Investigating late Pleistocene and Anthropocene flood deposits along North Boulder and Caribou Creek, Colorado Front Range

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Abstract

The Lake Devlin flood occurred 14 ka following the Pinedale last glacial maximum after the moraine damming Lake Devlin failed. The flood eroded a channel through the moraine as deep as 35 m and as wide as 130 m and deposited the eroded materials near the confluence of North Boulder Creek and Caribou Creek. Another, smaller flood occurred at the same location as the Lake Devlin flood, following the failure of a man-made earthen dam in the early 20th century. This later flood is referred to as the Caribou Creek flood. These floods had long lasting, morphological impacts on the landscape of North Boulder Creek Valley, as evidenced by the vast flood deposits found near the confluence of Caribou Creek and North Boulder Creek. The magnitude of the morphological impact brought about by each flood is inferred by mapping the extent of the flood deposits and estimating the peak discharge of each flood.

Lake Devlin flood deposits are located in a fan-shaped deposit near the dam failure, and on North Boulder Creek and Caribou Creek flood plains and terraces, where they commonly are intermingled with Caribou Creek flood deposits. The Lake Devlin flood also eroded valley tills down North Boulder Creek from the fan-shaped deposit, further altering North Boulder Creek Valley. The Caribou Creek flood deposits are more contained than the Lake Devlin flood deposits, only appearing on flood plains and terraces slightly above current river stage along Caribou Creek and North Boulder Creek.

Two different methods were utilized to measure channel width for the Lake Devlin flood in order to estimate an upper and lower limit peak discharge. The resulting upper and lower limits for the Lake Devlin flood are 2900 m^3/s and 1100 m^3/s, respectively. Only one method for measuring width is necessary to estimate the Caribou Creek flood peak discharge. The peak discharge for the Caribou Creek flood is 180 m^3/s.

1. Introduction

The current Rocky Mountain Front Range landscape is the product of tectonic uplift balanced by erosive geomorphic processes such as mass wasting, fluvial, and glacial processes. Much of the work done in understanding and modeling the geomorphology of the Colorado Front Range landscape has concentrated on steady, constant processes such as mobile regolith transport, canyon incision, basin exhumation, regolith production and transport, and the morphology of smooth mountaintops (Anderson et al., 2006). Catastrophic events, which are inherently much more difficult to account for when attempting to model landscape evolution, must also be understood to create a complete picture of the geomorphic evolution of such landscapes. Although these events are inconsistent processes affecting only portions of the landscape, the magnitude of the change brought about cannot be ignored.

One such catastrophic event is that of the Lake Devlin flood, which occurred after moraine dammed Lake Devlin drained into the North Boulder Creek Valley following the retreat of the Pinedale last glacial maximum (LGM). The Lake Devlin lacustrine sediments have been dated using carbon dating and optically stimulated luminescence in order to provide an indicator for the timing of the Pinedale glaciation in the Front Range (Madole, 1980, 1986, 2010; Leopold et al., 2008), but no work currently exists on the Lake Devlin flood deposits. This study maps the Lake Devlin flood deposits, determines the grain size distribution of these deposits, and estimates an upper and lower limit for the Lake Devlin flood peak discharge. In addition to the Lake Devlin flood during the late Pleistocene, the same techniques for determining discharge can be applied to the Caribou Creek flood, which occurred in the early 20th century after a man-made dam constructed at the same location also failed.

After estimating discharge and mapping the deposits of the Lake Devlin flood, an analysis of the dam failure chronology consistent with the data and methods used to estimate peak discharge is presented. Establishing the framework for analysis of the Lake Devlin flood in this paper provides a basis for future, more concentrated studies in the area that either verify or dismiss the results presented in this research.

1.1 Tectonic history and bedrock geology of the Colorado Front Range

The Colorado Front Range can be simply defined as the mountainous headwaters of the South Plate River, contained to the west by the continental divide and to the east by the Colorado high plains. The Colorado Front Range was the product of the Laramide Orogeny, a compressional tectonic episode that occurred between the late Cretaceous and early Tertiary, more specifically 75-35 Ma (Bird, 1998; Dickinson et al., 1988). Deformation has been attributed to subcrustal shear during subduction of the Farallon Plate (Bird, 1998). Others have proposed that upper crust detachment was the tectonic mechanism by which deformation occurred (Erslev, 1993). However, analysis of minor faulting in the Laramide Ranges suggest that shear shortening was the primary mechanism of deformation, and that the Colorado Front Range appears to have undergone additional rotation after initial deformation (Erslev et al., 2004). Since the Laramide Orogeny, the landforms that characterize the Colorado Front Range have been the products of geomorphic processes such as glaciation, river incision, regolith production, mobility, erosion, and deposition.

Pre-Laramide basement rocks in the Colorado Front Range consist largely of Cretaceous marine and Mesozoic fluvial/eolian/lacustrine deposits overlaying older plutonic intrusions and metamorphosed sedimentary units. Metamorphosed marine sedimentary and volcanic rocks represent the oldest rocks in the area. The most prevalent metasedimentary unit is a felsic unit interpreted to have originally been a large sub-marine fan deposit. The metamorphosed sedimentary rocks underwent two metamorphic events. During the first event, tight folds occurring in saturated marine sediments resulted in recrystallization of clay minerals. The second event occurred during the intrusion of the Boulder Creek Granodiorite, introducing new igneous materials and causing partial melting of older rocks. More recent Mesozoic and Cretaceous sedimentary rocks represent the youngest pre-Laramide rocks. The aforementioned metamorphosed sedimentary rocks, and the plutonic intrusions of the Boulder Creek Granodiorite and the Longs Peak Granite make up the majority of the bedrock in the Colorado Front Range. Lithified mafic-alkalic and alkali-calcic magmas that were introduced to the range during the Laramide Orogeny also constitute a portion of Colorado Front Range bedrock (Braddock and Cole, 1990).

1.2 Glacial history

Glaciers originating near the continental divide repeatedly advanced and retreated throughout the Pleistocene. The Bull Lake and Pinedale glacial episodes are the most recent, and therefore have had the greatest impact on the landscape observable today. Bull Lake glaciation in the Colorado Front Range occurred between 200 – 130 ka during marine isotope stage 6 (Madole, 1991). Cosmogenic dating near Yellowstone National Park has concurred that the Bull Lake last glacial maximum (LGM) occurred around 136 ka (± 13 ka) (Licciardi and Pierce, 2008). Pinedale glaciation in the Front Range began sometime before 33 ka and lasted until 12 ka (Madole, 2010). Cosmogenic dating of boulders from the Green Lake Valley Glacier in North Boulder Creek Valley indicate that the Pinedale LGM was reached by 21 ka and deglaciation began around 18 ka (Dühnforth and Anderson, 2011; Pierce, 2003). Pinedale glacial climate is associated with marine isotope stage 2 (Svendsen et al., 2004). Pinedale glaciation extended 15 km down valley from glacial headwalls and on average was 90% of the extent of Bull Lake glaciation (Dühnforth and Anderson, 2011; Pierce, 2003). Since Pleistocene glacial times, river incision, regolith production, and regolith mobilization have become the dominating geomorphic actors on the Colorado Front Range.

1.3 Geomorphic processes of the Colorado Front Range

Since the subsidence of the Laramide Orogeny and the Pinedale last glacial maximum during the Pleistocene, the landscape of the Front Range has been altered by a combination of glacial, colluvial, and fluvial geomorphic processes (Anderson et al., 2006). The Colorado Front Range can be subdivided into three regions based on the dominating geomorphic process since the Pinedale: a region of low topographic relief known as the subsummit surface that occupies the area near the east-west center of the Front Range; incised river valleys near the eastern High Plains boundary; and glacially carved valleys near the continental divide (Anderson et al., 2006).

The low-relief subsummit surface, which at one time spanned the entirety of the eastern two-thirds of the Colorado Front Range, is believed to be a product of chemical weathering and the calm climate of the Eocene (Chapin and Kelley, 1997). The undulating pediment surface remains today, but no longer extends eastward as far as the high plains. Instead the eastern portion of the Front Range that once looked very similar to the subsummit surface is now distinguished by the presence of deep bedrock valleys produced by river incision. The change from topographic smoothening of the Eocene to the incising river valleys is believed to have begun during the Pliocene following a change to a stormy and wet climate (Chapin and Kelley, 1997).

The eastern most portion of the Front Range is dominated by river valleys incising into bedrock. Because the rivers are incising into bedrock, lateral migration of channels is minimal. Therefore, we expect periods of sediment aggradation in the channel if sediment supply is large or incision if sediment supply is low and bedrock is accessible (Anderson et al., 2006). The steep valley walls suggest that incision has been the dominant of these two possible processes. The onset of bedrock incision can be attributed largely to either or a combination of both river profile response to base level lowering and decreasing river sediment discharge during interglacial periods. During glacial times large amounts of sediment enter into fluvial systems. Large sediment input (especially coarse sediment) will inhibit vertical incision as streams must entrain and remove material overlying bed surfaces before vertical incision can occur (Hancock and Anderson, 2002). The onset of an interglacial cycle will not result in immediate vertical incision. Instead, vertical incision will only occur after material overlying the bedrock is removed, which is determined by the river's competency and the nature of the sediment overlying the bed (Hancock and Anderson, 2002). Additionally, the lowering of base levels caused by the incision of streams in the High Plains has increased river competency and erosive capabilities, enhancing incision of the bedrock channels and producing more pronounced river valleys (Anderson et al., 2006).

The glacially carved alpine valleys in the western portion of the Front Range are recognizable by predominantly eastern facing arêtes near the glacial headwalls, U-shaped valley cross sectional profiles, and concave-up longitudinal profiles. Longitudinal profiles are the product of ice discharge rates, which are greatest at the equilibrium line elevation (ELA)

(MacGregor et al., 2000). The resulting profile after multiple advances and retreats is a steep concave profile from the headwall to the ELA of the glacial maximum and a much flatter profile from the ELA of the glacial maximum to the terminus (Anderson et al., 2006). Because this study area is directly tied to the glacial history of North Boulder Creek Valley, the glacially carved alpine valley subdivision is important.

1.4 Catastrophic events of the Colorado Front Range

Although much of the Colorado Front Range landscape is the result of consistent, long-term geomorphic processes (for example, glaciation, river incision, fluvial sediment transport, regolith production/mobility, and so forth) since the Laramide Orogeny, catastrophic events in the Front Range are also important when developing an understanding of the landscape evolution. Such catastrophic events include, but are not limited to, flooding, debris flows, and rock falls. Though spatially and temporally isolated, such events can produce erosion and transport rates that dwarf the consistent geomorphic processes. For example, the Lawn Lake earthen dam failure in the northern portion of the Colorado Front Range was able to transport boulders estimated to be as massive as 410 metric tonnes and produced peak discharges estimated to be at least 510 m^3/s (Jarrett and Costa, 1986).

One specific catastrophic event that occurred in the Colorado Front Range was the failure of moraine-dammed Lake Devlin. Lake Devlin existed during both the Bull Lake and Pinedale Glacial episodes. During Lake Devlin's Pinedale existence, the Green Lakes Valley and Arapahoe Glaciers converged and advanced down North Boulder Creek Valley. The combined glaciers built a lateral moraine that dammed meltwaters from the Horseshoe Creek and Rainbow

Lakes cirques, as well as meltwaters from a portion of the Middle Boulder Creek Glacier that overtopped the bounding mountain ridge, forming Lake Devlin (Figure 1) (Madole, 1986). Previous work regarding the failure of Lake Devlin has dated the existence of Lake Devlin and compared these dates to cosmogenic nuclide dates of Pinedale retreat in the North Boulder Creek Valley (Dühnforth and Anderson, 2011). Radiocarbon and optically stimulated luminescence dating of lacustrine sediments has determined Lake Devlin existed from 31-14 ka (Madole, 1986, 2010; Leopold et al., 2008). Around 14 ka, the moraine dam failed and Lake Devlin drained into North Boulder Creek Valley, resulting in a new channel through the moraine and depositing the eroded moraine material near the confluence of North Boulder Creek and Caribou Creek (Figure 2). Caribou Creek occupies the channel created during the dam failure. Lake Devlin produced at least 36 m of lake sediments during its existence during the Pinedale, Bull Lake, and possibly during pre-Bull Lake glaciations. Lake Devlin was approximately 2 km long, 200-460 m wide, and as deep as 60 m (Madole, 1980). Lake Devlin stored 12,000,000 – 55,000,000 m^3 of water during its existence based on the minimum and maximum dimensions given by Madole (1980). Lake Devlin developed a spillway to accommodate excessive lake inputs. The spillway carved through Proterozioc igneous rock and was .7 km long and as wide as 20 m (Madole, 1986).

Sometime during the 1920s or 1930s, an earthen dam constructed by the City of Boulder at the same location as the moraine dam that failed during the Lake Devlin flood also failed. This flood was smaller than the Lake Devlin flood and its deposits are found on low lying terraces and flood plains of Caribou Creek and North Boulder Creek. The man-made dam was roughly a quarter of the moraine dam's height, standing a little over 4.3 m above the Lake Devlin floor. The second flood event will be referred to as the Caribou Creek flood.

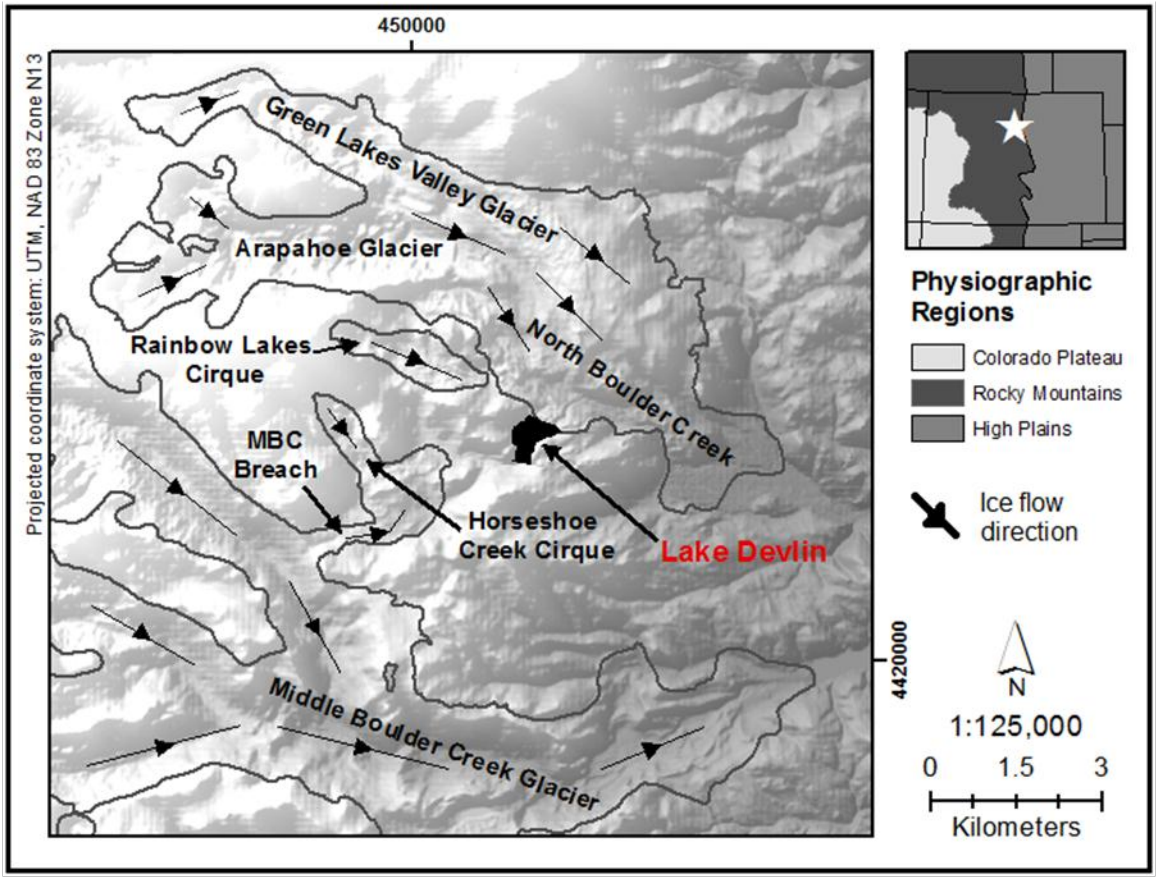

Figure 1. Location of Lake Devlin during the Pinedale last glacial maximum. Physiographic regions from Fenneman and Johnson, 1946. LIDAR data from Anderson et al., 2011. Pinedale extent data based on work by Madole et al., 1998.

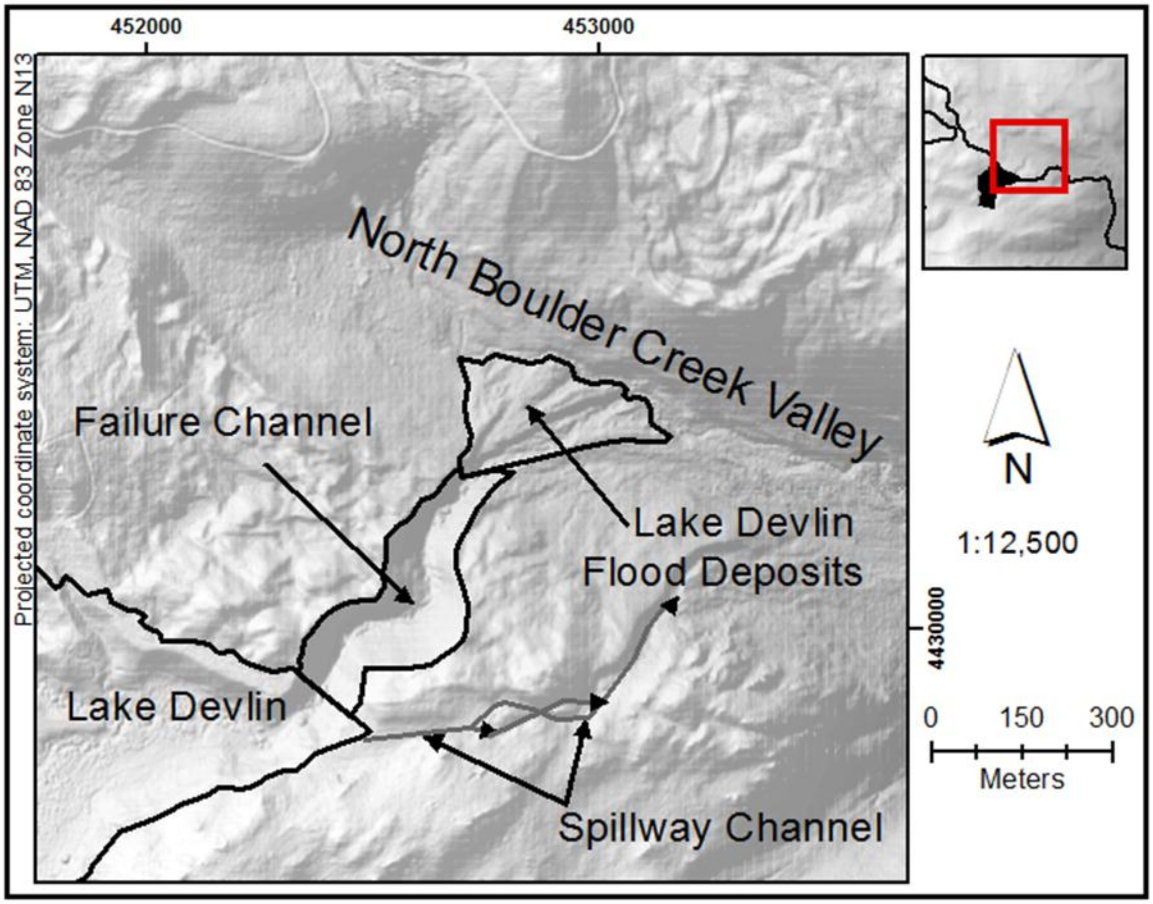

Figure 2. Location of the Lake Devlin flood deposits near the failed moraine, the failure channel, and the Lake Devlin spillway.

1.5 Research goals

The discharge and characteristics of each flood can be deduced by examining the deposits of each flood event. This research presents the location of the Lake Devlin and Caribou Creek flood deposits, peak discharge estimates for both flood events, and the sorting of the Lake Devlin flood deposits. Additionally, the research will attempt to determine if Lake Devlin flood deposits temporarily dammed meltwater from the Green Lakes Valley and Arapahoe Glaciers by comparing the sorting of sediment on the north shore of North Boulder Creek to the sorting of the Lake Devlin flood deposits.

2. Methods

Field mapping, sediment sample collection for grain size analysis, and b-axes measurements of transported boulders were collected in the field. Field mapping documented Lake Devlin and Caribou Creek flood deposits found near the North Boulder Creek – Caribou Creek confluence, as well as eight other types of deposits in the area. Sediment samples were also collected and utilized to assist with mapping. Grain size analysis of the sediment samples characterized the sorting of the flood and glacial deposits as well as deposits of unknown origin in the area.

Peak discharge estimates employ an empirical equation based on transported boulder size for velocity (Costa, 1983), the Manning equation for depth, and GIS analysis for width. The velocity estimate equation utilizes the five largest transported boulder sizes to estimate the peak velocity, which was employed to determine depth. Width was measured from a LIDAR Digital Elevation Model (DEM) thereby producing the inputs needed to estimate peak discharge.

2.1 Mapping

To determine the impact of the Lake Devlin flood on the landscape, geological materials near the location of the outburst flood were mapped using a Garmin eTrek mobile GPS device. Topographic characteristics of the landscape observed on LIDAR images provided the initial insight for where to expect different materials. For example, ice contact stratified deposits (ICSD) appeared as hummocky terrain with a few kettles present. Field mapping began by simply mapping the deposit contacts based on these topographic similarities and differences observed from the LIDAR image. Once in the field, mapping considered relative ages of materials based on weathering and lichen cover of boulders, as well as landforms such as lobes and terraces to verify or dismiss initial interpretations of deposits (Figure 3). For example, till has the same degree of weathering and lichen cover as the Lake Devlin flood deposits, but it does not have lobes or imbricated boulders. Similarly, deposits that show fluvial characteristics, but do not display weathering and lichen cover, are interpreted as post-Lake Devlin flood deposits, and are likely the deposits of the Caribou Creek flood. After noting characteristics of the various topographically different units and mapping the contacts of units, the fan-like Lake Devlin flood deposits and the other terraces near the confluence of North Boulder Creek and Caribou Creek were examined further. Again, Lake Devlin flood deposits were distinguished from glacial deposits based on clast roundness and the presence of imbricated boulders, and degree of weathering and lichen cover to distinguished Lake Devlin flood deposits from the younger Caribou Creek flood deposits. The field mapping of features and surficial units was used to construct a map in ArcGIS that differentiates deposits and individual terraces based on the aforementioned characteristics.

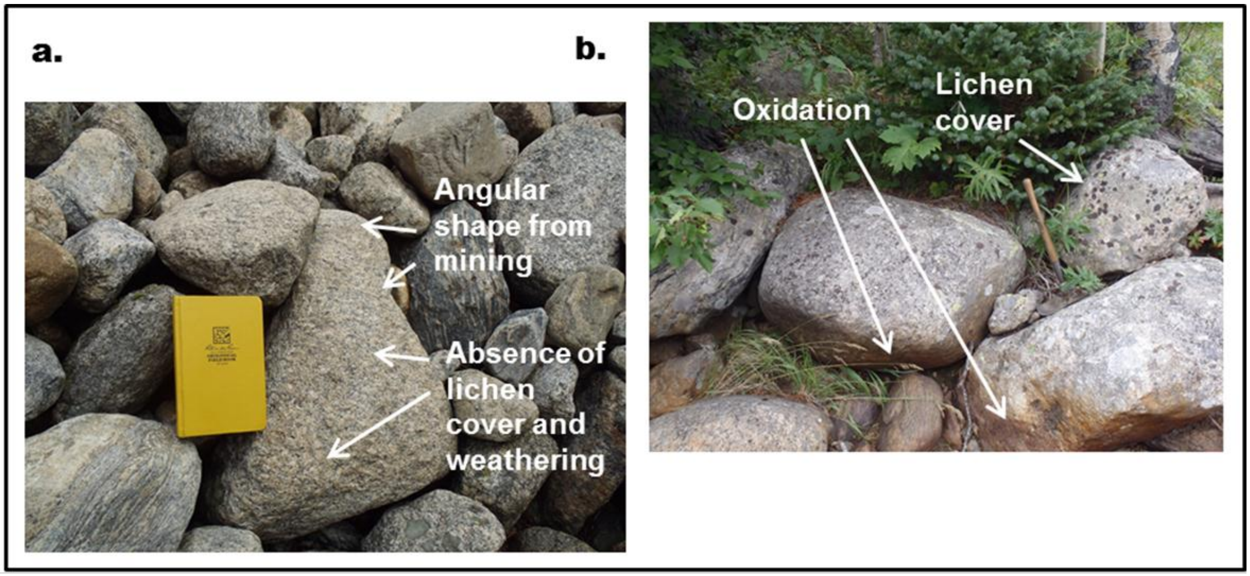

Figure 3. Side by side comparison of Caribou Creek and Lake Devlin flood deposits. (a.) Caribou Creek flood deposits absent of lichen cover and intense weathering. (b.) Weathered Lake Devlin flood deposits covered with lichen.

2.2 Grain size analysis

Grain size analysis samples were collected to describe the sorting of the Lake Devlin flood deposits, the glacial deposits, and other surficial materials near the confluence of North Boulder Creek and Caribou Creek. Samples were collected at least 0.5 m below the surface to obtain minimally weathered sediment representative of the original deposits. Exposures and dig-pits provided appropriate locations for taking samples that had experienced minimal weathering. Three grain size samples were collected to represent Lake Devlin flood deposits. Two came from site 030 and one came from site 157 (Figure 4). Two samples were collected at site 030 at different depths to examine any change in sorting with depth. A representative till sample was also collected, which is labeled as 149. Since site 149 has an exposure due to recent rock fall it provided an appropriate location for a pit with which to obtain a sample for till. The other samples from sites 128, 161, and 175 were collected to determine whether the deposits on the north side of North Boulder Creek resemble the Lake Devlin flood deposits. If so, this may suggest that deposits from the Lake Devlin flood extended across the North Boulder Creek valley floor, temporarily damming North Boulder Creek after the Lake Devlin flood. These samples were collected from sites 128, 161, and 175 (Figure 4).

In the laboratory, a 200 – 250 g random sample of each sediment collected was baked at a temperature of 82 - 91°C for several hours to remove any moisture. After initial baking, the dry weight of the sample was taken for percent volume by weight calculations. Samples were then wet-sieved over a number 200 sieve to remove particles finer than 0.075 mm (silt and finer). Samples were then baked again for several hours before being dry sieved on a Rotap RX – 29 sieve shaker. Sieve numbers utilized during dry sieving were: 5, 10, 18, 35, 60, 120, and 200. The mass of particles collected on each sieve was recorded and the weight percent of particles at each interval was calculated. Cumulative frequency curves were produced and uniformity coefficients calculated to quantitatively compare each sample. Uniformity coefficients were determined using the following equation:

$$\frac{D_{60}}{D_{10}} \tag{1}$$

where D_{60} is the particle diameter in millimeters at which 60 percent of the sample is finer, and D_{10} is particle diameter at which 10 percent of the sample is finer.

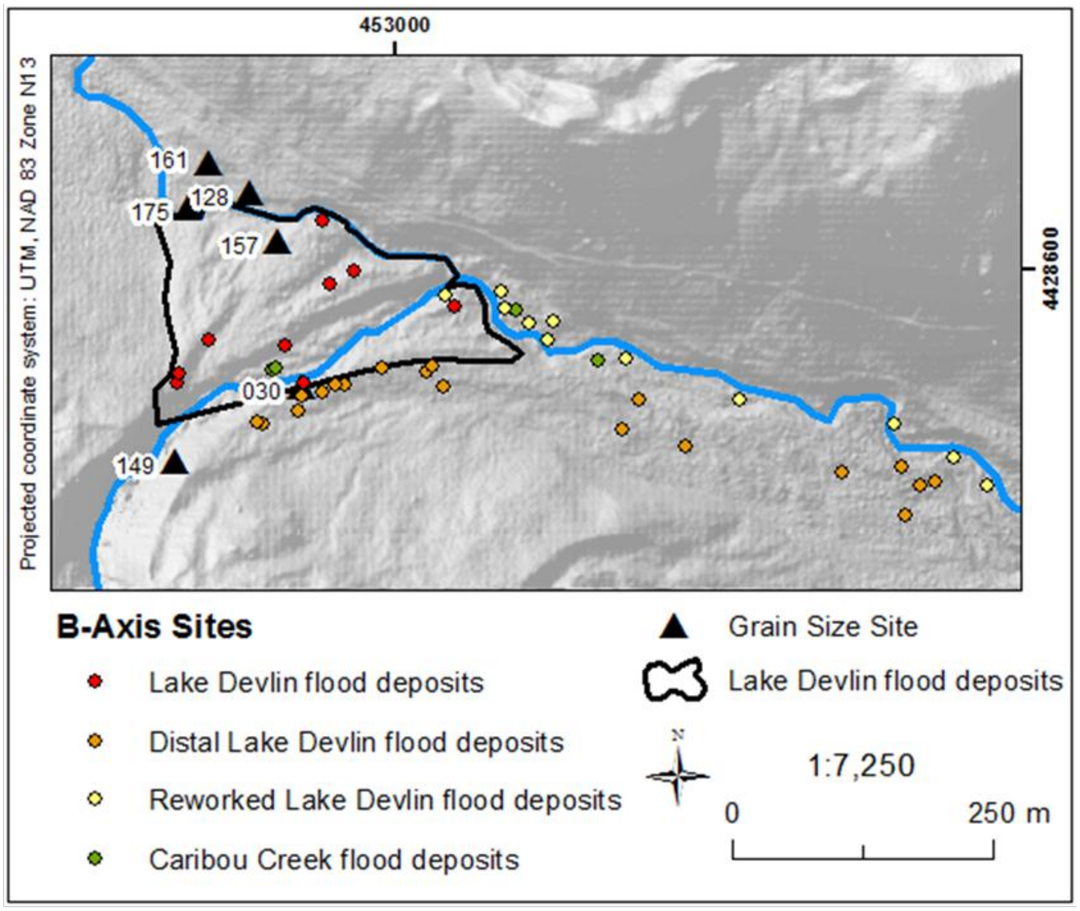

Figure 4. Field location of B-axis measurements and sediment samples.

2.3 Discharge

Peak discharge was estimated using field b-axes measurements of imbricated boulders from an equation estimated by Costa (1983). The approach used in this paper will utilize a velocity estimate as a function of particle diameter, the Manning equation to determine flood depth, and a GIS cross-section operation for channel width. Velocity and depth estimates were determined by the average size of the five largest particles transported during each flood. Two measurements of width from the LIDAR digital elevation model are used to estimate the upper and lower limit peak discharges for the Lake Devlin flood. Only one peak discharge estimate was determined for the Caribou Creek flood because the method by which width was measured for the upper limit Lake Devlin flood peak discharge is not applicable to the Caribou Creek flood.

2.3.1 Velocity

In the field, boulders displaying imbrication were measured in order to estimate flood velocity. Lichen cover and weathering of imbricated boulders allowed for classification of deposits as Lake Devlin flood deposits or Caribou Creek flood deposits. Lake Devlin flood boulders exhibit moderate lichen cover and weathering, whereas the Caribou Creek flood deposits do not. Measurements of Lake Devlin flood materials were divided further by location, ultimately producing a total of four categories of b-axis measurements: (1) Lake Devlin flood deposits; (2) Distal Lake Devlin flood deposits; (3) Reworked Lake Devlin flood deposits; (4) Caribou Creek flood deposits (Figure 4). Appendix 1 shows the coordinates and b-axis length measurements of each site shown in Figure 4. The Lake Devlin flood deposits are located in the fan-like landform outlined in Figure 2; these boulders were likely unaltered since deposition. The distal Lake Devlin flood deposits are found outside the main area of flood deposits. These boulders likely have not been remobilized since the Lake Devlin flood, but since these materials were deposited once the flood started flowing down North Boulder Creek, it is possible that these boulders were deposited under slightly different conditions than the axial deposits. Reworked Lake Devlin flood deposits are of Lake Devlin flood age, but are intermingled with material of Caribou Creek flood age and at locations that suggest reworking since the Lake Devlin flood, most likely by the Caribou Creek flood. Caribou Creek flood deposits are boulders deposited by the Caribou Creek flood based on lichen cover and weathering. The first two categories represent boulders deposited during the Lake Devlin flood, whereas the last two categories represent boulders last deposited during the Caribou Creek flood. The Lake Devlin flood deposits are the most representative of the peak outburst velocity during the Lake Devlin flood since they were deposited near the location of the dam failure under outburst depositional conditions as opposed to being deposited after floodwaters had been redirected down North Boulder Creek. Similarly, the Caribou Creek flood deposits are the most representative of the Caribou Creek flood since the reworked Lake Devlin flood deposits are boulders that happened to be on the channel bed during the flood and thereby do not necessarily represent material that was transported through the failure channel during the flood.

The equation utilized to estimate velocity from transported boulder size was determined by averaging the results of four different velocity estimate methods and regressing the average against the corresponding b-axis lengths of the largest transported boulders (Costa, 1983). The regression was run utilizing the average velocity estimate of the following four equations: the Helley balancing forces turning moments equation; the theoretical relationship equating fluid drag and lift forces to gravitational resistance for particle sliding; the United States Bureau of Reclamation riprap stability equation; and a basic data regression equation. The two theoretical methods are the Helley equation and the relationship between fluid drag and lift forces against gravitational resistance required for particle sliding, both of which solve for bed velocity. The bed velocity is converted to average velocity by multiplying bed velocity by 1.2. Both theoretical methods are based on equating fluid drag and lift forces to resisting forces. The Helley method estimates the velocity to overturn submerged particles by equating the resistance momentum of the particle with fluid, drag, and lift turning moments (Helley, 1969). The second theoretical method equates these forces to solve for the bed velocity required to initiate particle sliding instead of overturning (Bradley and Mears, 1980). After appropriate assumptions for mountainous channels are considered, this method estimates the bed velocity required to initiate sliding for a given particle size based on specific weight of the fluid and the particle, as well as the drag and lift necessary to overcome the gravitational and frictional resistance.

Two empirical methods for estimating flood velocity were also utilized. The United States Bureau of Reclamation equation was determined by data on riprap stability (Strand, 1973). The United States Bureau of Reclamation equation gives the highest velocity estimate of the four methods in alpine channels (Costa, 1983). The second empirical method was determined from a least-squares regression of particles at least 50 mm in diameter against corresponding flow velocities. The estimate based of the least-squares regression returns the lowest velocity estimates for floods in alpine channels (Costa, 1983). The second empirical equation was estimated by Costa (1983) for channels in the Colorado Front Range based on previous studies of velocities necessary to initiate motion of coarse particles (Sternburg, 1875; Hjulstrom, 1935; Sundborg, 1967; Malde, 1968; Birkeland, 1968; Baker, 1973).

The velocity estimates produced from the four aforementioned methods were utilized to estimate velocity required to transport 11 different particle sizes ranging from 50 to 3200 mm. The four results for each size were then averaged to produce a single, discreet estimate since no one method has proven better than another for paleo-flood velocity estimates in alpine channels. The average values of the four methods in previous studies were then regressed against the corresponding particle sizes. The resulting relationship, and the equation utilized to estimate velocity in this study, is shown in here,

$$v = 0.18\ D_I^{0.487} \tag{2}$$

where v is mean velocity and D_I is b-axis length (Costa, 1983).

2.3.2 Depth

Peak velocity estimates determined by Equation 2 were then utilized to solve for the depth of the peak discharge utilizing a rearranged Manning equation,

$$D = \left[v\ n/\sqrt{s}\right]^{1.5} \tag{3}$$

where D is depth, v is velocity, n is the roughness coefficient for the channel, and s is the slope of the channel. The slope of the failure channel was measured from the LIDAR DEM, measuring from the contact of the failed channel and Lake Devlin to the terminus of the failed channel. This assumes that slope is uniform throughout the failure channel. The slope of the failure channel was determined to be 0.117. A roughness coefficient of 0.124 was utilized as it represents an appropriate roughness coefficient for alpine channels with slopes of 0.10 (Costa, 1983).

2.3.3 Width

Two methods of width are utilized to estimate the upper and lower limit peak discharge estimates of the Lake Devlin flood. A range of discharge estimates is presented because of the uncertainty regarding channel dimensions during the peak discharge. Immediately following the initiation of the moraine dam failing, water must have overtopped moraine material that was not eroded during the initial dam break. In other words, the initial failure channel was not as deep at the beginning of the flood as it was after the flood. As the Lake Devlin flood continued, these materials were eroded and the channel bed was lowered until the waning stages of the flood, when the competence of the flood fell too low to cause further bed lowering. The peak discharge of the Lake Devlin flood could have occurred at any point during this dam break scenario. The peak discharge may have occurred immediately following the initiation of the failure while flood waters were overtopping and eroding the remaining dam materials, or it may have occurred later during the flood after all dam materials had been eroded in a channel similar to that of today's failure channel, or it may have occurred sometime in between.

From this dam break scenario, the maximum possible width of flood waters during the Lake Devlin flood peak discharge would have followed the initial overtopping, when flood waters theoretically may have been as wide as the current failure channel walls. Therefore, measuring the width of the entire failure channel gives the maximum possible width of the flood during peak discharge (Figure 5). This first width measurement method determined the width input used during the upper limit peak discharge estimation. In contrast, the narrowest possible width would be the channel width however many meters above the channel bed the Manning equation estimated the depth during peak discharge to be. The second method used the depth estimated by the Manning equation and cross sectional profiles to estimate channel width. The width determined by the second method provided the input used to determine the lower peak discharge estimate.

The first of the two width measurement methods estimates the depth used to calculate the peak discharge upper limit of the Lake Devlin flood. This method assumes that peak discharge occurred immediately after the dam began to fail, in a channel as wide and steep as the current failure channel, and as deep as the Manning equation estimates (Figure 5). Furthermore,

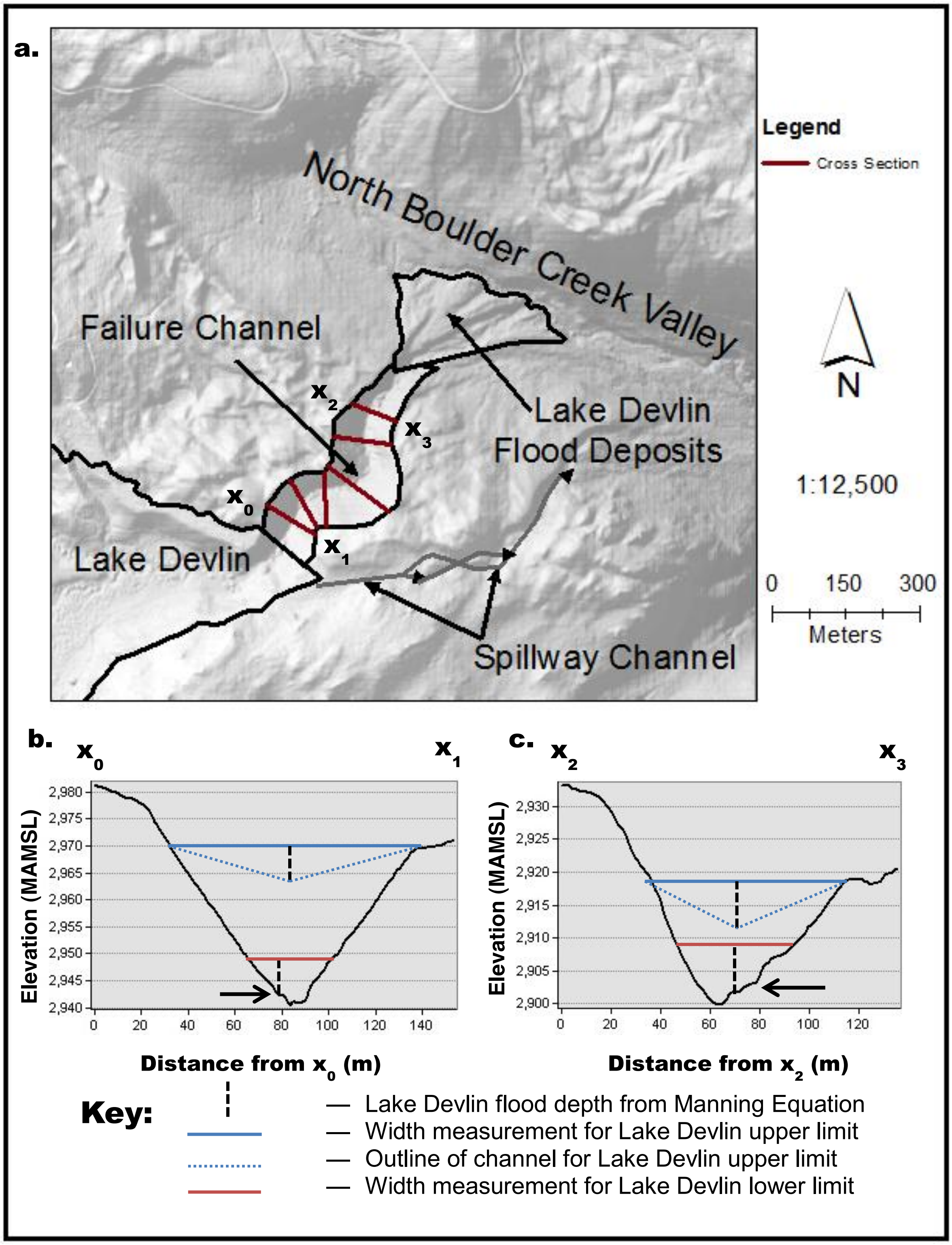

Figure 5. **(a.) Locations of the six cross sections used in determination of channel width for both methods used. (b.) Cross section of failure channel nearest to Lake Devlin with generalized width measurements for the Lake Devlin flood. (c.) Cross section of failure channel nearest to flood deposits with generalized width measurements for the Lake Devlin flood. Arrows indicate areas interpreted as channel bottom during the Lake Devlin flood.**

employing this method assumes that the current depth of the failure channel must be the result of erosion that occurred after the Lake Devlin flood peak discharge was reached.

In this first method, width was measured from one ridge of the failure channel, all the way across to the other, using the LIDAR DEM in ArcGIS. Six measurements of width were taken like this and averaged to produce the channel width ultimately used to determine the upper limit peak discharge of the Lake Devlin flood (Figure 5).

The first method is not employed for estimates of the Caribou Creek flood since it is highly improbable that the Caribou Creek flood occupied the entire failure channel produced during the Lake Devlin flood. In the field, the height of the wavecut platform on the moraine damming glacial Lake Devlin was measured using a laser rangefinder and found to be 21.3 m above the lake bottom. This infers that the Lake Devlin water level was regularly greater than 22 m, making it possible for the Lake Devlin flood to have attained a flood stage close to the height of the failure channel walls, which were measured to be about 1 – 2 m higher than the wavecut platform. The earthen dam that failed during the Caribou Creek flood was not nearly as tall as the moraine dam that failed during the Lake Devlin flood. Field measurements determined the height of sediments accumulated behind the dam to be 4.2 m above lake bottom, suggesting an initial water stage much lower than Lake Devlin and the failure channel walls. To summarize, the water stage behind the earthen dam was not nearly as close to the height of the failure channel ridges as the Lake Devlin was and, therefore, is not a reasonable candidate for the first method of estimating width.

The second method utilizes the depth estimates produced by the Manning equation and the cross sectional profile of the failure channel to estimate width. Six valley cross sections were obtained using 3D analyst in ArcGIS along the same six lines used in the first method. Two of the six cross sectional profiles are shown in Figure 5. Notice the terrace near the channel bottom in Figures 5(b) and 5(c). These are assumed to be cut terraces representative of the channel bottom during the Lake Devlin flood. To account for incision since the Lake Devlin flood, channel width was determined by adding the estimated depth to cut terrace elevations and measuring the failure channel width at said elevation. The average channel width from the six cross sections determined by this method for the Lake Devlin flood is 42.0 m with a standard deviation of 4.56.

Accounting for incision is not as necessary for the Caribou Creek flood since there is less than 90 years of incision to account for. Therefore, the Caribou Creek width was determined by adding the estimated depth to the current channel bottom and measuring across the channel. The average of the six width measurements was 22.2 m with a standard deviation of 3.37. Additionally, since the profile of the failure channel has only been minimally altered since the Caribou Creek flood, the peak discharge estimate for the Caribou Creek flood is neither an upper nor a lower limit.

The cross sectional area occupied during each flood event was determined by dividing the product of width and depth by two. The peak discharge for each flood was then estimated by multiplying the cross sectional area by the velocity estimated using Equation 3. In total, an upper and lower limit peak discharge was estimated for the Lake Devlin flood, and a peak discharge was estimated for the Caribou Creek flood.

3. Results

3.1 Mapping

Figure 6 shows the distribution of deposits near the failure channel of the Lake Devlin and Caribou Creek flood events. Several units existed prior to the Lake Devlin flood and remain undisturbed. ICSD is found on lateral moraine ridges of North Boulder Creek Valley. Characteristics of the ICSD include rolling surfaces, kettles, and scattered boulders ranging from <1 m to >3 m in diameter. Till is exposed along the North Boulder Creek Valley, near the southern lateral moraine. The topography of the till is much smoother than the ICSD, and pronounced relief is due to incision by ephemeral streams. Outwash deposited during the retreat of the combined Arapahoe and Green Lakes Valley glaciers is exposed at two locations south of North Boulder Creek. The valley wall on the north side of North Boulder Creek is bedrock thinly covered by colluvium. Exposed bedrock is observable at one location within the thinly covered bedrock on the northern valley wall. A more extensive bedrock exposure exists on the south valley wall near the spillway shown in Figure 2.

Two types of deposits are interpreted to contain original material from the Lake Devlin flood – Lake Devlin flood deposits and eroded till. The Lake Devlin flood deposit geometry generally resembles a fan. The surface of the Lake Devlin flood deposits forms terraces that include imbricated boulders throughout and terminate in large lobes. Part of the Lake Devlin flood deposits has since been incised by Caribou Creek. Lake Devlin flood deposits consist of eroded moraine material that occupied the failure channel before the flood. The eroded till has boulders with the same degree of weathering and lichen cover as Lake Devlin flood deposits. The materials are differentiated from other till deposits by the presence of imbricated boulder lobes that are parallel to North Boulder Creek. The eroded till consists of till that is covered by

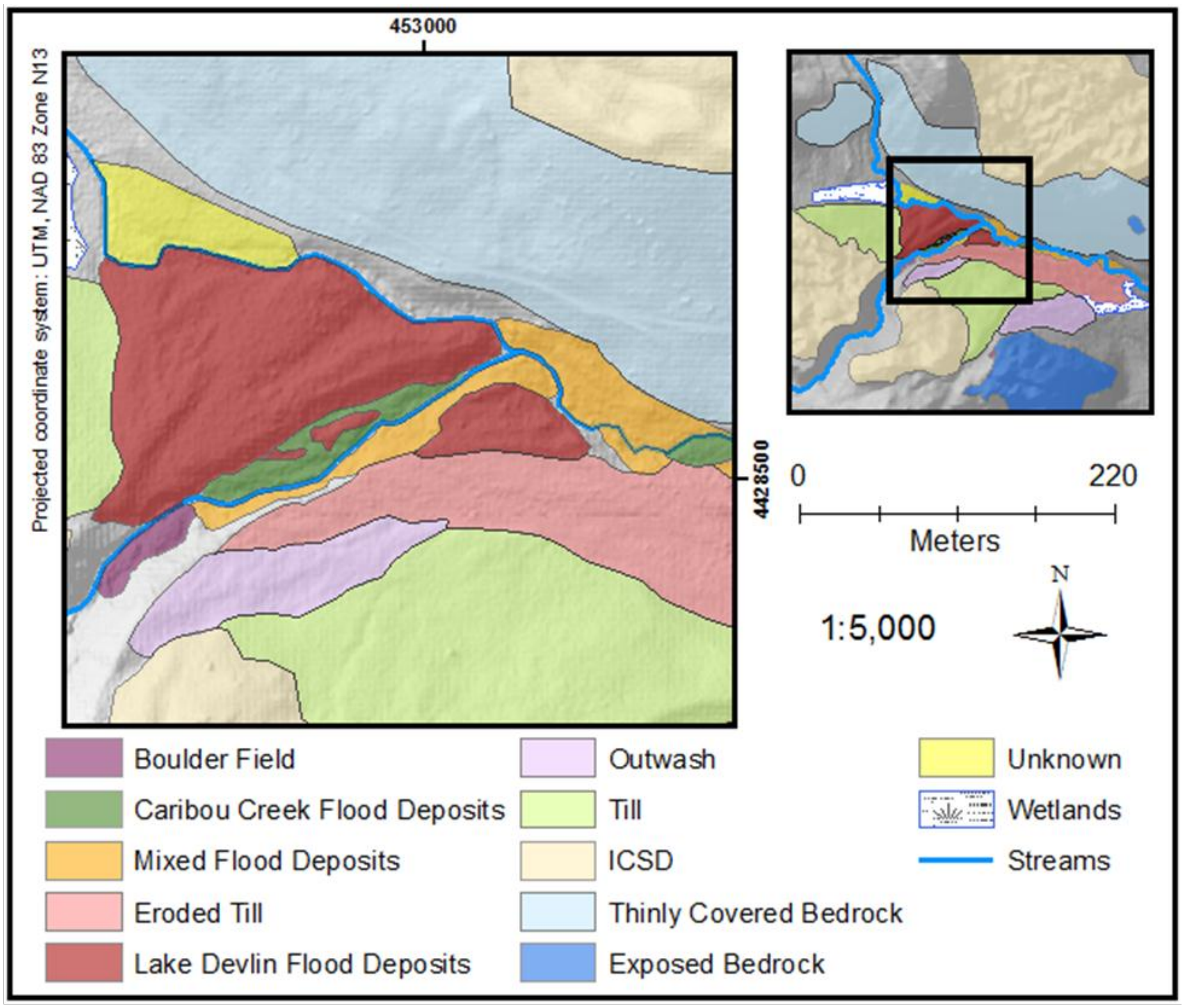

Figure 6. Map showing surficial materials found along Caribou Creek and North Boulder Creek near the Lake Devlin flood fan deposits.

deposits that were reworked after water from the Lake Devlin outburst began flowing down North Boulder Creek Valley.

Three additional deposits and areas of wetlands are also displayed in Figure 6. Caribou Creek flood deposits are characterized by imbricated boulders on terraces slightly above current river stage. They are differentiated from older flood deposits due to the lack of lichen cover and weathering. Areas shown as mixed flood deposits display imbricated boulders of both Lake Devlin flood age and Caribou Creek flood age and are found on Caribou and North Boulder

Creek flood plains. Mixed flood deposits were deposited at their current location during the Caribou Creek flood. Figure 6 also displays areas of unknown material, wetlands, and boulder fields, the latter of which is the result of rock fall. The area of unknown deposits were sampled for grain size analysis and compared to the sorting of the Lake Devlin flood deposits and the till deposits.

3.2 Grain Size Analysis

To help determine the origin of terrace material north of the confluence of North Boulder Creek and Caribou Creek referred to as unknown deposits in Figure 6, three sediment samples were collected for sieve analysis and compared to the representative till and Lake Devlin flood deposit samples. The sorting of each sample was quantified using uniformity coefficients (Equation 1). Recall that the sample from site 175 was collected from a terrace roughly 1 m above the current river level, whereas sample sites 128 and 161 are from a terrace roughly 4 m above the current river level. The results from grain size analysis (Figure 7) found that Lake Devlin flood deposits have uniformity coefficients within a range of 14 – 25, whereas the representative till sample has a uniformity coefficient that is much greater than 50. The three samples collected from sites 128 and 161 have nearly identical sorting to the till sample, whereas the sample from site 175 resembles fluvial deposition with a uniformity coefficient of 5. Since the sample from site 175 was collected from a terrace 1 m above current river stage and is better sorted than any of Lake Devlin flood samples, this terrace is likely composed of the floodplain deposits of North Boulder Creek, whereas the terrace from which samples 128 and 161 were collected likely are cut terraces composed of glacially deposited material.

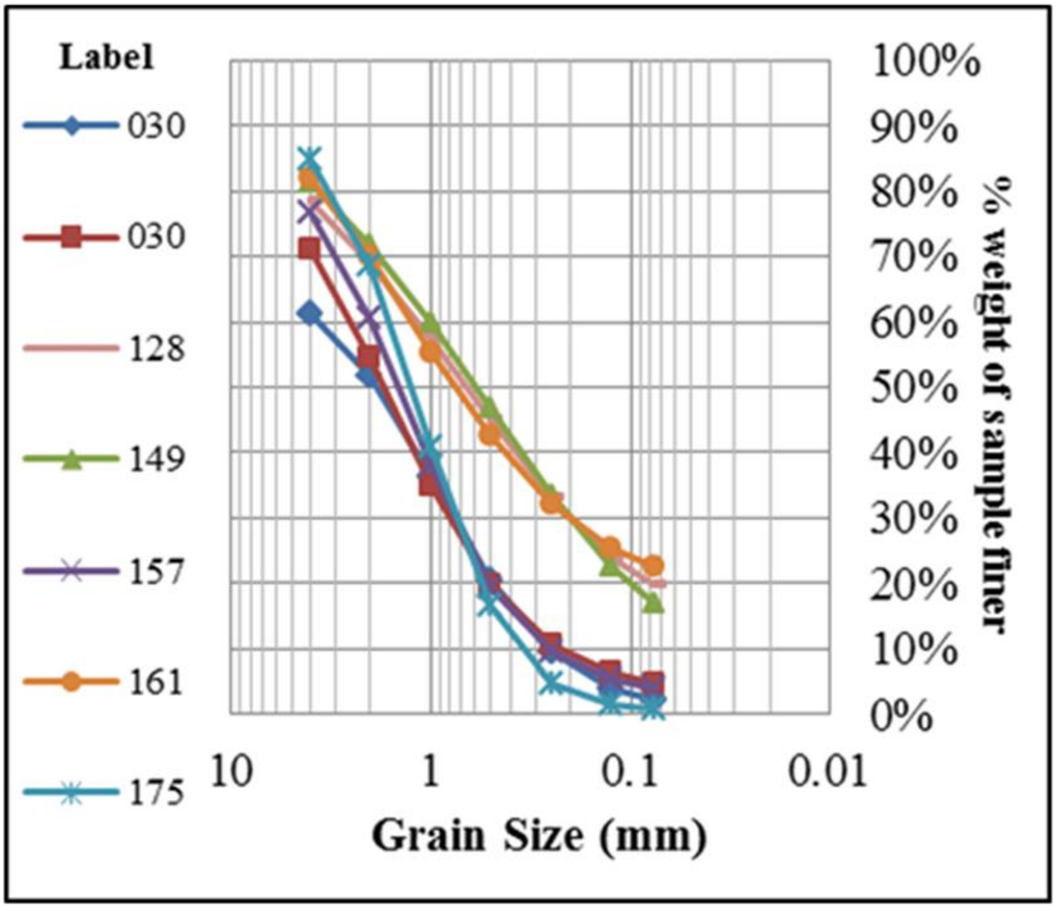

Figure 7. Cumulative distribution curves produced from grain size analysis. Site locations are shown and labeled in Figure 4.

3.3 Discharge

Velocity and depth results from the four categories of b-axis measurements are shown in Table 1. Peak velocity and depth are estimated based on the average b-axis length of the five largest transported boulders. Recall that the Lake Devlin flood deposits and distal Lake Devlin flood deposits represent boulders deposited during the Lake Devlin flood, whereas the reworked Lake Devlin flood deposits and Caribou Creek flood deposits represent boulders last deposited during the Caribou Creek flood. Since the mean b-axis lengths, and thereby velocity and depth of each flood are similar, the results of the deposits most representative of each flood event are utilized for peak discharge estimates. That is, the Lake Devlin flood deposits are used to determine the Lake Devlin flood peak discharge estimates and the Caribou Creek flood deposits are used to determine the Caribou Creek flood peak discharge.

The width estimate determined by the first width measurement method gave an average channel width of 114.17 m. An absolute upper limit peak discharge is estimated using this width. The upper limit peak discharge estimate based on the Lake Devlin flood deposit indicate that the Lake Devlin flood had a peak discharge around 2900 m^3/s (Table 2). For comparison, the distal Lake Devlin flood deposits produced just a slightly lower upper limit

Table 1. Number of b-axis measurements, mean of five largest b-axis measurements, peak velocity estimates, and depth estimates arranged by deposit

Deposit	*n*	Mean of 5 largest D_I (mm)	Velocity (m/s)	Depth (m)
Lake Devlin flood deposits	41	3020	8.9	5.8
Distal Lake Devlin flood deposits	53	2680	8.4	5.3
Reworked Lake Devlin flood deposits	38	1300	5.9	3.1
Caribou Creek flood deposits	16	1160	5.6	2.9

Notes: D_I = b-axis length

discharge estimate of 2600 m^3/s.

The second method used to measure the width of peak discharge during each flood event produces a lower limit peak discharge estimate for the Lake Devlin flood. This method was also utilized for the Caribou Creek flood. Averaging the width measurements from the six cross sections yielded average widths of 42.00 and 22.17 m for the Lake Devlin flood and Caribou Creek flood, respectively. The lower limit peak discharge of the Lake Devlin flood is estimated to be around 1100 m^3/s. The peak discharge estimate for the Caribou Creek flood is 180 m^3/s (Table 2).

Table 2. Upper and lower limit peak discharge estimates for Lake Devlin flood and the Caribou Creek peak discharge estimate.

Deposit	Velocity (m/s)	Depth (m)	Width (m)	Peak Q (m^3/s)
Lake Devlin flood deposits (upper limit)	8.9	5.8	114.17	2900
Lake Devlin flood deposits (lower limit)	8.9	5.8	42.00	1100
Caribou Creek flood deposits	5.6	2.9	22.17	180

Notes: Q = Discharge

4. Discussion

4.1 Mapping

One goal of the project was to map the location of the Lake Devlin flood deposits. Although a portion of the material transported during the Lake Devlin flood is present in the fan-like feature near the failure channel, it is unlikely that the volume of material removed from the moraine dam is accounted for in the fan. Some of this material was likely deposited further down North Boulder Creek Valley after the Lake Devlin flood was redirected. Additionally, some material originally deposited in the fan has been eroded by the incision of Caribou Creek and more recent flood events. The grain size analysis performed suggests that the unknown area does not contain Lake Devlin flood deposits. The samples from sites 128 and 161 indicate that the superior terrace largely consists of till material whereas the sample from site 175 indicates fluvial deposition. Lake Devlin flood deposits are found within the fan produced during the flood event, on the eroded till surface, and intermingled with Caribou Creek flood deposits on terraces slightly above current river stage along North Boulder Creek and Caribou Creek. From the lack of evidence of Lake Devlin flood deposits on the north shore of North Boulder Creek, two possible scenarios may have occurred. The first possibility is that distal fines of the Lake Devlin flood deposits occupied this area at one time but have since been eroded by North Boulder Creek. The second possible scenario is flood deposits never extended across the valley floor at that location.

The Lake Devlin flood deposits generally resemble a fan, and the sorting of particles and the topography of the deposits suggest high energy and nearly instantaneous deposition. The elevation of the Lake Devlin flood deposits is greatest in the western most extent and decreases down North Boulder Creek, suggesting erosion of these deposits as Caribou Creek migrated across and incised into them. The erosion of the Lake Devlin flood deposits is evidenced by the isolated Lake Devlin flood aged boulder deposits surrounded by Caribou Creek flood deposits (Figure 6) and the low-lying terraces of mixed flood deposits resulting from the Caribou Creek flood. Many of the boulders deposited during the Caribou Creek flood reside in these mixed flood deposits but there are areas of low-lying terraces that are predominantly Caribou Creek flood deposits. Considering Caribou Creek flood deposits are only found on the terraces slightly above current river stage, any Caribou Creek flood deposits found outside the mapped area are expected to be on similar terraces.

Two questions arise concerning the origin of boulders on the eroded till. The first question is the location at which boulders deposited on the eroded till were first entrained. If the boulders were eroded from the moraine dam, then the Lake Devlin flood maintained enough competence to keep transporting boulder sized particles after even after being redirected down North Boulder Creek. On the other hand, it could be that most of the boulder sized particles eroded from the moraine dam were deposited with the Lake Devlin flood deposits. In this scenario, local entrainment and deposition of boulders residing in the valley till prior to the flood compose the imbricated boulders on the eroded till. A combination of the two origins is most likely the case, but the true origin remains uncertain. The second question is whether or not the boulders were deposited under debris flow conditions. Following natural dam failures, easily erodible sediments can be incorporated into flood waters, which can change the fluid mechanics of the flow and cause discharge to increase instead of dissipate downstream of the dam failure (Costa and Schuster, 1988). If this was the case, material deposited during the Lake Devlin flood could extend much further downstream than initially thought. However, the scope of this study is concerned with mapping deposits and estimating peak discharge at the dam failure. Because there is no guaranteeing that any boulders deposited outside of the Lake Devlin flood deposits were transported through the failure channel used to determine cross sectional area, the Lake Devlin flood deposits are most representative of boulders transported through the failure channel during peak discharge.

4.2 Discharge

The second goal was to estimate the peak discharge of the two floods. Assuming that the Lake Devlin flood peak discharge occurred during the dam failure when the channel was 5.8 m deep and as wide as the current channel walls, a peak discharge of 2900 m^3/s was estimated for the Lake Devlin flood. The peak discharge estimate of 2900 m^3/s represents the absolute upper limit peak of the Lake Devlin flood.

If the true peak discharge was close to the upper limit estimate, the following scenario would have occurred. Peak discharge was reached shortly after the dam failure and then followed by a period of waning flow until Lake Devlin completely drained. During peak discharge, flood waters overtopped a portion of the damming materials that remained following the initiation of the failure, causing flood waters to flow through a channel roughly 114.17 m wide by 5.8 m deep. The slope of this channel is assumed to be the 0.117, the slope of the channel today. During and following peak discharge, the moraine dam continued to be eroded, thereby increasing the depth of the failure channel. Between peak discharge and the end of the Lake Devlin flood, the failure channel was eroded from the peak discharge depth of 5.8 m below the failure channel walls, to the channel depth inferred from cut terrace surfaces highlighted in Figure 5.

The lower limit peak discharge estimate for the Lake Devlin flood utilized the cut terraces to represent the channel bed during peak discharge and determined width by measuring the channel width 5.8 m above the cut terraces. The average of the six width measured with this method represents the narrowest possible channel width that the Lake Devlin flood peak discharge. The resulting lower limit peak discharge estimate for the Lake Devlin flood is 1100 m^3/s. In this scenario, the dam would have initially been eroded at a steady rate, slowly draining Lake Devlin. After a certain amount of steady erosion had occurred and Lake Devlin approached complete drainage, the remaining dam material would have had to fail instantaneously, causing the remainder of Lake Devlin to drain all at once. In this scenario, the peak discharge is reached following the collapse of any remaining dam materials in a channel roughly 42.0 m wide and 5.8 m deep. It is likely that the true peak discharge was actually reached sometime after the failure channel had been eroded past 5.8 m deep and before the channel depth after the flood, indicated by the cut terraces, was reached. As such, the true peak discharge lies somewhere between the limits presented.

Assuming the specific weight of the floodwaters remains constant, and the damming materials were not all eroded away instantaneously at the onset of the failure, the peak discharge likely occurred when the slope between the dam materials remaining and North Boulder Creek Valley was the greatest. This of course is not the whole case. Since the elevation of the valley, or the bottom of the slope, is steady relative to the dam height, it is only by increasing the dam height that the slope may be increased. If however the dam height is too high, the volume of water that is capable of overtopping the dam is limited. Therefore, both the channel slope and the volume of water capable of overtopping the dam are functions of the height of the remaining dam materials, but one is positively related to dam height while one is negatively related. Assuming everything else is constant throughout the flood, this simplified logic suggests that peak discharge occurred when some ideal balance between the slope of the channel and the volume of water capable of overtopping the dam was attained.

Since the Caribou Creek flood occurred less than 90 years ago, six width measurements of the channel 2.9 m above the current channel bottom were averaged to produce the Caribou Creek flood width. The resulting peak discharge estimate was 180 m^3/s. This estimate is straight forward compared to the Lake Devlin peak discharge estimates. This is because the channel today has only changed slightly since the Caribou Creek flood, whereas the Lake Devlin channel changed very drastically while the flood was occurring and experienced 14 ka of floods and stream response since the Lake Devlin flood.

As mentioned earlier during the discussion of the eroded till, the Lake Devlin flood had enough power after draining and redirecting down North Boulder Creek to keep boulder sized particles in suspension and/or entrain material further down North Boulder Creek from the outburst, possibly to the point of developing into a debris flow. Inferences regarding the possible development of a debris flow and the extent of the Lake Devlin flood deposits can be drawn from comparisons with studies of the Lawn Lake flood, which occurred in the Colorado Front Range roughly 70 km north of the Lake Devlin field area. The Lawn Lake flood occurred in 1982 as the result of a failed man-made dam in Rocky Mountain National Park. Lawn Lake was smaller than Lake Devlin is believed to have been, containing 831,000 m^3 of water compared to the minimum estimate of 12,000,000 m^3 for Lake Devlin. The Lawn Lake flood had a peak discharge of 510 m^3/s, which is almost half of the lower limit peak discharge estimate for the Lake Devlin flood (Jarrett and Costa, 1986). Similar to the Lake Devlin flood, the Lawn Lake flood flowed from a steep river into a gentler sloping basin river, producing a 172,000 m^2 fan-like deposit containing 279,000 m^3 of material in the basin. Although the boulder sized particles transported during the Lawn Lake flood were deposited in the fan, flood waters continued to carry finer particles as far as Lake Estes, roughly 12 km from the fan, likely due to increased competence after joining the basin river. This suggests that much of the coarse material removed from the moraine dam is found in the fan-like Lake Devlin flood deposits. Considering the difference in peak discharge of each flood however, the possibility of boulder sized particles being transported more than 580 m from the fan axis, which was the maximum distance for the Lawn Lake flood, cannot be ruled out (Jarrett and Costa, 1986).

5. Conclusions

This study has used relative dating methods, landforms, and grain size distributions to map the geologic deposits around the confluence of North Boulder Creek and Caribou Creek and has identified the Lake Devlin flood deposits, the Caribou Creek flood deposits, and other deposits that were affected by one or both of the floods. Additionally, this study has shown how the peak discharge of the Lake Devlin and Caribou Creek floods can be estimated using field measurements of particles transported during the flood and GIS analysis with high-resolution LIDAR digital elevation models.

Mapping of deposits further down North Boulder Creek is necessary before the true extent of the Lake Devlin and Caribou Creek flood deposits can be determined, but evidence from the Lawn Lake flood suggests that damming materials are likely located in close proximity to the fan. Following this logic, any Lake Devlin flood deposits found further downstream than the mapped area would have to be materials eroded from the valley till, and not from the failed moraine. However, considering the difference in peak discharges for the Lawn Lake and Lake Devlin floods, the Lawn Lake flood should not be used as an analog for Lake Devlin flood deposit extent.

Investigating soil profiles developing in the till upstream from the Lake Devlin flood deposits could provide a description of a paleosol to look for in eroded till exposures. If such a paleosol does exist in the eroded till, the overlying soil profile could be used to better describe the eroded till deposits, their origin and how they compare with young soils developing on the Lake Devlin flood deposits. Additionally, these paleosols would provide a way to measure flood deposit depth at various locations. Interpolating between recorded depths gives the mapped deposits a third dimension, from which the volume of the flood deposits can be calculated.

Discharge estimates can be enhanced by better estimating width from field observations of high water marks or determining the channel bottom based on field evidence. First, investigating the failure channel in the field for evidence of a high water mark from which to measure channel width from would provide the ideal width to use when estimating peak discharge. The high water mark will more accurately represent the maximum possible width than the first method used to determine width. The second way the width estimate can be enhanced would be to account for incision by confirming cut terraces as channel bottoms or using an average incision rate for steep, alpine channels to estimate the channel bed at the time of the flood.

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Appendix 1: B-axis measurement data and site location organized by site number

Site Number	Deposit[1]	Easting[2]	Northing	D_I 1[3]	D_I 2	D_I 3	D_I 4	D_I 5	D_I 6	D_I 7	D_I 8
4	1	452790	4428490	1.1	1.5	1.8	*	*	*	*	*
6	1	452820	4428533	1.5	1	3	2.6	2.1	*	*	*
11	1	452937	4428585	0.9	0.6	0.5	1.2	1	*	*	*
31	3	453048	4428575	0.75	0.75	0.75	*	*	*	*	*
33	1	452912	4428490	0.8	0.75	0.75	0.75	0.75	*	*	*
35	3	453331	4428475	1.5	0.95	0.85	0.8	*	*	*	*
37	1	452894	4428527	3.5	3.3	2.7	*	*	*	*	*
38	4	452881	4428503	1	0.95	0.9	*	*	*	*	*
78	4	453195	4428513	0.65	0.45	0.36	0.35	0.3	*	*	*
79	3	453221	4428514	0.8	0.75	0.7	0.58	0.44	0.44	0.36	0.32
83	2	453489	4428363	0.9	0.78	0.72	0.65	0.57	*	*	*
84	3	453569	4428393	0.85	0.97	*	*	*	*	*	*
85	3	453536	4428419	1.32	1.26	1.25	*	*	*	*	*
88	2	453487	4428410	1.25	1.24	1.15	*	*	*	*	*
94	2	453519	4428396	1.5	1.3	1.1	0.95	2.9	1.5	*	*
95	2	453503	4428392	2.1	2	1.9	1.7	1.6	1.4	1.3	*
96	2	453429	4428405	0.95	0.95	0.9	0.75	0.65	0.65	*	*
104	1	453057	4428564	3.2	3.2	1.65	*	*	*	*	*
107	2	452911	4428479	0.51	*	*	*	*	*	*	*
108	2	453046	4428487	0.79	*	*	*	*	*	*	*
109	2	453029	4428501	0.41	0.37	*	*	*	*	*	*
110	2	452988	4428506	0.46	0.38	0.36	*	*	*	*	*

(Continued)

111	2	452951	4428488	0.8	0.72	*	*	*	*	*	*
112	2	452943	4428489	0.45	*	*	*	*	*	*	*
113	2	452930	4428482	0.69	0.28	*	*	*	*	*	*
114	2	452907	4428463	0.75	0.6	*	*	*	*	*	*
115	2	452873	4428451	0.56	0.21	*	*	*	*	*	*
116	2	452867	4428452	0.58	*	*	*	*	*	*	*
117	2	453034	4428506	0.39	*	*	*	*	*	*	*
120	2	453219	4428445	0.72	0.55	*	*	*	*	*	*
123	2	453234	4428474	1.14	0.9	0.65	0.48	*	*	*	*
125	2	453279	4428430	1.2	0.98	0.56	0.83	*	*	*	*
133	3	453151	4428549	0.94	*	*	*	*	*	*	*
143	3	453480	4428452	1.12	0.73	0.57	*	*	*	*	*
150	1	452793	4428500	1.7	1.25	*	*	*	*	*	*
151	4	452886	4428504	0.83	0.75	0.5	0.22	*	*	*	*
154	1	452960	4428597	1.35	1.2	0.85	*	*	*	*	*
155	1	452930	4428646	1.12	1.06	0.81	*	*	*	*	*
168	3	453146	4428531	0.98	0.82	*	*	*	*	*	*
169	3	453129	4428548	0.83	0.62	0.58	0.44	0.4	0.35	*	*
170	4	453115	4428560	0.42	0.38	0.37	0.36	0.35	*	*	*
171	3	453106	4428562	0.49	0.47	0.4	*	*	*	*	*
172	3	453102	4428579	0.53	0.42	0.39	0.31	*	*	*	*

Notes: [1] Deposits are numbered as follows: 1 = Lake Devlin flood deposits; 2 = distal Lake Devlin flood deposits; 3 = reworked Lake Devlin flood deposits; 4 = Caribou Creek flood deposits; [2] Easting and northings are for UTM NAD 83 Zone N13; [3] D_I = b-axis length; all lengths are shown in meters