Senior Thesis: Revised Mapping of the Location and Extent of Glaciation in the Central Oregon Cascades Based on LiDAR Data

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Abstract
The glacial chronology of the central Oregon Cascades was initially described by Scott in the Metolius River basin (1977), then revised and expanded by Bevis to include the McKenzie River drainage (2008), the Whychus Creek drainage (2011a and 2011b) and the Deschutes River basin (2013). This updated chronology consists of two major periods of glaciation: 1) the Cabot Creek, correlated with oxygen-isotope stage 2 and the late Pleistocene Last Glacial Maximum (LGM); and 2) the Jack Creek, correlated with oxygen-isotope stage 6 and late middle Pleistocene glaciation. Scott and Bevis also recognized two advances during the Cabot Creek glaciation, the older Suttle Lake corresponding to the LGM, and the younger Canyon Creek corresponding to at least two minor readvances or stillstands at the close of the late Pleistocene. Although neoglacial activity was not included in the work of Bevis, Scott identified two phases of Late Holocene neoglaciation he named the Jefferson Park advances. The basis for the Scott-Bevis chronology was field mapping aided by aerial photos and topographic maps, and the use of relative dating techniques. Significantly, this chronology was developed prior to the advent of LiDAR coverage for the central Oregon Cascades. Our present investigation utilized available LiDAR data to remap the glacial deposits over much of the region covered by Scott and Bevis from LiDAR-based, shaded-relief maps we devised using 3D Analyst in ArcGIS 10.5. We compared previously mapped moraines and the extent of glacial deposits from topographic maps, to shaded-relief maps based on standard 10-meter resolution DEM data, and to our LiDAR maps (with a resolution of 1-2 meters). We recognized numerous moraines that were not previously mapped. While the master glacial chronology was ultimately unaffected by our work, much detail was added to the subtleties of field mapping. The maximum extent of the Jack Creek glaciation was revised in several locations, and revision of the Cabot Creek glaciation included recognition of unmapped Suttle Lake end moraines, but especially the recognition of recessional Canyon Creek moraines in many locations. We also added considerable detail to the location and extent of Jefferson Park moraines, distinguishing multiple Jefferson Park moraines of probable Little Ice Age origin throughout the region.

Introduction
The central Oregon High Cascades landscape is comprised of several spectacular stratovolcanoes, many other more youthful volcanic vents and lava flows; overprinted by numerous landforms of glacial origin. Classical cirques and U-shaped valleys, and a well-preserved sequence of end moraines exhibited in many tributaries are easily delineated, making this area ideally suited to collaborative glaciological research involving undergraduates. Several major watersheds draining the High Cascade crest in the vicinity of the Three Sisters-Mount Jefferson volcanic platform have been studied intensively by Dr. Bevis and his students, including the McKenzie River to the west (Bevis et al., 2008), and the Deschutes River to the east and northeast (Bevis and Hahn, 2011, Bevis and Sandor, 2011; and Bevis and Mooreland, 2013). The glacial geology of the central Oregon Cascades is relatively well known. Crandell (1965) reconstructed ice limits of the late Pleistocene LGM for the entire range based on a brief

survey of end moraines, suggesting an extensive, multi-lobed ice cap in the Mount Jefferson-Three Sisters area. Scott (1977) provides the most detailed description of the glacial history of the central Oregon Cascades in his study of the Metolius River valley which drains the eastern slopes of Mt. Jefferson, Three-Fingered Jack, and Mount Washington, immediately north of the Three Sisters area. He identified glacial features associated with three major periods of glaciation, identifying a middle Pleistocene glaciation (Abbot Butte), a late middle Pleistocene (Jack Creek) glaciation, and a late Pleistocene (Cabot Creek) glaciation, as well as Holocene neoglaciation. He interpreted the best preserved features of the area to correlate with the most recent and extensive regional late Pleistocene alpine glacial maxima of about 20 Ka (the Last Glacial Maximum, or LGM), naming it the Suttle Lake advance of the Cabot Creek glaciation. End moraines found higher in the watershed, deposited near the mouth of several the larger, northeast-facing cirques had similar weathering characteristics; Scott identified these as belonging to an extended stillstand or readvance during the close of the Cabot Creek glaciation, naming it the Canyon Creek advance. Scott et al. (1989) added to the reconnaissance work of Crandell (1965), reporting evidence for two former glacial episodes in the southwestern portion of the Three Sisters area, correlating the more recent and better preserved features with Scott's (LGM) Suttle Lake advance in the Mt. Jefferson area. They developed a reconnaissancelevel reconstruction of ice limits and ice surface elevations associated with the Suttle Lake advance, concluding that the entire area was covered by an extensive ice cap during the late Pleistocene LGM. Bevis et al. (2011a and 2011b) revised the mapping of glacial deposits of the upper Metolius and Whychus Creek drainages, identifying only two distinctive drift units, an older unit correlated with Scott's late middle Pleistocene Jack Creek glaciation, and a younger unit correlated with the late Plesitocene glaciation LGM Suttle Lake advance of Scott's Cabot Creek glaciation. Only the younger Suttle Lake advance was identified in the Whychus Creek area; and no attempt was made to map younger moraines of the Canyon Creek advance. Bevis and Mooreland (2013) completed glaciological mapping of the upper Deschutes River and Tumalo Creek watersheds draining the eastern to southern flanks of the Broken Top volcanic platform (an older, eastern extension of the Three Sisters), again only delineating LGM deposits in those drainages. Scott (1977) also mapped moraines and protalus ramparts in some of the highest cirques on Three-Fingered Jack and Mt. Jefferson, recognizing two phases of Late Holocene neoglaciation that he named the Jefferson Park advances.

However, it is significant to note that many details of field mapping related to this glacial chronology remain obscure. These watersheds cover a huge area of forests and mountainous terrain with limited access; much of it is roadless, contained within the boundaries of several wilderness areas. The mapping reported above was completed by aerial photo and topographic map surveys, with ground truthing by the use of relative dating techniques generally confined to accessible locations along Forest Service roads and hiking trails. The glacial deposits in many areas where mapped only during brief, field reconnaissance trips or from the interpretation of aerial photos, topographic maps, and maps devised from 10-meter resolution DEM data. With the advent of LiDAR technology, LiDAR map coverage (with a resolution of 1-2 meters) for much of the central Oregon Cascades is now available. This investigation utilized available LiDAR data to remap the glacial deposits over much of the region previously covered by Scott and Bevis from LiDAR-based, shaded-relief maps that we devised using 3D Analyst in ArcGIS 10.5, including revision or first-time mapping of end moraines related to the Jack Creek and Cabot Creek glaciations, as well as neoglacial activity.

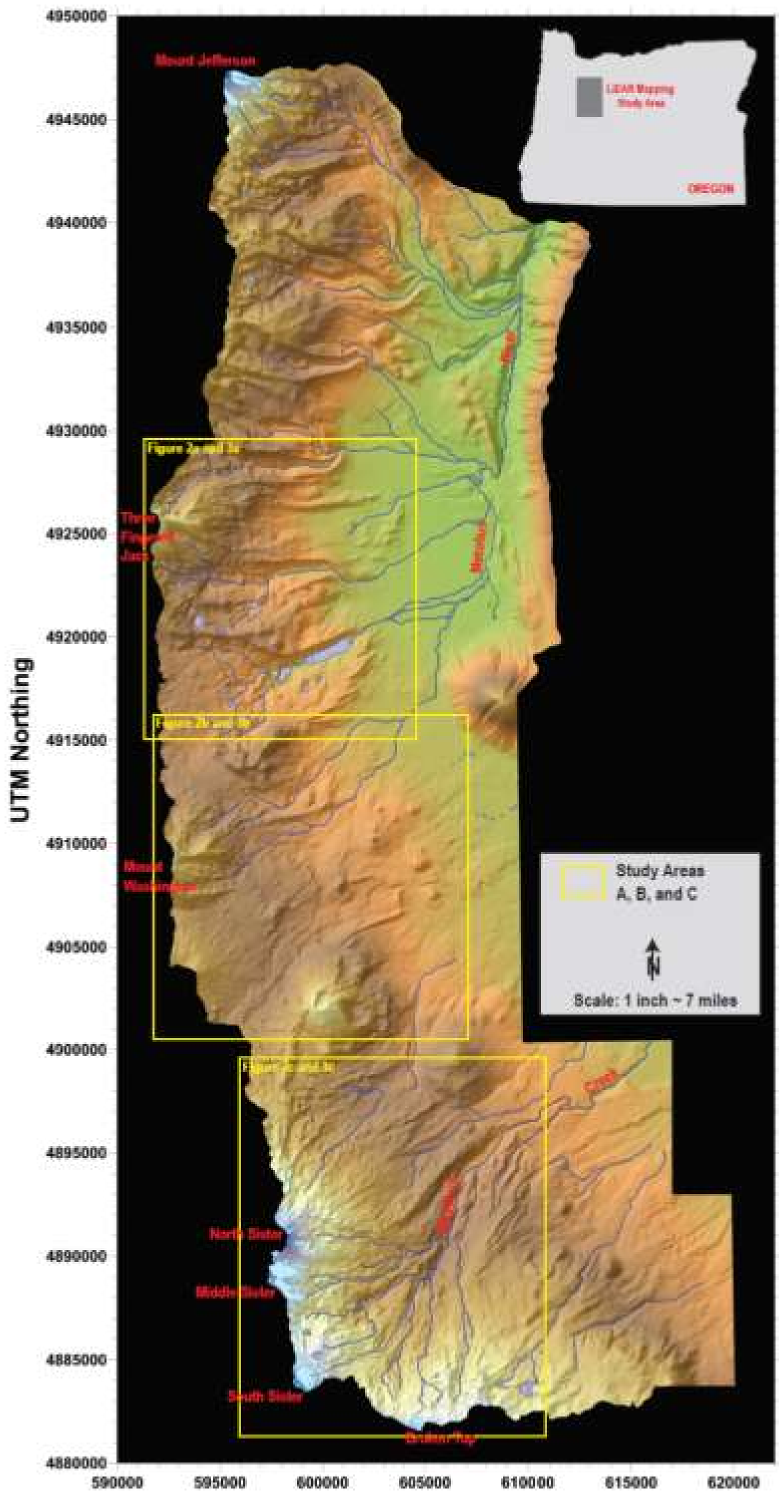


Figure 1. A shaded-relief map of the glaciated portions of the combined Metolius River and Whychus Creek drainages comprising the northern portion of the Deschutes River basin in the vicinity of the Three Sisters-Mount Jefferson volcanic platform; detailed LiDAR mapping Study Areas A, B, and C discussed in the text are outlined in yellow.

Methodology and Results

Figure 1 displays the upper Metolius River and Whychus Creek watersheds draining the east slope of the Oregon Cascades between Mount Jefferson and the Three Sisters. This region is the best studied portion of the range and is well suited for my refined LiDAR mapping project. Three areas within the larger region (outlined in Figure 1) were selected for more intensive analysis. Study Area A includes the watersheds of Jack Creek, Suttle Lake, and Cabot Creek, the drainages from which Scott (1977) defined his glacial chronology. Study Area B lies just south of study area A, an area draining from Mount Washington's eastern flank and McKenzie Pass that includes previously unmapped Jack Creek deposits; and Study Area C comprises of the entire Whychus Creek watershed which hosts a plethora of well-preserved end moraines of Cabot Creek and Jack Creek age. All three study areas also preserve an excellent set of end moraines from Scott's latest Pleistocene Canyon Creek and Holocene Jefferson Park advances.

Proceeding my initial collection of LiDAR data from the *State of Oregon Department of Geology and Mineral Industries* website the individual sections of 7.5 minute quadrangles were merged into a larger master map of the entire Metolius River-Whychus Creek watershed. In order to merge these LiDAR map segments, they had to first be converted into raster files using the 'Create Raster Dataset' tool. The newly created rasters could then be merged together using the 'Mosaic' tool. The complete LiDAR map was then superimposed by the completed topographic map of the corresponding region (it should be noted that the topographic maps did not need to be mosaiced together). In order to generate the smaller inset maps for Study Areas A, B, and C, I first used the 'Draw' tool to outline the area of interest on the GIS, then I clipped the data frame of the GIS through the 'Data Frame Properties' with the 'Clip to Shape' option. After the three Study Area maps had been configured, and superimposed on one another, I began identifying the glacial moraines using the LiDAR data. I used the 'Draw' toolbar again to trace the moraines as polylines. Moraines were correlated with the Jack Creek glaciation, the Suttle Lake and Canyon Creek advances of the Cabot Creek glaciation, and the Jefferson Park neoglaciation, chiefly on the basis of moraine morphology and relative position (elevation) within each respective watershed. My mapping was compared to a compilation of mapping data previously collected by Bevis and his students that included ground truthing using relative dating techniques to map moraine ages in the field, and adjustments were made as needed. Jack Creek moraines were readily distinguished by their subdued morphology and outer most or lowermost position in the watershed as shown in the inset map (Figure 4). Deposits of the Cabot Creek, Suttle Lake advance generally formed the largest and most contiguous moraines in each valley (often conjoining with adjacent valleys), and usually occur only slightly up-valley from Jack Creek moraines. Uniquely, these moraines also consistently display a characteristic hummocky topography with multiple, subparallel crests as shown in the inset map (Figure 4). The end moraines of the Cabot Creek, Canyon Creek advance occur considerably higher in the watershed, clustering within north to east facing cirques on only the tallest peaks (the Three-Fingered Jack, Mount Washington, North, Middle, and South Sister, and Broken Top stratovolcanoes); and usually consist of several nested moraine crests with well-preserved morphology as shown in the inset maps from the head of Canyon Creek (Figure 5a) and north flank of Broken Top (Figure 5b). Deposits of the Jefferson Park advances generally form a double set of sharp-crested moraines occupying the highest elevations within the same valleys (see Figure 5a and Figure 5b for examples). The photographs shown in Figure 6 display Canyon Creek and Jefferson Park moraines from the head of Canyon Creek (Figure 6a) and north flank of Broken Top (Figure 6b).

Once all of the glacial moraines were identified using the LiDAR data (shown in Figure 3) I separated the LiDAR and topographic maps, making six large separate maps. In order to properly show the difference in detail between the two types of maps I began examining the moraines drawn on the topographic maps. If there were any glacial moraines drawn that were not clearly visible on the topographic map, then they were deleted.

Figures 2a 2b 2c and 3a 3b 3c show the results of my efforts with end moraines identified and mapped in four colors: red = Jack Creek; violet = Suttle Lake (Cabot Creek); light blue = Canyon Creek (Cabot Creek); and green = Jefferson Park.

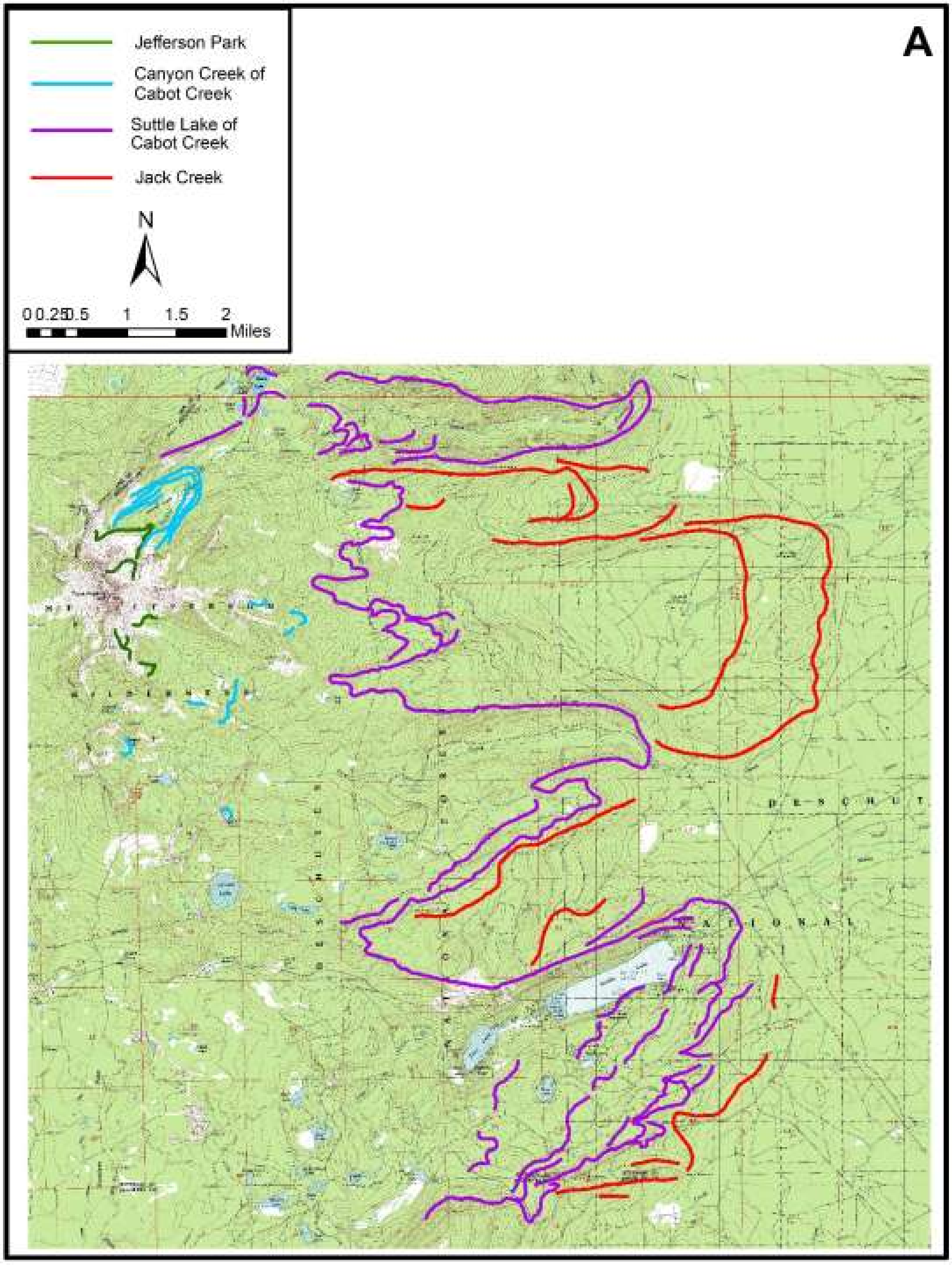

Jefferson Park
Canyon Creek of Cabot Creek
Suttle Lake of Cabot Creek
Jack Creek
N
0 0.25 0.5 1 1.5 2
Miles
A

Figure 2a.

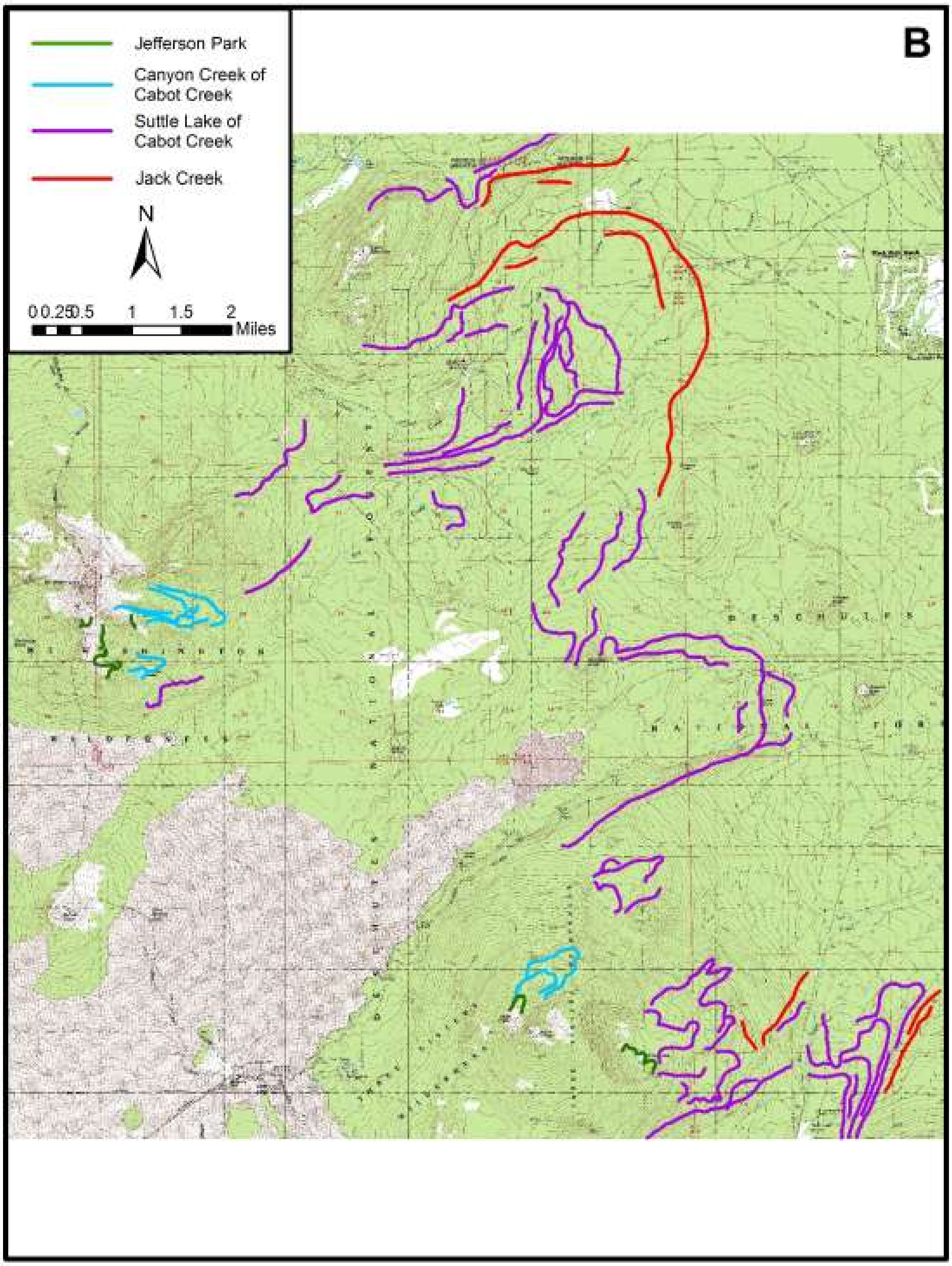

Jefferson Park
Canyon Creek of Cabot Creek
Suttle Lake of Cabot Creek
Jack Creek
N
0 0.25 0.5 1 1.5 2
Miles
B

Figure 2b.

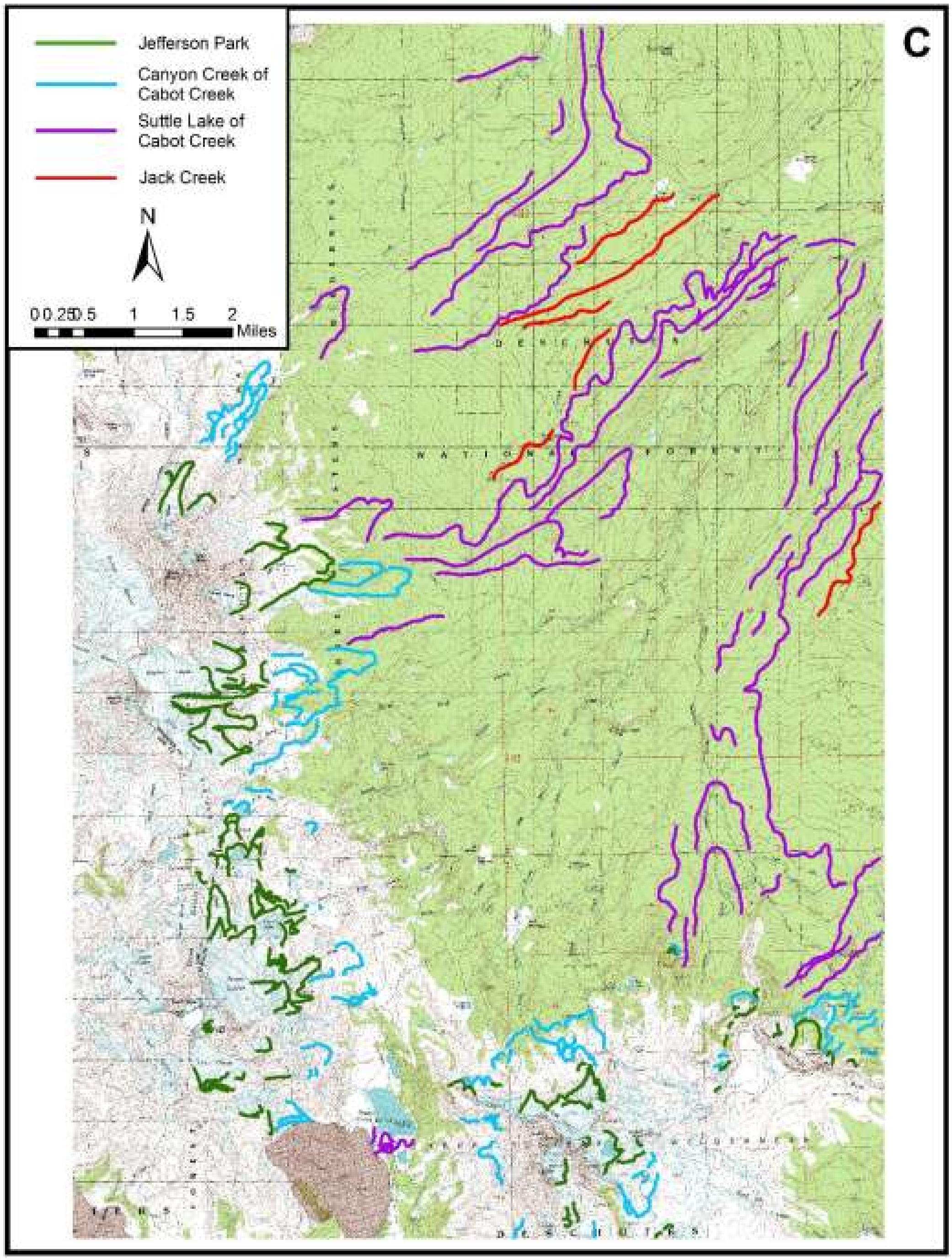


Figure 2c.
Figures 2a, 2b, 2c. End moraine maps for Study Area A, B, and C developed from digital raster files merged in ArcGIS; the maps display moraines associated with the Jack Creek glaciation in red; the Suttle Lake advance of the Cabot Creek glaciation in violet, the Canyon Creek advance of the Cabot Creek glaciation in light blue; and the Jefferson Park neoglacial advances in green.

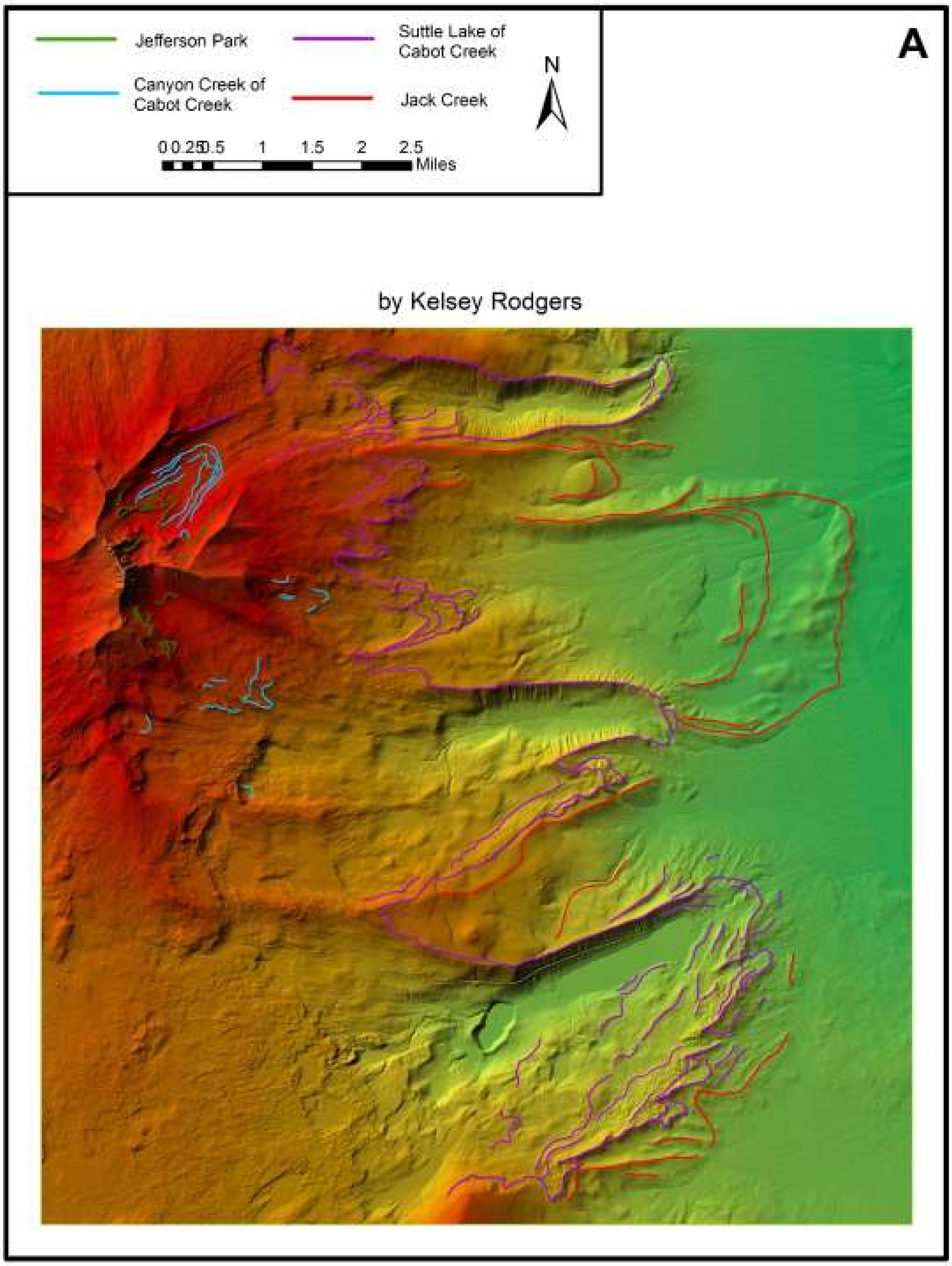

Jefferson Park
Suttle Lake of Cabot Creek
A
Canyon Creek of Cabot Creek
Jack Creek
N
0 0.25 0.5 1 1.5 2 2.5
Miles
by Kelsey Rodgers

Figure 3a.

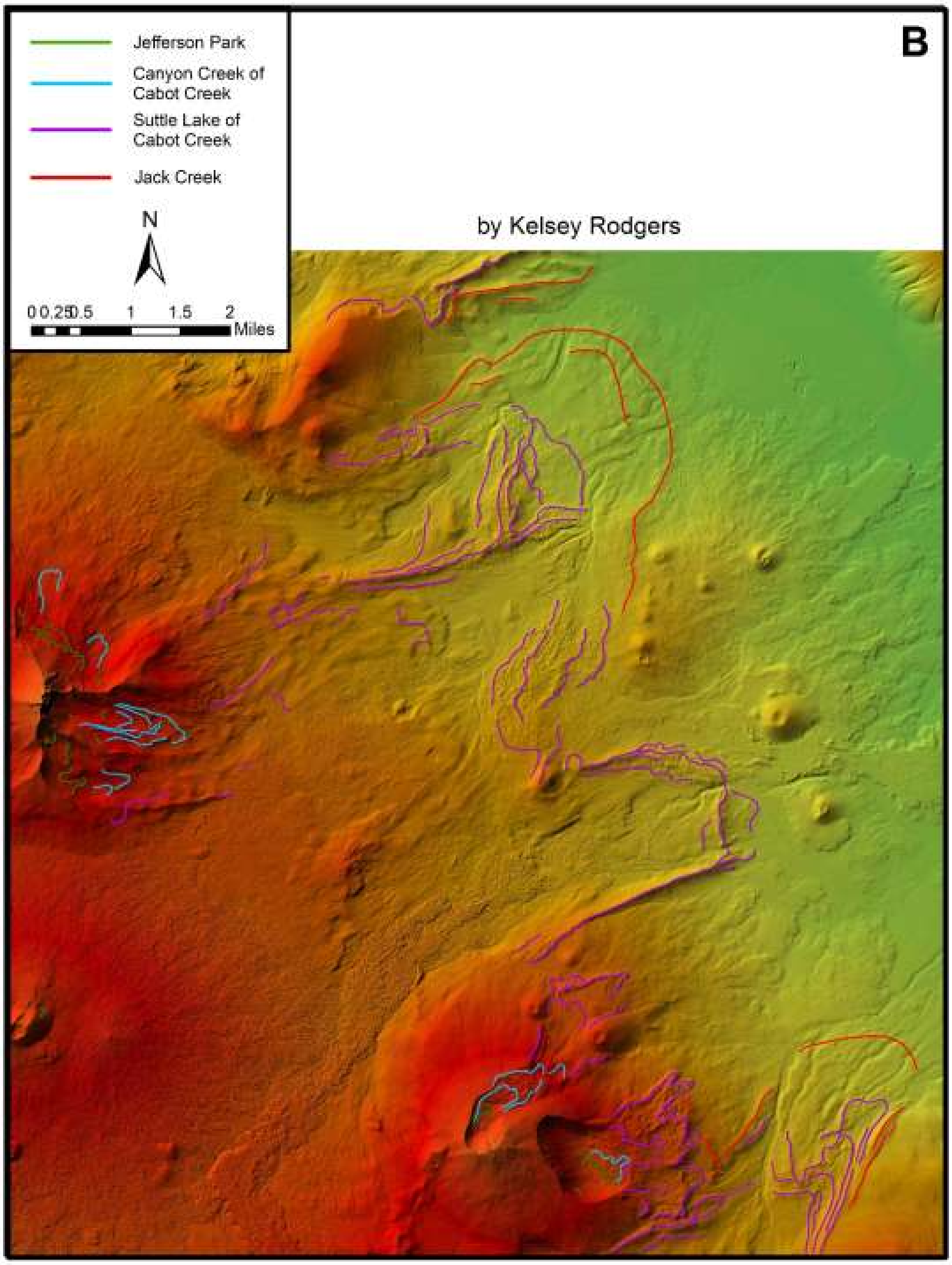

Jefferson Park
Canyon Creek of Cabot Creek
Suttle Lake of Cabot Creek
Jack Creek
N
0 0.25 0.5 1 1.5 2
Miles
B
by Kelsey Rodgers

Figure 3b.

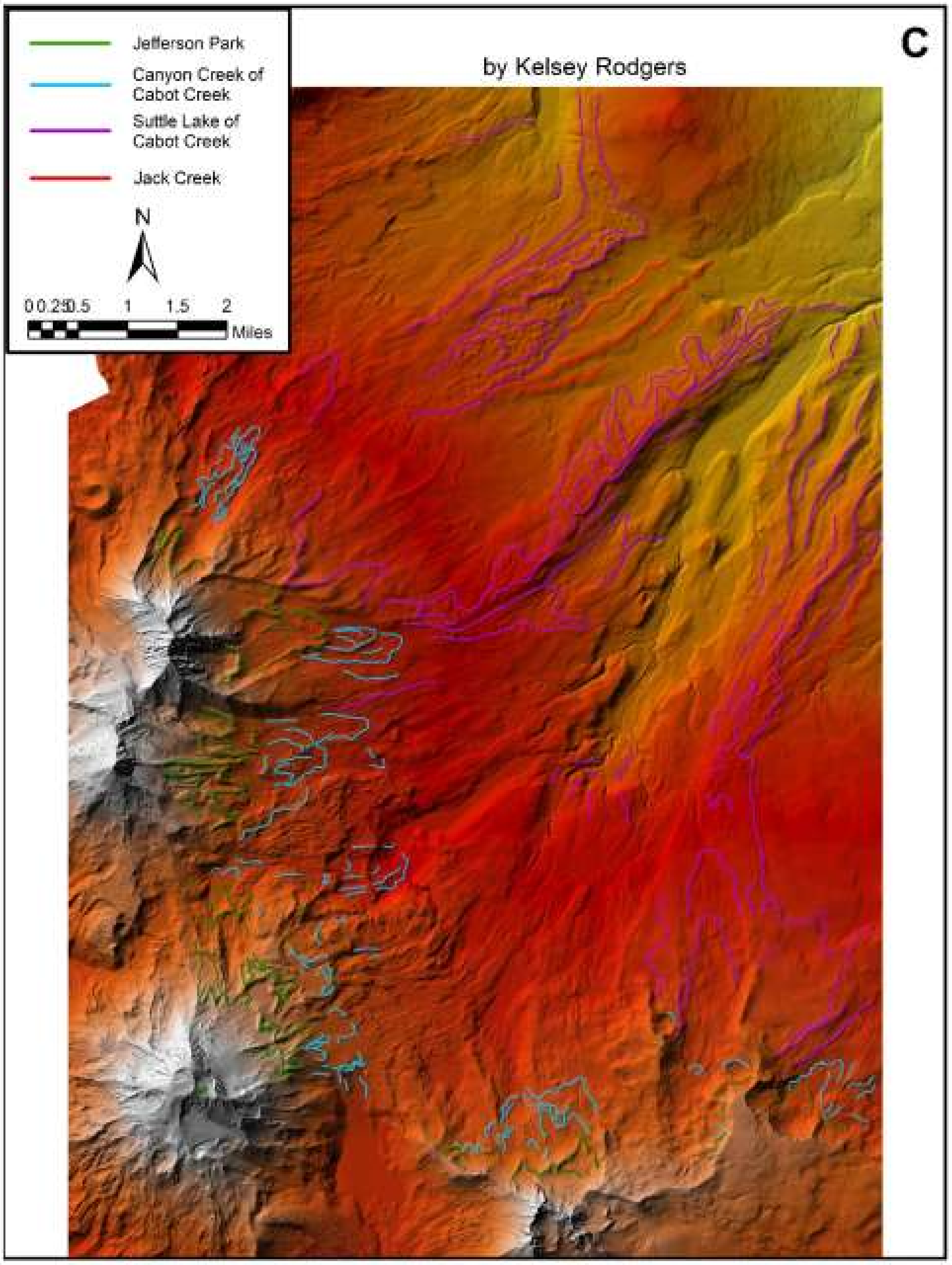


Figure 3c.

Figures 3a, 3b, 3c. End moraine maps for Study Area A, B, and C developed from digital LiDAR data converted to raster files and then merged in ArcGIS; the maps display moraines associated with the Jack Creek glaciation in red; the Suttle Lake advance of the Cabot Creek glaciation in violet, the Canyon Creek advance of the Cabot Creek glaciation in light blue, and the Jefferson Park neoglacial advances in green (inset maps and photographs discussed in the text are outline in yellow).

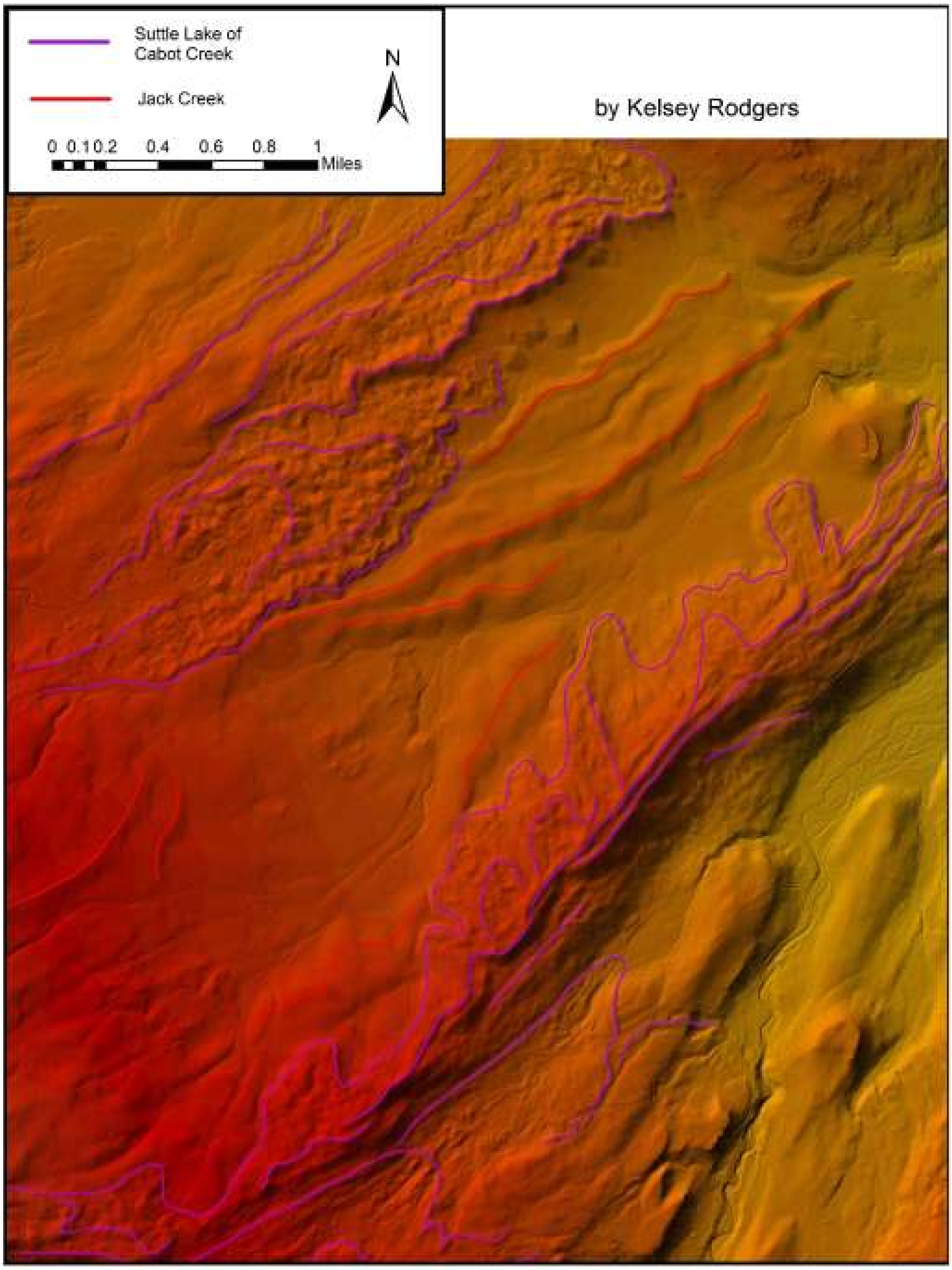
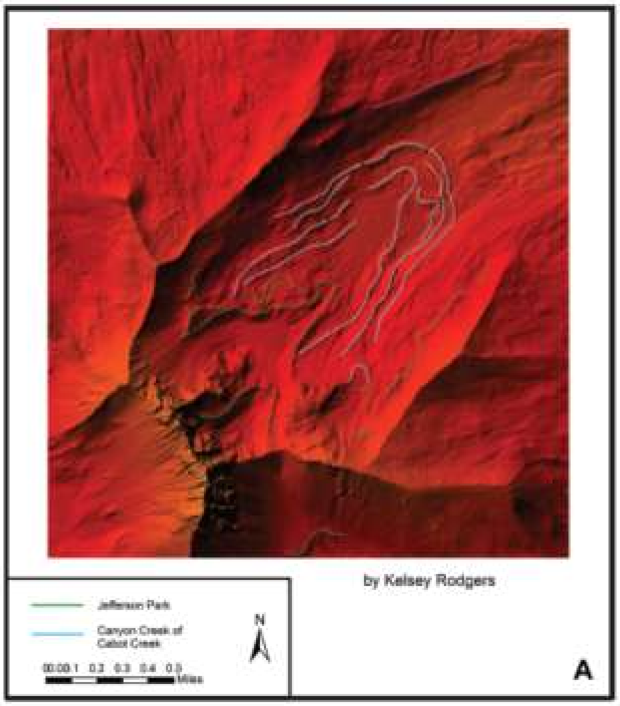


Figure 4. An inset map from Study Area C showing the large, subdued moraine crests of the Jack Creek glaciation, and the hummocky terrain and multiple, nested moraine crests characteristic of the Suttle Lake advance of the Canyon Creek glaciation.



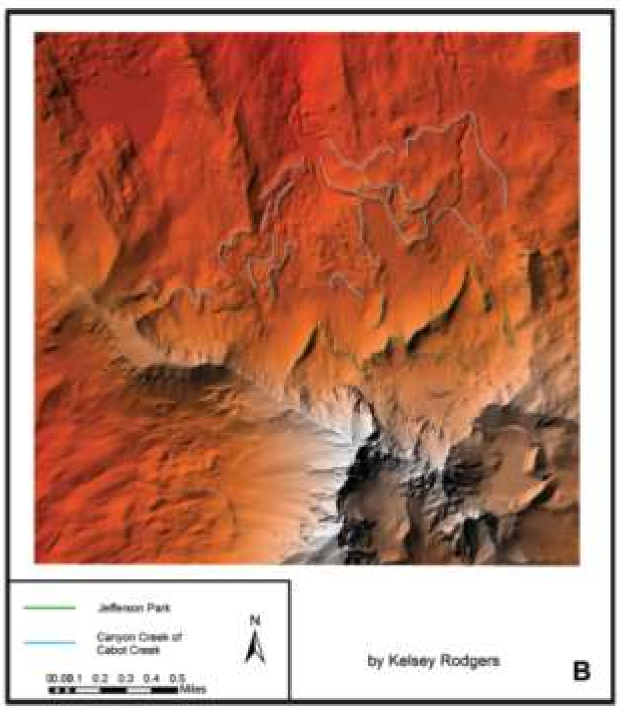


Figure 5. Inset maps from Study Area A and Study Area C showing the low amplitude, but sharpcrested moraines of the Canyon Creek advance of the Cabot Creek glaciation and the Jefferson Park neoglaciation; A) depicts the cirque formed at the head of Canyon Creek on the northeast flank of Three-Fingered Jack and B) depicts the cirque formed at the head of the East Branch of Whychus Creek on the north flank of Broken Top (see inset maps outline in Figure 3a and 3c).

Figure 6. Photographs from Study Area A and Study Area C showing the low amplitude, but sharp-crested moraines of the Canyon Creek advance of the Cabot Creek glaciation and the Jefferson Park neoglaciation; A) is from the cirque formed at the head of Canyon Creek on the northeast flank of Three-Fingered Jack and B) is from the cirque formed at the head of the East Branch of Whychus Creek on the north flank of Broken Top (see inset maps outline in Figure 3a and 3c).

A comparison of moraine morphological features observed between the two types of maps highlights the usefulness of the LiDAR imagery in distinguishing and differentiating glacial deposits. Moraines of the Jack Creek glaciation appear to be mappable at the resolution of both the topographic and LiDAR maps, although some of the more subdued moraines are more distinct on the LiDAR imagery. The shear bulkiness of the Suttle Lake moraines allows them to be readily observed and mapped on both types of map, but the unique subtlties of hummocky topography, multiple, nested moraine crests, and continuity of end moraines between adjacent watersheds that can be observed with the LiDAR maps are not portrayed very clearly at the low resolution of the topographic maps. The Cabot Creek moraines of the Canyon Creek glaciation are often low amplitude, making them too subtle to identify and map accurately on the topographic maps; however, they appear quite sharply on the LiDAR imagery and are easily traced. Jefferson Park neoglacial moraines are more readily distinguished on the topographic maps than their down-valley Cabot Creek counterparts, but the LIDAR maps pick up more, subtle, low amplitude moraine crests in several watersheds offering a more consistent picture of at least two Little Ice Age advances.

<u>Conclusions</u>

A brief comparative analysis of the moraine mapping from topographic maps and LiDAR imagery clearly shows that the LiDAR maps produced in ArcGIS portray end moraines in far greater detail and complexity than the 7.5 minute topographic maps. The moraines are easily observed and readily distinguished into Scott's four previously established age categories; although certain characteristics stand out. Jack Creek end moraines form subdued, rounded ridges that often lack their terminal portion; however, a residual elevated terminal moraine morphology does persist in several watersheds that is too low in amplitude to be visible on topographic maps. The hummocky, multiple-crested end moraines associated with the Suttle Lake advance of the Canyon Creek glaciation are uniquely visible on the LiDAR maps, but the details of this complex morphology are in most cases washed out and indistinct on the topographic maps. Finally, the multiple recessional moraines of the Canyon Creek's Cabot Creek advance and end moraines of Jefferson Park neoglacial advances are easily differentiated into multiple, sharp crests; crests that are in many cases too low in amplitude to be displayed at the resolution of the topographic maps.