5-2016

Applications of LiDAR in the study of landscape geomorphology, Sandwich Range, White Mountain National Forest

Sarah G. Koe

Bates College, skoe@bates.edu

Follow this and additional works at: http://scarab.bates.edu/geology_theses

Recommended Citation

Koe, Sarah G., "Applications of LiDAR in the study of landscape geomorphology, Sandwich Range, White Mountain National Forest" (2016). *Standard Theses*. 30.

http://scarab.bates.edu/geology_theses/30

This Open Access is brought to you for free and open access by the Student Scholarship at SCARAB. It has been accepted for inclusion in Standard Theses by an authorized administrator of SCARAB. For more information, please contact batesscarab@bates.edu.

Applications of LiDAR in the study of landscape geomorphology, Sandwich Range, White Mountain National Forest

Bates College Geology Department Thesis

Presented to the Faculty of the Department of Geology, Bates College,
in partial fulfillment of the requirements for the Degree of Bachelor of Arts

by
Sarah Koe

Lewiston, Maine
April 8th, 2016

Acknowledgments

Eight months later, many thanks to give:

First, to my advisor, Dyk Eusden. Thank you for years of advice, instruction and support with everything from conjugate pairs to projected coordinate systems.

Second, to all my geology professors: Bev Johnson, John Creasy, Mike Retelle, Genevieve Robert. Thank you for expanding my eyes to such a diverse and complex discipline. And to Matt Duval, thank you for presenting a calm and strategic face to ArcGIS and all its technical complications.

Third, to the NRCS team in St. Johnsbury for the LiDAR and supporting information. This study would not exist without either.

Fourth, a senior thesis is always more enjoyable when you have someone to share it with. Special thanks to my fellow Geo seniors for being my someones to share every late night, and looming deadline with. Thank you also to my Vale St. housemates, friends, mom, dad and Peter for general support, company, etc.,

Finally, thank you to Kanye, Rihanna, the Hamilton Soundtrack and the m&m jar at the interlibrary loan desk.

Contents

Acknowledgments	iii
1. Introduction	1
1.1 Purpose	1
1.2 Study Area	2
1.3 Tectonic Setting	4
1.3.1 Appalachian Tectonics	4
1.3.2 Mesozoic Rifting and associated volcanics	5
1.3.3 Deformation history	8
1.3.4 Bedrock	8
1.4 Pleistocene glacial and Holocene postglacial periods	12
1.5 Remote analysis	13
Evolution of technologies	13
LiDAR	14
1.6 Research Objectives	14
2. Methods	15
2.1 Introduction	15
2.2 Remote analysis methods	15
2.2.1 Landscape Classification	17
2.2.2 Landscape classification units	19
2.2.2.1 Bedrock control	19
2.2.2.2 Fluvial control	20
2.2.2.3 Glacial control	22
2.2.3 Lineament Mapping	24
2.2.3 Floodplain mapping	26
3. Results	16
3.1 Introduction	16
3.2 Landscape classification mapping	16
3.3 Landscape classification units	19
3.3.1 Bedrock control	19
3.3.1.1 Bedrock, exposed (BRe)	19
3.3.1.2 Bedrock, non-exposed, Brc	19
3.3.2 Fluvial control	20
3.3.2.1 fluvial, active channel (Fac)	20
3.3.2.2 Fluvial, alluvial fan (Faf)	20
3.3.2.3 Fluvial, floodplain (Ffp)	21
3.3.2.4 Fluvial, terrace (Ft)	21
3.3.2.5 Fluvial, surface water (Fsw)	22
3.3.2.6 Fluvial, fluvial depression -- extinct, (Fwe)	22
3.3.3 Glacial control	23
3.3.3.1 Glacial, boulders (Gb)	23
3.3.3.2 Glacial, dissected till (Gds)	23
3.3.3.3 Glacial, hummocky till (Ght)	24

3.3.3.4 Glacial, linear features (Glf)	24
3.3.3.5 Glacial, meltwater (Gmw)	25
3.3.3.6 Glacial, meltwater channels (Gmwc)	25
3.3.3.7 Glacial, non-dissected till (Gnds)	26
3.4 Bedrock mapping	30
3.4.1 Bedrock control	30
3.4.2 Lineament mapping	30
3.5 Fluvial mapping	35
3.6 Glacial mapping	37
4. Discussion	40
4.1 Introduction	40
4.2 Lineament analysis	40
4.2.1 Lineament analysis classified by age	40
4.2.2 Comparison of remote analysis to field-based mapping	41
4.3 Swift River terrace age mapping	46
Evidence for Glacial Lake Pigwacket	48
52	
4.4 Glacial analysis	53
4.4.2 Glacial flow indicators	53
4.4.3 Evidence of deglaciation	59
Model for deglaciation: active ice retreat vs. stagnation zone retreat	60
4.4.4 Glacial lakes	65
4.5 Feature verification	69
5. Conclusion	72
5.1 Remote analysis findings	72
5.1.1 Landscape classification mapping	72
5.1.2 Bedrock mapping	72
5.1.3 Fluvial mapping	72
5.1.4 Glacial mapping	73
5.2 Future work	73
Bibliography	75

List of Illustrations

Figure 1.1 Lidar imagery represented in a shaded relief image with an azimuth and altitude of 315/45. Orientating features within the study region include Mt. Trip pyramid, Mt. Whiteface, Mt. Passaconaway, Mt. Chocorua, and the Kancamangus Highway.	3
Figure 1.2 Simplified lithotectonic map of the Appalachian Mountains from Wintsch et al., 2014, modified from van Staal, 2005. Generalized representation of metamorphic effects on major terranes and plutonic intrusion. Study location represented by black dot in the Peri-Laurentian arcs.	5
Figure 1.4 designation of the Central Atlantic Magmatic Province (CAMP), understood as the mechanism behind the rifting of Pangea into Laurasia and Gondwana during the early Mesozoic. Extension created from the ascending mantle plumes is evidenced by igneous intrusions into brittle extensional features, eg. dike swarms (McHone, 2000). Study area indicated by black dot.	6
Figure 1.4 Model for caldera collapse understood to be the source of ring-dike emplacement in the White Mountains (Ramberg, 2008).	7
Figure 1.5 modified from Lyons et al., (1997) figure 1.6, with study area contained within black box Members of the White Mountain Magma Series (WMMS) include the Conway Granite (Jc1b), the Mount Osceola Granite (Jo1h) and a porphyritic syenite (J7x).	9
Figure 1.6 Bedrock Geologic Map of New Hampshire by Lyons et al. (1997). Study area included in black box.	10
Figure 1.7 Bedrock unit polygons overlain on a shaded relief map of the greater study region. Study region is dominated by Conway Granite (Jc1b), and Mt. Osceola Granite (Jo1h), both dated to the Jurassic. Bedrock polygons modified from Lyons et al., (1997) Geologic Map of New Hampshire (figure 1.5 and 1.6).	11
Figure 1.8 Reconstruction of Laurentide Ice Sheet over north America during periods of maximum extent during the last glacial maximum (left), and present ice extent (right). Note that all of New Hampshire is covered by the LIS during the quaternary (Blakely, 2011).	12
Figure 1.9 A comparison of LiDAR imagery (top) to a USGS topographic map (bottom) of the same region surrounding Mt. Trip pyramid. LiDAR reveals features hidden through topographic representation such as lineaments, and fluvial features.	13
Figure 1.10 Hillshade image of processed LiDAR imagery with illumination from azimuths of 315 and 45 degrees and an altitude of 45 degrees. Bare-earth image which processed LiDAR provides will be the inception point for all aspects of remote analysis undertaken in this study.	15
Figure 2.1 a) LiDAR collection occurred on October 28 and November 3-6 in 2014. Color swatches designate the date of area collection. Flights moved northwards, beginning with 10/28 in blue, and ending with 11/6 in red. See figure 1.0 study area map to orient lidar collection area. b) Bare earth point density map of study designated by original tiles. Designates point density for each return relative to the tile. Density is determined by dividing the number of returns per tile by the area of the tile. Regions with higher returns ie. more vegetation and urban areas -- not applicable in this study -- would have a lower bare earth point density.	16
figure 2.2. comparison of mosaicked DEM raster (top) and the original elevation data tiles (bottom). Tiles were mosaicked together to form a seamless elevation raster. This raster provides the basis for many spatial analysis calculations performed in ArcMap 10.3.	16

Figure 2.3 LiDAR derived maps from the mosaicked DEM used for remote analysis. a. An aspect map of region, b. hillshade map of region with an azimuth of 315° and an altitude of 45°, c. slope map indicating degree of steepness.	17
Figure 2.4 Polygon classification of three main landscape control regimes: bedrock (red), fluvial (blue) and glacial (green). a) boundary between glacial and bedrock features, b) boundaries between bedrock, glacial and mountain streams in fluvial category, c) fluvial control of Swift River, d), example of three regimes	18
Figure 2.5 From Haugerud et al., 2003 (left) and Haugerud, 2009 (right). Examples of landscape classification of LiDAR imagery for geomorphic mapping	19
Figure 2.6 Bedrock control unit: exposed bedrock (BR _e). Highlighted yellow boxes indicate characteristic texture of exposed bedrock--with visible lineaments, abrupt changes in elevation. Blue lines represent a few lineament features in other regions of exposed bedrock.	19
Figure 2. 7 Bedrock control, covered (BR _c) with a thin layer of soil and/or vegetation. BR _c denoted by blue polygon on the left. Contact between glacially controlled regions and BR _c regions is often indicated by the very fine texture, lacking changes abrupt changes in elevation. Lineaments are visible in bedrock	20
Figure 2. 8 Fluvial control, floodplain (F _{fp}). Complete control denoted by blue polygon on the left -- Notice the curved boundary as a result of the extinct meandering river channels. Paleo terrace levels within the floodplain represented on the right. Colors relate terraces of the same elevation, indicating the same terrace.	20
Figure 2.9 Fluvial control, active channel (F _{ac}), Water processed out of LiDAR imagery but active river channel demoted by a large and consistent elevation change from surrounding floodplain (blue polygon on left). Width of channel is consistent (green and red lines on right).	21
Figure 2.10 Fluvial control, terraces (F _t), illustrated through polygons on the right and left. Terraces are often cut by newer terraces. Elevation data obtained from DEM rasters is often used to delineate terrace plans of the same age.	21
Figure 2.11 Fluvial control, surface water (F _{sw}), surface waters are processed out of LiDAR, and result in a smoothed and homogenous surface.	21
Figure 2.12 Fluvial control, alluvial fans (F _{af}), Alluvial fans are found in between high peaks and fluvial regions. Characterized by finely grained run-off streams.	22
Figure 2.13 Glacial control, dissected till (G _{ds}), channels which cut through medium-grained textured surface. Surface is less more rounded than exposed bedrock, but less than hummocky till. Blue polygon indicates entire region of dissected till on left. Red lines denote the characteristic, closely spaced channels.	22
Figure 2.14 Glacial control, eskers and moraines (G _{lf}), linear features both parallel and perpendicular to bedrock	23
Figure 2.15 Glacial control, non-dissected till (G _{nds}), smooth-textured with a rounded relief. Elevation changes are minimal. Lacks dissection channels.	23
Figure 2.16 Glacial control, hummocky till (G _{ht}), Hummocky till contains large rounded relief.	23
Figure 2.17 Glacial control, boulders (G _b), small rounded features cluster around higher regions, normally around bedrock but overlain on non-dissected till.	24

Figure 2.18 Glacial control, meltwater channels (Gmwc), present parallel to topography. Channels are non-braided depression on down-sloping surfaces (light blue polygons, left). Intercut (red and pink lines) by new, active channels (yellow lines).	24
Figure 2.19 Lineaments traced on a) shaded relief image with an azimuth and altitude of 315/45, b) shaded relief image with an azimuth and altitude of 45/45, and c) a slope map.	25
Figure 2.20 Methods for lineament mapping modified from Mabey et al., (1994).	25
Figure 2.21 Transect elevations derived from the 3D analyst tool were used to classify floodplane levels. Elevation drawn on a DEM at 100% transparency, overlain on a shaded relief map of the Swift River.	26
Figure 2.22 stages of floodplain mapping using the global polynomial interpolation tool. a) point features added to targeted field, b) gradient produced by polynomial interpolation with elevation data assigned to points, c) raster generated from plane in (b) subtracted from original DEM (a).	27
Figure 3.1, simplified landscape classification map of entire study region. Polygons designate bedrock (red), fluvial (blue) and glacial (green) controlled regions. Polygons displayed at 30% transparency, overlying a 315/45 hillshade at 50% transparency and a 45/45 hillshade.	18
Figure 3.2 examples exposed bedrock features in LiDAR	19
Figure 3.3 examples of non-exposed bedrock features in LiDAR.	19
Figure 3.4 examples of active channel features in LiDAR	20
Figure 3.4 examples of alluvial fan features in LiDAR.	20
Figure 3.5 examples of floodplain feature in LiDAR	21
Figure 3.6 Terraces of various ages contained within floodplain.	21
Figure 3.7 examples of surface water feature in LiDAR.	22
Figure 3.8 example of extinct surface water in LiDAR.	22
Figure 3.9 example of boulder features in LiDAR	23
Figure 3.10 examples of dissected till in LiDAR	23
Figure 3.11 examples of hummocky till in LiDAR.	24
Figure 3.12 examples of linear features in LiDAR	24
Figure 3.13 examples of meltwater environment water feature in LiDAR	25
Figure 3.14 examples of meltwater channel features in LiDAR	25
Figure 3.15 examples of non-dissected till features in LiDAR	26
Figure 3.16 detailed map of landscape classification of Sandwich Region, WMNF. Three regimes of bedrock, fluvial and glacial control are subdivided into fifteen categories--bedrock (2), fluvial (6), glacial (7). Polygons at 40% transparency, overlain on a 315/54 hillshade at 50% transparency and a 45/45 hillshade.	27
Figure 3.17. a) meltwater channels (Gmwc and Gmw), b) Gmwc, Gmw, hummocky till (Ght), and fluvial features, c) Gmwc, Gmw, and bedrock (BRe), d) in-and-out Gmwc with an active channel (Fac) and non-dissected till (Gnds), e) linear features (Glf) in a Gmw region with active fluvial interaction, f) linear features on Gnds with Gmwc, and Fac, g) Glf on hummocky till, h) alluvial fan (Faf) with Ght, Fac, and other fluvial features.	28

Figure 3.17 continued. i) floodplain (Ffp), Fac, and dissected till (Gds), j) mountain Fac surrounded by Gds and BRe, k) evidence of fluvial depression (Fwe) with Gnds, Gds and Fac, l) surface water (Fsw) with Gnds, m) Ght and fluvial interaction, n) BRe and Gnds , o) boundary between bedrock control, BRe and covered bedrock (BRc), another boundary within bedrock controlled regions.	29
Figure 3.18 Bedrock controll polygons overlain on shaded relief image. Bedrock units dated by Lyons et al., (1997) in Geologic Map of New Hampshire, figures 1.5 and 1.6. Red lines indicate contacts between formations.	31
Table 3.1 Modified from USGS and Lyons et al., 1997. Rock formations within regions of bedrock control for the Sandwich Region, WMNF with symbol, and age rock description. Symbol colors related to bedrock map in figure 3.17.	32
Figure 3.18 Lineament map with a scale of 1:76,000. Lineaments are the topographic expression of planar features in bedrock controlled regions eg. faults, fractures. Orientation assigned to lineaments through cogo direction tool in Ars. Lineaments symbolized as red lines.	33
Figure 3.19 Rose diagrams of lineaments from major formations within study area: Devonian Kinsman Granodiorite (Dk2x), Jurassic porphyritic syenite (J7x), Jurassic Conway Granite (Jc1b), Jurassic Mount Osceola Granite (Jo1h), Cretaceous gray augite-hornblende-biotite monzonite (K7c), Cretaceous arge mesoperthitic phenocrysts in a pink to gray quartz syenite	34
Figure 3.20 Elevation map of the Swift River flodplain overlain on a shaded relief image. Elevation data indicates changes relative to the active channel as well as changes along the Swift River. Elevation grades down towards the east. Ages relative to channel elevation were useful in determining transect contacts.	35
Figure 3.21 Elevation transects along alluvial fans originating from the northern side of the Sandwich mountains and moving towards the Swift River. Elevation profile used to verify contacts between alluvial fan and forms of glacially derived till. Lowest region indicates point of intersection with modern fluvial, ie. the Swift River floodplain.	35
Figure 3.20 Elevation transects from various points along the Swift River floodplain. Transects taken in regions with a wide floodplain and the presence of multiple terraces. Transects derived from DEM and 3D mapping tool. Terraces of multiple ages can be seen in flat regions across floodplain. Lowest elevation plane in transect is the active channel.	36
Figure 3.21 Meltwater channel and linear feature close up maps of study area. Meltwater controlled landscapes are confined to the southern flanks of the mountainous middle section of the study area.	37
Figure 3.22 Elevation transects of meltwater channels derived from digital elevation model, drawn south to north in the southern region of the study area -- on the southern flanks of Mt. Whiteface and Mt. Chocorua.	37
Figure 3.23 Photographs from visits to the Sandwich Region of the S. White Mountains: a) bedrock exposed summit of Mt. Chocorua. Granite is part of the Mt. Osceola Formation (Lyons et al., 1997) and exhibits large, exposed fracture planes. b) bedrock features at the summit of Mt. Chocorua. c) fractures at the summit of Mt. Whiteface in the Conway Granite (Lyons et al., 1997). Fractures trend NW-SE and E-W. d) non-exposed bedrock summit of Mt. Chocorua. Structural features ie. fractures, are still visible through soil and vegetation cover.	38
Figure 3.23 continued. e) View from southern bank of the Swift River looking south towards terrace levels. Picture taken from second terrace in region, with stairs leading up a second riser to a third terrace. f) view of Swift River, Fac, in landscape control region. Boulders along banks of river are	

often not visible in LiDAR. g), mountain stream flowing from Mt. Tripyramid, also a representation of Fac. H. Stream in a meltwater controlled region, active.	39
Figure 4.1 Rose plots of data collected from the peak of Mt. Chocorua a) lineament data obtained from LiDAR, b) field-based strike and dip data.	42
Table 4.1 Lineaments classified by age of hostrock with orientations trends classified into major, secondary and minor categories, if applicable. *Note that the two minor categories are only used for Jurassic trend classification, and hold equal weight in terms of orientation trend prevalence.	43
Figure 4.2 Lineament mapping of bedrock units a. Jurassic, b. Silurian, c. Devonian, d. Cretaceous. Simplified from formation units (figure 3.19).	43
Figure 4.3 Bedrock units of Lyons et al., 1997 simplified by age (Jurassic, Silurian, Devonian, Cretaceous) and overlain by mapped lineaments (red lines).	44
Figure 4.4. Scale based mapping of Mt. Chocorua. a-c) mapping of lineaments at a scale range of 1:2,000-3,000, d-f) mapping of lineaments at a scale range of 1:13,000-15,000.	45
Figure 4.5 Elevation profiles along the Swift River annotated with designations between terraces (T1-3), the active channel (Fac), downcutting features -- risers (R1-3), as well as correlative guides between terrace elevations (dotted segments).	46
Figure 4.6 Fluvial mapping of a section of the Swift River in the northern region of study area: a) polygon interpretation of terraces within floodplain, terrace 1 being the lowest and youngest, terrace 3 highest the oldest, b) a DEM normalized along the elevation plane of the active Swift River using the Global Polynomial Interpolation Tool, c) bare hillshade of region indicating patterns of fluvial dynamics evident in the LiDAR.	47
Figure 4.7 Surficial mapping in the S. White Mountain region. Aside from Goldthwait (1950)'s surficial map of New Hampshire, no state-wide mapping effort has been completed. Grey 7.5 quadrangle tiles (Mt. Tripyramid and Mt. Chocorua) contain the study region, and do not have completed surficial maps, blue 7.5 minute quadrangle tiles do not contain surficial maps in digital or accessible formats, red 7.5 minute quadrangle tiles have surficial mapping accessible in either digital or non-digital formats.	49
Figure 4.8 Surficial deposits around the Swift River in the SW corner of the N. Conway West 7.5 minute quadrangle. Qalf (orange) represent alluvial fan deposits, and Qlps is a unit of the Glacial Lake Pigwacket from the Conway Stage. Qalf present at higher elevations, ranging from 1500-1000 feet, Qlps present at lower elevations surrounding the river, >1000 feet. Polygons of the two surficial units were digitized from the georeferenced N. Conway West map and appear overlain at 50% transparency on a USGS topographic 7.5 minute map of the N. Conway West quadrangle (USGS, 2015). Blue insets represent study area in the Mt. Tripyramid and Mt. Chocorua 7.5 minute quadrangles.	50
Figure 4.9 Elevation of Swift River Floodplain in the southern region of study area. Floodplain grades down from west to east.	51
Figure 4.10 Fluvial landscape unit for alluvial fan, Faf, overlain on a shaded relief image. Alluvial fans in the study region are found at elevations between 1000 and 1500 feet, and can be compared to the Nelson and Goldsmith unit, Qalf.	51
Figure 4.11 Transects across the swift river from east to west. a) Transect from a western region of the Swift River floodplain, b) transect from a central region of the Swift River floodplain, c) transect from a eastern region of the Swift River. Maximum depth along transect (red) indicates the position of the	

active channel. Channel depth increases from east to west indicating a downsloping river gradient.	52
Figure 4.12 Glacial striae features present in western region of the greater study area. Found in regions of glacial control, look to involve the interaction of surficial cover and scoured bedrock. Linear quality of striae are oriented parallel relative to others in the same region, and often reflect localized topographic environment. While the dominant trend of flow direction indicators in the study region exhibits a SE flow direction (a,b,e,f) other reflect diversion around high peaks (c,d). The relative orientations of flow direction in the western extent of the greater study region are present in figure.	54
Figure 4.13 Glacial flow direction in western extent of greater study area. Glacial striae (red lineaments) reveal both regional trends of glacial flow and localized glacial flow indicative of topographic conditions during glaciation. Orientation of SE-NW lineaments reflect regional ice flow to the southwest, while the more E-W orientation of lineaments reflects localized variations as a result of higher topographic features to the north and south.	55
Figure 4.14 Flow direction map generated with glacial striae present in the western section of the greater study area and Goldthwait's 1938, Surficial Geology of New Hampshire Map, georeferenced to LiDAR of eastern study region. Flow direction indicators from Goldthwait (black arrows) indicate SE and SSE orientation of glacial flow. Glacial flow interpreted by blue arrows, in a general SE direction with localized variations.	56
Figure 4.15 Simplified glacial flow direction map derived from glacial striae and flow direction indicators from Goldthwait et al., (1938).	57
Figure 4.16 Flow direction features found in the literature a) Smither and Peterson, 2014 flow direction oriented east to west, b) Livingstone et al., 2010, flow direction to the southwest, c) Smith et al., 2016, flow direction to the southeast, d) Sherrod et al., 2004, flow direction to the southwest, e) Kovanen and Slaymaker, 2004, flow direction to the west-southwest, f) Dyess and Hansen, 2014, flow direction to the south-southwest.	58
Figure 4.17 a) Lateral meltwater channels identified by Syverson and Mickelson, 2008, b) a diagram of in-and-out channels also from Syverson and Mickelson, 2008. Both the meltwater channels and the in-and-out channels reveal characteristics of the meltwater channels present in the study area.	60
figure 4.18 . Model for meltwater channel formation as a result of deglaciation. Meltwater channels (M1-M4) form as ice front (IF1-IF4) lower. Meltwater channels in exhibit a dipped topographic relief, due time-dependent erosion.	60
Figure 4.19. Normalized elevation along meltwater channels (parallel to topography) -- see methods and the Global Polynomial Interpolation tool. Profiles reveal six meltwater channels along transects (T1, T2, T3).	61
Figure 4.20 Time slice map of glacial extent constructed from meltwater channels in the SW corner of study region (green box featured in location map. Elevation of meltwater channels used as indicators of glacial retreat elevations downvalley to the south. Stages of deglaciation in a-e, and represented as a single series in f. Elevations are relative to lateral channels and do not indicate actual elevation of features.	62
Figure 4.21 Timeslice map of glacial extent constructed from meltwater channels in the SW and SE corners of study area (green box featured in location map indicates extent of mapping. Slight change in relative elevations of deglaciation stages compared to figure 4.10.	63
Figure 4.22 Timeslice map of ice extent of entire study region from a correlation of three complex of meltwater channels: in the SW, SE and NE corners.	64

Figure 4.23 Model for the existence of Glacial Lake Sawyer, and an ice filled Swift River Valley proposed by Held (2014). Ice damns to the south and north of Glacial Lake Sawyer, which recede and allow Glacial Lake Sawyer to drain into the Swift River Valley. Ice damns downriver create Glacial Lake Swift which occupies the Swift River Valley in the study region. Figures modified from Held (2014).	65
Figure 4.24 Ice extent during Glacial Lake Sawyer (Held, 2014) to the west. Ice margins were modified from Held (2014), and placed at 475 meters to account of topographic changes along the Swift River.	66
Figure 4.25 model for ice extent during the period of proposed Glacial Lake Sawyer (Held, 2014). Ice extent model mapped below elevations of 475 meters, represented by white with blue dots. Glacially dammed lakes which occurred contemporaneous to Glacial Lake Sawyer are present at elevations between 530 and 475 meters, represented by blue polygons with a 30% transparency.	67
Figure 4.26 Glacial outwash terraces on the western side of Sabbaday Brook, with Mt. Tripyramid and The Foot Killer to the west and Potash Mountain to the east. Terraces occur at four elevations, symbolized as color polygons on a shaded relief map and as T ₁ through T ₄ on the transect drawn from west to east across the terraces on a digital elevation model.	68
Figure 4.27 Glacial outwash terraces may be used to establish a model for lake drainage during down-valley glacial retreat. Glacial lakes (blue) lower as ice (white, dots) retreat. Terraces represent periods of ice positioning and lower lake level elevations.	68
Figure 4.28. Lidar comparison between features present in the study area (left column, A, C, E, G) and previously studied and mapped units presented in Peterson and Smith, 2013 (right column, B, D, F, H). A. Waterville River Valley featuring rounded indentations in surficial geology. B. Similar indentation topography from A. classified as kettle holes in Peterson and Smith, 2013. C. a curved feature mapped as a linear feature in landscape classification map (figure 3.3). D. Similar linear feature classified as an esker in Peterson and Smith, 2013. E. Glacial control unit of hummocky tilly present in landscape classification map. F. Topography classified as hummocky till by Peterson and Smith, 2013. G. Linear features with patterned surficial. H. Similar feature classified as Crag and tails, indicative of ice flow direction.	71

1. Introduction

1.1 Purpose

Light Detection and Ranging (LiDAR) has advanced the role of remote analysis in the field of geology. The purpose of this study is to evaluate and classify landscape geomorphology in a region in east-central New Hampshire through remote analysis of LiDAR imagery. The study area is located in the southern portion of the White Mountain National Forest, in central-eastern NH, between the Kancamagus Highway to the north and the Mts. Whiteface, Trip Pyramid, and Chocorua to the south and east. Reasons for this study are twofold: 1. to analyze fluvial, glacial and bedrock landscape geomorphology in the Sandwich region of the White Mountain National Forest through 2014 LiDAR imagery and 2. to determine the applicability of feature identification and landscape analysis through initial remote analysis and secondary field checking.

To understand the geology of the WMNF it is first necessary to explore the roles which tectonics and deformation assumed in the region. A Wilson cycle began in the Neoproterozoic with a constructive phase of ocean crust resulting in the rifting of Rodinia and the formation of Laurentia, Gondwana and the Iapetus Ocean. Extension occurred from 750 Ma to 500 Ma. Between 485 and 290 Ma slab rollback along the western coast of Gondwana generated a series of terrane ribbons which moved westward, along with Gondwana, and accreted onto Laurentia. These events can be classified as the Taconic Orogeny in the Ordovician, the Salinic Orogeny in the Silurian, the Acadian Orogeny in the Devonian, the Neoacadian Orogeny in the Devonian to Carboniferous and the Alleghanian Orogeny in the Permian. The result formed the supercontinent, Pangea, and is evidenced by the Appalachian Mountains (Hatcher, 2010; Hibbard et al., 2010; Hibbard et al., 2007, Moench and Aleinikoff, 2001, van Staal et al., 2015, Waldron et al., 2014).

Pangea fragmented during the late Triassic and early Jurassic to form Gondwana and Laurasia. North-south unzipping of the supercontinent resulted in brittle deformations. Evidence of said divergence is visible in the fractures, faults and intrusions present along the divergent margin, specifically in the Appalachian Mountains (Faure et al., 2006). The rifting of Pangea marked the end of the second Wilson Cycle. Glacial and interglacial phases followed during the Pleistocene. The effect was an expansive erosion of the Appalachian mountains, and exposure of brittle tectonic features through physical and chemical weathering (Bradley, 1981; Thompson et al., 2001, Roden-Tice et al., 2012).

The White Mountains represent a critical location for the study Appalachian tectonics. Investigations have ranged from structural analysis of fractures (Hibbard et al., 2007), to glacial studies (Bradley, 1981; Bromley et al., 2015; Balco and Schaefer, 2006; Koteff and Pells, 1985; Thompson, 1999; Balco et al., 2009) and analysis of igneous intrusion (Moench and Aleinikoff, 2003; McHone and Bulter, 1984; Dorais, 2003). The topography of the WMNF offers a wide variety of geologic signatures and evidence for geologic processes. Geomorphologists, in particular, have focused on the WMNF to investigate the relationships and developments between bedrock, surficial and glacial geology (Roden-Tice et al., 2000; Thompson et al., 1999; 1981; Ridge, 2004; Thompson and Fowler, 1989).

A history of bedrock mapping in the WMNF began in the 1800s and has included contributors such as Jackson (1844), Billings (1955), Lyons (1997), Thompson and Eusden. Surficial and fluvial studies include Goldthwait (1948) and Goldsmith (1999). Over the last two centuries, as mapping techniques

have improved and new technologies have been adapted for geological purposes, the approach taken to mapping the WMNF has evolved to place a greater emphasis on remote analysis. The introduction of tools which allow spatial data to be collected over a wide area have changed the direction of geologic mapping. In the last half century, mapping methods have made increasing use of Landsat imagery--the first remote sensing technique first used in the 1970s, the global positioning system (GPS)--first used in the 1990s, and interferometric synthetic aperture radar (InSAR)--digital elevation data beginning in 1999. During the 2000s the accuracy of these instruments improved, and the relationship between geologic mapping and remote analysis grew more dependent (USGS, 2013; NOAA, 2013).

Light detection and ranging (LiDAR) first drew interest in the early 1990s. Like InSAR it is a digital elevation tool, but unlike InSAR it generates a bare-earth image of the surveyed area. LiDAR used in conjunction with airborne swath mapping techniques has given geologists a high-resolution recreation of surface topography without the limitation of vegetative layers. Since the 1990s, the LiDAR has played an increasingly important role in geomorphic investigations; both improving remote sensing techniques, and furthering the field of inquiry (Roering et al., 2013).

In the WMNF, LiDAR has been used for soil surveying purposes (Dekett et al., 2013). Past studies of LiDAR in the southern region have been conducted by Sturtevant (2014) and Held (2014) as geomorphic and structural studies. Both these studies operated on the knowledge that LiDAR, as a relatively new tool to geologic analysis, requires further investigation. Both studies included preliminary field investigations in the field followed by LiDAR analysis. While comprehensive and illuminating, both studies concluded that field checking should be required after LiDAR analysis to verify findings.

1.2 Study Area

The White Mountain National Forest is located in central New Hampshire and a small portion of eastern Maine. It occupies 800,000 acres of protected forest, and draws recreational outdoor enthusiasts from around the country since the early 1800s. The area assessed in this project is a portion in the southeast corner of the WMNF (figure 1.0). It includes from west to east: Mt. Trip pyramid, the Bowl Area, the Sandwich Range, Mt. Passaconaway and Mt. Chocorua. The northern extent terminates along the Swift River. The region is dominated by igneous intrusions from the Triassic, specifically the Conway and Mt. Osceola granites. There are also smaller pockets of Silurian rock such as the Madrid, Smalls Falls and Perry Mountain Formation, and even smaller regions contain Devonian rock. In total the region extends 10 miles from east to west, and 7 miles from the Swift River to the southern boundary of the WMNF. It offers a range of structural, glacial and fluvial controlled sites, and a chance for a geomorphic analysis of regional interactions.

Figure 1.1 Lidar imagery represented in a shaded relief image with an azyimuth and altitude of 315/45. Orientating features within the study region include Mt. Tripyramid, Mt. Whiteface, Mt. Passaconaway, Mt. Chocorua, and the Kancamagus Highway.

1.3 Tectonic Setting

1.3.1 Appalachian Tectonics

The formation of the White Mountains begins with the tectonics of the Appalachian Orogeny. Between 750 and 500 Ma, the supercontinent, Rodinia, separated to form the two continents of Laurentia and Gondwana and the Iapetus Ocean. During this period the eastern coast of Laurentia a passive plate margin developed, allowing for the accumulation of sediment along the continental rise. At the same time, there was an active plate boundary along the west coast of Gondwana. This boundary exhibited tectonic behavior associated with destructive behavior such as volcanism and seismic activity. 500 Ma, the first stages of the Appalachian Orogeny were initiated with the rifting of a ribbon-like plate, Ganderia, from Gondwana (Figure 1.2). The rifting was the result of slab rollback associated with the active margin. The rifting of Ganderia signified the end of a constructive phase of ocean-crust building for the Iapetus Ocean, and the beginning of a destructive phase responsible for the closing of the Iapetus Ocean. At 480 Ma an ocean-ocean subduction zone in the western Iapetus Ocean collided with the passive Laurentia margin. And at 450 Ma, Ganderia rifted to form the Tetagouche-Exploits Sea and developed a active subduction margin on the leading western edge resulting in a second collision. The arc-continental series of collisions are understood as the Taconic Orogeny (Thompson et al., 1999, Bradley, 1983, van Staal et al., 2015, Wintsch et al., 2014; Hatcher, 2010).

During the Taconic Orogeny in the Ordovician, further rifting occurred along Gondwana resulting in the formation of the Avalon Plate and the intervening Theic Ocean. This was followed by further rifting along Gondwana and the formation of a third plate, Gander and the Rheic Ocean. In the same period, the Tetagouche-Exploits Sea began to close as a result of destructive margins, and moved west. The Salic Orogeny was the result of the collision of the remaining portion of Gander, split off by the Tetagouche-Exploits Sea. The Salinic Orogeny occurred during the Silurian, and is thought to have been less of an intense collision than the Taconic (van Staal et al., 2015; Hatcher, 2010).

During the Silurian, subduction margins on either side of Avalon resulted in the closing of the Iapetus and Theic Oceans (to the west and east sides, respectively). Avalon progressed westward into the early Devonian and between 420 and 390 Ma, the Acadian Orogeny occurred as Avalon subducted under the Laurentia margin. While the Taconic and Salinic Orogenies were important in building landmass in New Hampshire, and specifically the White Mountains, these regions were significantly deformed by the Acadian Orogeny. Evidence for salinic deformation and metamorphism is a prominent feature in the WMNF (Hibbard et al., 2006, Hatcher, 2010, van Staal et al., 2015; Wintsche et al., 2014).

The closing of the Rheic Ocean and the collision of Meguma with the Laurentia margin occurred after the Acadian Orogeny, in the Devonian and Carboniferous. The result was the Neoacadian Orogeny, and like the Salinic Orogeny, displays evidence for less severe deformation in the White Mountains. The final orogenic event of Appalachian tectonics was the Alleghanian Orogeny in the Permian. During this time, Gondwana collided with Laurentia to form the supercontinent Pangea. The collision marked the end of a full Wilson Cycle. Like the preceding Neoacadian Orogeny, the tectonic implication for the Alleghanian Orogeny were mild in the White Mountains (Hibbard et al., 2006, Hatcher, 2010, van Staal et al., 2015; Wintsche et al., 2014).

Figure 1.2 Simplified lithotectonic map of the Appalachian Mountains from Wintsch et al., 2014, modified from van Staal, 2005. Generalized representation of metamorphic effects on major terranes and plutonic intrusion. Study location represented by black dot in the Peri-Laurentian arcs.

1.3.2 Mesozoic Rifting and associated volcanics

By the end of the Paleozoic Era, Pangea was formed and resided just north of the equator. Beginning in the Mesozoic Era, Pangea began a new Wilson Cycle and began to rift, forming the continents of Laurasia and Gondwana. First stages of rifting occurred at a south-west orientation into the early Triassic, 240 to 210 Ma, and resulted in northeast trending brittle deformation features. Second stages of rifting at an east-west orientation in the late-Triassic and Jurassic resulted in N to NE trending brittle deformation features. It is believed that the mechanism behind the rifting of Pangea was a ascending superplume from the core-mantle boundary. The rising superplume effectively pushed Pangea in opposing directions, resulting in the fragmentation of the supercontinent. The superplume is known as the Central Atlantic Magmatic Province (CAMP), and is believed to be the cause of extinctions at the end of the Triassic Period (figure 1.3). Evidence for CAMP is apparent in now-exposed dike swarms. Rising magma from CAMP filled in the features associated with brittle deformation, resulting in dikes oriented in relationship to the divergent stress fields (McHone et al., 1988).

Mesozoic rocks in New England are the result of igneous intrusions from the Central Atlantic Magmatic Province. The intrusions contain associated volcanic and plutonic rocks from the Triassic, Jurassic and Cretaceous Periods and are classified as the White Mountain Magma Series. Of the igneous Mesozoic igneous rocks in New Hampshire, the majority belong to the White Mountain Plutonic-Volcanic Suite. These rocks are characterized as Early Jurassic granitic plutons, generally in a circular pattern on a map view. These features often have associated arcuate (ring-shaped) igneous intrusions surrounding their center. Based on studies of these features, it is believed that igneous intrusions in New Hampshire were the result of a caldera-collapse and subsequent intrusion development process. Creasy and Eby (1993), propose that the process follows a caldera domming, eruptive, collapse and resurgence. In the first stage intrusions of magma dome the landscape (figure 1.4). This is followed by a second stage of violent eruptions which result in the emptying of the magma chambers. In the third stage, the emptied chambers collapse under the weight of expelled material (hot ash, volcanic debris) resulting in the formation of

calderas. In stage four, subsequent ash flows erupt around the arcuate forms of the calderas, along with intrusions of similar nature. The final stage was the intrusion of younger granites into older extrusive material. Today, evidence for the caldera collapse model is evident through the ring-dyk features which surround the circular shapes of many of the White Mountains (Creasy and Eby, 1993; Ramberg, 2008).

Figure 1.4 designation of the Central Atlantic Magmatic Province (CAMP), understood as the mechanism behind the rifting of Pangea into Laurasia and Gondwana during the early Mesozoic. Extension created from the ascending mantle plumes is evidenced by igneous intrusions into brittle extensional features, eg. dike swarms (McHone, 2000). Study area indicated by black dot.

Stage I Caldera doming

Stage II Initial eruptions

Stage II Main eruption

Stage III Collapse of roof along ring fracture

Figure 1.4 Model for caldera collapse understood to be the source of ring-dike emplacement in the White Mountains (Ramberg, 2008).

1.3.3 Deformation history

Deformation of the White Mountains reflects the periods of mountain building during Appalachian orogenies, as well as the fragmentation of Pangea during the Mesozoic era. The Acadian orogeny, as stated above, had the largest impact on the WMNF. Deformation during the Devonian resulted in both brittle faulting and ductile folding. Faults are difficult to see in the field, and most often recognized when rock formations not commonly found together, occupy the same region. This signifies the presence of a fault as a vehicle for rock relocation. The Moose River, Mahoosuc, Acadian, Foster Hill and Greenough Springs are prominent fault examples which express brittle deformation during the Devonian. Ductile deformation from Appalachian tectonics are far more common in the WMNF, and much easier to examine in the field. Two main episodes of folding in the Acadian and the Neoacadian are found in the region. Often, folds from the Acadian were refolded in the Neoacadian, resulting in a complex network of ductile deformation structures.

Deformation resulting from Mesozoic rifting of Pangea is evidenced by brittle features. During initial stages of divergence in the Triassic and Jurassic, tensile stress was oriented in a NW-SE direction. As a result, brittle NE-striking structures formed, and were often intruded by rising magma. During the Cretaceous, stress fields changed as rifting progressed to a N-E orientation. Fractures during this period formed in an E-W orientation and some also filled with intruding basalt. Prominent faults from the Mesozoic Era include the Ammonoosuc, Eustis Hill, and Northerly faults. These have N-NE strikes and westward sloping dips (McHone et al., 1988, Marzoli et al., 1999, McHone, 2000).

1.3.4 Bedrock

The bedrock of the White Mountains is a direct result of Appalachian tectonics and associated volcanics with the rifting of Pangea. The White Mountains contain rocks which date back to the Ordovician from the Gander plate as a result of the Taconic Orogeny. The oldest rocks in the White Mountains are found on the westernmost site, and include sedimentary and volcanic rocks, and igneous intrusions. Formations from the Ordovician include the Albee and Partridge Formations, the Oliverian Domes and the Ammonoosuc Volcanics.

In the eastern regions of the WMNF, the area of focus for this study, there are rocks from the Silurian and Devonian periods and Mesozoic era. Silurian rocks include the Rangeley, Perry Mountain, Smalls Falls and Madrid Formations. The Rangeley Formation originated as sediment deposits in the Tetagouche-Exploits Basin and dates to around 460 Ma. The Perry Mountain and Smalls Falls also originated in the Tetagouche-Exploits Basin, but were deposited during a time of deoxygenation and chemical reduction as a result of basin closure. These formations date to around 440 Ma, late in the Taconic Orogeny. The youngest Salinic rocks found in the White Mountains are in the Madrid Formation. These are post-Salinic, pre-Acadian, around 420 and 400 Ma. Like the Rangeley Formation, these rocks were deposited during a period of oxygenation (Creasy and Eby, 1993).

Rocks from the Devonian Period include the Littleton Formation and intrusive rocks related . The Littleton Formation is the youngest sedimentary rock found in the White Mountains at around 400 Ma. It was formed during the Acadian Orogeny. Intrusive formations in the region include the Wildcat Granite, the Bethlehem Gneiss, the Kinsman Granodiorite and other small diorite and tonalite plutons. These intrusive rocks were a result of crustal thickening from the continental-continental subduction of the Avalon plate under the Gander plate. The subduction resulted in the westward movement of the leading orogenic front during the Acadian Orogeny. Crustal thickening resulted in the formation of magmas which

make up the Devonian granites present in the White Mountains (Creasy and Eby, 1993; McHone, 1999, Foland and Faul, 1977).

Aside from rocks originating from the Appalachian orogenies, the White Mountains contain intrusive evidence for the Mesozoic rifting of Pangea (figures 1.5, 1.6 and 1.7). Two Jurassic rocks dominate the WMNF: the Conway Granite and Mt. Osceola Granite. The Conway is a medium-to-coarse-grained, pink, biotite bearing, two-feldspar granite. The Mt. Osceola is a feldspar, amphibole and pyroxene bearing granite. Both the Conway and Mt. Osceola granites are crosscut by stage four and five ring dikes. These ring dikes are Albany porphyritic quartz syenite, which is pink to grey with a fine-grained matrix. The region of focus considered for this study is dominated by the Conway and Mt. Osceola granite, with some Devonian formation in the west and Silurian formations in the southwest (Creasy and Eby, 1993; McHone, 1999).

10

Bennett, D. S., Wittkop, C.A., and Dicken, C.L., 2006, Bedrock Geologic Map of New Hampshire - A Digital Representation of the Lyons and others 1997 map and ancillary files: U.S. Geological Survey Data Series 215, scale 1:250,000, CD-ROM.

Figure 1.7 Bedrock unit polygons overlain on a shaded relief map of the greater study region. Study region is dominated by Conway Granite (Jc1b), and Mt. Osceola Granite (Jo1h), both dated to the Jurassic. Bedrock polygons modified from Lyons et al., (1997) Geologic Map of New Hampshire (figure 1.5 and 1.6).

1.4 Pleistocene glacial and Holocene postglacial periods

The last glacial maximum occurred in the late Pleistocene, between 100,000 to 12,000 years ago. During this time, large portions of the earth lay beneath kilometer-thick sheets of ice. The largest was the Laurentide Ice Sheet (LIS) (figure 1.4), which had a maximum area of 13,000,000 km² and a height of 3,000 m. At maximum extent, it covered large portions of North America, covering all of New Hampshire and terminating to the SE off the coast of New England and in the east in the Gulf of Maine (Bromley et al., 2015). It is proposed that during periods of heightened ice formation, the tallest peaks in the White Mountains were covered by 1100 meters of ice (Bradley, 1981). Due to the immense erosional force of glacial growth and retreat, previously glacially modified landscapes are overprinted by subsequent glacial activity. Today, the White Mountains display evidence from only the last period of glacial activity, the Wisconsin Glaciation, around 30,000 years ago (Koteff and Pessl, 1981 and Bradley et al., 1981). During the Wisconsin Glaciation, flow direction was oriented towards the southeast, although localized topographic features caused small scale variations to flow direction. Glacial flow is studied through the analysis of features associated with glacial interactions with surface topography. These include but are not limited to: u-shaped valleys, hummocky terrain, till and stratified drift deposits, streamline features such as drumlins, and striations and grooves (Anderson and Borns, 1994). Analysis of these features add to and understanding of paleo-glacial extent and retreat. The White Mountains are of particular importance to the reconstruction of glacial events due to the topographic barrier which their height facilitates (Bradley et al., 1981).

The end of Pleistocene glaciation resulted in the retreat of the LIS northwards. Deglaciation of the White Mountains occurred around 11,700 years ago. As the earth warmed in the interglacial Holocene, non-glacial interactions assumed an increased role in the shaping of surface topography. Fluvial and mass movement are two processes which came to dominate the post-geologic history of the White Mountains (Bradley et al., 1981). Glacial lakes and stages of base level lowering events contribute to modern deformation of the landscape (Thompson, 1999; Davis and Holland, 1997; Nelson and Goldsmith, 2000).

Figure 1.8 Reconstruction of Laurentide Ice Sheet over north America during periods of maximum extent during the last glacial maximum (left), and present ice extent (right). Note that all of New Hampshire is covered by the LIS during the quaternary (Blakely, 2011).

1.5 Remote analysis

Evolution of technologies

The development of geologic mapping has evolved from a process of small scale analysis followed by large scale inference to a process of large scale analysis followed by small scale inference. These changes are the result of the transition of mapping practices rooted in field observations to ones emphasizing remote analysis. Changes to geologic mapping would not be possible with the succession of mapping technology. Prior to remote analysis, field data collection involved sketches, plane table/alidade surveys, inclinometers, and altimeters. Field observations, while essential to the study of geology, hinder mapping efforts for several reasons. First, some techniques involve high degrees of human error and susceptible to subjective decision making. Second, field observations are highly time consuming, and result in the slow production of geologic maps. In the last fifty years, tools available for the collection of data through remote analysis have improved beyond field-based mapping practices. In 1972, the United States introduced the first remote sensing technology for geologic analysis in the form of the Landsat Project. It produced 80-meter satellite imagery of the earth. Landsat imagery allowed for geologists to begin the incorporation non-field based information into their analysis. Imagery from the Landsat Project was gained relevance with the development of the global position system (GPS). GPS data provided satellite imagery with a spatial referencing tool. The integration of satellite imagery and GPS resulted

Figure 1.9 A comparison of LiDAR imagery (top) to a USGS topographic map (bottom) of the same region surrounding Mt. Tripyramid. LiDAR reveals features hidden through topographic representation such as lineaments, and fluvial features.

in a computer-based spatial analysis mapping and data management tool developed, the Geographic Information System (GIS) (Roering et al., 2013; Church, 2013; Pavlis et al., 2010).

Although useful for some spatial analysis, a combination of satellite imagery and GPS referencing was insufficient for broad advancements in geologic investigations. Until 1999, GIS-based analysis lacked elevation data and therefore was limited to a two-dimensional plane of analysis. In 1999, Interferometric Synthetic Aperture Radar (InSAR) was introduced, allowing for the collection of elevation data. From InSAR, digital elevation models (DEMs) were generated and integrated with satellite imagery and GPS in GIS. Over the years, the accuracy of these technologies has improved: landsat data from 80m to 15m resolution, GPS data from 100m to <10m accuracy, and InSAR technology from 90m to 30m elevation resolution (Roering et al., NOAA, 2013; USGS, 2013).

LiDAR

Light Detection and Ranging (LiDAR), generates elevation data from laser point clouds at high resolutions. When collected via swath mapping through airplane mounted lasers, processed LiDAR produces bare earth imagery of the surface of the earth (Webster, 2006). As a result of greater availability and advancements in quality, the presence of LiDAR in geologic research has grown in the last 15 years. Although LiDAR was first developed in the 1990s, it was not widely used for academic research purposes until the end of the twentieth century due to high operational costs of private interest shareholders. In 2003, the National Science Foundation created the National Center for Airborne Laser Mapping (NCALM), which allowed for an increase in LiDAR collection. The evolution of LiDAR based geomorphic research has increased steadily with the wider availability and quantity of data. Technological advancements are also responsible for this increase. Like other remote sensing technologies mentioned previously, improvements have been made through higher LiDAR sampling frequency. From the early 1990s to current projections, sampling frequency has moved from 103 points per second (PPS), to $>1.5 \times 10^3$ pps. This translates to bare-earth point densities of between 1 and 10 per meter, dependent on vegetation density of targeted region. Full waveform LiDAR has allowed for a more detailed, 3D characterization of areas of high vegetation. Green wavelength LiDAR allows for bathymetric data to be collected from shallow, non-turbid regions. And the progression of georeferencing technology has allowed for more precise correlations between aircraft orientation and data collection (Pavlis et al., 2010, Roering et al., 2010).

LiDAR has advanced the field of geomorphic enquiry for several known reasons. It provides a new foundation from which to map, but prior to fieldwork and post-field analysis. In addition, it has been applied to methods of prediction of morphic processes, and their subsequent description. LiDAR has also been used to identify unexpected landforms, as well as providing a larger perspective from which to analyze geomorphic relationships (Roering et al., 2013). Studies of LiDAR have included bedrock analysis (Pavlis and Bruhn, 2011), glacial analysis (Dyess and Hansen, 2014), and fluvial studies (Haugerud, 2009; Haugerud et al., 2003).

1.6 Research Objectives

Using 2014 1-meter resolution LiDAR (figure 1.10), this study examines structural, fluvial and glacial features in the southernmost region of the White Mountain National Forest, New Hampshire. Initial stages involve the processing of imagery through ArcGIS and the creation of high-resolution relief maps. Through the remote analysis of the study area, it will be possible to identify regions by their control

mechanism, ie. bedrock controlled areas as compared to glacially controlled areas. Secondary stages will involve a field-based study where findings from processed LiDAR data are confirmed with visits to the area of study. Since LiDAR as a tool for surficial study is new, field checks are essential to the integrity of the project. Often, previously unrecognized features are visible through the LiDAR imagery and therefore necessitate on-site exploration. Finally, research will conclude with detailed lineament, rock type (eg. contacts), glacial and fluvial studies of the study area combining lineament, streambed elevation and glacial mapping. LiDAR has been used to re-map geologic contacts, remap fluvial impacts and better understand glacial movements. Even in its beginning stages, it is allowing with sweeping advancements to the field. This study is one of many which will help to grow the field and explore the possibilities of LiDAR as a critical tool in geologic study.

Figure 1.10 Hillshade image of processed LiDAR imagery with illumination from azimuths of 315 and 45 degrees and an altitude of 45 degrees. Bare-earth image which processed LiDAR provides will be the inception point for all aspects of remote analysis undertaken in this study.

2. Methods

2.1 Introduction

The methods used to study for this study are twofold: initial remote analysis of LiDAR and subsequent targeted field work. Information and observations ascertained from remote analysis requires verification from field truthing. Once a positive correlation between findings derived from both remote analysis and field-based research, it is possible to extrapolate future remote analysis findings without added field work.

2.2 Remote analysis methods

Airborne LiDAR collection occurred on October 28 through November 6, 2014 over the course of five flights (figure 2.1). Four returns (first, second, third and last) were measured and processed at a 1-meter resolution by Photo Science, Inc. The resulting dataset comprised of 163, 2 km² tiles each containing digital elevation data. Processed LiDAR contains elevation data of the bare earth. Bare earth is defined as terrain free of vegetation and man-made features--ie. buildings, bridges, vehicles. Point cloud laser pulses are released and measured per meter of ground from an airborne LiDAR device. The timing of laser contact with surface reveals changes in elevation at a meter resolution. Returns with varying elevation data represent meter areas with more than one elevation, ie. features smaller than 1 meter. Multiple return data is analyzed to determine the presence of non-bare earth substrate (figure 2.1).

ArcGIS 10.3--which includes ArcMap, ArcScene and ArcCatalog--was used for remote analysis of the processed LiDAR data. It was decided that due to the timeline and scope of the project, it would be beneficial to narrow the field of research from the initial 163 tiles. Based on factors such as prominent features (specific mountains, rivers, valleys), a smaller study area was created which included 67 of the original tiles. The resized study area was constrained by the natural northern border of the Swift River Valley, and the national park boundaries to the south. The eastern extent was predetermined to data collection and bisects a section of the WMNF. The western extent of the study region was constrained to include the Conway and Mt. Osceola Granite intrusions, and follows river valleys when possible. DEM tiles were mosaicked into a continuous DEM (figure 2.2).

Elevation data alone does not convey the necessary information for remote analysis of LiDAR. For this reason, further classification of the data was necessary. This included hillshade, slope and aspect maps (figure 2.3 a-c). Hillshade maps (figure 2.3 b) were created from the elevation raster through the Hillshade tool. Hillshade maps display surface relief based on the angular orientation of the sun (azimuth and altitude). Due to the orientation of features in the study area (especially the NE-SW trend of lineaments), it was necessary to generate several hillshades with different illuminations (azimuth values and altitude values). What was visible from one illumination was often not from another. The two hillshades used most frequently had a azimuth and altitude of 45/45 and 315/45. Use of multiple hillshades will be discussed in more detail in the lineament analysis section of this chapter. Aspect maps (figure 2.3 a) display the orientation of surface planes through numerical compass values between 0 and 359.9, clockwise from north. A flat surface is said to have an aspect of -1. Aspect maps display the downslope direction derived from raster cell's z-value. Slope maps represent the slope of a given surface.

Figure 2.1 a) LiDAR collection occurred on October 28 and November 3-6 in 2014. Color swatches designate the date of area collection. Flights moved northwards, beginning with 10/28 in blue, and ending with 11/6 in red. See figure 1.0 study area map to orient lidar collection area. b) Bare earth point density map of study designated by original tiles. Designates point density for each return relative to the tile. Density is determined by dividing the number of returns per tile by the area of the tile. Regions with higher returns ie. more vegetation and urban areas -- not applicable in this study -- would have a lower bare earth point density.

figure 2.2. comparison of mosaicked DEM raster (top) and the original elevation data tiles (bottom). Tiles were mosaicked together to form a seamless elevation raster. This raster provides the basis for many spatial analysis calculations performed in ArcMap 10.3.

Figure 2.3 LiDAR derived maps from the mosaicked DEM used for remote analysis. a. An aspect map of region, b. hillshade map of region with an azimuth of 315° and an altitude of 45°, c. slope map indicating degree of steepness.

2.2.1 Landscape Classification

Methods for geomorphic mapping were developed through principles outlined by Haugerud, (2009) (figure 2.5). In general, these followed an inductive approach to landscape analysis--meaning that features were consistently identified based on a characteristic set of surface conditions (slope, elevation, texture). Landscape classification can be broken down into three general categories of surface control: bedrock-controlled regions, glacially controlled regions and fluvially controlled regions. Due to erosion and transportation processes, bedrock controlled regions are found at high elevation, and fluvially controlled regions at low elevation, with glacial features between at mid-elevations.

Each category may be further subdivided into a series of features characteristic of either bedrock, glacial or fluvial control. A catalogue of these features may be referred to in figures 2.6 through 2.18. To distinguish between these regions, polylines were drawn between points of contact. Several sets of contact polylines were drawn in order to gain a better understand of the different features present in the study area. After revisional stages, these polylines were converted to polygons associated with the control features. Difficulties in classification vary depending on terrain. For example, it is easy to designate an active channel due to the large difference in elevation between an active and inactive channel. However, between there are often places of transition separating features. In these instances, the designation of boundaries is more difficult. Classifying regions of hummocky till from non-dissected till is often difficult due to more gradual transitions. The process of classification can be somewhat subjective at first. The bedrock, glacial and fluvial regimes which influenced and shaped the region are evident in processed LiDAR imagery through the following signatures: exposed bedrock regions are characterized through rough, densely-spaced jagged texture intersected by lineaments ranging from 3 to 23 m in

length, generally striking NE-SW. Bedrock overlain by thin surficial deposits still displays lineaments, but exhibits a smoother, more uniform surface. Bedrock controlled regions in the study region are found at the highest elevations (2000-4000 ft). Glacial features include but are not limited to: hummocky till which shows a rounded topography, organized in a grid-like pattern with individual features measuring less than 200 ft across. Till which appears as homogeneous and defined by smooth sloping topography, is either dissected by fluvial channels of 1-2 meters, 3-4 meters apart or not. Meltwater channels appear as deep features, around 110 meters across, parallel to contours on the SW side of mountains. Linear eskers and moraine glacial features, and post glacial boulder deposits are also found. Glacial regions are present at lower elevations (1000 to 2000 feet). Fluvial features in the region include inactive, raised and active terraced floodplains, and active river channels, and alluvial fans (present between 1600 and 1400 feet). Fluvial features are found at the lowest elevations in the study region. The goal of landscape classification is the generation of a landscape geomorphology map of the study region which reaches the level of detail exhibited by Haugerud, (2009) and Haugerud et al., (2003) (figure 2.5).

Figure 2.4 Polygon classification of three main landscape control regimes: bedrock (red), fluvial (blue) and glacial (green). a) boundary between glacial and bedrock features, b) boundaries between bedrock, glacial and mountain streams in fluvial category, c) fluvial control of Swift River, d), example of three regimes

Figure 2.5 From Haugerud et al., 2003 (left) and Haugerud, 2009 (right). Examples of landscape classification of LiDAR imagery for geomorphic mapping

2.2.2 Landscape classification units

Landscape units classified in order of three simplified classification units: bedrock, fluvial and glacial. Each landscape unit displays a characteristic lidar imagery in shaded relief images. Often, a unit will exhibit several characteristics. Forming and understanding of these qualities was the first step in identifying and separating units from the shaded relief images. To describe methods for this process a library of unit features was generated with annotations -- indicators of what qualities are used in the identification and mapping process. Two images are used: one with an outline of the unit itself, and a second with annotated characteristic qualities. A formal legend with the same landscape units will be presented in chapter 3.

2.2.2.1 Bedrock control

Thin layers of vegetation or soil do not impair LiDAR recognition of underlying bedrock. For this reason, classification of bedrock regions may be subdivided into exposed (figure 2.6) and non-exposed (2.7). Covered bedrock often exhibits a smoother relief than exposed bedrock. Boundaries between bedrock and glacially controlled regions are made through the presence (or lack of presence) of lineament features.

Figure 2.6 Bedrock control unit: exposed bedrock (BRe). Highlighted yellow boxes indicate characteristic texture of exposed bedrock--with visible lineaments, abrupt changes in elevation. Blue lines represent a few lineament features in other regions of exposed bedrock.

Figure 2. 7 Bedrock control, covered (BCc) with a thin layer of soil and/or vegetation. BRc denoted by blue polygon on the left. Contact between glacially controlled regions and BRc regions is often indicated by the very fine texture, lacking changes abrupt changes in elevation. Lineaments are visible in bedrock

2.2.2.2 Fluvial control

Fluvially controlled regions may be subdivided through further classifications between active and inactive regions. The entire floodplain is clearly visible through the LiDAR imagery (figure 2.8). Within the floodplain, it is possible to distinguish the active channel based on a more distinct boundary and greater depth (figure 2.9). Higher terrace elevations are also visible through the imagery (2.10). One method for mapping old terrace elevations and floodplains is overlaying elevation data on existing hillshade feature classes (figure 2.21). Through this method it is easier to visualize and draw connections between fluvial features of the same time period through their corresponding elevation. This method requires multiple elevation intervals for a small region given larger changes in landscape slope. Another classification within fluvial controlled regions is surface water. LiDAR processing eliminates surface waters, ie. lakes, ponds, streams. Therefore, it appears as a flat surface in LiDAR (figure 2.11).

Figure 2. 8 Fluvial control, floodplain (Ffp). Complete control denoted by blue polygon on the left -- Notice the curved boundary as a result of the extinct meandering river channels. Paleo terrace levels within the floodplain represented on the right. Colors relate terraces of the same elevation, indicating the same terrace.

Figure 2.9 Fluvial control, active channel (Fac), Water processed out of LiDAR imagery but active river channel demoted by a large and consistent elevation change from surrounding floodplain (blue polygon on left). Width of channel is consistent (green and red lines on right).

Figure 2.10 Fluvial control, terraces (Ft), illustrated through polygons on the right and left. Terraces are often cut by newer terraces. Elevation data obtained from DEM rasters is often used to delineate terrace plans of the same age

Figure 2.11 Fluvial control, surface water (Fsw), surface waters are processed out of LiDAR, and result in a smoothed and homogenous surface.

Figure 2.12 Fluvial control, alluvial fans (Faf), Alluvial fans are found in between high peaks and fluvial regions. Characterized by finely grained run-off streams.

2.2.2.3 *Glacial control*

Glacially controlled regions contain a plethora of sub-features. Glacially dissected till (figure 2.13) are classified based on characteristic channels on which originate below bedrock contact, and terminate in fluvial controlled regions. Generally, these appear on sides of steeply sloping mountains. The width and length of channels varies across the study region. Hummocky till (figure 2.16) exhibits a rough, dotted texture with small bumps over regions of flatter ground. The size of bumps are often uniform, and regularly occur alongside fluvial features. Non-dissected till (figure 2.15) has a smooth texture, but is found in steeper sloping areas like dissected till. Boulders (figure 2.17) appear on LiDAR. Some are present in the region on steeper sloping regions. These have a characteristic rounded texture, much more discernible than the hummocky till texture. Depositional linear glacial features like eskers and moraines (figure 2.14) are also present in the region. These have prominent ridge lines and present at low, gradually-sloping regions of the study area. Erosional glacial meltwater channels (figure 2.18) are also present. These have a distinct channel which cross-cut till. The meltwater channels present in the study area run parallel to ridgelines, whereas channels cutting through till run perpendicular to ridgelines.

Figure 2.13 Glacial control, dissected till (Gds), channels which cut through medium-grained textured surface. Surface is less more rounded than exposed bedrock, but less than hummocky till. Blue polygon indicates entire region of dissected till on left. Red lines denote the characteristic, closely spaced channels.

Figure 2.14 Glacial control, eskers and moraines (Glf), linear features both parallel and perpendicular to bedrock

Figure 2.15 Glacial control, non-dissected till (Gnds), smooth-textured with a rounded relief. Elevation changes are minimal. Lacks dissection channels.

Figure 2.16 Glacial control, hummocky till (Ght), Hummocky tilly contains large rounded relief.

Figure 2.17 Glacial control, boulders (Gb), small rounded features cluster around higher regions, normally around bedrock but overlain on non-dissected till

Figure 2.18 Glacial control, meltwater channels (Gmwc), present parallel to topography. Channels are non-braided depression on down-sloping surfaces (light blue polygons, left). Intercut (red and pink lines) by new, active channels (yellow lines).

2.2.3 Lineament Mapping

Lineaments were collected following methods developed by Mabey et al., (1994). Workflow for lineament collection involved multiple stages of lineament collection, and accuracy testing (figure 2.20). Lineaments were drawn as line shapefiles with cogo fields added to the feature upon creation, and updated frequently. Two hillshade illuminations (figure 2.19 a and b) and one slope map (figure 2.19 c) were used to draw two sets of lineaments (in line with Mabey et al., step 1: “multiple trials/multiple images”). Once three data sets of lineament line shapefiles were collected, the three sets were overlaid. Lineaments not present in both datasets were eliminated, unless individual reasons applied. For example, if one illumination prevented the illumination of a lineament, but the other did (ie. the lineament was only evident in one of the data sets) then it was included. The exclusion of non-coincident lineaments from the dataset resulted in the reduction of lineament data.

Figure 2.19 Lineaments traced on a) shaded relief image with an azimuth and altitude of 315/45, b) shaded relief image with an azimuth and altitude of 45/45, and c) a slope map.

Figure 2.20 Methods for lineament mapping modified from Mabey et al., (1994).

2.2.3 Floodplain mapping

To map fluvial changes a combination of hillshade analysis, digital elevation modeling and vertical transect trends were utilized. Based on methods proposed by Salcher et al., (2010), regarding cross cutting relationships, polygons features were used to designate different terraces along the floodplain. However, polygon classification alone was not enough for modeling the entire floodplain. Extended channel meandering of younger stages in the fluvial record, terraces were sometimes recut by younger incisions multiple times. Sometimes this appeared to represent three stages of ages in a sequential order instead of a non sequential order. Therefore, it was necessary to use both digital elevation modeling and transect data from the 3D analysis toolbar to decipher between terrace elevations and their respective ages.

To effectively utilize elevation data in LiDAR analysis it is sometimes necessary to normalize local elevation changes to explore other elevation trends. For example, the Swift River does not exist on a single elevation plane, but rather has a downstream gradient that can be modeled as a tilted plane. The Global Polynomial Interpolation tool was employed to adjust for vertical changes in specific areas in the study region. In order to do this, it is first necessary to collect point elevation data within a point feature class (figure 2.22). These points are then assigned elevation values through the Extract Values to Points tool, with the point feature class as the feature input, and the study region DEM as the raster input. Once points has been assigned an elevation value, they can be used as the input for the Global Polynomial Interpolation tool with order equal to one (a flat plane), and the processing extent equal to same as display. The result -- a plane with a slope calculated from point elevations--is used to normalize the original DEM. To do so, the Raster Calculator tool is used to subtract the original DEM from the Global Polynomial Interpolation plane. This produces a DEM with new elevation values.

Elevation data was also used to create elevation transects across the floodplain (figure 2.21). These provided several important pieces of information. First, they verified the presence of the active channel. As stated previously, water like vegetation is removed during LiDAR processing. This results in a characteristically flat and smooth surface which reveals no relief nor distinguishable texture. Surface waters such as lakes and ponds elsewhere in the study area exhibit the same feature. The active channel in the swift river is therefore easily classified from the rest of the floodplain. To verify this signature as the active floodplain, elevation transects are used because the active channel is the lowest point in in the elevation profile. Elevation profile also reveals -- and often verifies -- terrace elevations. This is useful in correlating terraces on either sides of the active channel. As visible in the elevation profile, terraces of the same elevation on opposing sides of the active channel are easily correlated.

Figure 2.21 Transect elevations derived from the 3D analyst tool were used to classify floodplane levels. Elevation drawn on a DEM at 100% transparency, overlain on a shaded relief map of the Swift River.

Figure 2.22 stages of floodplain mapping using the global polynomial interpolation tool. a) point features added to targeted field, b) gradient produced by polynomial interpolation with elevation data assigned to points, c) raster generated from plane in (b) subtracted from original DEM (a).

3. Results

3.1 Introduction

The goal of this study is to understand the geomorphic processes which influenced the geology of the study region, and to explore the role of LiDAR may play in geomorphic applications of remote analysis. With this focus, LiDAR analysis through ArcGIS was subdivided into four regions of study. First, initial landscape classification between bedrock, fluvial and glacial controlled region was further classified into the following fifteen subsections: exposed and non-exposed bedrock, alluvial fans, two floodplain elevations, active channels, surface water, regions of fluvial depressions, glacial boulders, dissected till, non-dissected till, hummocky till, linear glacial features, regions of meltwater erosion, and inactive meltwater channels. Second, an investigation into bedrock structure was accomplished through analysis of pre-existing bedrock mapping from Lyons et al., (1997) as well as lineament data collection and subsequent analysis. Third, targeted fluvial mapping of the Swift River floodplain in the northernmost section of the study region was accomplished through terrace elevation mapping. And fourth, and understanding of the glacial history of the study region included ice flow reconstruction, meltwater channel mapping and the identification and mapping of linear features -- moraines and eskers. The following chapter includes a series of maps and figures intended to visually represent LiDAR remote analysis.

3.2 Landscape classification mapping

Landscape mapping of the entire study region was modeled after Haugerud et al., (2009) and Haugerud (2003). The study region was classified based on controlling mechanism, ie. bedrock control, fluvial control or glacial control (figure 1). Bedrock regions in the study region are found at elevations >600 feet, and fluvial regions are mostly confined to elevations <370 feet. Glacial controlled regions are located in the intervening elevations. Examples of exceptions include mountain streams, and high deposits of glacial debris, ie. non-dissected till.

Detailed landscape classification followed simplified landscape classification. This involved the subdivision of the three primary control groups into fifteen control sub-classifications (figure 3.2). Bedrock controlled regions were found to contain either exposed bedrock (3.2a) or non-exposed bedrock (3.3). Unlike exposed bedrock regions, non-exposed bedrock (BRc) regions exhibit a smooth texture in processed LiDAR while still revealing large lineament features. Exposed bedrock (BRe) is characterized by a rough and jagged texture, intersected with lineament features. Both exposed and non-exposed bedrock are found at elevations >600 feet, and are normally adjacent to glacially controlled regions, although in some instances, high mountain fluvial channels cut through bedrock regions.

Fluvial controlled regions contain five sub-regions: the active channel (3.4), alluvial fans (3.5), floodplain (3.5) terrace levels at three elevations (3.6), surface waters (3.7), and extinct water deposits (3.8). Active channels (Fac) are used to classify any region which exhibited the most recent presence of fluvial interaction of the landscape -- at the time when LiDAR data was collected. Fac features are present in large floodplain regions, such as the Swift River Valley in the northern region of the study area, and in steep regions as mountain streams (figure 3.9). Alluvial fans (Faf) are found in the northern portion of the study region, on depositing sediments from mountainous regions into the Swift River Valley. Alluvial

fans deposited sediments from high elevations into low-lying fluvial controlled regions. They contain a high concentration of inactive, braided streams which flow outwards from intersection of high and flat topography. Flood plains (Ffp, Ffp_2) are present around the active channel of the Swift River, as well as outwash rivers in the southern portion of the study region. Floodplain mapping was accomplished by elevation mapping, described in the fluvial portion of this chapter. Floodplains are flat regions, sometimes containing oxbows and the occasional fluvial deposit of sediments. Surface waters (Fsw) such as lakes and ponds are removed during initial LiDAR processing with vegetative cover. Therefore, regions which contain surface water exhibit a flat surface. The flat surface does not exhibit a textured relief because elevation of water is removed. Lakes and ponds are surrounded by higher elevations of glacially deposited material. Regions of extinct water deposits (Fwe), are surfaces of flattened topography in regions of high topographic change. These areas are often confined or look to be confined at one point. They are interpreted to be regions which once contained confined surface water, but were eroded away by subsequent fluvial deposition.

Glacial controlled regions contain seven sub regions: boulders (3.9), dissected till (3.10), hummocky till (3.11), linear features (3.12), meltwater regions (3.13), meltwater channels (3.14), and non-dissected till (3.15). A single area containing boulders (Gb) was found on the NE side of Mt. Mexico, in the south-central region of the study area. Boulders appear as dot-like features in LiDAR in a high-density region. Individual boulders are present in other places of the study region, but there was only one field of boulders. Dissected till (Gds) occupied regions between bedrock and mountain streams in the central portion of the study region. Dissected till was characterized by closely spaced channels which cut through glacial till in a V-pattern. The density of dissection channels varied across the study region. Gds is confined to steep topographic regions. Hummocky till (Ght), was also found between bedrock and fluvially controlled regions. Ght exhibited a rounded topographic signature of weathered glacial till. Sometimes Ght could be said to possess a lattice-like erosional pattern. Linear features (Glf) were present in the form of moraines and eskers. Moraines are oriented parallel to topography, and eskers are oriented perpendicular to topography. Moraines were often segmented, only stretchy for a few hundred feet at the longest. Often they exhibited a lobate geometry. Moraines and eskers were primarily confined to the southern regions of glacial control in the study area, and were found with meltwater-controlled regions. Meltwater controlled regions (Gmw), were found in the Northern and Southern regions of the study area. Gmw exhibited a smoothed texture, and were intersected by deep, extinct channels, and active channels. Meltwater channels (Gmwc) intersect meltwater regions. Gmwc are wide channels which parallel surface topography, with flattened bottoms and are intersected by active mountain streams. Non-dissected till (Gnds) was found between bedrock and fluvial regions. It exhibits a smooth surface, not cut by channels, and lacks a high relief pattern.

Figure 3.1, simplified landscape classification map of entire study region. Polygons designate bedrock (red), fluvial (blue) and glacial (green) controlled regions. Polygons displayed at 30% transparency, overlying a 315/45 hillshade at 50% transparency and a 45/45 hillshade.

3.3 Landscape classification units

3.3.1 Bedrock control

3.3.1.1 *Bedrock, exposed (BRe)*

Densely textured signature. Rough and often jagged fragments. Lineaments are expressed as abrupt linear changes in texture or intersection of feature. Often contains one or multiple patterns of orientation, often related to lineament orientation. Imagery exhibits a shiny quality. Exposed bedrock controlled regions are found in highest elevations in study area.

Figure 3.2 examples exposed bedrock features in LiDAR

3.3.1.2 *Bedrock, non-exposed, Brc*

Smoothed and non-textured signature. Lack of rough or sharp features results in a homogenous surface that is clear of prominent features. Transitions between elevation appear on a gradient as opposed to jagged changes. Imagery also exhibits a shiny quality. Non-exposed bedrock controlled regions are found at the highest elevations in the study area, often adjacent to exposed bedrock units.

Figure 3.3 examples of non-exposed bedrock features in LiDAR

3.3.2 Fluvial control

3.3.2.1 *fluvial, active channel (Fac)*

Water processed out of LiDAR imagery but active river channel demoted by a large and consistent elevation change from surrounding floodplain. Width of channel is consistent.

Figure 3.4 examples of active channel features in LiDAR

3.3.2.2 *Fluvial, alluvial fan (Faf)*

Alluvial fans are found in between high peaks and fluvial regions. Characterized by finely grained run-off streams.

Figure 3.4 examples of alluvial fan features in LiDAR

3.3.2.3 *Fluvial, floodplain (Ffp)*

Feature encompasses the entire floodplain--including active channel, extinct channel and old terraces. Notice the curved boundary as a result of the extinct meandering river channels. Boundary between floodplain is often adjacent to dissected or non-dissected till.

Figure 3.5 examples of floodplain feature in LiDAR

3.3.2.4 *Fluvial, terrace (Ft)*

Terrace controlled regions are represented within some floodplain regions. Terraces are limited by intersecting channels and other terraces of older or younger stages of base-level lowering. Terraces exhibit a fine grained, smooth texture.

Figure 3.6 Terraces of various ages contained within floodplain

3.3.2.5 *Fluvial, surface water (Fsw)*

Surface waters are removed out in initial stages of lidar processing. In shaded relief image they have a flat, and 1-dimensional appearance. Signature is distinctly synthetic. Representative of a single elevation, related to the presence of current surface water.

Figure 3.7 examples of surface water feature in LiDAR

3.3.2.6 *Fluvial, fluvial depression -- extinct, (Fwe)*

Regions of flat exposure that do not reveal the smoothed surface of processed-out water. These regions are therefore interpreted to be extinct surface water regions.

Figure 3.8 example of extinct surface water in LiDAR

3.3.3 Glacial control

3.3.3.1 *Glacial, boulders (Gb)*

Small rounded features cluster around higher regions, normally around bedrock but overlain on non-dissected till

Figure 3.9 example of bouldar features in LiDAR

3.3.3.2 *Glacial, dissected till (Gds)*

Channels which cut through medium-grained textured surface. Surface is less more rounded than exposed bedrock, but less than hummocky till. Blue polygon indicates entire region of dissected till on left. Red lines denote the characteristic, closely spaced channels.

Figure 3.10 examples of dissected till in LiDAR

3.3.3.3 *Glacial, hummocky till (Ght)*

Hummocky till contains rounded topographic expression. Mounded, lumpy texture sometimes in a grid pattern. Size of hummocks vary, but are normally of uniform size in a localized region. Lacks jagged or rough expression.

Figure 3.11 examples of hummocky till in LiDAR

3.3.3.4 *Glacial, linear features (Glf)*

Elongate and rounded features in a curved or linear grouping. Occur on top of other glacial controlled regions of till or meltwater, sometimes intersected by modern fluvial features. Long region oriented parallel or perpendicular to local topography.

Figure 3.12 examples of linear features in LiDAR

3.3.3.5 *Glacial, meltwater (Gmw)*

Regions where meltwater and icefront regression has eroded and smoothed surface conditions. Features are laterally intersected to topography by meltwater channels (Gmwc). Exhibits a similar texture to non-dissected till controlled regions.

Figure 3.13 examples of meltwater environment water feature in LiDAR

3.3.3.6 *Glacial, meltwater channels (Gmwc)*

Wide channels without dissected till margins intersect glacial till parallel to topography. Occur in groupings of three to five channels at increasing elevation. Channels retain a similar width, sometimes intersect with other channels and are often intersected by modern fluvial at a perpendicular angle.

Figure 3.14 examples of meltwater channel features in LiDAR

3.3.3.7 *Glacial, non-dissected till (Gnds)*

Smooth-textured with a rounded relief. Elevation changes are minimal. Lacks dissection channels.

Figure 3.15 examples of non-dissected till features in LiDAR

Figure 3.16 detailed map of landscape classification of Sandwich Region, WMNF. Three regimes of bedrock, fluvial and glacial control are subdivided into fifteen categories--bedrock (2), fluvial (6), glacial (7). Polygons at 40% transparency, overlain on a 315/54 hillshade at 50% transparency and a 45/45 hillshade.

Figure 3.17. a) meltwater channels (Gmwc and Gmw), b) Gmwc, Gmw, hummocky till (Ght), and fluvial features, c) Gmwc, Gmw, and bedrock (BRc), d) in-and-out Gmwc with an active channel (Fac) and non-dissected till (Gnds), e) linear features (Glf) in a Gmw region with active fluvial interaction, f) linear features on Gnds with Gmwc, and Fac, g) Glf on hummocky till, h) alluvial fan (Faf) with Ght, Fac, and other fluvial features.

Figure 3.17 continued. i) floodplain (Ffp), Fac, and dissected till (Gds), j) mountain Fac surrounded by Gds and BRE, k) evidence of fluvial depression (Fwe) with Gds, Gds and Fac, l) surface water (Fsw) with Gds, m) Ght and fluvial interaction, n) BRE and Gds, o) boundary between bedrock control, BRE and covered bedrock (BRc), another boundary within bedrock controlled regions.

3.4 Bedrock mapping

3.4.1 Bedrock control

Bedrock mapping of exposed and non-exposed bedrock consisted of lineament mapping and designating regions of bedrock control by their formal formation classification. Although the primary goal of this study was not to construct a tectonic history of the study area, bedrock analysis was used to assess the applicability of remote analysis for future tectonic reconstruction. Lineament analysis of specific formations with pre established ages and tectonic histories was a useful way for these reasons.

Bedrock polygons were clipped by regions of bedrock control due to the availability of data obtainable through remote analysis. The region is dominated by Jurassic age granites (Conway Granite, Mt. Osceola Granite, Passaconaway Granite), with some Cretaceous, Devonian and Silurian rock in the western region. In total, the bedrock controlled regions of the study area feature twelve formation units from Lyons et al., 1997 (table 3.1). To understand how the formations varied in terms of tectonic structure, lineaments were recorded for the entire study region (figure 3.18) and analyzed by the specific region (figure 3.19).

3.4.2 Lineament mapping

Lineaments are indicator planar structural features such as fractures, joints and folds (Twidale and Bourne, 2007). Chemical weathering at the surface results in topographic expressions which appear in LiDAR as sharp, linear features which intersect regions of bedrock control. Lineaments were collected in accordance with the methods outlined by Mabee et al., 1999 in three stages: initial collection, domain analysis overlap, and the omission of non-coincident findings. Two sets of lineaments were collected through the use of a 315/45 hillshade and a 45/45 hillshade. Lineaments perpendicular to the light source to one illumination were more difficult to measure than when they were oriented parallel to the light source. Therefore, it was important to collect lineament data with two hillshade values. Over 5000 lineaments were drawn using both the 315/45 and 45/45 hillshade. These two sets were overlain and masked through the extraction tool to generate a dataset with 2000 lineaments (figure 3.18).

A domain analysis of lineaments was performed by intersecting the lineament feature class with the bedrock previously clipped Lyons et al., 1997 bedrock polygons (figure 3.5b). Therefore it was possible to generate datasets which subdivided lineament data by age and formation. To analyze lineament data by rock formation, stereonet were generate for formations with >20 lineaments (figure 3.19).

Figure 3.18 Bedrock controll polygons overlain on shaded relief image. Bedrock units dated by Lyons et al., (1997) in Geologic Map of New Hampshire, figures 1.5 and 1.6. Red lines indicate contacts between formations.

Symbol	Formation	Age	Unit description
Jc1b	Conway Granite	Jurassic	Conway Granite - Typically pink, coarse-grained mesoperthitic biotite (amphibole-free) granite; locally fine-grained or porphyritic.
Jo1h	Mount Osceola Granite,	Jurassic	Mount Osceola Granite, Granite containing hornblende and, locally, hastingsite, ferrohedenbergite, or fayalite.
J7x	Porphyritic syenite	Jurassic	Porphyritic syenite - Hastingsite or hornblende and (or) hedenbergite are present.
Dk2x	Kinsman Granodiorite	Devonian	Kinsman Granodiorite - (Kinsman Quartz Monzonite of Billings, 1955) - Foliated granite, granodiorite, tonalite, and minor quartz diorite; large megacrysts of potassium feldspar characteristic; garnet locally abundant.
K9B	Augite-hornblende-biotite gabbro	Cretaceous	Augite-hornblende-biotite gabbro - Fine- to coarse-grained.
K4x	Large mesoperthitic phenocrysts in a pink to gray quartz syenite	Cretaceous	Large mesoperthitic phenocrysts in a pink to gray quartz syenite porphyry of “Albany type” - Alkaline amphibole or fayalite may be present. Part of Ossipee Mountain Complex of Kingsley (1931).
K7C	Gray augite-hornblende-biotite monzonite	Cretaceous	Gray augite-hornblende-biotite monzonite.
Dw3A	Winnepesaukee Tonalite	Devonian	Winnepesaukee Tonalite (Winnepesaukee Quartz Diorite of Billings, 1955) - Gray, massive to foliated tonalite and minor quartz diorite, granodiorite, and granite. Probably coeval with Spaulding Tonalite.
Srl	Lower part of Rangeley Formation	Silurian	Lower part of Rangeley Formation - Gray, thinly laminated (5-25 mm) metapelite with local lentils of turbidites and thin quartz conglomerates in western New Hampshire. Sparse calc-silicate pods and cotecule. Probably equivalent to member B of Rangeley Formation of Maine.
Sru	Upper part of Rangeley Formation	Silurian	Upper part of Rangeley Formation - Rusty-weathering, pelitic schist, metasandstone, and local coarse-grained metasandstone lentils; calc-silicate pods common; minor cotecule. Probably equivalent to member C of Rangeley Formation of Maine.
Sp	Perry Mountain Formation, undivided	Silurian	Perry Mountain Formation, undivided - Sharply interbedded quartzites, light-gray nongraphitic metapelite, and “fast-graded” meta-turbidites. Cotecule layers common.
Sf	Fitch Formation	Silurian	Fitch Formation - Metamorphosed limestone, calcareous sandstone, siltstone, and dark pelitic schist; lower contact is unconformable on the Clough Quartzite. Fossiliferous.

Table 3.1 Modified from USGS and Lyons et al., 1997. Rock formations within regions of bedrock control for the Sandwich Region, WMNF with symbol, and age rock description. Symbol colors related to bedrock map in figure 3.17.

Figure 3.18 Lineament map with a scale of 1:76,000. Lineaments are the topographic expression of planar features in bedrock controlled regions eg. faults, fractures. Orientation assigned to lineaments through cogo direction tool in Arc. Lineaments symbolized as red lines.

Figure 3.19 Rose diagrams of lineaments from major formations within study area: Devonian Kinsman Granodiorite (Dk2x), Jurassic porphyritic syenite (J7x), Jurassic Conway Granite (Jc1b), Jurassic Mount Osceola Granite (Jo1h), Cretaceous gray augite-hornblende-biotite monzonite (K7c), Cretaceous arge mesoperthitic phenocrysts in a pink to gray quartz syenite

3.5 Fluvial mapping

Fluvial mapping of the study region was targeted on a northern region which contained portions of the Swift River Valley (3.7 inset). Fluvial mapping involved terrace mapping for paleo-stream elevations. This classification allowed for the construction of both extinct active channels, and helped to shape and understanding of past fluvial and glacial interactions. Floodplain elevations were Digital elevation models (figure 3.20) as well as transect data were used to construct three terrace elevation levels (chapter 4). Using processing tools discussed in chapter 4, elevation mapping of the Swift River floodplain was used to investigate the relationship between fluvial indicators and base-level lowering events and the possibility of glacial lakes in the region. Elevation data collected through transect profiles of the Swift River floodplain displayed three terrace elevations, and three downcutting events (risers) (figure 3.21).

Figure 3.20 Elevation map of the Swift River floodplain overlain on a shaded relief image. Elevation data indicates changes relative to the active channel as well as changes along the Swift River. Elevation grades down towards the east. Ages relative to channel elevation were useful in determining transect contacts.

Figure 3.21 Elevation transects along alluvial fans originating from the northern side of the Sandwich mountains and moving towards the Swift River. Elevation profile used to verify contacts between alluvial fan and forms of glacially derived till. Lowest region indicates point of intersection with modern fluvial, ie. the Swift River floodplain.

Figure 3.20 Elevation transects from various points along the Swift River floodplain. Transects taken in regions with a wide floodplain and the presence of multiple terraces. Transects derived from DEM and 3D mapping tool. Terraces of multiple ages can be seen in flat regions across floodplain. Lowest elevation plane in transect is the active channel.

3.6 Glacial mapping

Glacial analysis included the identification and mapping of ice flow indicators and the mapping of linear features and meltwater channels. Through large scale ice flow mapping and small scale linear and meltwater channel mapping, it is possible to better understand the role which glaciation and glacial retreat played in shaping the Sandwich region in the WMNF.

Figure 3.21 Meltwater channel and linear feature close up maps of study area. Meltwater controlled landscapes are confined to the southern flanks of the mountainous middle section of the study area.

Figure 3.22 Elevation transects of meltwater channels derived from digital elevation model, drawn south to north in the southern region of the study area -- on the southern flanks of Mt. Whiteface and Mt. Chocorua.

Figure 3.23 Photographs from visits to the Sandwich Region of the S. White Mountains: a) bedrock exposed summit of Mt. Chocorua. Granite is part of the Mt. Osceola Formation (Lyons et al., 1997) and exhibits large, exposed fracture planes. b) bedrock features at the summit of Mt. Chocorua. c) fractures at the summit of Mt. Whiteface in the Conway Granite (Lyons et al., 1997). Fractures trend NW-SE and E-W. d) non-exposed bedrock summit of Mt. Chocorua. Structural features ie. fractures, are still visible through soil and vegetation cover.

Figure 3.23 continued. e) View from southern bank of the Swift River looking south towards terrace levels. Picture taken from second terrace in region, with stairs leading up a second riser to a third terrace. f) view of Swift River, Fac, in landscape control region. Boulders along banks of river are often not visible in LiDAR. g), mountain stream flowing from Mt. Tripyramid, also a representation of Fac. H. Stream in a meltwater controlled region, active.

4. Discussion

4.1 Introduction

LiDAR of the Sandwich Range region of the White Mountains reveals a complex series of features. The identification and delineation of features into landscape control units was necessary to form an understanding of regional trends of operating geologic mechanisms: bedrock controlled regions, fluvial controlled regions, and glacial controlled regions. Given preexisting understandings of the regions, combined with the relative positions and interactions between the control groups it is possible to state: 1. Bedrock geology in the region is dominated by igneous intrusions during mesozoic rifting (Lyons et al., 1997), 2. glacial regimes occurred during the quaternary during both glaciation and deglaciation (Thompson et al., 1999), 3. the resulting surface continues to be eroded by fluvial interactions with both bedrock controlled areas, and glacially controlled areas. As evidenced by the detailed landscape control map (figure 3.3), regions of bedrock control are found in the highest elevations, fluvial control dominates the lowest elevations and glacially controlled regions persist in the intervening space.

To form an understanding of landscape evolution it is necessary to verify landscape features with known LiDAR features from the literature. This chapter is subdivided into five sections: the first four providing examples of how features viewed in the lidar may be interpreted as evidence for geologic processes, the fifth presents an examination of specific lidar features against published accounts and subsequent classification of lidar features.

4.2 Lineament analysis

4.2.1 Lineament analysis classified by age

A total of 3,017 lineaments were traced within bedrock controlled regions of the study area. These lineaments were collected based on methods from Mabey et al., (1994) and therefore represent several stages of data collection and verification. Lineaments traced within bedrock serve as topographic signatures for linear geologic features. Chemical and physical weathering of fault and fracture structures in exposed bedrock enables enhanced visibility (Twidale and Bourne, 2007). These features register in the high resolution 1-meter LiDAR imagery through processes of differential erosion as lineament features. Lineament mapping serves as a clue towards the orientation of structural features within bedrock, and therefore may be applied in an investigation of the region's tectonics.

Ages of bedrock controlled regions were obtained from the New Hampshire state bedrock map of Lyons et al., (1997). Bedrock units processed in GIS as georeferenced polygon shapefiles were used to extract lineaments in the study area and classify their contents based on formation and age (see results section). As outlined in chapter 1, the study region is dominated by three Jurassic formations: the Conway Granite (Jc1b), the Mt. Osceola Granite (Jo1h), and a porphyritic syenite (J7x). The westernmost bedrock exposures contained rock formations from the Cretaceous, Devonian, and Silurian. Given the limited representations of formations within these three age groups, it was not possible to collect sufficient lineament data to perform a comprehensive analysis based on formation classification alone (stereonet based on ages of largest formations in chapter 3). Therefore, lineaments were extracted and analyzed in groupings based on age: Jurassic, Silurian, Devonian, Cretaceous (figure 4.3).

Jurassic-age lineaments, the largest collection of lineaments (2,522) displayed a strong orientation trend of SW-NE trending lineaments with a secondary set trending WNW-ESE, and two minor sets trending WSW-ENE and NNW-SSE (table 4.1). The size of the Jurassic lineament data set meant that it was possible to distinguish these four sets of lineament orientation based on high correlation trends (figure 4.11a). It was less possible to identify as many trends with the Silurian (253 lineaments) and Devonian (123 lineaments) groupings, and much less possible with the Cretaceous (35 lineaments) group.

All four age-based lineament collection exhibited a trend of SW-NE in the major or secondary classification. This was strongest in the Jurassic grouping, and less visible in the Cretaceous grouping. However, this comparison is again not lacking in data bias due to the large difference in data collection size. There was also a strong WNW-ESE trend in orientations for the Jurassic, Silurian and Devonian groupings.

Irrespective of specific tectonic regimes responsible for the orientation of lineaments in the study area, it is possible to conclude that lineament collection through LiDAR is capable of detecting patterns of lineament alignment. Without any understanding of the geologic setting, it is possible to conclude based on the trends of lineament orientation that a tectonic fabric is revealed through lineament exposures in LiDAR. Based on the strong correlation of lineaments oriented in four orientation patterns in the Jurassic grouping it may be inferred that, given sufficient lineament data, it is possible to classify patterns within specific regions of bedrock. When LiDAR is viewed with the naked eye, it is possible to visualize orientation of lineaments in localized collections, but it is equally useful to construct a dataset of lineaments by a determined classification -- in this case age based on rock-type. The limited orientation analysis possible from the Cretaceous lineament grouping implies this same point, but from the opposite direction. Without a large amount of lineament data available it is more difficult to determine orientation trends. Although lineaments collected seemed to fall into a few orientation categories, the small sample size meant that the correlation of these orientations groupings with limited at best. Lineament analysis undertaken in this study reveals the importance of a large sample size for the effort to be at all relevant or useful for remote mapping efforts.

Orientation of lineaments may be assessed in the context of tectonic history. The study area experienced the effects of Appalachian orogenies as well as Mesozoic extension. Given this active past, it should be possible to see evidence for past tectonic events in lineament data. The NE-SW trend of lineaments present in the Jurassic-age bedrock is comparable to regional trends structural data. The orientation of a NE-SW lineament reflects a paleostress in a NW-SE orientation. Dyke swarms in the region have been found to contain an NE-SW orientation. These swarms are dated back to the Jurassic and reflect rifting events during the creation of the Atlantic Ocean (Faure et al., 2006; Faure et al., 1996; McHone et al., 1987). The NE-SW trending lineaments present in the study area reflect this extensional history. Although lineaments may not reflect dykes, the fracture pattern reflects the extensional pattern reflected in LiDAR imagery.

4.2.2 Comparison of remote analysis to field-based mapping

Another aspect of this study was the usefulness of LiDAR analysis in comparison to field-based mapping. Strike and dip measurements taken from the exposed bedrock peak of Mt. Chocorua (in the easternmost region of the study area) compared to lineament data collected remotely indicates a disparity between the two methods. Lineament data collected from remote analysis of LiDAR (figure 4.1a) indicates a strong major orientation of NW-SE oriented lineaments, and a secondary SW-NE orientation of lineaments. Field mapping (figure 4.1b) found a major WNW-ESE orientation with a secondary NE-SE orientation.

A comparison of the two stereonet (figure 4.1) points to a possible discrepancy between field-based mapping and the remote analysis of LiDAR. Held (2014) also found a discrepancy between lineaments collected remotely and data from planar features found in the field.

To understand the difference, a study of scale-based mapping was undertaken. Since field-based mapping involved the mapping of planar surfaces accessible in the field, it might be assumed that larger planar features would be weighted differently in mapping. These larger planar features may appear more frequently through remote analysis, while small scale planar features would be overlooked. One possible explanation for the differences between the two data sets may be that smaller orientation trends are not as easily registered through remote analysis as they are in the field. This could explain the large WNW-ESE. orientation trend found in the field, and the apparent lack of such a trend in the LiDAR.

Scale-based mapping was accomplished by remapping the Mt. Chocorua peak where field-based mapping occurred. The second pass at lineament mapping occurred at a smaller scale, between 1:2,000 and 1:3,000 as opposed to the 1:12,000 and 1:13,000 scale which all other lineament mapping occurred. Lineament mapping efforts at a larger scale and small scale reveal the registration of different lineament orientation trends (figure 4.4). Small-scale lineament collection exhibit two orientation trends (described above and represented in the rose diagram in figure 4.4 a, and 4.4c), while large scale lineament collection in the same region displays a dominant major trend of a SW-NE orientation with a minor NW-SE orientation. The two data sets reveal a disparity based on scale of lineament mapping.

Figure 4.1 Rose plots of data collected from the peak of Mt. Chocorua a) lineament data obtained from LiDAR, b) field-based strike and dip data.

Age	Major	Secondary	Minor*	Minor*
Jurassic	NE-SW	WNW-ESE	ENE-WSW	NNW-SSE
Silurian	NE-SW	WNW-ESE	NW-SE	
Devonian	NE-SW	WNW-ESE	NNW-SSE	
Cretaceous	NW-SE	NE-SW		

Table 4.1 Lineaments classified by age of hostrock with orientations trends classified into major, secondary and minor categories, if applicable. *Note that the two minor categories are only used for Jurassic trend classification, and hold equal weight in terms of orientation trend prevalence.

Figure 4.2 Lineament mapping of bedrock units a. Jurassic, b. Silurian, c. Devonian, d. Cretaceous. Simplified from formation units (figure 3.19).

Figure 4.3 Bedrock units of Lyons et al., 1997 simplified by age (Jurassic, Silurian, Devonian, Cretaceous) and overlain by mapped lineaments (red lines).

Figure 4.4. Scale based mapping of Mt. Chocorua. a-c) mapping of lineaments at a scale range of 1:2,000-3,000, d-f) mapping of lineaments at a scale range of 1:13,000-15,000.

4.3 Swift River terrace age mapping

Instances of fluvial change are recorded in the floodplain of the Swift River. Three terrace elevations and three down cutting events (risers) illustrate three periods of incision and three stages of base level lowering. Through elevation mapping relative to the active channel, polygon delineation (figure 4.6 a and b) and transect analysis (figure 4.5) it was possible to discern events responsible for the present LiDAR signature of the swift river valley.

Figure 4.5 Elevation profiles along the Swift River annotated with designations between terraces (T1-3), the active channel (Fac), downcutting features -- risers (R1-3), as well as correlative guides between terrace elevations (dotted segments).

Figure 4.6 Fluvial mapping of a section of the Swift River in the northern region of study area: a) polygon interpretation of terraces within floodplain, terrace 1 being the lowest and youngest, terrace 3 highest the oldest, b) a DEM normalized along the elevation plane of the active Swift River using the Global Polynomial Interpolation Tool, c) bare hillshade of region indicating patterns of fluvial dynamics evident in the LiDAR.

Evidence for Glacial Lake Pigwacket

Goldthwait (1950)'s surficial map of New Hampshire provides the last state-wide surficial mapping effort. 7.5 minute quadrangles from around the study region in both New Hampshire and Maine were used to construct a more recent understanding of surficial geology (figure 4.7). No recent surficial information exists for the study area -- contained within the Mt. Tripyramid and Mt. Chocorua 7.5 quadrangles. The closest surficial maps to the study area exist for land to the northeast: the North Conway West, and North Conway East quadrangles (Nelson and Goldsmith, 2000). In addition, the Fryeburg 7.5 minute quadrangle (Thompson, 2014) and the Brownfield 7.5 minute quadrangle (Davis and Holland, 1997) surficial maps provide information for the Maine side of the White Mountains.

The Swift River which flows through the northernmost section of the study region (controlled by landscape units Fac, Ffp and Fal), extends into the southwest corner of the North Conway West 7.5 minute surficial map (Nelson and Goldsmith, 2000). The river is surrounded by two surficial units: Qalf and Qlps. Qalf contains alluvial fan deposits dated to either the Pleistocene or Holocene. Qalf units are poorly sorted, sand gravel grading to sand, deposited by on mountain slopes by late-glacial streams. The unit also represents Pleistocene, poorly to well sorted, stratified sand, silt and gravel. The second interpretation of the unit indicates glacial lakes as the mechanism for deposition, or glacial streams. Qlps is a unit representing the Conway stage of Glacial Lake Pigwacket (Nelson and Goldsmith, 2000). Qlps is one of six glaciolacustrine deposits representing Glacial Lake Pigwacket (Qlpr, Qlpe, Qlpb, Qlph and Qlpc). Deposits contain fluvial and lake-bottom silt and sand from the lake. Lake level of Pigwacket was controlled by an ice dam to the southeast initially, and then by residual ice and till deposits with the northern migration of the ice during deglaciation. During the Conway Stage of Lake Pigwacket, lake level was controlled by a till barrier to the East (in North Conway East).

Evidence for Glacial Lake Pigwacket is present in the North Conway East, The Fryeburg and the Brownfield 7.5 minute quadrangles (figure 4.7). Qlpf and Qlpc are present in the North Conway East quadrangle. These deposits reflect the Conway Stage and the Fryeburg Stage of Glacial Lake Pigwacket. Deposits indicate that the Conway Stage had a lake level of 15-20 feet (4.5-6 meters) higher than the Fryeburg Stage. Lake level during the Fryeburg state is determined to be around 435 feet, while lake level during the Conway Stage is determined to be around 450 feet (Nelson and Goldsmith, 2000). Lake Pigwacket deposits are also mapped in the Brownfield and Fryeburg quadrangles (Thompson, 2014). Units Plpb, Plpf, Plpk, Plpp, Plpo and Plo represent stages of the glacial lake deposits. Plpb is similar to the lake bottom sediment units mapped by Nelson and Goldsmith (2000) -- contained with Qlps. Plpf represents the Fryeburg stage, mapped as the Qlpf by Nelson and Goldsmith (2000). Other deposits reflect evidence for the glacial lake in the Kerzer Valley (plpk), Pleasant Mountain (Plpp), Oak Hill (Plpo). Plp represents undifferentiated deposits (Thompson, 2014). Evidence for Glacial Lake Pigwacket is also found in the Brownfield quadrangle (David and Holland, 1997). Units consistent with Thompson (2014) are Plpb, Plp, Plpf, and Plpo.

The two stages which effected surficial geology closest to the Swift River were the Conway and Fryeburg stages at 45 feet (137 meters) and 400-420 feet (121-128 meters) respectively (Thompson, 1999, Davis and Holland, 1997). These elevations are derived from deposit elevations in the Saco River Valley to the East of the Swift River. Deposits around the Swift River, Qalf and Qlps are present at elevations of 1000-1500 feet and <1000 feet respectively.

The Swift River floodplain in the study area has an minimum elevation of around 1115.5 feet (340 meters) and maximum elevation of around 1328.7 feet (405 meters) (figure 4.9). These changes in

floodplain level are correlated to position along the floodplain. The floodplain is oriented at a gradient, sloping towards the east, as seen in a DEM overlay of a shaded relief map (figure 4.9). The lowest elevation is found at the easternmost point along the floodplain, whereas the highest point on the floodplain is found at the westernmost point. Changes in floodplain elevation are also evident in transects taken at various stages along the Swift River (figure 4.11). Transects along the river indicate a maximum depth (the active channel, Fac) which decreases eastward along the Swift River. The Swift River has a depth of <1000 feet in the North Conway East 7.5 minute Quadrangle (Nelson and Goldsmith, 2000).

Given these changes to elevation, correlating the presence of surficial units from Nelson and Goldsmith (2000) to units found in the study area is more difficult. Alluvial fans in the study region (figure 4.12) are

Figure 4.7 Surficial mapping in the S. White Mountain region. Aside from Goldthwait (1950)'s surficial map of New Hampshire, no state-wide mapping effort has been completed. Grey 7.5 quadrangle tiles (Mt. Tripyramid and Mt. Chocorua) contain the study region, and do not have completed surficial maps, blue 7.5 minute quadrangle tiles do not contain surficial maps in digital or accessible formats, red 7.5 minute quadrangle tiles have surficial mapping accessible in either digital or non-digital formats.

found at a maximum elevation of around 1384 feet (422 meters). These elevations are present at a similar elevation as the alluvial fan deposits from the North Conway West quadrangle, which reside between 1000 and 1500 feet. It is possible that the alluvial fan unit of Nelson and Goldsmith (2000), Qalf, could be expanded to regions of the Swift River in the study area. The units mapped in the landscape classification map as alluvial fans (Faf), could therefore be deposits of Qalf. Field checking and extensive surficial mapping would be needed to verify a correlation of the two units.

The Conway stage deposit of Lake Pigwacket present around the Swift River, Qlps, is found at elevations <1000 feet in the North Conway West quadrangle map (Nelson and Goldsmith, 2000). It falls in the flattened floodplain region of the map. This map unit could be extended to the the landscape unit for the study region, Ffp. Due to changes in elevation, the floodplain landscape unit is present at elevations between >1000 to <1500 feet. Although Qlps is found at elevations <1000 feet in the North Conway West quadrangle map, it is possible that the unit could be extended to the study region and the unit Ffp. However, like a possible correlation between Qalf and Qaf, the correlation between Qlps and Qfp is not possible without extensive surficial mapping.

Should it be found that there was a similarity between surficial units in the study region around the Swift River and the units mapped not only by Nelson and Goldsmith (2000) but also by Thompson (2014) and Davis and Holland (1997), it may be possible to understand how the lake lowering events of Glacial Like Pigwacket effected the glacial and fluvial controlled regions around the Swift River in the study area. Surficial mapping of the Mount Chocorua and Mount Tripynamid 7.5 minute quadrangles is clearly necessary.

Figure 4.9 Elevation of Swift River Floodplain in the southern region of study area. Floodplain grades down from west to east.

Figure 4.10 Fluvial landscape unit for alluvial fan, Faf, overlain on a shaded relief image. Alluvial fans in the study region are found at elevations between 1000 and 1500 feet, and can be compared to the Nelson and Goldsmith unit, Qalf.

Figure 4.11 Transects across the swift river from east to west. a) Transect from a western region of the Swift River floodplain, b) transect from a central region of the Swift River floodplain, c) transect from a eastern region of the Swift River. Maximum depth along transect (red) indicates the position of the active channel. Channel depth increases from east to west indicating a downsloping river gradient.

4.4 Glacial analysis

4.4.2 Glacial flow indicators

LiDAR expressions of glacial flow were present in the study area and the adjoining region. Given the scope of this research project, the original swath of LiDAR collected by the NRCS was refined into a smaller study area, as mentioned in Chapter 3. However, glacial flow indicators were more prevalent in the initial, larger region, and therefore glacial flow mapping took place on a larger scale than other mapping efforts undertaken in the rest of the study.

Glacial flow direction was interpreted from a series of linear features, classified as glacial striae. These features exhibit lineaments in a parallel pattern in regions of bedrock overlain by shallow surficial geology (interpreted to be till). Mapping of these features was accomplished through the same methods applied to lineament mapping taken from Mabee et al. (1994).

The LiDAR signature and classification of glacial striae was derived from a grouping of recent literature regarding remote glacial analysis through LiDAR (Dyess and Hansen, 2014; Kovanen and Slaymaker, 2004; Przybylski, 2008; Kalm, 2012; Greenwood and Clark, 2009; Smith et al., 2006; Wright, 2015; Livingstone et al., 2010; Peterson and Smith, 2014.).

Smith and Peterson, (2014) classify the feature as “glacially lineated landscapes” (figure 4.12a). Livingstone et al., (2010) describe a similar landscape as “strongly lineated glacial terrain” (figure 4.12b), Smith et al., 2006 classify a set of lidar features as crag and tail “a linear, generally ovate landform consisting of a bedrock hill and an attached ridge of less resistant rock (either superficial deposit or bedrock, or both)” (figure 4.12c). Sherrod et al., (2004) characterize the unit: “exposed late Quaternary glacial sediments (till, sand, and gravel-filled channels) deposited by last-glacial ice sheets” and deformation patterns within consistent with glacial ice flow (figure 4.1d). Kovanen and Slaymaker, (2004) classify the units as lineations (figure 4.12e). And Dyess and Hansen (2014) classify the unit as lineaments as part of a “surficial geomorphic fabric controlled dominantly by glaciation and erosion” (figure 4.13f). These features are comparable to features found in the study area (figure 4.9a-f). All examples, both from the study area and those found in the literature, exhibit a strong linear orientation of parallel features. These linear features are present in regions of bedrock overlain by deformed sedimentary cover. From the comparison between features present in the study area and features present in the literature, it is possible to conclude that the presence and relative orientation of said features signifies glacial erosion. The orientation of linear striae indicates flow direction during glaciation.

Based on flow direction of glacial striae found in the study area, as well as glacial flow mapped by Goldthwait et al., (1938) it is then possible to extrapolate a flow direction (figures 4.13, 4.14, 4.15). Linear striae were used in the creation of a glacial flow map (figure 4.15). This map includes a portion of the study area not classified other places in the study, but the same methods for landscape classification were assumed while signifying glacial flow direction. Lineaments were only drawn in glacially controlled regions to ensure that bedrock lineaments were not used in the analysis.

The orientation of glacial striae indicates glacial flow at both a localized scale and a regional scale. Topographic differences in the region, ie. the presence of high peaks, control the orientation of glacial striae. During glaciation, ice flow would orient around high topographic features differently than low topography. These changes are evident in flow direction diversion trending parallel to high topographic features. Regionally, there is a strong correlation of flow indicated by a NNW-SSE orientation of striae

lineaments.

The orientation of glacial flow indicators reflects patterns of glaciation mapped elsewhere in the White Mountain region, and broader New England. During quaternary glaciation, as the Laurentide Ice sheet grew to reach its glacial maximum, ice flowed in a SE direction across New England. Based on the presence and orientation of glacial flow indicators in the study area, it may be inferred that these represent phases of ice advance aligned with the LIS.

Figure 4.12 Glacial striae features present in western region of the greater study area. Found in regions of glacial control, look to involve the interaction of surficial cover and scoured bedrock. Linear quality of striae are oriented parallel relative to others in the same region, and often reflect localized topographic environment. While the dominant trend of flow direction indicators in the study region exhibits a SE flow direction (a,b,e,f) other reflect diversion around high peaks (c,d). The relative orientations of flow direction in the western extent of the greater study region are present in figure.

Figure 4.13 Glacial flow direction in western extent of greater study area. Glacial striae (red lineaments) reveal both regional trends of glacial flow and localized glacial flow indicative of topographic conditions during glaciation. Orientation of SE-NW lineaments reflect regional ice flow to the southwest, while the more E-W orientation of lineaments reflects localized variations as a result of higher topographic features to the north and south.

Figure 4.14 Flow direction map generated with glacial striae present in the western section of the greater study area and Goldthwait's 1938, Surficial Geology of New Hampshire Map, georeferenced to LiDAR of eastern study region. Flow direction indicators from Goldthwait (black arrows) indicate SE and SSE orientation of glacial flow. Glacial flow interpreted by blue arrows, in a general SE direction with localized variations.

Figure 4.15 Simplified glacial flow direction map derived from glacial striae and flow direction indicators from Goldthwait et al., (1938).

Figure 4.16 Flow direction features found in the literature a) Smither and Peterson, 2014 flow direction oriented east to west, b) Livingstone et al., 2010, flow direction to the southwest, c) Smith et al., 2016, flow direction to the southeast, d) Sherrod et al., 2004, flow direction to the southwest, e) Kovanen and Slaymaker, 2004, flow direction to the west-southwest, f) Dyess and Hansen, 2014, flow direction to the south-southwest.

4.4.3 Evidence of deglaciation

Syverson and Mickelson, (2008), study lateral meltwater channels (sometimes called ice-marginal channels) formed (and forming) during the modern deglaciation of Burroughs Glacier, in Glacier Bay National Park, Alaska (figure 4.17a, b). This contemporary deglaciation can be used as a modern proxy to better understand the deglaciation of New Hampshire. Lateral meltwater channels form parallel to topography and therefore parallel to the former ice margin. In periods of stagnation, or limited ice recession, erosion occurs along the ice margin within exposed cover. This erosion leads to the formation of lateral meltwater channels. The orientation and elevation of these features may be used to infer the stages of ice extent during deglaciation (Syverson and Mickelson, 2008; Mickelson, 2007; Atkins and Dickinson, 2007).

Several locations within the Sandwich Range study area contained wide channel networks parallel to topography. These features--classified as meltwater channels--were found within glacially-controlled regions, between high-elevation bedrock regions and lower-elevation fluvial regions. The most expansive example of meltwater channels were found in the SW corner of the study area. Elevation data, obtained from the original LiDAR DEMs, were used to classify meltwater channels. These elevations were normalized along a synthetic elevation plane parallel to the floor of meltwater channels. As a result, localized elevation gradients did not impact reconstruction of ice extent (figure 4.19).

The meltwater channel network present in the SW corner was found to contain five channels (figure 4.20f). These channels represent five stages of deglaciation in the region. The oldest channel -- highest elevation -- represents the first point from which ice extent may be modeled (figure 4.20a). This elevation frequently coincides with the contact between glacial and bedrock control. Four more channels at decreasing elevations are present in this complex (figure 4.20b-e). Modern fluvial outwash dissects the lowest elevation plane in some regions (figure 4.20e). As the ice sheet melted and thinned, meltwater channels formed at decreasing elevations.

The SW complex of meltwater channels is useful in terms of understanding ice extent dynamics on a localized scale, but can also be applied to the larger study region. Just as it was possible to normalize the elevation along a single meltwater channel, it was also possible to use the same technique to relate two meltwater channels across complex divides. Elevation values from the highest meltwater channel in the SW were used in combination with elevations from the highest channel in the SE corner to create a false elevation plane across the study area. Figure 4.21 represents ice extent in the southern region of the study area. Meltwater channels in the SW corner contain similar elevation trends to channels in the SE corner. Both complexes exhibit lowering events, although the SW corner has a larger vertical gradient and has a great number of channels. Ice extent (figure 4.21a-e) initially dominates all expect bedrock controlled region.

Ice extent positions were modeled across the entire study region through the correlation of meltwater channels on in the SW, SE and NE corners. Meltwater channel complexes in these three locations provided elevations for deglaciation stages. Meltwater channel networks reveal five stages of deglaciation (figure 4.22). Time-slice mapping of the entire study region demonstrates lowering ice extent, from all but bedrock exposed regions (figure 4.22a) to an almost ice-free study region (figure 4.22e).

Because elevations were normalized parallel to meltwater channels, elevation values do not provide exact elevations of deglaciation. They instead represent respective elevation differences in the study area. Therefore, elevations in figures 4.20-4.22 are not homogenous, and are sometimes negative. Time slice mapping through the correlation of meltwater channel complexes was based on the assumption that rates

and elevations of decreasing ice extent were homogenous through the entire study area. Deglaciation of the White Mountains involved the recession of glacial margins towards valley centers (Goldthwait, 1938; Thompson, 1999; Balco and Schaefer, 2006; Balco et al., 2009; Bromley et al., 2015). It was therefore assumed that regions conducive to the formation of meltwater channels would reflect a time-elevation correlation.

Model for deglaciation: active ice retreat vs. stagnation zone retreat

The position of lateral meltwater channels on the South side of the Sandwich Range Mountains do not support the theory of large scale, active ice deglaciation across New England during the Younger Dryas warming period. Instead, the presence of meltwater channels indicates valley-down deglaciation of dead ice. A dead ice model for deglaciation implies that as a result of deglaciation, large masses of ice would detach from the active glacier and melt in a downward direction. The orientation of meltwater channels in the study area implies that deglaciation occurred in stages from higher elevations to the valley floor -- controlled by modern fluvial interaction with surficial topography. As ice melted, lateral meltwater channels would form off of ice marginal contact with topographic feature. During stages of melting, ice margin position would move downslope. Phases of downslope melting are recorded by the positions of meltwater channel in several regions in the study area. However, the presence of lateral meltwater channels does not

Figure 4.17 a) Lateral meltwater channels identified by Syverson and Mickelson, 2008, b) a diagram of in-and-out channels also from Syverson and Mickelson, 2008. Both the meltwater channels and the in-and-out channels reveal characteristics of the meltwater channels present in the study area.

figure 4.18 . Model for meltwater channel formation as a result of deglaciation. Meltwater channels (M1-M4) form as ice front (IF1-IF4) lower. Meltwater channels in exhibit a dipped topographic relief, due time-dependent erosion.

Figure 4.19. Normalized elevation along meltwater channels (parallel to topography) -- see methods and the Global Polynomial Interpolation tool. Profiles reveal six meltwater channels along transects (T1, T2, T3).

Figure 4.20 Time slice map of glacial extent constructed from meltwater channels in the SW corner of study region (green box featured in location map). Elevation of meltwater channels used as indicators of glacial retreat elevations downvalley to the south. Stages of deglaciation in a-e, and represented as a single series in f. Elevations are relative to lateral channels and do not indicate actual elevation of features.

Figure 4.22 Timeslice map of ice extent of entire study region from a correlation of three complex of meltwater channels: in the SW, SE and NE corners.

4.4.4 Glacial lakes

Held (2014) proposed the presence of Glacial Lake Swift in the floodplain of the Swift River valley (contained within the study area.) His study of LiDAR to the southwest indicated the presence of an earlier lake, Glacial Lake Sawyer, which occurred due to the presence of two ice dams--one located at the western end of the Swift River valley in the study region (Held, 2014). As deglaciation progressed, these ice dams melted and the lake drained to the NE and SE. The SE draining of the lake caused the formation of Glacial Lake Swift (figure 4.23). Held proposes a second ice dam at the eastern end of the Swift River which dammed the Glacial Lake Swift for a period. Based on the paleoshoreline proposed by Held (2014), Glacial Lake Swift would have reached a maximum elevation of 383 meters.

Should Held (2014) be correct in the positioning of a glacial ice dam at the eastern region of the study area, and the occurrence of Glacial Lake Swift, the glacial deposits (Qalf and Qlps) mapped by Nelson and Goldsmith (2000) could represent subsequent stages of deglaciation, after the draining of Glacial Lake Swift. Lake Pigwacket--which resides to the east of the proposed glacial lakes Sawyer and Swift, could be a younger glacial lake than glacial lakes Swift and Sawyer.

Lateral meltwater channels discussed in section 4.4.3 are evidence of down-valley deglaciation. Glacial outwash terraces found in Glacial Lake Sawyer are a second form of evidence of this style of deglaciation in the Swift River Valley. The ice which remained in valleys during deglaciation of the Laurentide Ice Sheet from the White Mountains would melt from high elevations initially, and from lower elevations regions in the following stages of melting. The model for deglaciation from high regions, down through the Swift River proposed by Held (2014) is supported by the presence of glacial outwash terraces and lateral meltwater channels.

Figure 4.23 Model for the existence of Glacial Lake Sawyer, and an ice filled Swift River Valley proposed by Held (2014). Ice dams to the south and north of Glacial Lake Sawyer, which recede and allow Glacial Lake Sawyer to drain into the Swift River Valley. Ice dams downriver create Glacial Lake Swift which occupies the Swift River Valley in the study region. Figures modified from Held (2014).

The model proposed by Held (2014) of deglaciation for the Swift River Valley has implications for deglaciation to the south of the Swift River floodplain--outside of Held's study area. Glacial Lake Swift reached a maximum elevation of 554 meters, as derived from terrace elevations in the region once occupied by the glacial lake (Held, 2014). By imposing the ice model which extended over the subsequent Glacial Lake Swift, it is possible to examine other regions once occupied by water at the time of Glacial Lake Sawyer. Valley floodplains to the south of the Swift River, and the proposed Glacial Lake Swift, and mapped in figure 3.3 as having evidence of surface water (Fwe), may now be interpreted as glacially dammed lakes (figure 4.25).

Glacially dammed lakes to the south of the Swift River, all exhibit a wide and smoothed floodplain with modern fluvial erosion in the center. These regions, as mentioned above, are classified as Fwe due to the flat and smoothed texture they exhibit. Also, these regions have a consistent elevation profile, and are surrounded by units of glacially dissected till. In all cases, there is a natural barrier between portions of the proposed glacial lakes and the floodplain. Water in the glacial lakes would be isolated by the presence of a glacial dam in the Swift River, and reissue behind both surficial and ice barriers.

In a model for ice extent and glacial lakes during Glacial Lake Sawyer (figure 4.25), a maximum ice extent is mapped as >475 meters, and glacial lakes are mapped at elevations between 475 and 530 meters. Elevations for the two model components are based on landscape classification mapping units, and the dissected till-bedrock contacts (figure 4.25). As ice receded downvalley, water from the glacial lakes would flow down into the Swift River Valley--into the proposed Glacial Lake Swift.

Glacial outwash terraces occur on the western side The Foot Killer and Mount Tripyramid, along Sabbaday Brook, similar to those present in Held (2014). Terraces are present at four elevation ranges, symbolized by their maximum elevation (figure 4.26). Changes in elevation along terrace are believed to be caused by localized changes in topography. Terraces are symbolized by their maximum elevation: T_1 at 480 meters, T_2 at 485 meters, T_3 at 490 meters and T_4 at 495 meters. Lowering water level would caused erosion at lowering elevations. The collection of four terrace elevations in this location reflect four episodes of base level lowering.

Figure 4.24 Ice extent during Glacial Lake Sawyer (Held, 2014) to the west. Ice margins were modified from Held (2014), and placed at 475 meters to account of topographic changes along the Swift River.

Figure 4.25 model for ice extent during the period of proposed Glacial Lake Sawyer (Held, 2014). Ice extent model mapped below elevations of 475 meters, represented by white with blue dots. Glacially dammed lakes which occurred contemporaneous to Glacial Lake Sawyer are present at elevations between 530 and 475 meters, represented by blue polygons with a 30% transparency.

Figure 4.26 Glacial outwash terraces on the western side of Sabbaday Brook, with Mt. Tripyramid and The Foot Killer to the west and Potash Mountain to the east. Terraces occur at four elevations, symbolized as color polygons on a shaded relief map and as T₁ through T₄ on the transect drawn from west to east across the terraces on a digital elevation model.

Figure 4.27 Glacial outwash terraces may be used to establish a model for lake drainage during down-valley glacial retreat. Glacial lakes (blue) lower as ice (white, dots) retreat. Terraces represent periods of ice positioning and lower lake level elevations.

4.5 Feature verification

For this purposes of this study, and future applications of LiDAR for geomorphic mapping, it is important to ground the identification and classification of landscape units in other studies of similar focus. The methods used to classify landscape units developed by Haugerud et al., (2003), are useful for grouping understanding large geomorphic trends, however they are lacking in small-scale identification of individual features. Once a unit or feature is identified it can be classified, therefore it is necessary to perform a comparative analysis on features present in the study area with features in other regions.

Peterson and Smith (2013) have developed a legend for the geomorphic landscape units of Sweden. While not all units are relevant to the study, there are clear similarities by several of the units. Like New England and the Laurentide Ice Sheet, Sweden's landscape has been shaped by glaciation and deglaciation of the Fennoscandian Ice Sheets. Similar glacial and glaciofluvial landscapes and landforms are present in the study region of this project and regions mapped by Peterson and Smith. Figure 4.28 provides a comparison between landscape units and landforms present in the study area (left column, A, C, E, G) and legend items from Peterson and Smith, 2013 (right column, B, D, F, H).

Peterson and Smith classify figure 4.28b as kettle holes. Kettles holes indicate deglaciation in glacial sediments. Their presence in the study region add to evidence of deglaciation already supported by meltwater channels, moraines and eskers. The same texture of rounded depression is classified as kettle holes by Salcher et al., 2010 and Burke et al., 2015. Based on comparisons of LiDAR-derived imagery, it is concluded that the regions of the study area which display the circular depression pattern symbolized in figure 4.28a contain kettle holes and are therefore representative of deglaciation.

The linear feature pictured in figure 4.28c displays similar qualities to esker features classified by Peterson and Smith, (2013). Similar classifications of the feature appear in Gallagher and Balme, 2015 -- also classifying the linear features as eskers. Eskers indicate ice recessional environments, and are present at several locations in the study region. The landscape unit of glacial linear feature (landscape classification map, figure 3.3), can therefore be subdivided into eskers and moraines -- depending on the orientation and relative position of the feature to deglaciation.

The landscape unit named hummocky till (landscape classification map, figure 3.3) fits in terms of classification and topographic signatures across designations in other geomorphic studies with LiDAR (Gallagher and Balme, 2015, Dowling et al., 2015, Desiage et al., 2015). Hummocky till exhibits a rounded and texture signature in processed LiDAR imagery. Raised features within the landscape unit are raised slightly, and uniformly spaced.

Figure 4.28g is one example of a linear glacial feature with a strong directional orientation and pattern of a point feature transitioning into a linear line. All linear features are oriented in the same direction. This feature reoccurs of the study area, but it is difficult to classify the region because it displays both sub-features of bedrock texture and surficial signatures. Peterson and Smith, 2013, classify a similar-looking unit as craig and tail, and associate the feature with glacial flow. However, craig and tail examples in classified LiDAR often have a more pronounced difference between the rounded head unit and the streamline tail. Like the crag and tail units of Peterson and Smith, the units have a linear component with parallel orientations. The two images seem to compare differing amounts of surficial material. This difference could explain differing elements of the two features.

Figure 4.28. Lidar comparison between features present in the study area (left column, A, C, E, G) and previously studied and mapped units presented in Peterson and Smith, 2013 (right column, B, D, F, H). A. Waterville River Valley featuring rounded indentations in surficial geology. B. Similar indentation topography from A. classified as kettle holes in Peterson and Smith, 2013. C. a curved feature mapped as a linear feature in landscape classification map (figure 3.3). D. Similar linear feature classified as an esker in Peterson and Smith, 2013. E. Glacial control unit of hummocky tilly present in landscape classification map. F. Topography classified as hummocky till by Peterson and Smith, 2013. G. Linear features with patterned surficial. H. Similar feature classified as Crag and tails, indicative of ice flow direction.

5. Conclusion

5.1 Remote analysis findings

From processed LiDAR from the Sandwich Region of the White Mountain National Forest this study produced a series of maps and GIS-based analysis through the processes of remote analysis and targeted field checking. The goal of this study was to understand how past tectonic and glacial, and modern fluvial regimes have deformed and shaped the landscape presented in the LiDAR. Through the use of shaded relief maps, digital elevation models, and a series of GIS 3D and spatial analysis tools this was possible. Broadly, the components of this study are broken down into four regions of study: landscape classification mapping, bedrock, glacial and fluvial analysis.

5.1.1 Landscape classification mapping

Modeled on LiDAR-derived geomorphic mapping by Haugerud et al., (2003) and Haugerud (2009), a landscape classification map was produced with 15 landscape control units. Bedrock controlled regions (BR) occupied 31.4% of the study area. Bedrock controlled regions were subdivided into exposed (BRe) and non-exposed (BRc) units. Fluvial controlled regions occupied (F) occupied 11.1% of the study region and were subdivided into six categories: the active channel (Fac), alluvial fans (Faf), floodplain (Ffp), terraces (Ft), confined surface water (Fsw), extinct water depressions (Few). Glacial controlled regions (G) occupied the remaining 57.5% of the study area and were subdivided into: boulders (Gb), dissected till (Gds), hummocky till (Ght), linear features (Glf), meltwater (Gmw), meltwater channels (Gmwc), non-dissected till (Gnds).

5.1.2 Bedrock mapping

Lineament data revealed several classifications of orientation. Two major orientations trends with orientations NE-SW and WNW-ESE were found in bedrock controlled regions. When lineaments were classified by age, it was found that Jurassic-age lineaments in igneous intrusive formations (the Conway Granite and the Mount Osceola Granite) exhibited a more homogenous structural fabric while older Silurian and Devonian bedrock exhibited a more anisotropic pattern. These differences in lineament orientation patterns illustrate more complex tectonic fabric in older Silurian and Devonian formations and a more homogenous tectonic fabric in younger Jurassic formations. The trend of lineament orientations suggests a possible correlation to stress and strain regimes during the tectonic history of the study region.

5.1.3 Fluvial mapping

Fluvial mapping was targeted around the Swift River in the southernmost region of the study area. The Swift River study area contained alluvial fans, a floodplain, several terrace elevations, and an active channel. Elevation mapping with the use of transects and digital elevation models revealed three terraces elevations and three downcutting events. While no surficial mapping beyond Goldthwait et al., (1950) exists for the Swift River contained within the study region, glacial deposits from Glacial Lake Pigwacket exist along the Swift downstream and to the east of the study region in the North Conway West quadrangle (Nelson and Goldsmith, 2000). Given the decreasing elevation of the Swift River floodplain and active channel within the study area, it is possible to assume that these units, Qalf and Qlps, correlate with Faf and Ffp, respectively.

5.1.4 Glacial mapping

The majority of glacial control in the study region was dominated by hummocky till, dissected till and non-dissected till. These units are evidence of glaciation and deglaciation during the Quaternary. Meltwater channels are found in three locations in the study area, and are orientated parallel to topography. LiDAR signatures of lateral meltwater channels mapped by Syverson and Mickelson (2008) were used to identify the landscape units of Gmwc and Gmw. Lateral meltwater channels form parallel to topography and are caused by downvalley recessions of glacial ice. Collections of meltwater channels in the study area indicate four to five stages of glacial recession during deglaciation. Downvalley glacial recession is further supported by the presence of glacial outwash terraces and the proposal of four glacial lakes on the southern side of the Swift River. These glacial lakes occurred due to ice extent in the Swift River region, effectively trapping water in mountain valleys.

5.2 Future work

Remote analysis of the study area with LiDAR imagery revealed a landscape controlled by complex tectonic, glacial and modern fluvial regimes. Future work is needed to both confirm the validity of remote analysis interpretations and also to apply findings in a more concrete way. Field checking in targeted regions of control groups would confirm landscape units beyond their current classification based on signatures in LiDAR imagery. Age dating of meltwater channels and of terrace elevations is also necessary for purposes of glacial and surficial reconstruction. In addition, surficial mapping of the entire study region is needed.

Bibliography

- Atkins, C. B., and Dickinson, W. W., 2007, Landscape modification by meltwater channels at margins of cold-based glaciers, Dry Valleys, Antarctica: *Boreas*, v. 36, no. 1, p. 47-55.
- Balco, G., Briner, J., Finkel, R. C., Rayburn, J. A., Ridge, J. C., and Schaefer, J. M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: *Quaternary Geochronology*, v. 4, no. 2, p. 93-107.
- Bradley, D. C., 1981, Late Wisconsinan Mountain Glaciation in the Northern Presidential Range, New Hampshire: *Arctic and Alpine Research*, v. 13, no. 3, p. 319-327.
- Bromley, G. R. M., Hall, B. L., Thompson, W. B., Kaplan, M. R., Garcia, J. L., and Schaefer, J. M., 2015, Late glacial fluctuations of the Laurentide ice sheet in the White Mountains of Maine and New Hampshire, USA: *Quaternary Research*, v. 83, no. 3, p. 522-530.
- Creasy, J. W., and Eby, G. N., 1993, Ring dikes and plutons: A deeper view of calderas as illustrated by the White Mountain igneous province, New Hampshire: *Field Trip Guidebook for the Northeastern United States*: Amherst, Massachusetts, Department of Geology and Geography, University of Massachusetts, Contribution, no. 67, p. N1-N25.
- Davis, P. T., Holland, W. R., 1997, Brownfield Quadrangle, Maine: Department of Conservation: Maine Geological Survey, scale 1: 24,000.
- DeKett, R. G., Long, R.F., Philippe, J., 2015, Natural Resource Conservation Service of the U.S. Department of Agriculture, St. Johnsbury, VT.
- Desiège, P.-A., Lajeunesse, P., St-Onge, G., Normandeau, A., Ledoux, G., Guyard, H., and Pienitz, R., 2015, Deglacial and postglacial evolution of the Pingualuit Crater Lake basin, northern Québec (Canada): *Geomorphology*, v. 248, p. 327-343.
- Dorais, M. J., 2003, The petrogenesis and emplacement of the New Hampshire plutonic suite: *American Journal of Science*, v. 303, no. 5, p. 447-487.
- Dowling, T. P. F., Spagnolo, M., and Möller, P., 2015, Morphometry and core type of streamlined bedforms in southern Sweden from high resolution LiDAR: *Geomorphology*, v. 236, p. 54-63.
- Dyess, J., and Hansen, V. L., 2014, Application of Lidar to resolving tectonic and glacial fabrics in glaciated terrain: An example from an Archean granite-greenstone belt, northeastern Minnesota: *Geosphere*, v. 10, no. 5, p. 987-997.
- Dyke, A. S., 1993, Landscapes of cold-centred Late Wisconsinan ice caps, Arctic Canada: *Progress in Physical Geography*, v. 17, no. 2, p. 223-247.
- Eby, G. N., Krueger, H. W., and Creasy, J. W., 1992, Geology, geochronology, and geochemistry of the White Mountain batholith, New Hampshire: *Geological Society of America Special Papers*, v. 268, p. 379-398.
- Eusden, J. D., Thompson, W. B., Fowler, B. K., Davis, P. T., Bothner, W. A., Boisvert, R. A., and Creasy, J. W., 2013, *The Geology of New Hampshire's White Mountains*, Durand Press, Lyme, NH.
- Eyles, N., Putkinen, N., Sookhan, S., and Arbelaez-Moreno, L., Erosional origin of drumlins and megaridges: *Sedimentary Geology*.
- Faure, S., Tremblay, A., and Angelier, J., 1996, Alleghanian paleostress reconstruction in the northern Appalachians: Intraplate deformation between Laurentia and Gondwana: *Geological Society of America Bulletin*, v. 108, no. 11, p. 1467-1480.
- Faure, S., Tremblay, A., Malo, M., and Angelier, J., 2006, Paleostress analysis of Atlantic crustal extension in the Quebec Appalachians: *The Journal of geology*, v. 114, no. 4, p. 435-448.
- Glasser, N. F., Glacial meltwater erosion and sedimentation as evidence for multiple glaciations in west Wales: *Boreas*, v. 33, no. 3, p. 224-237.
- Goldthwait, J. W., Goldthwait, R.P., Goldthwait, L., Louge, R.J., Meyers, T.R., Page, L.R., White, G.W., 1950, *Surficial Geology of New Hampshire*, scale 1:250,000.
- Greenwood, S. L., and Clark, C. D., 2009, Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics: *Quaternary Science Reviews*, v. 28, no. 27-28, p. 3101-3123.
- Greenwood, S. L., Clark, C. D., and Hughes, A. L. C., 2007, Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: Application to the British Ice Sheet: *Journal of Quaternary Science*, v. 22, no. 6, p. 637-645.

- Hardt, J., Hebenstreit, R., Lüthgens, C., and Böse, M., 2015, High-resolution mapping of ice-marginal landforms in the Barnim region, northeast Germany: *Geomorphology*, v. 250, p. 41-52.
- Hatcher, R. D., 2010, The Appalachian orogen: A brief summary: *Geological Society of America Memoirs*, v. 206, p. 1-19.
- Haugerud, R. A., 2009, Preliminary Geomorphic Map of the Kitsap Peninsula, Washington, 2009-1033.
- Hibbard, J. P., Van Staal, C. R., and Rankin, D. W., 2007, A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen: *American Journal of Science*, v. 307, no. 1, p. 23-45.
- , 2010, Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician-Permian: *Geological Society of America Memoirs*, v. 206, p. 51-69.
- Kalm, V., 2012, Ice-flow pattern and extent of the last Scandinavian Ice Sheet southeast of the Baltic Sea: *Quaternary Science Reviews*, v. 44, p. 51-59.
- Kleman, J., 1994, Preservation of landforms under ice sheets and ice caps: *Geomorphology*, v. 9, no. 1, p. 19-32.
- Koteff, C., and Pessl, F., 1985, Till stratigraphy in New Hampshire: correlations with adjacent New England and Quebec: *Geological Society of America Special Papers*, v. 197, p. 1-12.
- Kovanen, D. J., and Slaymaker, O., 2004, Relict Shorelines and Ice Flow Patterns of the Northern Puget Lowland From Lidar Data and Digital Terrain Modelling: *Geografiska Annaler: Series A, Physical Geography*, v. 86, no. 4, p. 385-400.
- Livingstone, S. J., Evans, D. J. A., and Ó Cofaigh, C., 2010, Re-advance of Scottish ice into the Solway Lowlands (Cumbria, UK) during the Main Late Devensian deglaciation: *Quaternary Science Reviews*, v. 29, no. 19-20, p. 2544-2570.
- Lyons, J. B., Bothner, W.A., Moench, R.H., and Thompson, J.B., Jr., 1997, Bedrock geologic map of New Hampshire: U.S. Geological Survey, scale 1: 250,000.
- Mabee, S. B., Hardcastle, K. C., and Wise, D. U., 1994, A Method of Collecting and Analyzing Lineaments for Regional Scale Fractured Bedrock Aquifer Studies: *Groundwater*, v. 32, no. 6, p. 884-894.
- Marzoli, A., Renne, P. R., Piccirillo, E. M., Ernesto, M., Bellieni, G., and Min, A. D., 1999, Extensive 200-Million-Year-Old Continental Flood Basalts of the Central Atlantic Magmatic Province: *Science*, v. 284, no. 5414, p. 616-618.
- McHone, J. G., and Butler, J. R., 1984, Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean: *Geological Society of America Bulletin*, v. 95, no. 7, p. 757-765.
- McHone, J. G., Ross, M. E., and Greenough, J. D., 1987, Mesozoic dyke swarms of eastern North America: Mafic dyke swarms. Edited by HC Halls and WF Fahrig. *Geological Association of Canada, Special Paper*, v. 34, p. 279-288.
- Moench, R. H., and Aleinikoff, J. N., Revised Middle Ordovician U-Pb age for the volcanic Clear Stream Member, NE New Hampshire: regional impact2001, Volume 33.
- Moench, R. H., and Aleinikoff, J. N., 2003, Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England: *Physics and Chemistry of the Earth, Parts A/B/C*, v. 28, no. 1, p. 113-160.
- Nelson, A. E., Goldsmith, R., 2000, Surficial Geologic Map of the North Conway East Quadrangle, Carroll County, New Hampshire: New Hampshire Department of Environmental Services, scale 1: 24,000.
- Pavlis, T. L., and Bruhn, R. L., 2011, Application of LIDAR to resolving bedrock structure in areas of poor exposure: An example from the STEEP study area, southern Alaska: *Geological Society of America Bulletin*, v. 123, no. 1-2, p. 206-217.
- Photo Science, Inc., 2012, White Mountain National Forest LiDAR metadata
- Przybylski, B., 2008, Geomorphic traces of a Weichselian ice stream in the Wielkopolska Lowland, western Poland: *Boreas*, v. 37, no. 2, p. 286-296.
- Ridge, J. C., 2004, The Quaternary glaciation of western New England with correlations to surrounding areas: *Developments in Quaternary Sciences*, v. 2, p. 169-199.
- Roden-Tice, M. K., Tice, S. J., and Schofield, I. S., 2000, Evidence for differential unroofing in the Adirondack Mountains, New York State, determined by apatite fission track thermochronology: *The Journal of geology*, v. 108, no. 2, p. 155-169.
- Roering, J. J., Mackey, B. H., Marshall, J. A., Sweeney, K. E., Deligne, N. I., Booth, A. M., Handwerger, A. L., and Cerovski-Darriau, C., 2013, 'You are HERE': Connecting the dots with airborne lidar for geomorphic fieldwork: *Geomorphology*, v. 200, p. 172-183.

- Salcher, B. C., Hinsch, R., and Wagreich, M., 2010, High-resolution mapping of glacial landforms in the North Alpine Foreland, Austria: *Geomorphology*, v. 122, no. 3–4, p. 283-293.
- Sherrod, B. L., Brocher, T. M., Weaver, C. S., Bucknam, R. C., Blakely, R. J., Kelsey, H. M., Nelson, A. R., and Haugerud, R., 2004, Holocene fault scarps near Tacoma, Washington, USA: *Geology*, v. 32, no. 1, p. 9-12.
- Smith, M. J., Rose, J., and Booth, S., 2006, Geomorphological mapping of glacial landforms from remotely sensed data: An evaluation of the principal data sources and an assessment of their quality: *Geomorphology*, v. 76, no. 1–2, p. 148-165.
- Syverson, K. M., and Mickelson, D. M., 2009, Origin and significance of lateral meltwater channels formed along a temperate glacier margin, Glacier Bay, Alaska: *Boreas*, v. 38, no. 1, p. 132-145.
- Tarolli, P., 2014, High-resolution topography for understanding Earth surface processes: opportunities and challenges: *Geomorphology*, v. 216, p. 295-312.
- Thompson, W. B., 1999, Surficial Geology of the Fryeburg 7.5-minute Quadrangle, Oxford County, Maine: *Maine Geological Survey* v. 99, no. 8, p. 1-20.
- Thompson, W. B., and Fowler, B. K., 1989, Deglaciation of the upper Androscoggin River valley and northeastern White Mountains, Maine and New Hampshire: *Studies in Maine geology*, v. 6, p. 71-88.
- Thompson, W. B., Fowler, B. K., and Dorion, C. C., 1999, Deglaciation of the northwestern white mountains, New Hampshire: *Géographie physique et Quaternaire*, v. 53, no. 1, p. 59-77.
- Twidale, C. R., and Bourne, J. A., 2007, Fractures as planes of dislocation and two-way translocation: Their significance in landform development: *Physical Geography*, v. 28, no. 3, p. 193-217.
- Van Staal, C. R., Wilson, R. A., and McClelland, W., 2015, Discussion: Taconian orogenesis, sedimentation and magmatism in the southern Quebec-northern Vermont Appalachians: Stratigraphic and detrital mineral record of Iapetan suturing: *American Journal of Science*, v. 315, no. 5, p. 486-500.
- Waldron, J. W. F., Schofield, D. I., Murphy, J. B., and Thomas, C. W., 2014, How was the Iapetus Ocean infected with subduction?: *Geology*, v. 42, no. 12, p. 1095-1098.
- Wintsch, R. P., Yi, K., and Dorais, M. J., 2014, Crustal thickening by tectonic wedging of the Ganderian rocks, southern New England, USA: Evidence from cataclastic zircon microstructures and U–Pb ages: *Journal of Structural Geology*, v. 69, p. 428-448.