significant El Nino precipitation, of 1956-1957 may have activated the destabilized flank of the existing Holocene-aged landslide. The droughts open fissures in the DDLC surface that allow pore-water fluctuations from precipitation and, thus, slump failure, much like freeze-thaw action opens fissures in the basalt and, thus, slope failure resulting in the toreva blocks of the greater Grand Mesa. The mobilization of the DDLC is part of the dry-wet process that gradually leads to slope instability rather than a single precipitation event. The landslide is now under intermittent slow creep with pulses of flow response and adjustment following the dry-wet precipitation cycles that occurred in 1978 and 1982-1986 as well as 1994 and 1995-1999. The low precipitation year of 2002 did initiate movement on the DDLC, but the high precipitation winters of 2005 and 2007 nor the high precipitation El Nino year of 2006-2007 did not initiate a growth response of reaction wood in any but one of the trees sampled on the DDLC. It is possible that the landslide is reaching stability and should be observed in upcoming years during strong dry-wet ENSO cycles for validation.

Future research pertaining to this study area, to the region, and use of the study findings and the methodology could be extensive. After this next El Nino period, the magnitude of response on the complex, if any at all, could be evaluated for indicators that the complex is or is not approaching stability. This study could be duplicated at the same site with the two-core system for dendrogeochronological dating. The drainage capacity and depth of the re-worked glacial till could also be investigated in conjunction with dry-wet cycle periods. A similar study could be conducted on the Mesa Creek landslide to provide insight to the Colorado Department of Transportation (CDOT) for monitoring and mitigation. Outside of the methods or findings of this particular study, extensive landslide inventory mapping is called for on Grand Mesa to aid monitoring and mitigation through the Colorado Geological Survey (CGS) and the United States Geological Survey (USGS). This study, along with similar studies conducted in the region could be compiled and used to supplement LIDaR mapping of the region for the benefit of CGS and CDOT.

Most significantly, the road damage to SH 65 above and below the DDLC necessitates investigation, particularly in relation to the ancient Holocene-aged landslide that fills the valley. The ancient landslide necessitates investigation because of this road instability; because another landslide has already been identified within its bounds that is two miles south from the DDLC on SH 65 but at a higher elevation; because it is poorly drained; because it is highly traveled; in a larger-scale investigation of the DDLC study relating movement to dry-wet cycles of weather patterns and the ENSO; and in light of the tragedy of the West Salt Creek landslide in 2014 to assess any similarities in form and response. Also, if the deep fissures on the DDLC from 2002 have opened infiltration of precipitation down to the basal failure of the DDLC, thus, draining the DDLC from below into the ancient landslide body needs to be investigated.

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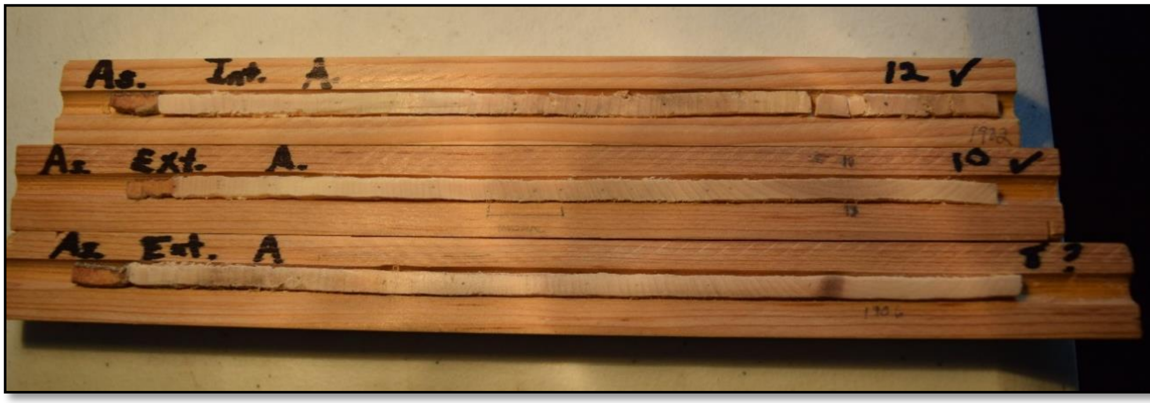
APPENDIX A

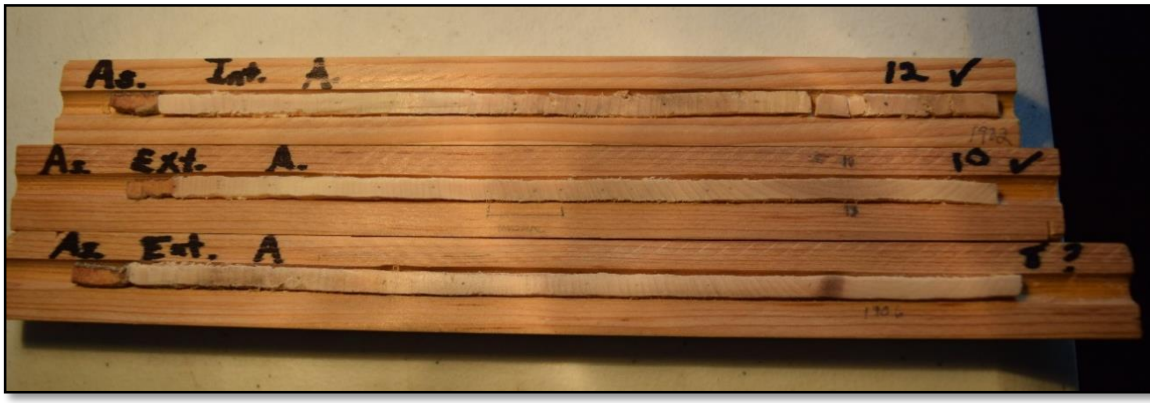


External Duck Scarp (EDS)

External Bum Bungelow (EBB)

External Bum West (EBW)

.



External Duck Scarp (EDS)

External Bum Bungelow (EBB)

External Bum West (EBW)

Internal Duck Scarp (IDS) (N)

Internal Duck Scarp (IDS) (S)

Internal Duck Toe (IDT) (N, E)

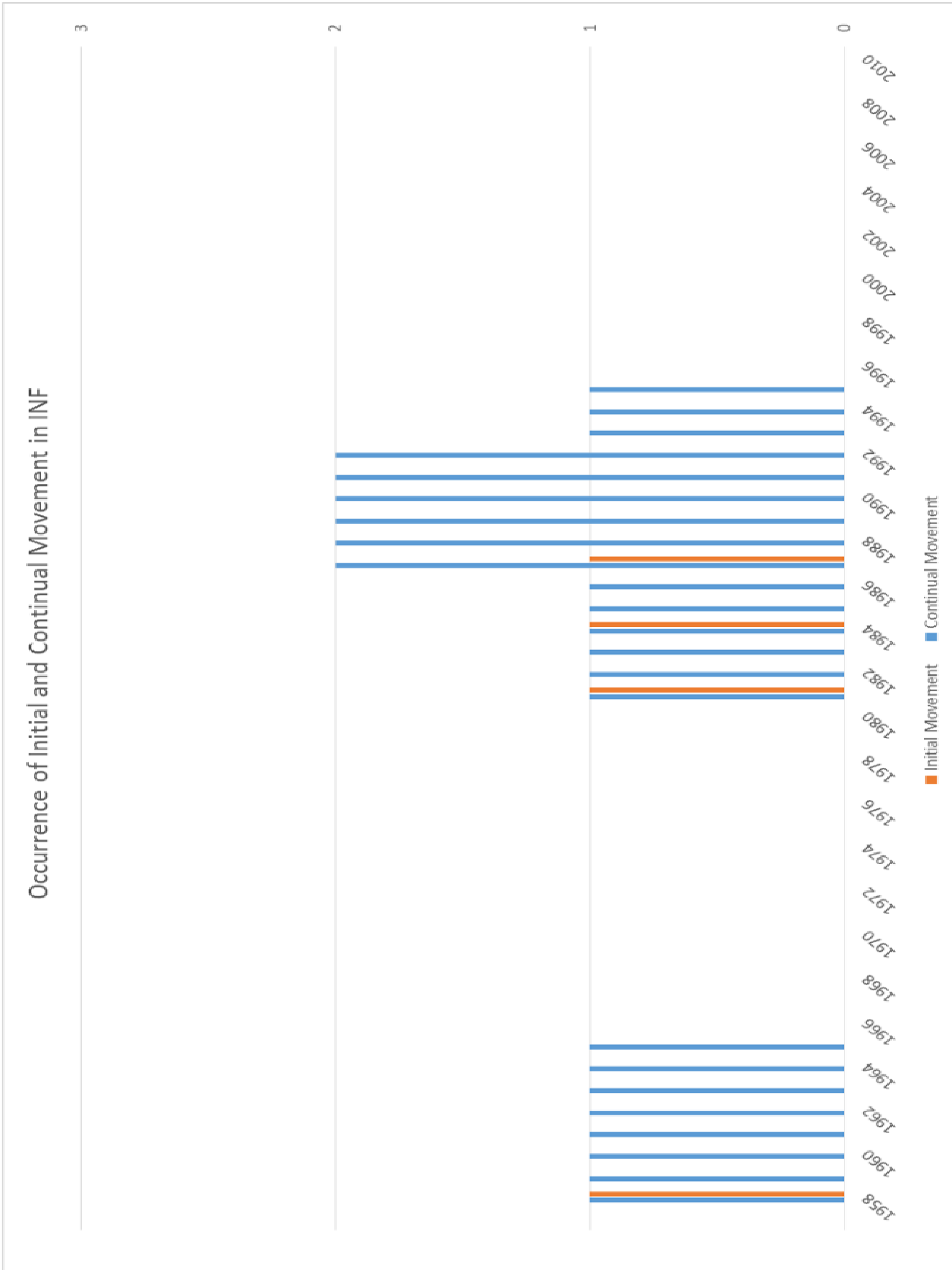
Internal Duck Toe (IDT) (W, S)

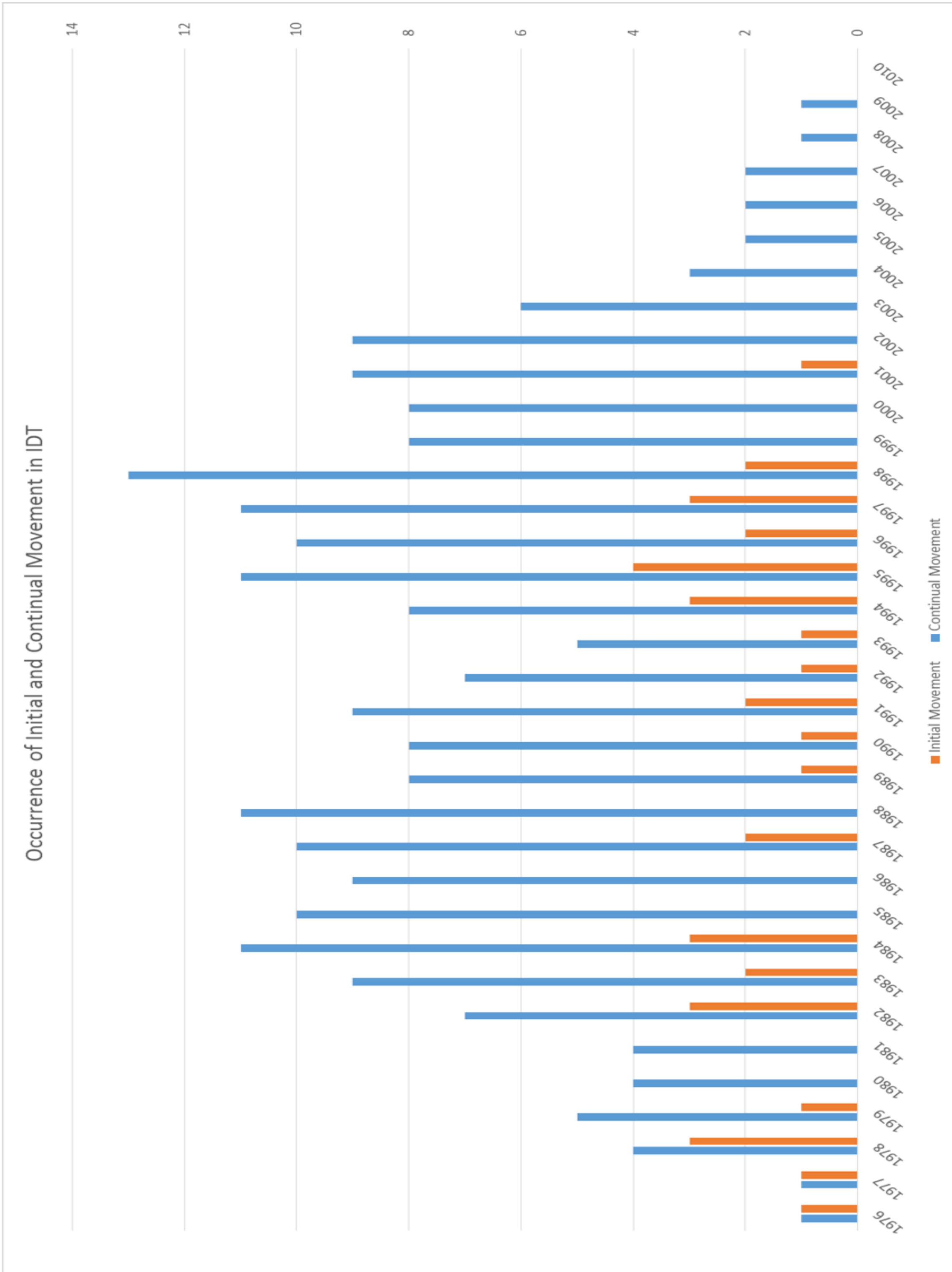
Internal Bum Bungalow (IBB)

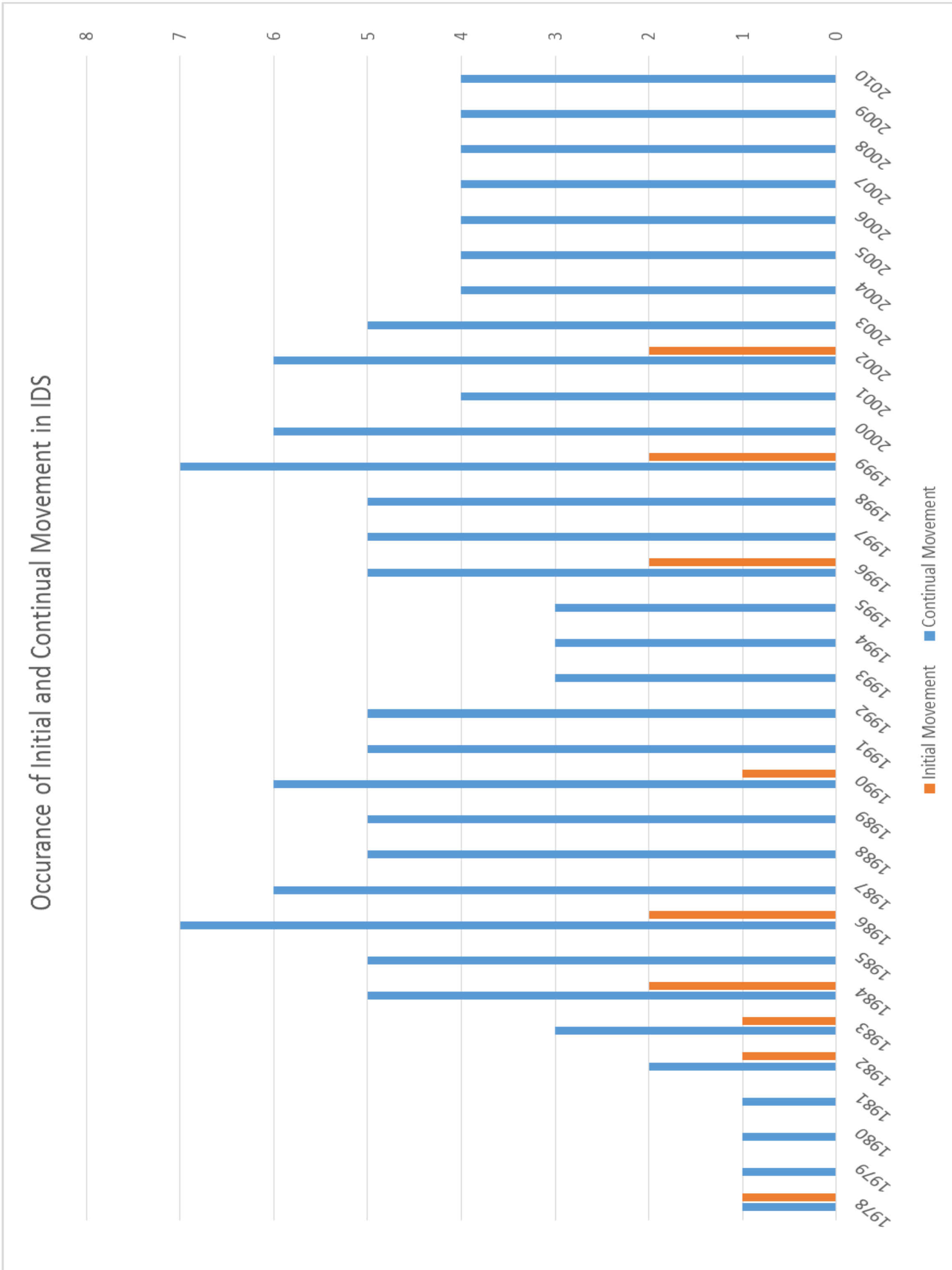
Internal Bum Bungalow (IBB)

Internal Banana Dance (IBD)

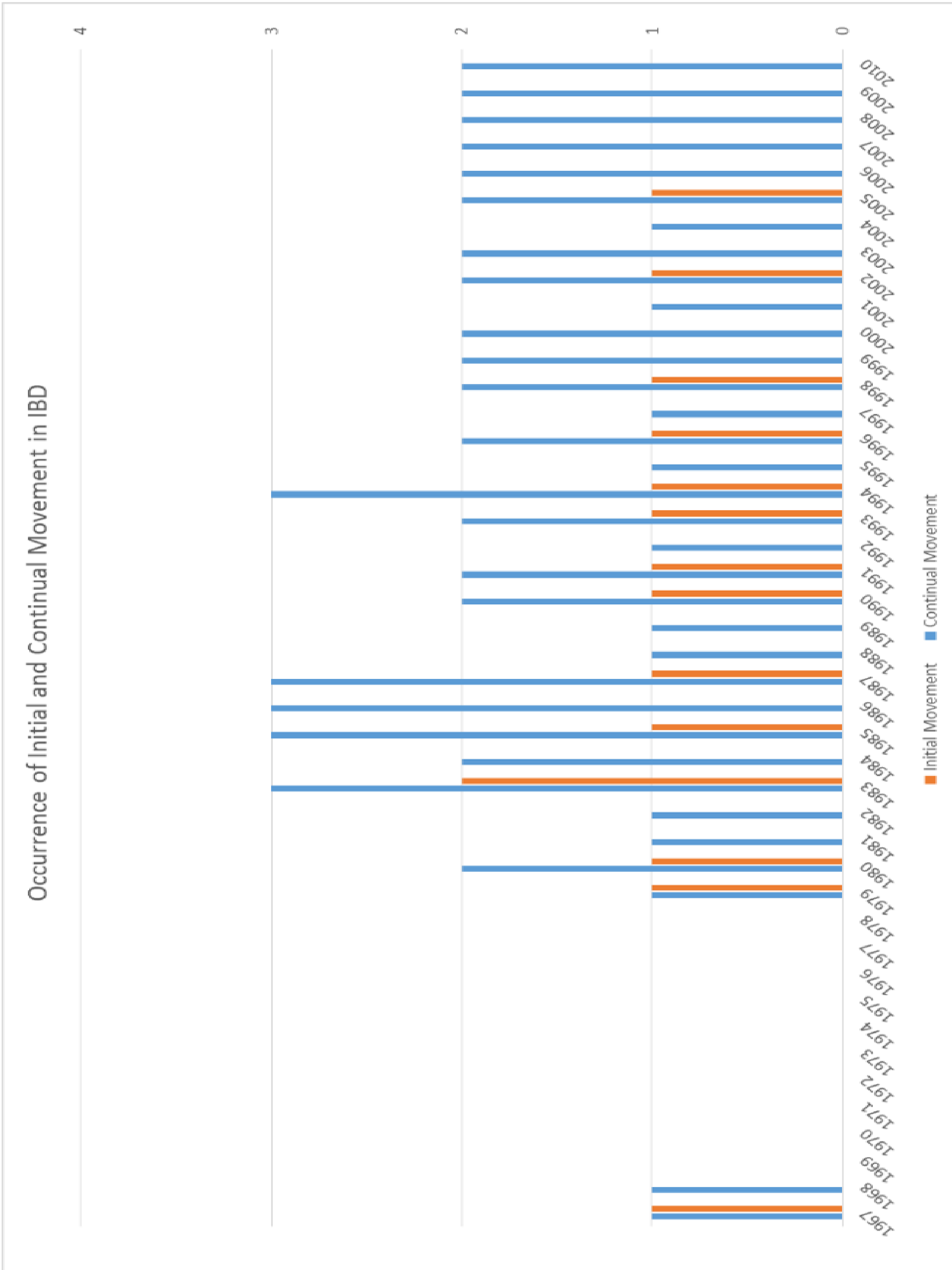
APPENDIX B


Occurrence of Initial and Continual Movement in INF
Initial Movement
Continual Movement


Occurrence of Initial and Continual Movement in IDT
0
2
4
6
8
10
12
14
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Initial Movement
Continual Movement



Occurance of Initial and Continual Movement in IDS
0
1
2
3
4
5
6
7
8
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1996
1995
1994
1993
1992
1991
1990
1989
1988
1987
1986
1985
1984
1983
1982
1981
1980
1979
1978
Initial Movement
Continual Movement


Occurrence of Initial and Continual Movement in IBD
0
1
2
3
4
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
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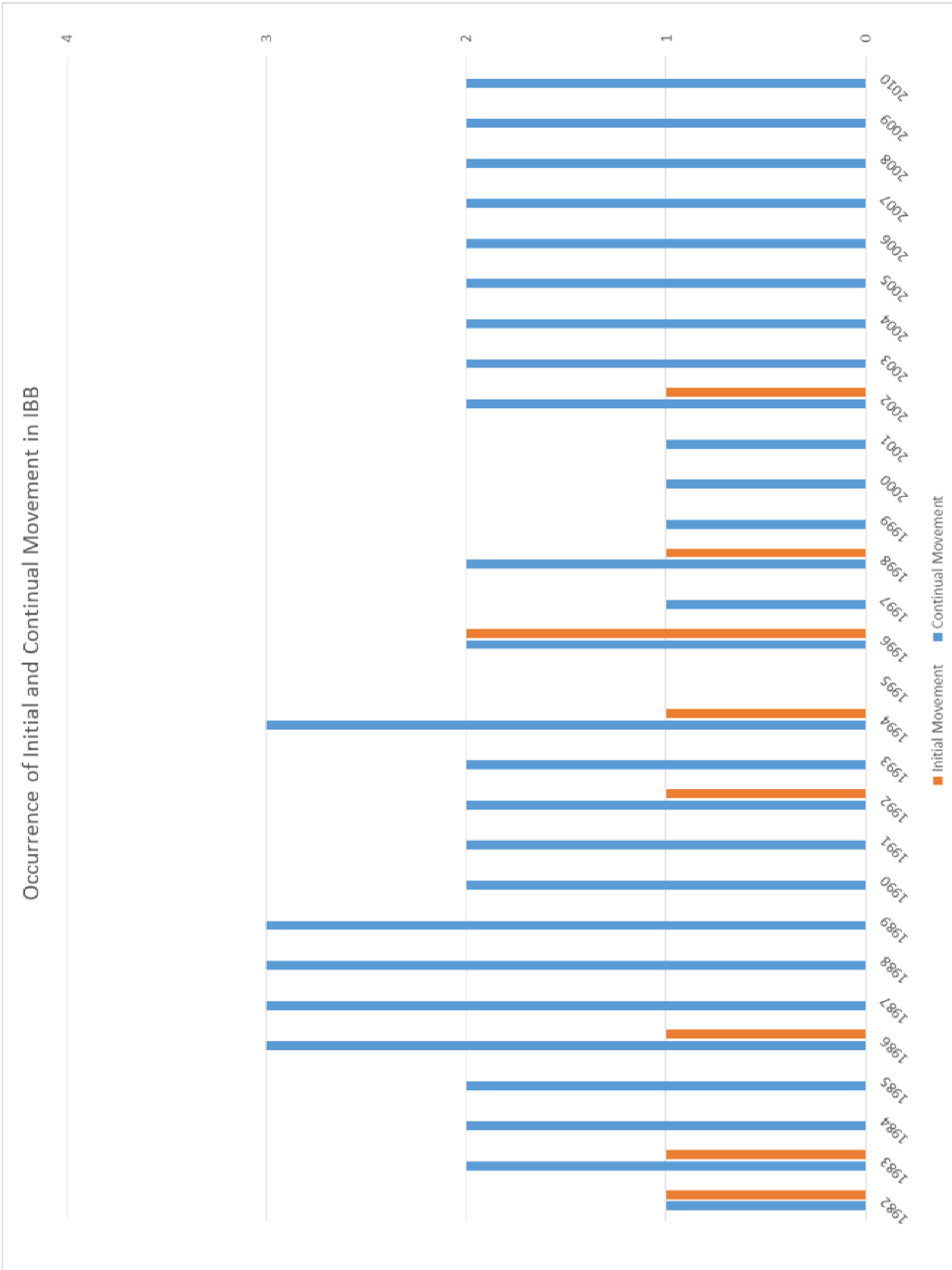
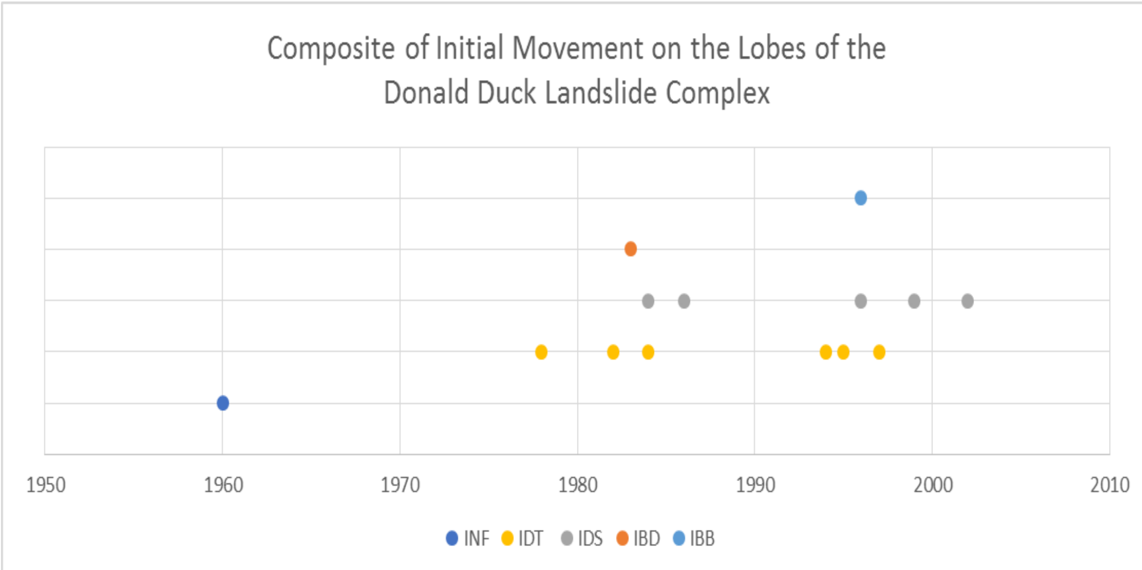
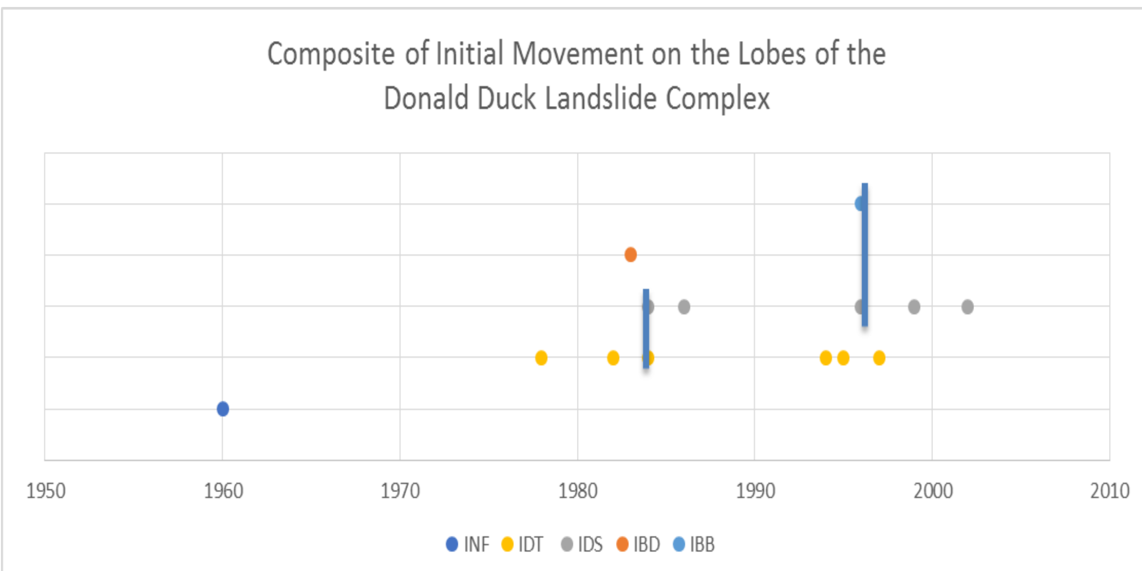
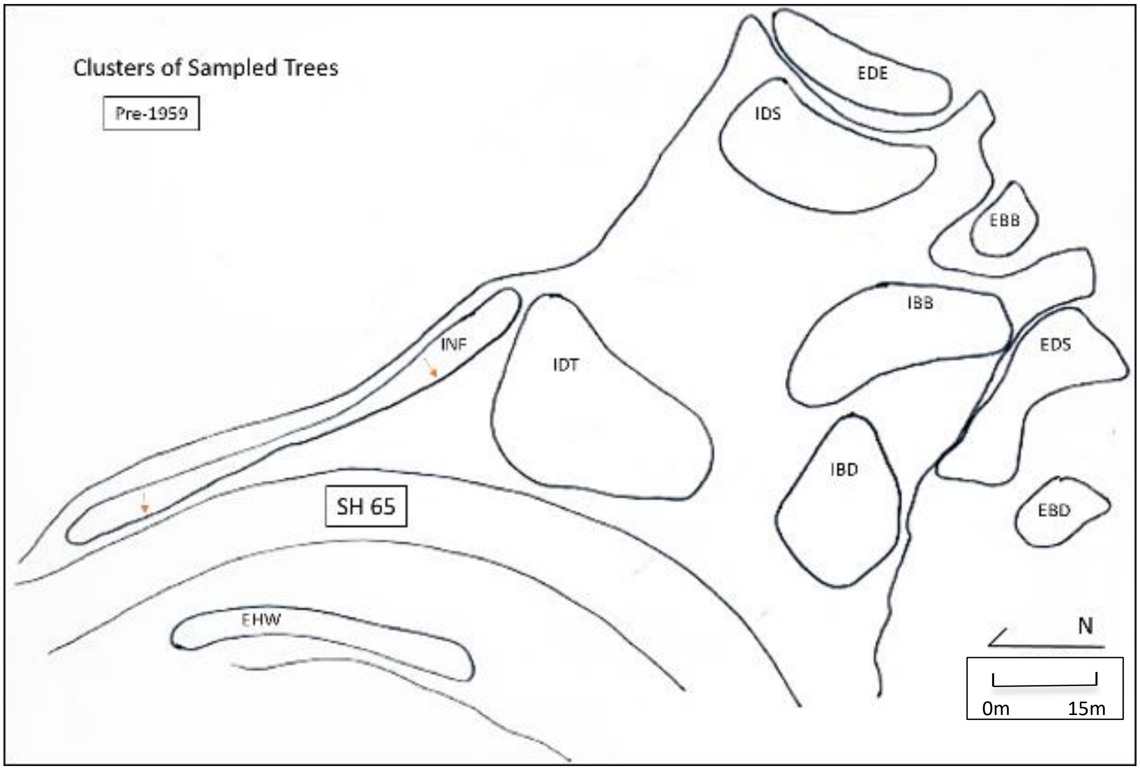
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Initial Movement
Continual Movement

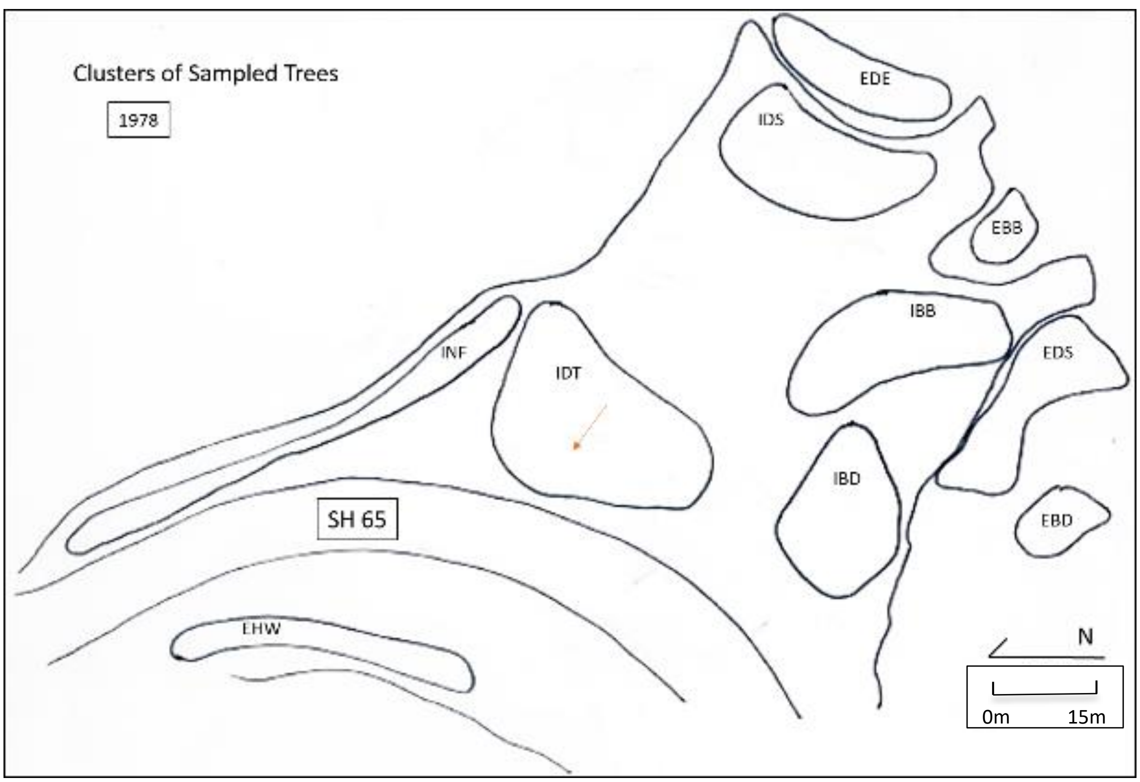

Occurrence of Initial and Continual Movement in IBB
0
1
2
3
4
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1996
1995
1994
1993
1992
1991
1990
1989
1988
1987
1986
1985
1984
1983
1982
Initial Movement
Continual Movement

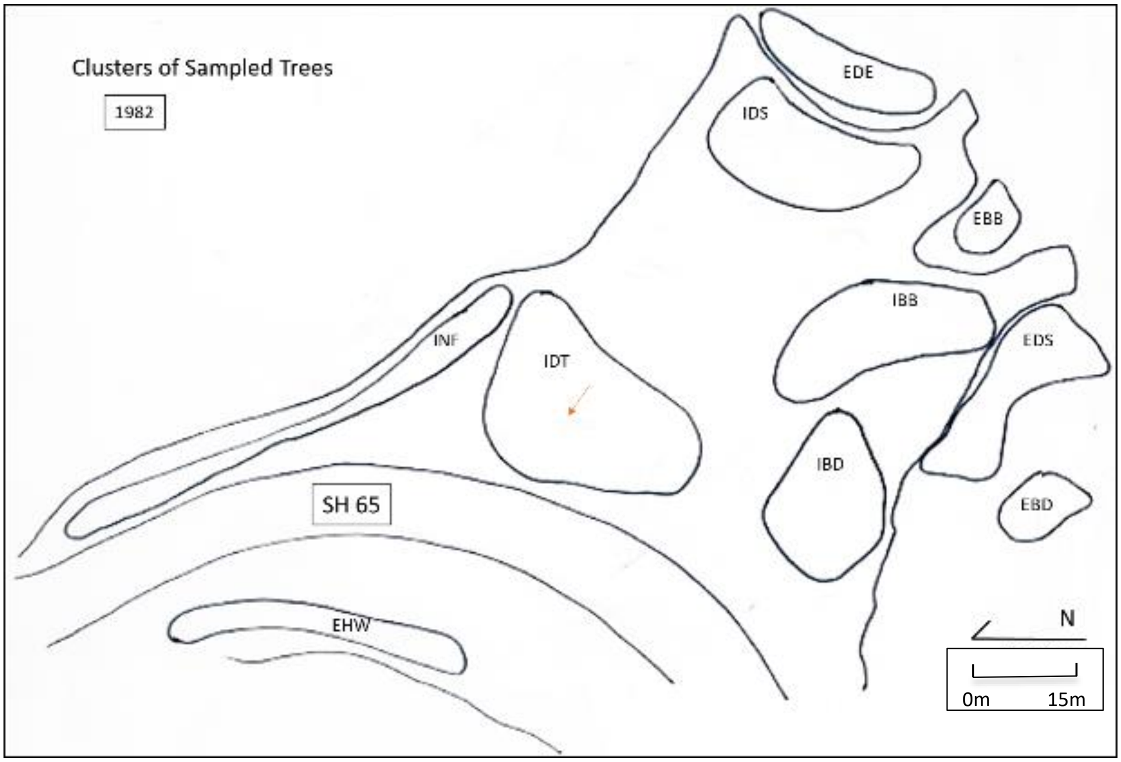

Composite of Initial Movement on the Lobes of the Donald Duck Landslide Complex
1950
1960
1970
1980
1990
2000
2010
INF
IDT
IDS
IBD
IBB

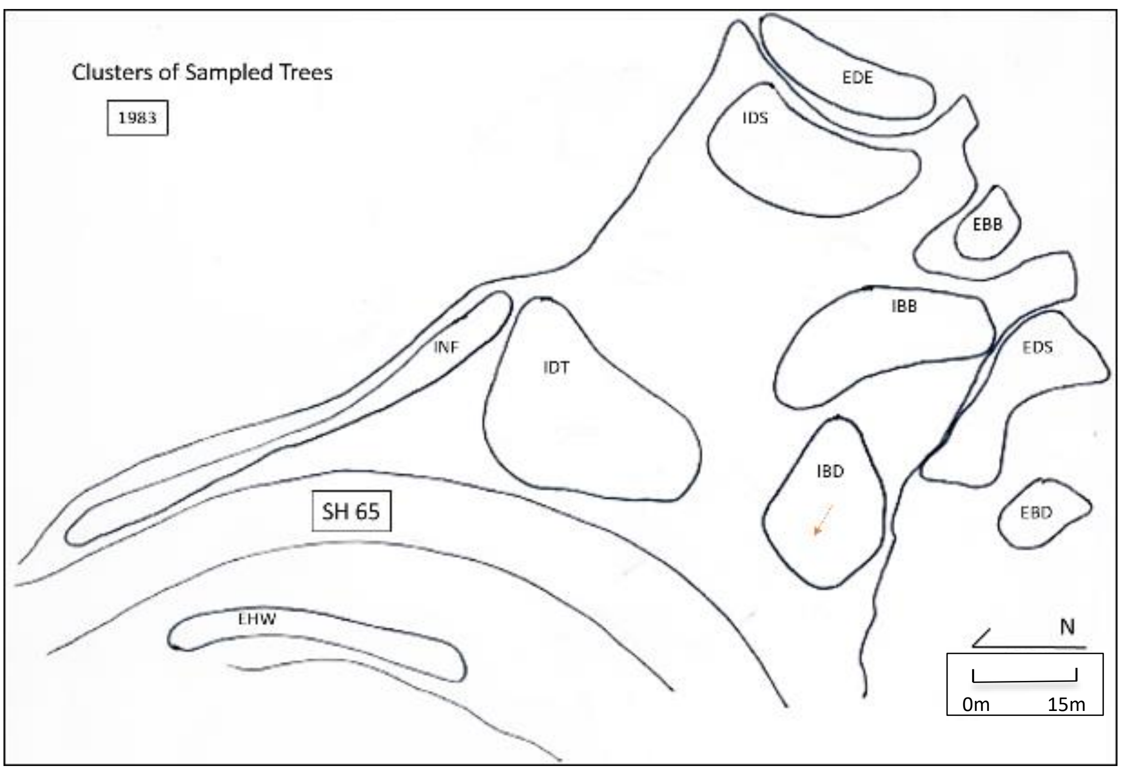

Composite of Initial Movement on the Lobes of the Donald Duck Landslide Complex
1950
1960
1970
1980
1990
2000
2010
INF
IDT
IDS
IBD
IBB

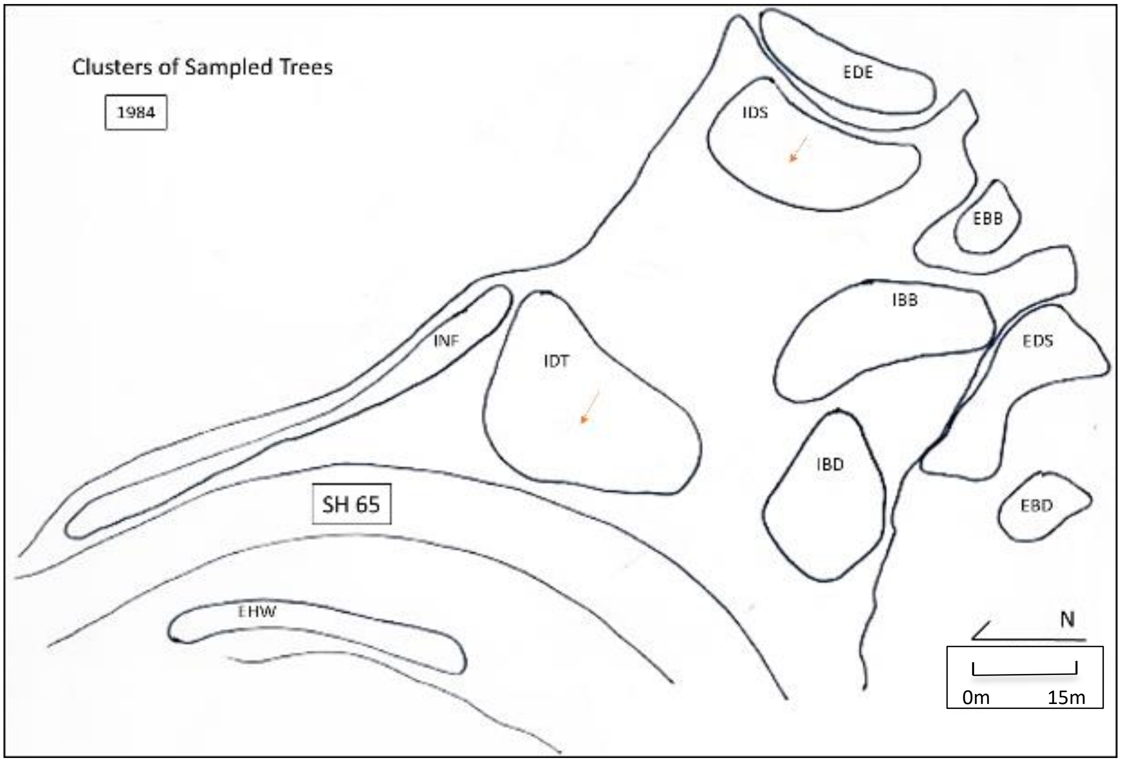
APPENDIX C

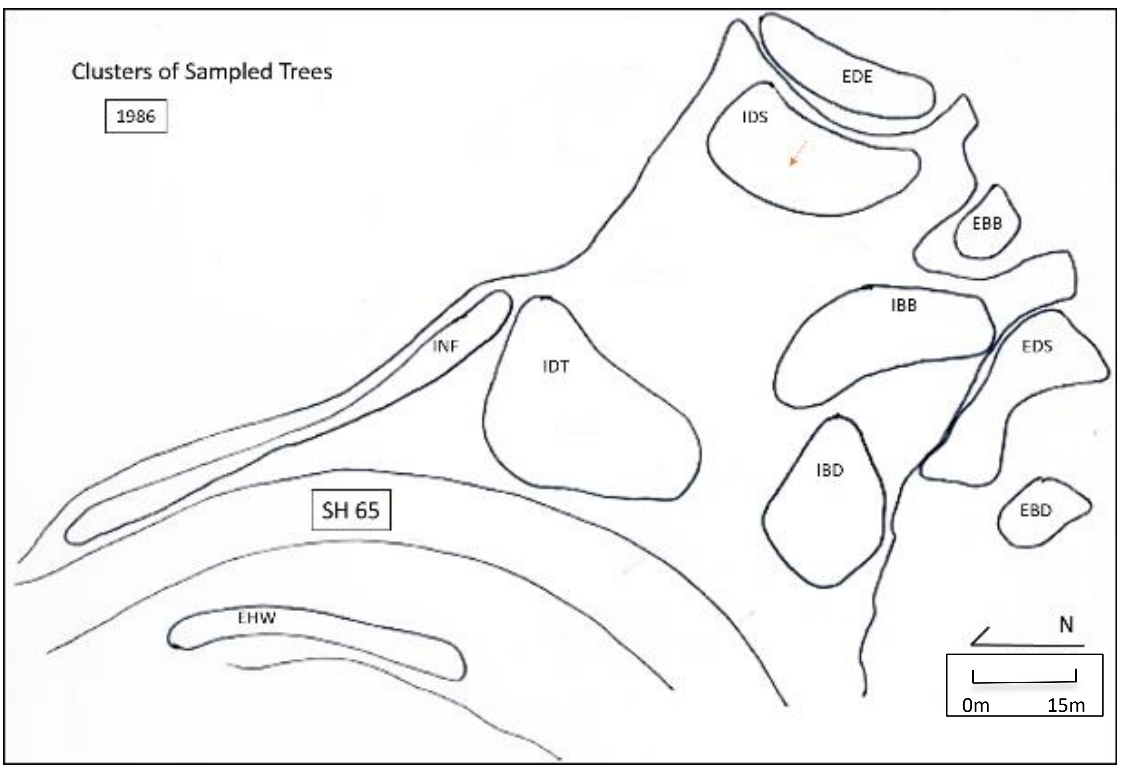

Clusters of Sampled Trees
Pre-1959
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m

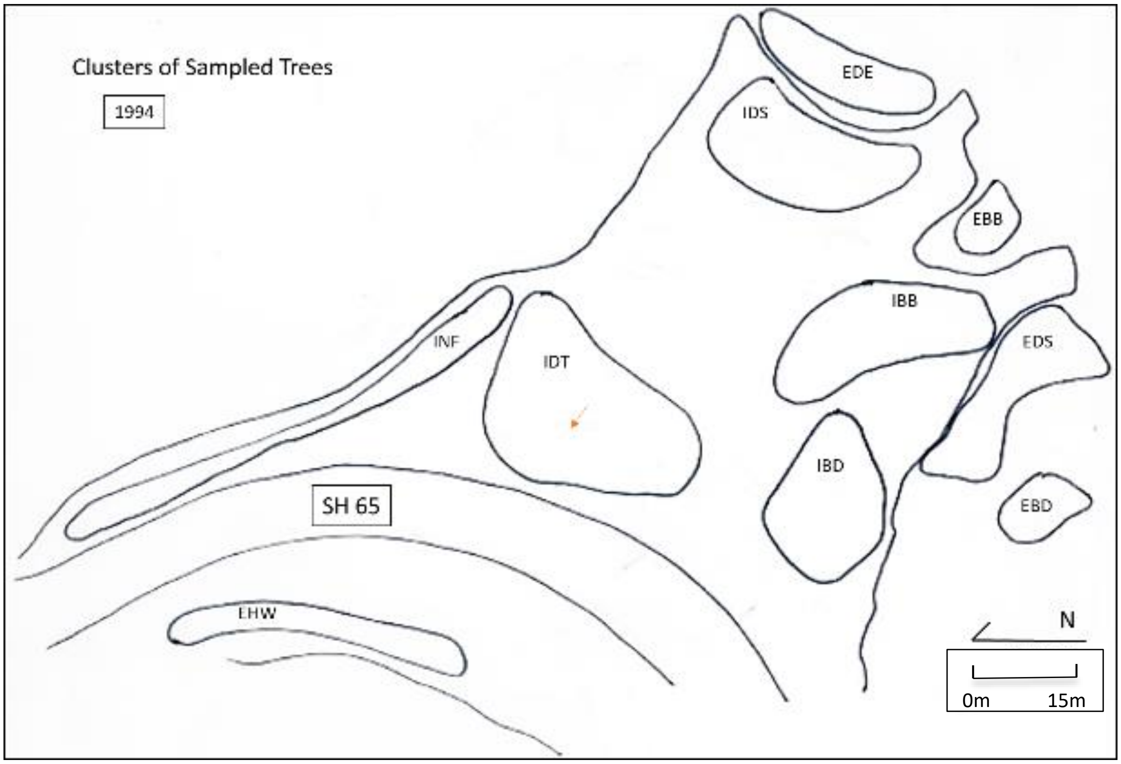

Clusters of Sampled Trees
1978
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m

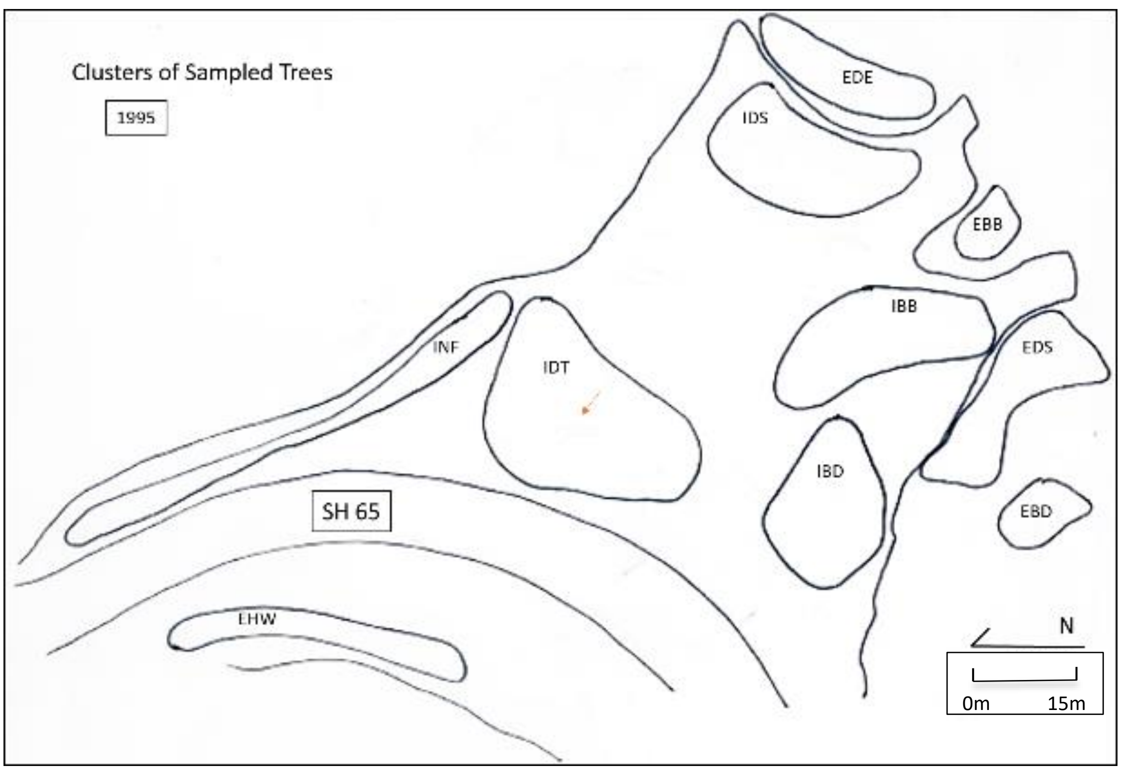

Clusters of Sampled Trees
1982
EDE
IDS
EBB
IBB
INF
IDT
EDS
IBD
SH 65
EBD
EHW
N
0m
15m


Clusters of Sampled Trees
1983
EDE
IDS
EBB
IBB
INF
IDT
EDS
IBD
SH 65
EBD
EHW
N
0m
15m


Clusters of Sampled Trees
1984
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1986
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1994
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1995
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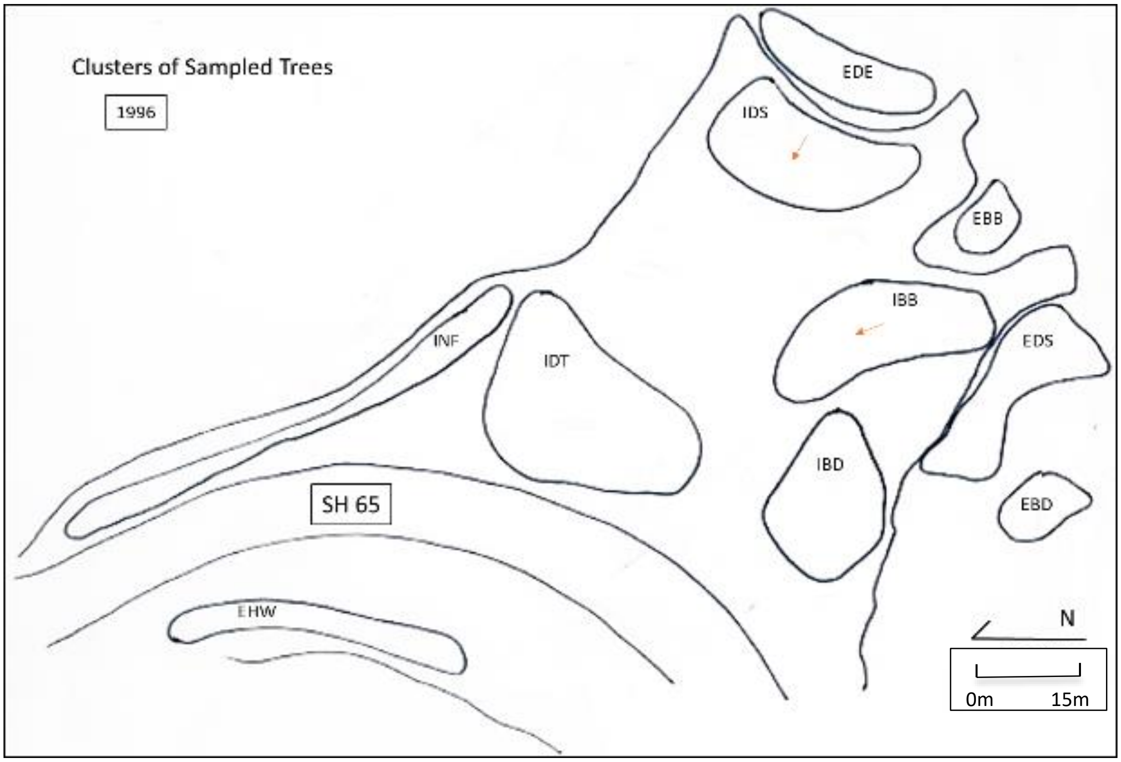
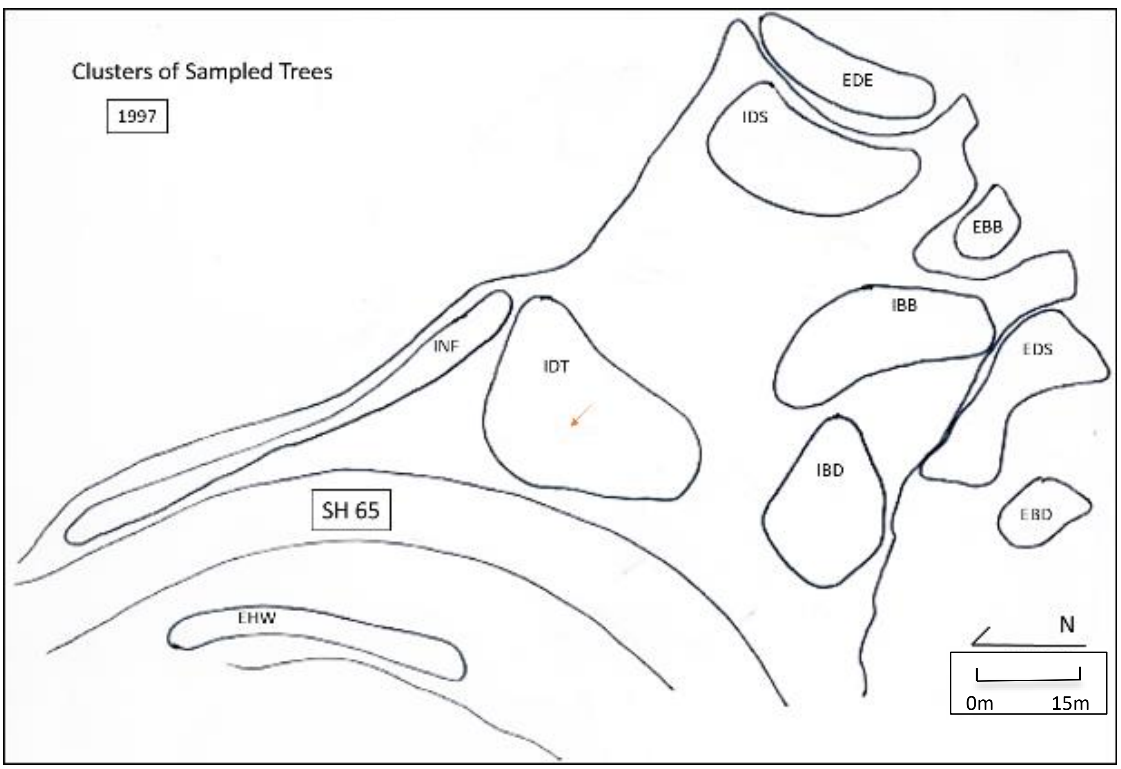
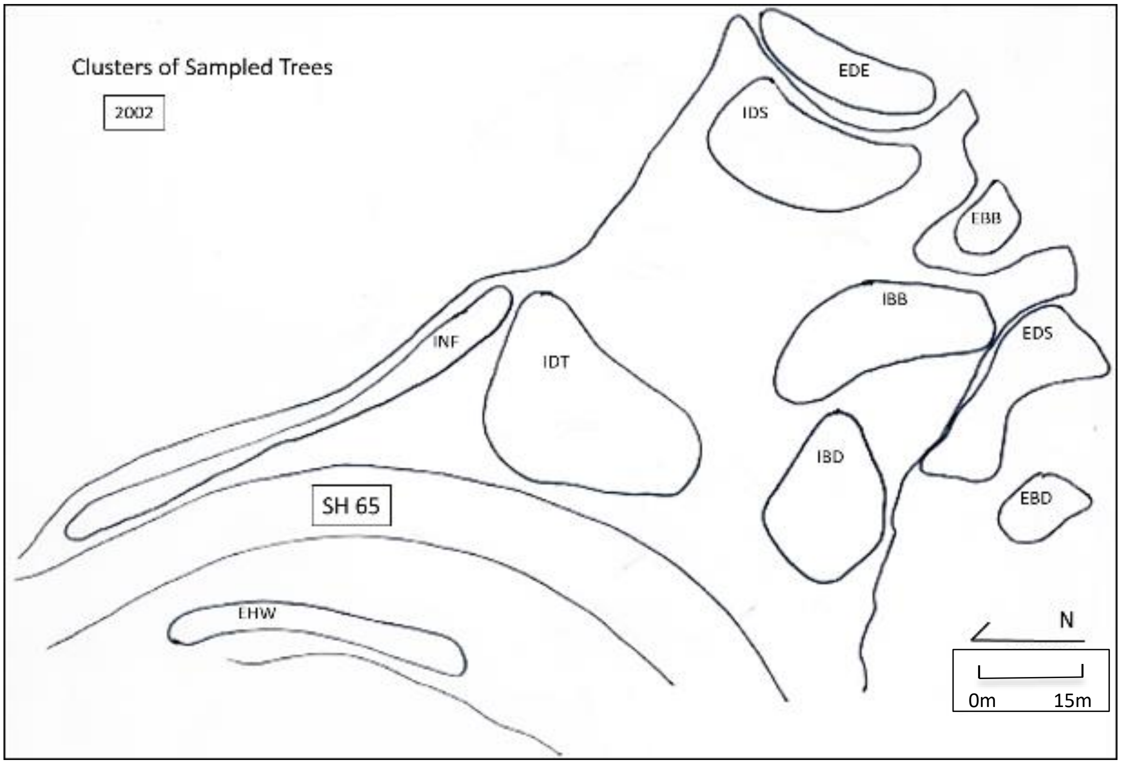
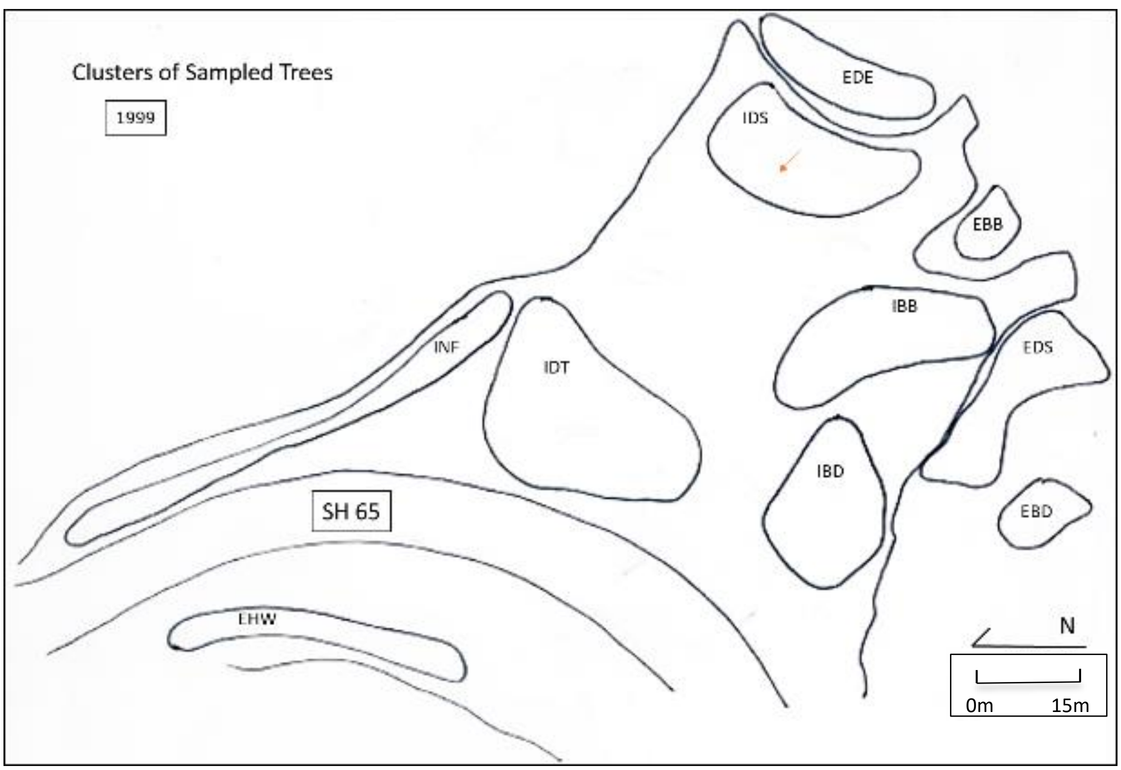
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1996
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1997
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
2002
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m


Clusters of Sampled Trees
1999
EDE
IDS
EBB
IBB
EDS
INF
IDT
IBD
EBD
SH 65
EHW
N
0m
15m