

Glacial conditioning of stream position and flooding in the braid plain of the Exit Glacier foreland, Alaska



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ABSTRACT

Flow spilling out of an active braid plain often signals the onset of channel migration or avulsion to previously occupied areas. In a recently deglaciated environment, distinguishing between shifts in active braid plain location, considered reversible by fluvial processes at short timescales, and more permanent glacier-conditioned changes in stream position can be critical to understanding flood hazards. Between 2009 and 2014, increased spilling from the Exit Creek braid plain in Kenai Fjords National Park, Alaska, repeatedly overtopped the only access road to the popular Exit Glacier visitor facilities and trails. To understand the likely cause of road flooding, we consider recent processes and the interplay between glacier and fluvial system dynamics since the maximum advance of the Little Ice Age, around 1815. Patterns of temperature and precipitation, the variables that drive high streamflow via snowmelt, glacier meltwater runoff, and rainfall, could not fully explain the timing of road floods. Comparison of high-resolution topographic data between 2008 and 2012 showed a strong pattern of braid plain aggradation along 3 km of glacier foreland, not unexpected at the base of mountainous glaciers and likely an impetus for channel migration. Historically, a dynamic zone follows the retreating glacier in which channel positions shift rapidly in response to changes in the glacier margin and fresh morainal deposits. This period of paraglacial adjustment lasts one to several decades at Exit Glacier. Subsequently, as moraine breaches consolidate and lock the channel into position, and as the stream regains the lower-elevation valley center, upper-elevation surfaces are abandoned as terraces inaccessible by fluvial processes for timescales of decades to centuries. Where not constrained by these terraces and moraines, the channel is free to migrate, which in this aggradational setting generates an alluvial fan at the breach of the final prominent moraine. The position of this fan is glacially conditioned but the process of migration of the braided channels across it is not. This broad perspective on channel controls identifies incipient avulsion into the roadside forest as part of a long-term fan-building process independent from changes in streamflow or sediment load.

1. Introduction

Exit Glacier is one of the most accessible glaciers in Alaska, spilling from the Harding Icefield to near sea level in a broad valley near Seward, AK (Fig. 1). Each summer, > 100,000 visitors drive to visitor facilities at the end of Herman Leirer Road, the only road in Kenai Fjords National Park, where a short walk takes them to the glacier terminus. The glacier's gradual retreat, though not unusual in the context of other Alaskan glaciers, has become a highly visible symbol of the effects of climatic change on glaciers (Rampton, 2015). Park interpretive staff and exhibits focus visitor attention on this retreat, and it

is therefore not surprising that glacier change was one of the first suspects when, in 2009, the proglacial stream that emerges from Exit Glacier exhibited a notable increase in spilling from its active braid plain, damaging the Park entrance road (Fig. 2).

Beginning in 2009, flow from an unnamed proglacial stream here referred to by its local name, Exit Creek, overtopped a 300-m section of Herman Leirer Road at least annually, forcing road closures and costly road repairs and restricting visitor access to one of the most visited national parks in Alaska during the middle of the summer tourist season. The main channels of Exit Creek parallel the road > 100 m away (Fig. 2) and had only occasionally spilled sufficiently to overtop

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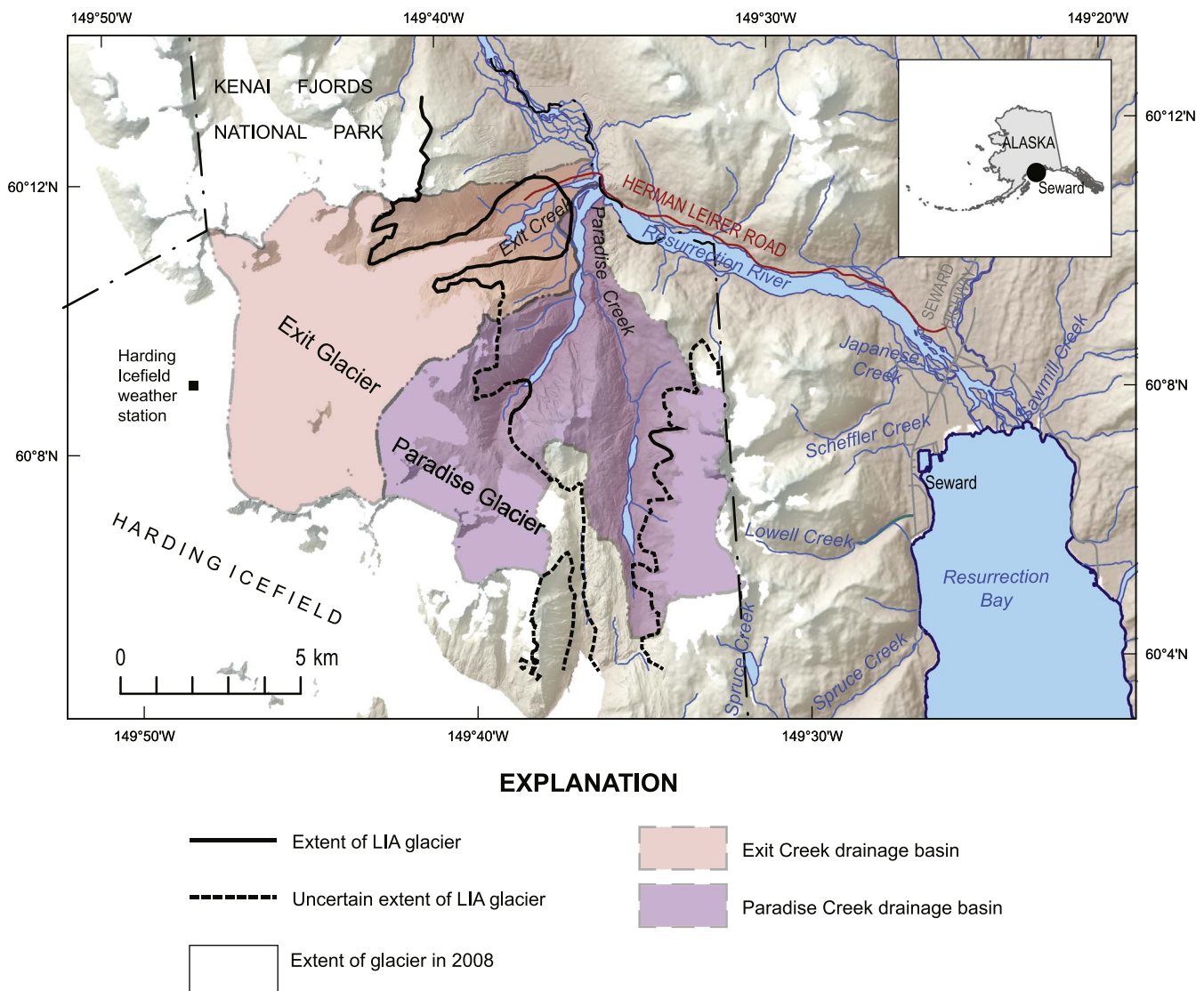


Fig. 1. Map of Exit Creek and Paradise Creek, Alaska, locations, drainage area boundaries, and maximum extent of Little Ice Age (early 1800s) glaciers. Base map is from the National Map. Modern glacier boundaries are from Randolph Glacier Inventory. Drainage area boundaries and maximum Little Ice Age glacier extents are available as Supplementary data.

the road since at least the construction of a road bridge over the Resurrection River in the mid-1980s (Tetreau, 1993; Barber, 2003; Gray, 2003; Martin, 2006) and likely since road construction in the early 1970s (Sloan, 1985). A 2002 study (Barber, 2003; Gray, 2003) attributed the occasional road flooding to Exit Creek spilling into the roadside forest but concluded from the limited topographic data available at the time that Exit Creek was stable. In 2013, the National Park Service (NPS) sought a reassessment of the river and watershed conditions leading to the more frequent flooding. Their goal, which motivated the work presented here, was to understand the likely persistence of the flooding problem and to have a scientific basis to evaluate the efficacy of various road improvement options.

In light of Exit Glacier's well-documented history of post-Little Ice Age (LIA) retreat since the early 1800s (Wiles and Calkin, 1994; Cusick, 2001), we initially approached the cause of increased flooding by examining the first-order forcing mechanisms for fluvial change. Discharge (from shrinking glaciers—the *deglaciation discharge dividend*; Collins, 2008) and sediment yield (from newly exposed, unvegetated proglacial terrain; Leonard, 1986) typically increase in a *paraglacial* period during and following deglaciation (Church and Ryder, 1972). Our interest grew to include other processes directly conditioned by glaciation, including the constraints imposed on a stream channel's

lateral position and longitudinal gradient by unstable post-glacial landforms such as moraines, alluvial fans, and abandoned fluvial terraces (e.g., Gurnell et al., 2000; Marren and Toomath, 2013) and also by the glacier itself (e.g., Shreve, 1972). In environments without these transient constraints, the tendency of a braided river to shift rapidly within a braid plain makes the suite of historical channel positions a useful predictor of future fluvial paths (Curran and McTeague, 2011). In braid plains conditioned by recent deglaciation, however, changes in channel position—and hence flood hazard—require consideration of more complex processes than simple historical occupation. The glacier loss presently common in Alaska and the Pacific Northwest establishes a widespread setting for potentially dynamic controls on fluvial systems.

Here, we present results of a broad assessment of the hydrology and geomorphology of Exit Creek. We interpret the present condition in the context of glacial and geomorphic changes that have occurred since the LIA in the entire proglacial valley, and evaluate the degree to which historical fluvial occupation can describe expected future reoccupation in a paraglacial setting. We draw attention, in particular, to the history of transient channel adjustments that are, in our view, critical for understanding the most recent history of flooding on the Exit Glacier access road.

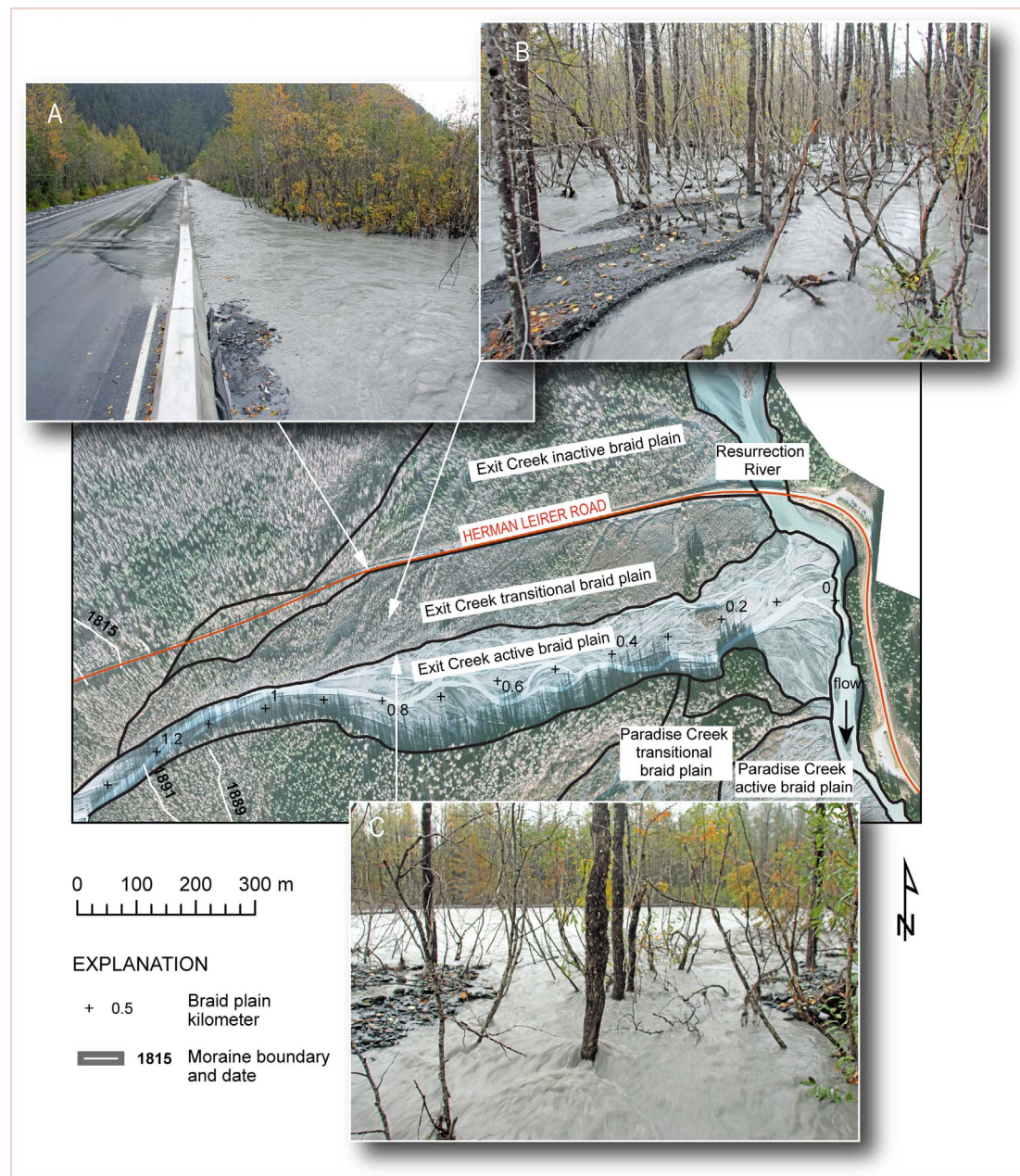


Fig. 2. Photographs during a flood of Herman Leirer Road on 6 September 2013. Background image is an orthophoto showing low flow conditions on 12 October 2012 and modern channel extents (ca. 2012). (A) Flow coalescing near the roadway, inundating the roadside ditch, and flooding onto the roadway through relief slots in the temporary concrete barricade. (B) Flow from multiple breaches braiding around bars of fresh sediment in the forest. (C) A breach in the Exit Creek braid plain at BPK 0.8.

1.1. Physical setting

Exit Creek drains a 57-km² basin in the Kenai Mountains near Seward, AK (Fig. 1). The Kenai Mountains form the eastern side of the Kenai Peninsula and include rugged peaks up to 2000 m in elevation dissected by several deep valleys, including the Resurrection River valley near the study area. The Exit Creek basin is underlain by rocks of the Upper Cretaceous Valdez Group, a widespread lithologic unit consisting primarily of marine sedimentary rocks formed at the edge of the subducting Pacific Plate. Granitic plutons have been mapped elsewhere among exposed rocks of the Harding Icefield, and it is possible that minor outcrops exist beneath the glaciers of the study area (Tysdal and Case, 1979). High-elevation, glacier-covered or sparsely vegetated slopes transition to mixed deciduous and coniferous forests in the lowland valleys. The Exit Creek basin reaches 1660 m in elevation and is more than two-thirds covered by Exit Glacier (Fig. 3), a land-

terminating outlet lobe of the Harding Icefield, an 1800-km² ice-covered plateau in the southern Kenai Peninsula. Adjacent to Exit Creek is the 60-km² Paradise Creek basin, which is one-third glacier covered and originates in an outlet lobe of the Harding Icefield on the west side of the basin and isolated glaciers on the east side of the basin. Exit Creek and Paradise Creek share a broad glacier foreland (Fig. 3B), which we define as the presently unglacierized terrain between the modern glacier margins and the downstream confluence with Resurrection River, which flows into the Pacific Ocean near Seward, ~14 km downstream. Although the main channels of Exit and Paradise creeks presently discharge independently to the Resurrection River, the fluvial and broader geomorphic histories of these two basins are closely related; we therefore include the Paradise Creek basin in our study area.

Exit Glacier's history of late Holocene fluctuation is closely linked with that of Paradise Glacier and other nontidewater outlets of the Harding, which like many glaciers of the Kenai Mountains experienced



Fig. 3. Photographs of (A) Exit Glacier and Exit Creek viewed from near the 1951 moraine and (B) Paradise Creek at the confluence with Resurrection River (foreground) and the Exit-Paradise glacier forelands extending to Exit Glacier (center background).

general periods of LIA expansion in the twelfth, seventeenth, and nineteenth centuries (Barclay et al., 2009). Exit Glacier's post-LIA retreat from a terminus position only ~1 km from the Resurrection River began in the early 1800s and progressed very slowly through the remainder of the nineteenth century. As with most land-terminating glaciers of the Harding Icefield, Exit Glacier subsequently retreated more rapidly, with only minor and short-lived re-advances, during the twentieth and early twenty-first centuries. That ~2 km retreat exposed a gently sloping, dominantly alluvial foreland that transitions abruptly to steep bedrock near the margin of the modern glacier terminus.

The study area lies within a part of the Kenai Mountains bordering the Gulf of Alaska, where coupled topographic and maritime influences yield large amounts of precipitation and moderate temperatures. Data extracted from the Oregon State University PRISM Climate Group's 771-m gridded reanalysis products (Gibson, 2009a, 2009b, 2009c) show average basinwide temperature and precipitation in the Exit and Paradise creek drainage basins that are cooler and wetter than nearby subarctic, coastal Seward. The basins are similar to each other, collectively have an average January low temperature of -11°C and an average July high temperature of 13°C , and receive an annual average of 276 cm of precipitation. Although an average of at least 9 cm of precipitation falls in every month, June and July are the driest months and September and October are the wettest.

2. Methods

To determine the geomorphic and hydrologic factors associated with the recent overbank flooding, we capitalized on the relatively rich history of remotely sensed data for the Exit Glacier area. These data provided a window into over a half century of glacier and fluvial conditions, which we supplemented with available modern climate and hydrology data. We conducted fieldwork to ground-truth and supplement the remote sensing data.

2.1. Mapping

Remotely sensed elevation data and recent and historical aerial imagery (see Supplementary data, Table A1) formed the basis for mapping, measurement, and interpretation of geomorphic features. A 2-m pixel resolution digital elevation model (DEM) created from 2008 LiDAR data provided bare-earth elevation data and hillshade models for most of the study area. A project-specific 2012 photogrammetrically derived 1-m DEM provided elevation data for analysis of change along unvegetated portions of Exit Creek and the lower part of Paradise Creek. Aerial photos and orthophotos of sufficient resolution and image

quality for historical comparisons of landscape change were available for decadal-scale intervals from 1950 to 2005, for 2007, and for 2012. Topographic maps from 1911 and 1950 provided historical data for analysis of glacier and channel positions. We supplemented mapping data with field observations from 2012 to 2014 reconnaissance of the Exit-Paradise glacier forelands and selected features previously mapped by others. All map delineations were drawn on-screen by heads-up digitizing in a geographic information system (GIS) at scales noted. Locations along streams are denoted with braid plain kilometers (BPK), as measured upstream from each stream's confluence with Resurrection River.

Modern and late-LIA maximum glacier boundaries reflect a combination of published sources and new mapping. To determine modern upper elevation boundaries of Exit Glacier and Paradise Glacier, where these glaciers merge at their flow divides with other glaciers of the Harding Icefield, we relied upon patterns of ice movement determined from flow vectors computed using offset techniques between 31 December 2006–15 February 2007 and 25 January 2010–12 March 2010 satellite image pairs (Burgess et al., 2013), and also upon crevasse orientations in the 2007 orthophoto. Modern terminus positions were taken from the Randolph Glacier Inventory (Pfeffer et al., 2014). Moraine positions and ages that document the post-LIA retreat history of Exit Glacier were adopted directly from Cusick (2001). The farthest downstream terminal moraine fragment mapped by Wiles and Calkin (1994) reflects the glacier's late-LIA maximum advance. We used the 2008 LiDAR hillshade model, supplemented by aerial photography (Table A1), to identify additional terminal moraines, lateral moraines, and trimlines that reflect this LIA maximum advance for Exit Glacier and Paradise Glacier. We digitized these features at about 1:5000 to map a continuous lower boundary of these adjacent glaciers during the late-LIA maximum. Together, the tight complex of moraines from the late 1800s forms a prominent topographic feature that we refer to here as the LIA moraines.

Surface water basin boundary delineations for Exit Creek and for Paradise Creek were modified from Stark et al. (2015) watershed delineations to reflect additional sources of information. The manual delineations incorporated traditional topographic divides determined from 2008 LiDAR data and topographic maps, the modern glacier boundaries, and field and aerial photo observations. On the glacier forelands, alluvial fans—recognized from their cone-shaped profile and location emanating from a current or inferred previous water source—create an ambiguous divide between Exit and Paradise basins. This ambiguity is reflected by the path of historic and contemporary trans-basin flow from Paradise Creek into Exit Creek and required an arbitrary distinction between the two basins. Above the LIA moraines, the

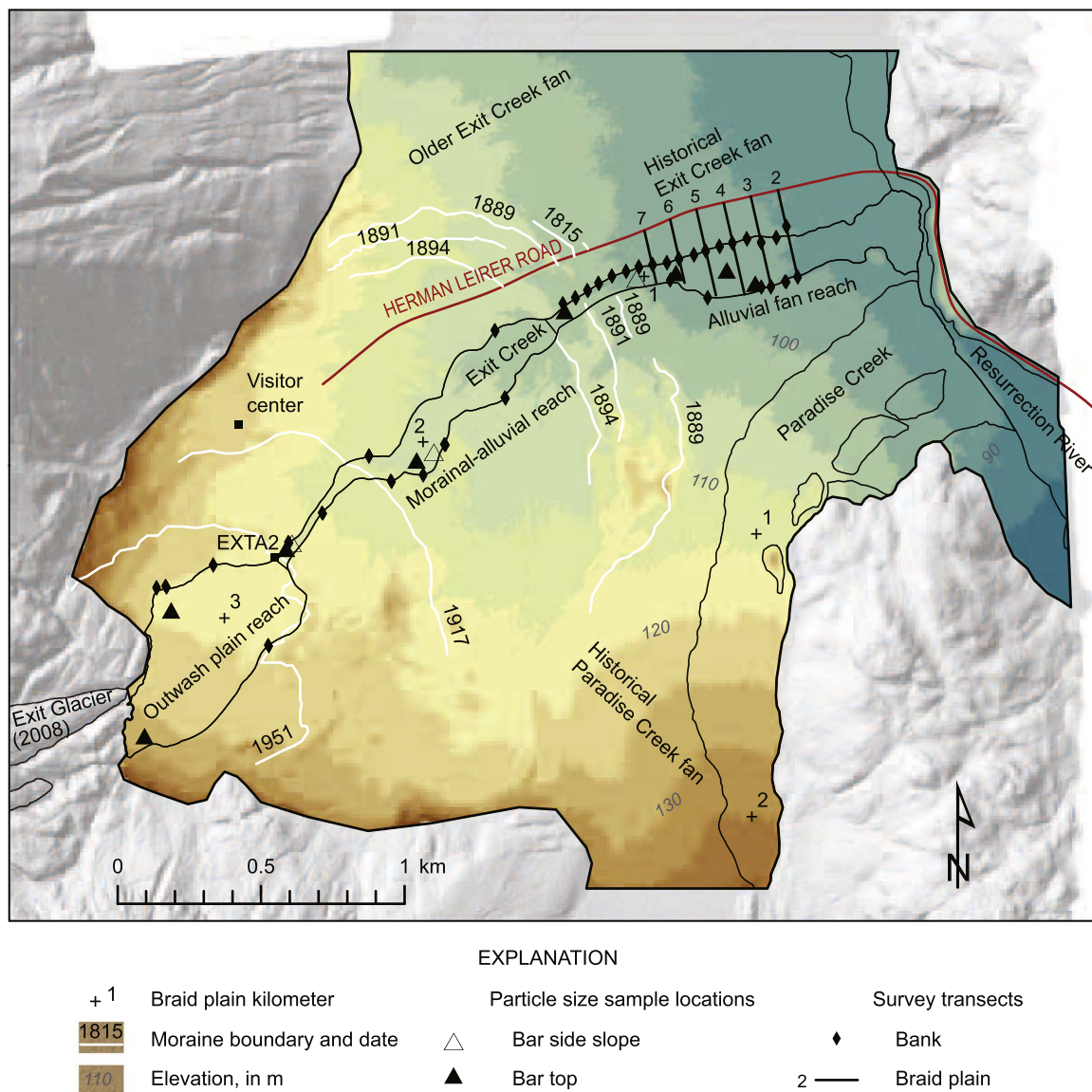


Fig. 4. Geomorphic features, topography, and sample and survey locations in the Exit-Paradise glacier forelands. Background is 2008 LiDAR data, shaded at 5-m intervals from 80 to 150 m in the forelands. Glacier boundary is from the 2008 LiDAR. Moraine boundaries are from Cusick (2001). Active braid plain boundary, braid plain kilometer locations, and transect data are available as Supplementary data.

western margin of the transbasin flow path was adopted as the divide between Exit and Paradise creeks; below that moraine, we used the western (left) bank of Paradise Creek in 2012.

For the purposes of this study, we divided modern Exit Creek into three reaches demarcated by channel patterns and lateral constraints. These geomorphic reaches correspond to glacier positions: an *outwash plain reach* between the modern glacier terminus and the 1951 moraine, a *morainal-alluvial reach* between the 1951 moraine and the LIA moraines, and an *alluvial fan reach* between the LIA moraines and Resurrection River (Fig. 4).

Modern channel extents were delineated along the lower parts of Exit and Paradise creeks at a scale of 1:2000 from the 2012 orthophoto and elevation data, supplemented where necessary by the 2005 orthophoto (Table A1). We included interpretation of vegetated former fluvial surfaces that differed from existing mapping of strictly wetted channels and bare areas by Stark et al. (2015). Channel boundaries were mapped as the toes of stream banks because bank tops were less discernible. We use braid plain terminology to describe the distribution of multiple channels over an area, defining the active braid plain as the modern suite of wetted channels, intervening or adjacent largely

unvegetated bars, and vegetated islands (the active floodplain of van der Nat et al., 2002; Curran and McTeague, 2011). The inactive braid plain is defined as a vegetated former braid plain still accessible by braiding without substantial bank erosion. We defined transitional braid plain as a vegetated area outside the active braid plain where the orthophoto or field observations show freshly mobilized sediment and/or disturbed vegetation. For the upper parts of Exit and Paradise Creeks, we delineated only the active braid plain.

For historical channel extents, where the dynamic processes of deglaciation, fan building, and transbasin flow complicate detailed delineation of braid plain activity, we simply mapped the maximum extent of prior fluvial occupation in the oldest high-resolution aerial photography available (1950; Table A1). This undifferentiated envelope includes circa-1950 active channels, bare areas, and vegetated areas showing evidence of prior channel occupation, relying in particular on patterns of preferential vegetation growth along channel margins, which preserve evidence of channel form on a multidecadal scale. The historical channel extents polygon includes wetted areas and inactive braid plain but also reflects the fact that some channel movements were governed by processes in addition to braiding. It therefore also includes

surfaces occupied by former glacier drainage but presumably no longer accessible by braiding. For simplicity, the historical channel extents polygon also includes isolated nonfluvial features such as bedrock or moraines stranded within the fluvial features.

We used vegetation structure from aerial photographs, a proxy for vegetation age, to determine dates of last fluvial occupation. Observations of successive decadal aerial images for the Exit-Paradise glacier forelands (Table A1) showed that about a decade after the last surface disturbance of an area, low shrubs occupied 20–30% of the area (Williams, 2014). Ground observations of a vegetation chronosequence in the Exit Glacier valley by Helm and Allen (1995) found slightly less plant cover after one decade, a difference that might result from uncertainty in time of abandonment or differences in choice of area sampled. About three to four decades after abandonment, cottonwood (*Populus balsamifera*) crowns became visible in the aerial photos but covered < 10% of the area, similar to the Helm and Allen (1995) Cottonwood Stage. In the orthophotos, conifer (mostly *Picea sitchensis*) crowns became visible shortly after cottonwood crowns, and the two were well-mixed five to six decades after abandonment. Channel forms generally were not discernible in aerial imagery past this time. These observed patterns of revegetation on abandoned fluvial surfaces created an index that, when applied to vegetated surfaces in the oldest available photos (1950 and 1961), produced estimated dates of fluvial occupation for those surfaces to the nearest decade.

Topographic change in Exit Creek and the lower part of Paradise Creek for the period 2008–2012 was computed by comparing the 2008 and 2012 DEMs (Table A1). The DEM differences were calculated in ArcGIS using standard map algebra, excluding densely vegetated areas where photogrammetric methods cannot penetrate the canopy. Error propagation (Brasington et al., 2003), using stated errors for the 2008 LiDAR and estimated errors for the 2012 data set based on typical values for photogrammetric surveys, resulted in a composite vertical error of 0.38 m. This was applied as a spatially uniform minimum level of detection to the DEM of difference by removing cells having values of ± 0.4 m. This simplified approach to creating a DEM of difference and addressing error precludes accurate volumetric estimates of deposition and erosion (Wheaton et al., 2010) but provides a general assessment of the spatial distribution and amount of substantial elevation change.

Glacially eroded sediment becomes available for fluvial transport through direct delivery (as glacial outwash) and through delayed transport of previously eroded material that is exposed by glacial retreat. These processes vary in space (between Exit and Paradise basins) and in time (over the span of LIA glacier advance and subsequent retreat), and we did not attempt to quantify these variations. We combined the mapping products with field observations to qualitatively characterize this variability, with a goal of understanding the potential role of sediment supply in the evolution of the Exit Creek fluvial system.

2.2. Streamflow and weather data

For Exit Creek, streamflow data needed to definitively detect changes in flood frequency or to determine that the likely factors contributing to such changes are lacking. As an alternative, we assessed the relationships among streamflow patterns, likely drivers, and road flooding by examining discontinuous local weather and stage records and also streamflow records from similar basins in the region.

Daily weather data recorded at a station near the Exit Glacier visitor facilities (Fig. 4) is discontinuous during periods of road closure, which are common during flooding. For a more continuous index of basinwide conditions, precipitation and temperature records were obtained from the Harding Icefield weather station (Western Regional Climate Center, 2014), located on the icefield 1 km beyond the upper Exit Creek basin boundary (Fig. 1) at an elevation of 1280 m. Because meltwater runoff from the glacier (in the sense of Cogley et al. (2011): melting snow and glacier ice) generally corresponds to air temperature (Ohmura, 2001),

Harding Icefield average air temperature was adopted as an index of glacier meltwater runoff.

Daily observations of stage collected since 1987 at a NOAA observation station at the relatively stable channel through the 1951 moraine (Fig. 4), EXTA2 Exit Glacier Creek (National Weather Service, 2014), indicated rising or falling streamflow patterns at daily to seasonal scales. Road closures during road floods created gaps in the record that prevented determination of the date of annual peak streamflow. No rating curve has been established for EXTA2, so year-to-year changes in stage magnitude may reflect channel changes and cannot be reliably interpreted as indicative of interannual flow variations.

General daily streamflow patterns for Exit Creek can be inferred by analogy to curves compiled from the mean for a period of streamflow data on other Alaska glacierized basins (Wiley and Curran, 2003, Fig. 2; Curran, 2012, Fig. 3A). For a specific example of mean daily streamflow patterns and the timing of annual peak streamflows in a glacierized basin, we examined data from Wolverine Creek near Lawing, AK (USGS streamgage 15236900). The Wolverine Creek basin, located about 45 km to the east, at 24 km² and with 72% glacier cover in a mountainous area bordering the Gulf of Alaska, is similar to the Exit Creek basin and has a streamflow record that spans a period in the 1960s and 1970s and a period after 2000.

We applied these various data sets to interpretation of the streamflow drivers most likely responsible for Exit Creek streamflow on road flooding dates. We inferred snowmelt as the responsible factor when a noticeable continual increase in Exit Creek stage occurred during the spring months, similar to that observed for streamflow in Wolverine Creek or typical glacierized basins. After the period of spring snowmelt, glacier meltwater runoff was assumed to be a responsible factor when Harding Icefield average air temperatures exceeded 0 °C for at least 2 days, a period estimated to allow for substantial runoff to reach the stream, before flooding started. Rainfall was assumed to be a factor when cumulative Harding Icefield precipitation equaled or exceeded 25 mm of rain on or within 2 days prior to the flooding date.

2.3. Fieldwork

From autumn 2012 to autumn 2014, we completed ground reconnaissance, surveys, and geomorphic characterization of Exit Creek, its flooded forest areas, and selected areas along lower Paradise Creek. The distribution of median particle size along Exit Creek was documented with samples collected in June 2013 at the tops of eight unvegetated mid-channel and lateral bars, a relatively consistent geomorphic environment. An additional three sample sites on visually coarser bar sideslopes provided a better representation of bed material. Samples consisted of 100 particles collected along a 5 m by 5 m grid and tallied into classes using a metal gravelometer template. We made visual estimates of particle sizes along the lower 2 km of Paradise Creek.

In 2011, NPS partnered with the U.S. Forest Service to conduct a Global Positioning System Real-Time Kinetic (GPS-RTK) survey of braid plain transects at BPK 0.47 (transect 2) and BPK 0.57 (transect 3), extending from the edge of the roadway to the far side of the braid plain. From 10 to 12 June 2013, we used the 2011 monuments in a GPS-RTK resurvey of the original points on transects 2 and 3 every 15 m along each transect and established additional points delineating slope breaks at major channels to provide a measure of short-term braid plain surface elevation change. Resurveys of four reference nails left in 2011 along Herman Leirer Road matched previous values to within an average of 1.3 cm horizontally and 1.5 cm vertically. Survey points along the preexisting transects lacked markers, so they were relocated using the navigational capabilities of the GPS-RTK to within several centimeters horizontally, except at in-channel points where flow conditions prevented wading access. We established additional transects numbered 4–7 at BPK 6.7, 7.6, 8.7, and 9.6, respectively, for future resurveys and for comparison to remotely sensed elevation data.

From 12 to 26 June 2013, a similar GPS-RTK survey was used to profile banks at points -3 , -1 , 0 , 1 , and 3 m from the top of the bank in short transects perpendicular to the braid plain at 24 locations along the left bank and 12 locations along the right bank. On 23 and 24 June 2013, when stream water levels were neither low nor at flood levels, we used a total station to calculate local water surface slopes from points spaced an average of 80 m apart along most of Exit Creek. Reach slopes were summarized from these measurements.

3. Results

3.1. LIA history of the Exit-Paradise glacier forelands

The glacial and fluvial histories of the Exit and Paradise creek basins provide context for their modern geomorphology and hydrology. Recent flooding of Herman Leirer Road has occurred within a proglacial landscape that was significantly impacted by the LIA advance, and subsequent retreat, of upstream glaciers. The evolution of that landscape during and after the LIA involved interplay between the blocking influence of glacier ice, subsequent moraine deposition, and finally the reworking capacity of the fluvial system, resulting in the development of the modern geomorphic features that have conditioned the recent behavior of Exit Creek.

3.1.1. Glacier fluctuations

Portions of the Exit-Paradise glacier forelands were overrun by glacier advances repeatedly during the LIA. These advances commenced with a first known LIA advance sometime around A.D. 1170 and culminated with a final, and most extensive, advance to Exit Glacier's LIA maximum position around A.D. 1815, based on a tree-ring date on the oldest visible moraine. These dates, and others presented below, are based primarily on work by [Cusick \(2001\)](#), who relied on dendrochronological data collected and analyzed by himself and also by [Wiles and Calkin \(1994\)](#) and [Ahlstrand \(1983\)](#). We do not know the extent of Exit Glacier's retreat prior to the first LIA advance, but Cusick presented evidence that the first LIA advance overran mature forest that covered at least some of the foreland and also that forests farther downvalley, beyond the LIA maximum advance and near the confluence with Resurrection River, have likely been undisturbed by glacier advance for at least 4000 years.

Our reconstruction of the maximum LIA advance of Exit and Paradise glaciers ([Fig. 1](#)) relies on these dates in the Exit basin and infers that the timing of glacier fluctuations in the unstudied Paradise basin was broadly similar to those in the Exit basin. Dashed lines in [Fig. 1](#) show areas where the precise location of the glacier margin was indeterminate, typically in locations where steep terrain and active mass movements have combined to obscure evidence of prior glacier boundaries. Some of the mapped features were probably formed asynchronously, in particular in the Paradise basin.

For our purposes the location of the terminus is more important than precise timing: Exit Glacier advanced to within ~ 1 km of Resurrection River; while Paradise Glacier terminated much farther up its own valley, ~ 6 km from the Resurrection River confluence. Along the axis of modern Exit Creek, the LIA advance ([Fig. 1](#)) separates the foreland into two distinct zones: one—which includes most of the alluvial fan reach—that has remained unglacierized for at least 4000 years, and another—encompassing the morainal-alluvial and outwash plain reaches—that has been covered by glacier ice once or more within the last ~ 200 years ([Fig. 4](#)).

Within the proximal zone, the history of post-LIA maximum glacial retreat is reflected by numerous terminal moraines; the most conspicuous are shown in [Fig. 4](#). Based on the position of the A.D. 1889 moraine, glacier retreat was initially slow after the A.D. 1815 maximum and accelerated around the start of the twentieth century. Terminus position retreat since 1889, as measured perpendicular to the glacier margin in the middle of the Exit basin, has averaged 20 m/y, with

periodic minor readvances ([Kurtz and Baker, 2016](#)). The most recent (2008) mapped margins of Exit Glacier and Paradise Glacier—which continue to retreat—are shown in [Fig. 1](#). These changing glacier margins provided the physical boundaries for glacier foreland development and the evolution of a new fluvial system downstream of the glacier margin.

3.1.2. Glacier foreland development

At the LIA maximum ([Fig. 1](#)), exactly where Exit Creek emerged from the broad terminus is not known, and probably varied among multiple channels over time; but it is unlikely that the creek remained confined to the boundaries of the present active channel. At a glacier terminus, thickened ice along the centerline of the glacier valley commonly steers subglacial water flow toward the sides of the glacier, particularly in cases where the subglacial topography is relatively flat ([Shreve, 1972](#)), as it was under Exit Glacier's LIA terminus. During the 100+ year period when Exit Glacier was at or near its LIA maximum position, it is therefore likely that a significant fraction of Exit Creek's discharge was directed toward one or both of the alluvial fans that are still prominently visible to either side of (north and south of) the former terminus ([Fig. 4](#), *older Exit Creek fan* and together with Paradise Creek on the *historical Paradise Creek fan*, respectively). Sediments that comprise these fans were largely deposited during and/or prior to the LIA maximum glacier advance; the northern fan has been inactive since then, while the southern fan has continued to receive sedimentation from modern Paradise Creek.

At some point after the LIA maximum, at least by 1911 but probably earlier ([Martin et al., 1915](#)), Exit Creek breached the outboard terminal moraine and has since that time been confined at the head of the alluvial fan reach to a position just north of the valley centerline ([Fig. 4](#)). Based on channel cross-cutting relationships, we interpret another breach in the LIA moraines, ~ 250 m southeast of the present channel location, as older than the post-1911 channel position and likely inactive since that time. Downstream of the LIA moraines, Exit Creek is unconstrained by primary glacial deposits and has migrated over an area that includes the mapped alluvial fan reach and *historical Exit Creek fan* ([Fig. 4](#)). The topographic expression of this fan, along with sparse vegetation and obvious channels in a 1950 aerial photo ([Fig. 5A](#)) clearly attest to occupation of an active braid plain north of the modern Herman Leirer Road alignment sometime in the early-middle twentieth century. After 1950, active channels shifted southward toward Paradise Creek, eroding into the narrow strip of alluvium between the two creeks ([Fig. 5B](#)).

Upstream of the LIA moraines, multiple threads of Exit Creek migrated across and around terminal moraine loops deposited during the early to mid-twentieth century ([Fig. 5](#)). As Exit Creek emerged from the retreating terminus of the glacier, its outflow channel(s) typically occupied fundamentally different locations from the flowpaths eventually attained as the glacier retreated beyond a given moraine. Within the morainal-alluvial reach ([Fig. 4](#)), the 1950 aerial photograph shows that at any given glacier position in the valley, channels were initially constrained within intermorainal troughs that guided flow along curved paths from glacier side to valley center ([Fig. 5A](#)). These channels eventually coalesced into a single pathway along the valley center between a prominent breach through the 1951 moraine, which has subsequently provided a long-lived constraint on the lateral position of the creek and its longitudinal profile and on the LIA moraines. For the last few decades, Exit Creek has migrated primarily within the growing outwash plain reach, upstream of the 1951 moraine ([Fig. 4](#)). The tendency of dynamic ice-marginal channels to migrate during glacier retreat toward the valley centerline continues with our observation of the abandonment, in 2016, of a decades-old ice-marginal channel on the south side of the terminus in favor of a primary outflow channel closer to the valley centerline.

Once Exit Glacier's ice-marginal channels were abandoned in favor of newer, topographically lower channels along the valley center,

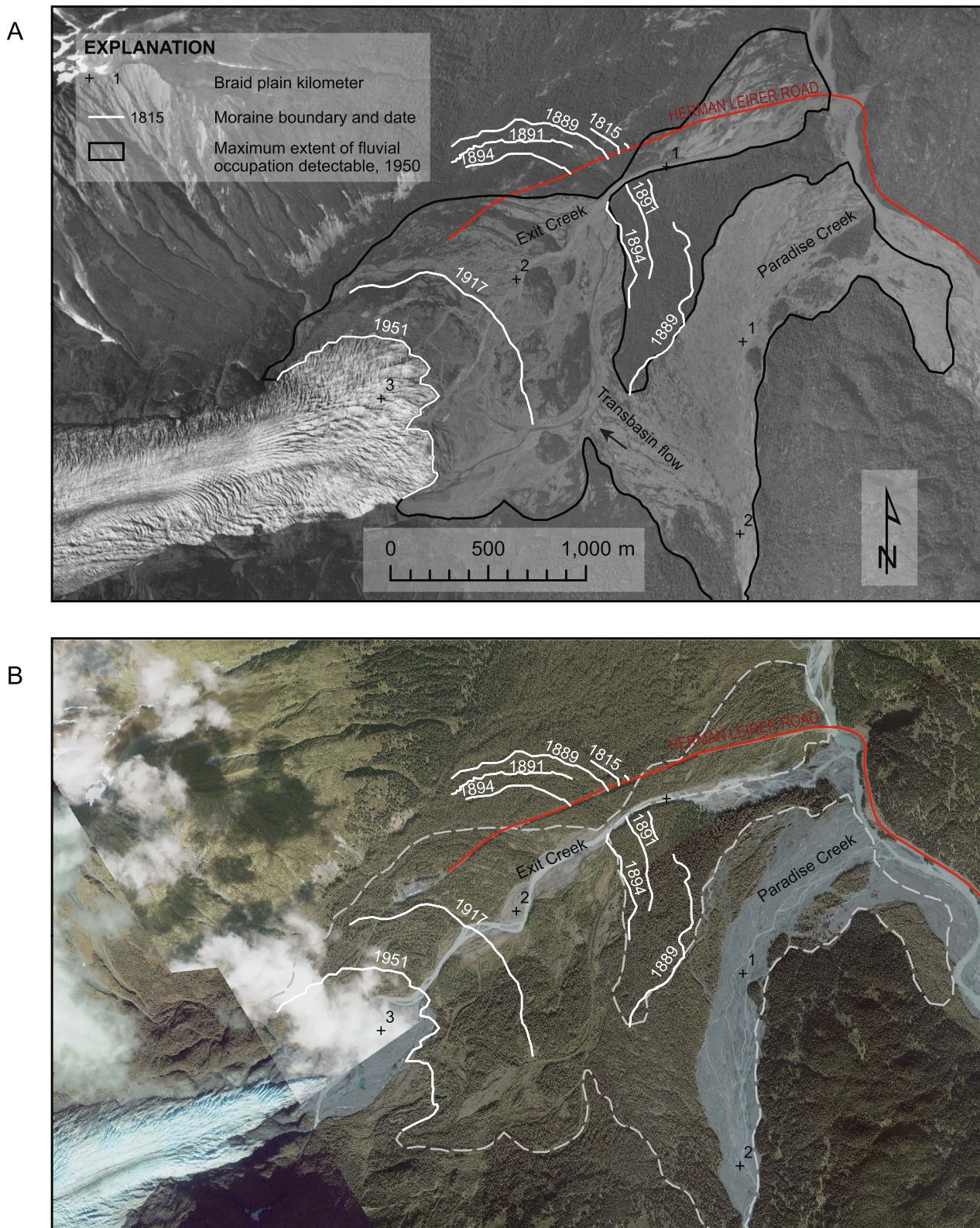


Fig. 5. Comparison of (A) 1950 and (B) 2005 fluvial conditions in the Exit-Paradise glacier forelands. The historical channel extents (circa-1950; solid line in A) are repeated as a dashed line in (B) for reference. Note the clear evidence of transbasin flow from Paradise Creek to Exit Creek in 1950. The visitor center and parking area are visible as an unvegetated area at the end of Herman Leirer Road in (B). Moraine boundaries are from Cusick (2001). The 1950 channel extents are available as Supplementary data.

particularly once these new channels were confined within long-lived moraine breaches, available evidence suggests that abandoned channels become fluvial terraces unavailable for reoccupation for periods of at least decades to centuries. The 1950 aerial photograph shows that the

total area affected at that time by fluvial activity extended well beyond the present day active braid plain (Fig. 5A). From the mid-1970s forward, riparian vegetation has colonized abandoned channels to the north and south of the active braid plain between the LIA and 1951

moraines (Fig. 5B). The visitor center at the west end of Herman Leirer Road (Figs. 4 and 5B), for example, occupies a fluvially reworked surface that is now elevated at least 5 m above the present water surface and has little prospect, under current conditions, for renewed occupation by Exit Creek.

In one notable exception, however, vegetation patterns in the earliest (1950) aerial photograph clearly demonstrate that the southern portion of Exit Creek's morainal-alluvial reach was, independently from changes in Exit Creek, occupied by transbasin water flow from neighboring Paradise Creek (Fig. 5A). A broad (~0.5 km) outwash fan crosses from the western side of Paradise Creek into the southern edge of the Exit Creek braid plain, breaching the 1889 moraine at the southern end of the present-day moraine remnant. Water flow was not discernible in the 1950 photo, but the transbasin fan was covered only in sparse vegetation categorized as open low scrub (Viereck et al., 1992). More recent aerial photography shows open low scrub developing on outwash fans within 5–10 years after cessation of significant fluvial activity, suggesting that the transbasin fan was delivering some fraction of Paradise Creek's water and sediment load to Exit Creek as late as the early 1940s (Williams, 2014). Although revegetation of the fan continued after 1950, and no evidence is seen in subsequent aerial photos of substantial new flow from Paradise into Exit Creek after that time, 2013 fieldwork confirmed the presence of minor flow ($\ll 1 \text{ m}^3/\text{s}$) from Paradise Creek into the Exit foreland in a recently reactivated channel across the heavily brush-covered transbasin fan. This continued minor transbasin flow demonstrates the absence of a defined topographic divide between the outwash fans of Exit and Paradise creeks, and the consequent potential for more substantial flows from Paradise Creek to again occupy fluvial terraces that are otherwise abandoned by the flows of Exit Creek itself.

3.2. Modern hydrology and fluvial geomorphology

In recent decades, Exit Creek shifted channels frequently within the active braid plain but moved little beyond the active braid plain. The modern hydrology and fluvial processes of Exit Creek provide context and boundaries on further likely post-glaciation modifications to channel position and road flooding.

3.2.1. Hydrology and recent road flooding

Our inventory of road floods (see Supplementary data, Table A2) confirms a sudden change from the isolated occurrence of roadway erosion in 1993 (Tetreau, 1993; Gray, 2003) and road overtopping by 0.3 m in 1995 (Gray, 2003) to a prolonged period of 1–3 road floods per year between 2009 and 2014. However, no road floods were documented in 2015 or prior to construction that raised the roadbed in summer 2016.

Our 2012–2014 field observations of the Exit Creek transitional braid plain and comparisons to historical aerial photos (Figs. 2 and 6) showed progressive and substantial evidence of recent modification by Exit Creek road-flooding flows. Prior to the recent flooding, the forest floor between the lower 1 km of the Exit Creek active braid plain and Herman Leirer Road was laced with former channels, some of which are visible in the 1950 aerial photo (Fig. 6B). Most of these channels had reforested, but some were occupied nearly continually by groundwater seepage, as observed by others, notably Sloan (1985) and Gray (2003). None of this seepage, which consisted of clear water easily distinguished from turbid Exit Creek flow, constituted an amount of flow considered a flood hazard to the road. Observations during a road flood on 6 September 2013 noted widespread flooding into the roadside forest (Fig. 2). Shallow, diffuse flow spilled from the braid plain into the forest where no banks were present (BPK 0.7–0.8); channelized flow poured from small breaches of low braid plain banks at BPK 0.9–1.0 and from the upstream-most breach at BPK 1.25, immediately downstream of the LIA moraines. Large woody debris jams partially blocked many of the breach locations. In the forest, spilled flow followed former

channels and new diffuse pathways, ultimately coalescing into a wide flooded area against the road (Fig. 2A). Following several days of flooding, fresh fluvial sediment on the forest floor graded from cobbles near the active braid plain (Fig. 2C) to gravel at mid-forest and then to a layer of sand near the roadside ditch. Recent channel development on the forest floor graded from a series of short, unvegetated incipient channels up to a meter deep near the active braid plain to small bar structures by mid-forest (Fig. 2B). By 2014, the effects of flooding had killed most conifers and severely stressed deciduous trees throughout the road flooding zone. No continuous, well-developed channels, nor channels large enough to convey a substantial part of Exit Creek flow, were present in the forest nor had erosion felled trees within the forest.

We compare the record of road flooding with available Exit Creek stage records and weather data in Fig. 7. In general, Exit Creek stage shows a marked step-like increase in late May or June during 2009–2014 (Fig. 7). The highest recorded daily stages, however, typically occurred from mid- to late-summer (July–September). These patterns correspond well to a sharp increase in mean daily streamflow in spring (corresponding to stream ice breakup and snowmelt) and a subsequent period of even higher summer streamflow (from glacier meltwater runoff supplemented by rainfall) documented in other glacierized basins (Fountain and Tangborn, 1985). The timing is similar to patterns at nearby Wolverine Creek, where mean daily streamflow begins to rise in late April or May and reaches a maximum in early August. Annual peak streamflows at Exit Creek cannot be detected from the incomplete stage record; but in 28 years of streamflow data at Wolverine Creek only one annual peak streamflow occurred in the spring, and most annual peak streamflows occurred in July through October (most commonly in September). We infer that peak streamflows at Exit Creek primarily occur in summer and fall, driven by glacier meltwater runoff, rainfall, or a combination of the two.

Using Harding Icefield climate records (Fig. 7), we interpret Exit Creek streamflow during periods of road flooding as primarily rainfall-related, particularly in September and October, or rainfall and glacier-melt related, particularly in July and August (Table A2). No road floods occurred during the likely peak snowmelt season (May and June). The July 2011 flood occurred in mid-summer, during warm air temperatures in the absence of rainfall, and is attributed primarily to glacier-related melt. During the 2009–2014 period maximum rainfall exceeded the 24-h, 1 year or 7-day, 1 year precipitation frequency (Perica et al., 2012) only in the regional rainstorm of September 2012, suggesting that the period of increased flooding was not dependent on locally or regionally notable precipitation. In July 2009, a prolonged period of high temperatures on the Harding Icefield (and the highest temperature on record 2009–2014) ended on 17 July, more than a week before the next road flood (Fig. 7).

3.2.2. Fluvial geomorphology

Bank heights and the corresponding degree of confinement along Exit Creek vary by geomorphic reach (Fig. 8). Between the valley headwall and the LIA moraines, a defined bank is always present at the edge of the active braid plain, reaching a maximum height of 2–3 m at moraine crests. Downstream of the LIA moraines where the stream emerges onto the alluvial fan, bank heights become smaller relative to the upper reaches of the stream on the right bank (as viewed looking downstream) and become negative for most of the left bank, such that in places only a change in vegetation marks the boundary between the active and transitional braid plain (Fig. 2).

Exit Creek particle size and water surface slope distribution and magnitude appear unlikely to present substantial barriers to sediment transport. The median particle size (D_{50}) of bar tops was relatively constant along the length of Exit Creek, ranging from 12 to 27 mm (medium to coarse gravel) except for a noticeable coarsening to 95 mm (small cobbles) near the head of the outwash plain (Fig. 9; Supplementary data, Table A3). Particle sizes coarsened only slightly on bar sideslopes. Boulders occurred at prominent moraines, including an

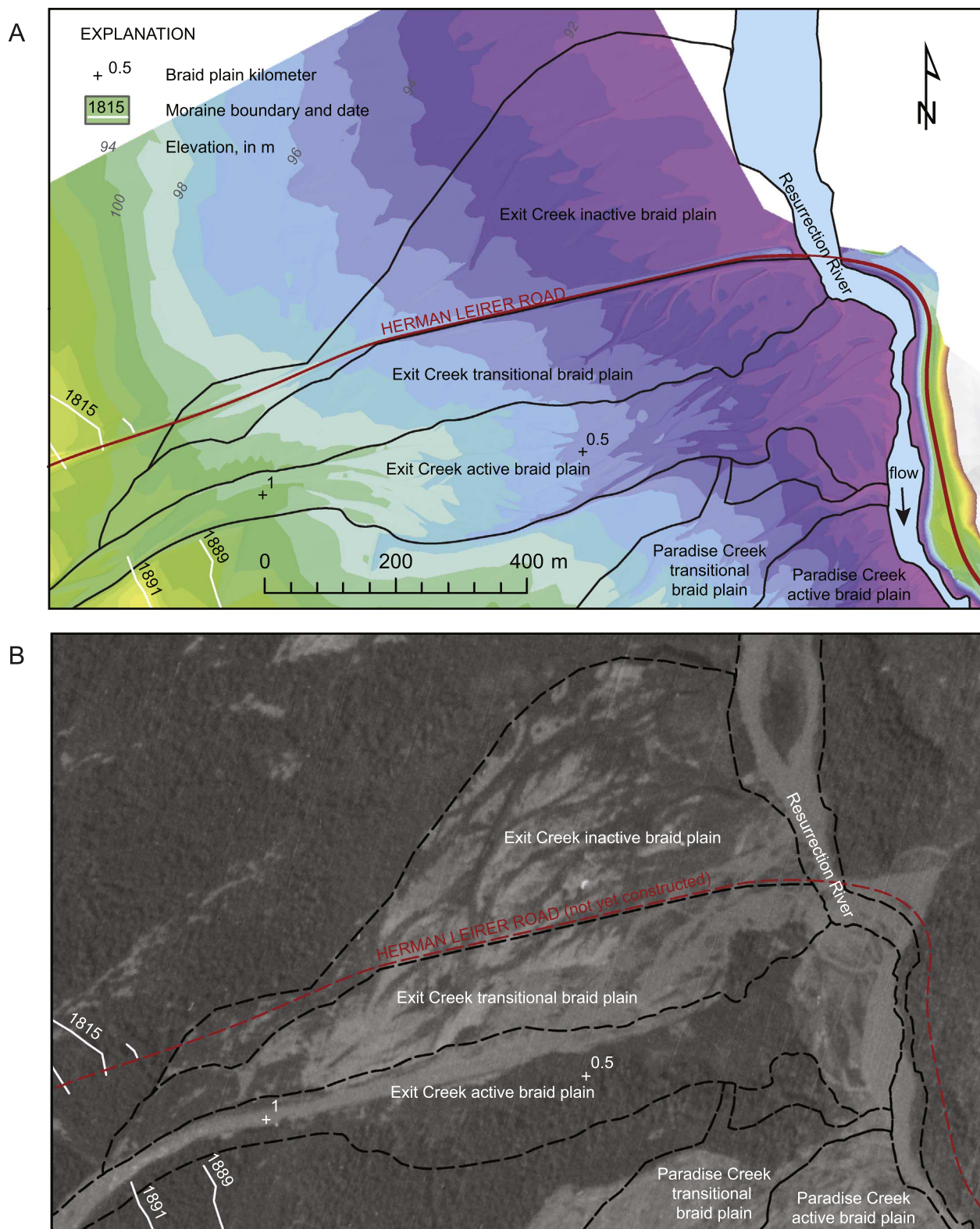


Fig. 6. Modern channel extents (ca. 2012) at the LIA moraines and along the alluvial fan reach mapped on (A) 2012 Exit Creek topography and (B) 1950 aerial photo. Detailed braid plain features (solid line in A) are repeated as dashed line in (B) for reference. LiDAR data in (A) are shaded at 1-m intervals. Moraine boundaries are from Cusick (2001). Modern (2012) channel extents are available as Supplementary data.

extended riffle at the 1951 moraine, and at the head of the outwash plain. Local Exit Creek water surface slopes were steepest near the glacier, reaching 0.02 within 100 m of the bedrock headwall. The surveyed water surface profile, which closely matched the profile extracted from the 2012 DEM, declined consistently in a downstream

direction without notable variability (Fig. 10). Surveyed, reach-averaged water surface slopes were 0.013 for the outwash plain, 0.009 in the morainal-alluvial reach, and 0.008 on the alluvial fan reach.

Comparison of surface topography from the 2008 LiDAR-derived DEM and the 2012 photogrammetrically derived DEM confirms the

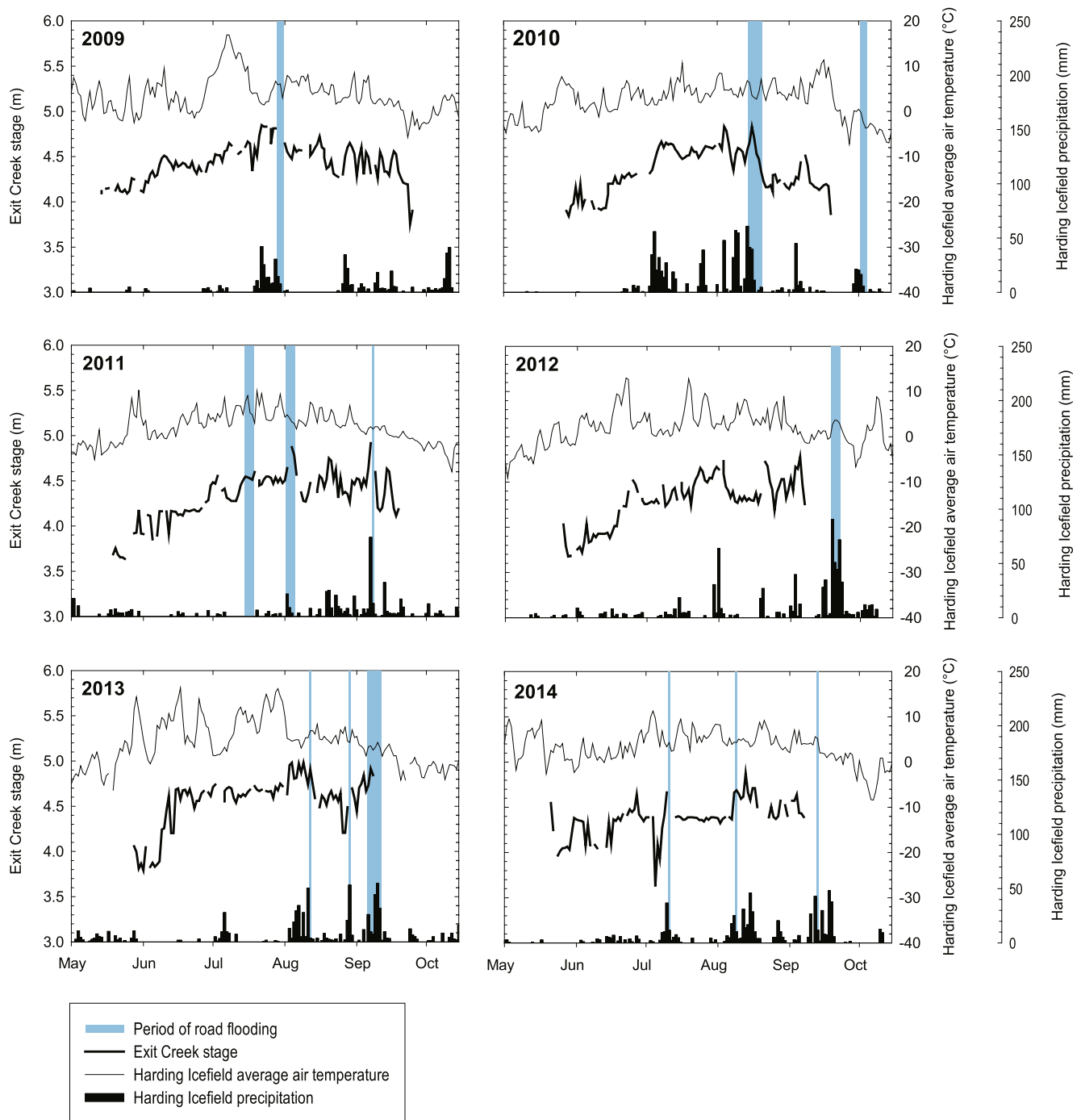


Fig. 7. Dates of flooding (transparent bars) of Herman Leirer Road within 1 km of Resurrection River bridge near Exit Glacier, Alaska, 2009–2014. Floods are plotted with corresponding Exit Creek stage, Harding Icefield average air temperature, and Harding Icefield precipitation.

capacity for sediment transport, showing a predominant pattern of aggradation in Exit and Paradise creeks throughout most of the foreland (Fig. 11). In Exit Creek, aggradation of 0.4–2 m forms a mosaic of barforms across the braid plain from BPK 0.5–1 and channel fill from BPK 1–2. The 2011–2013 repeat GPS-RTK ground survey of transects 2 and 3 confirmed significant channel change in the active braid plain near BPK 0.5 and shows aggradation in the vegetated area outside the active braid plain (Fig. 12). Channel migration prevented fair comparison of elevation difference at most individual points in the active braid plain, and point spacing obscured some channels. Although this prevented us from obtaining accurate estimates of average elevation change across the entire transects, inspection of areas without large

channels, such as near the left edge of the active braid plain, suggests aggradation of 0.1–0.4 m in the active braid plain over this 2-year period. The transects and 2012 DEM (Fig. 6A) also clearly show that the active braid plain is elevated above the vegetated area and road; for the 2013 survey of Transect 3, the elevation of the road is about the same as the elevation of the channel thalweg and 1 m below the top of active bars.

Erosion in Exit Creek from 2008 to 2012 occurred as limited bank erosion in all reaches and localized minor channel excavation in the outwash plain. The most substantial bank erosion detected occurred along the left bank of the outwash plain, where 330 m of bank retreated up to 5 m, and along the outer bend of a meander in the morainal-

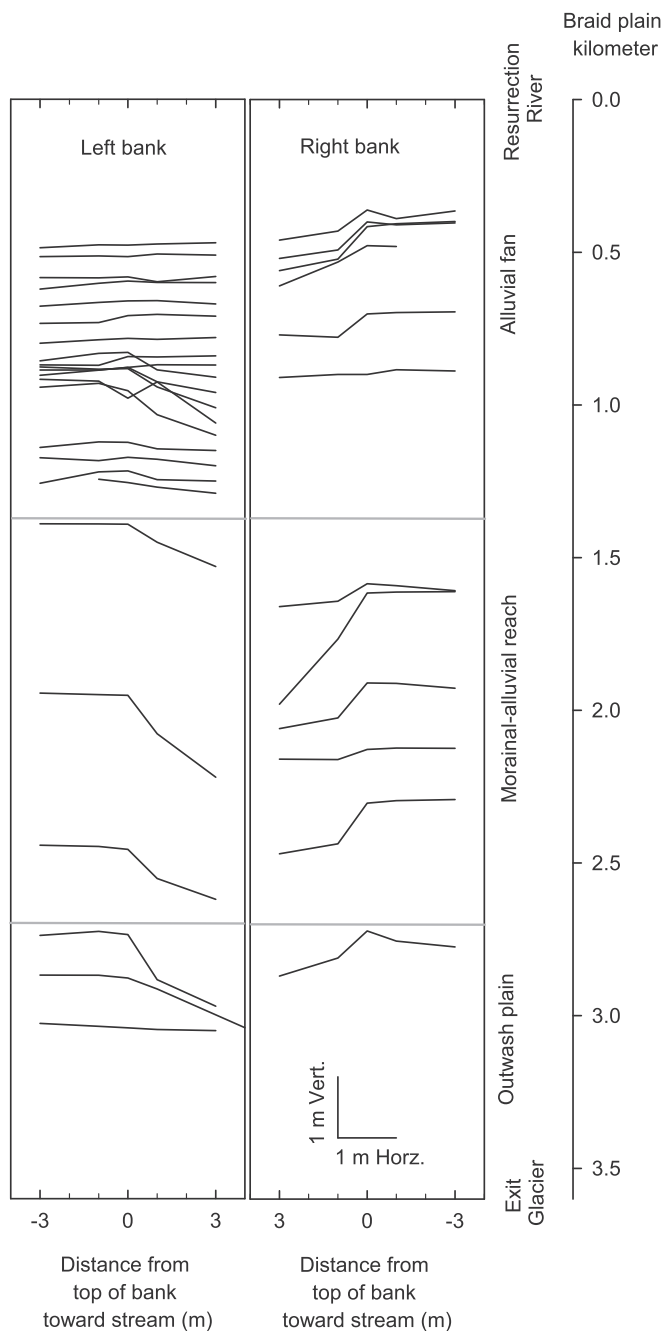


Fig. 8. Bank profiles at the margin of the active Exit Creek braid plain 2013. The streamwardmost point on each transect corresponds with the transect location along the stream, plotted as BPK on the y-axis. The vertical scale on each plotted transect equals the horizontal scale. Bank profile survey data are available as Supplementary data.

alluvial reach, where 200 m of bank retreated up to 9 m, corresponding to the locations of documented NPS bank erosion concerns along a visitor trail in the outwash plain and a visitor campground respectively. For context, inspection of shadows in historical aerial imagery (Table A1) showed no evidence of cutbank height increases or decreases that would indicate appreciable incision or aggradation since the 1970s, but bank erosion along the left bank of the outwash plain caused the banks to retreat laterally 25–65 m during that period.

Channel change at the confluence of Exit Creek and Resurrection River appears to have been minor, suggesting that Resurrection River has played a relatively minor role in shaping Exit Creek or affecting Exit Creek streamflows. In 2003, Barber (2003) concluded from a field inspection and review of Alaska Department of Transportation and Public

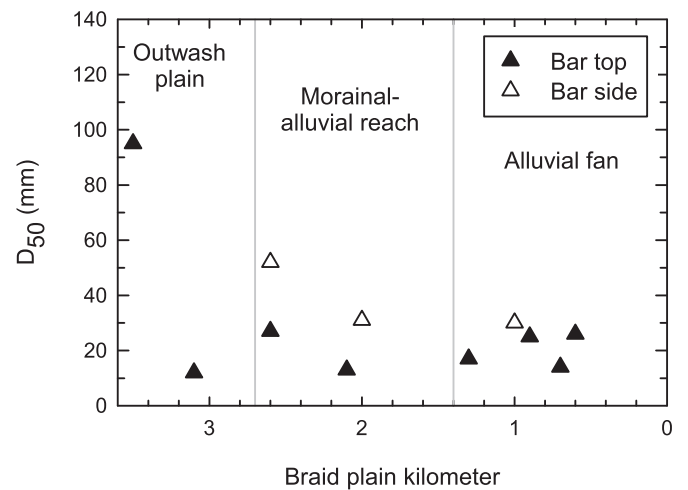


Fig. 9. Median particle size of bar tops and bar sideslopes along Exit Creek. Particle size data and additional results are available as Supplementary data.

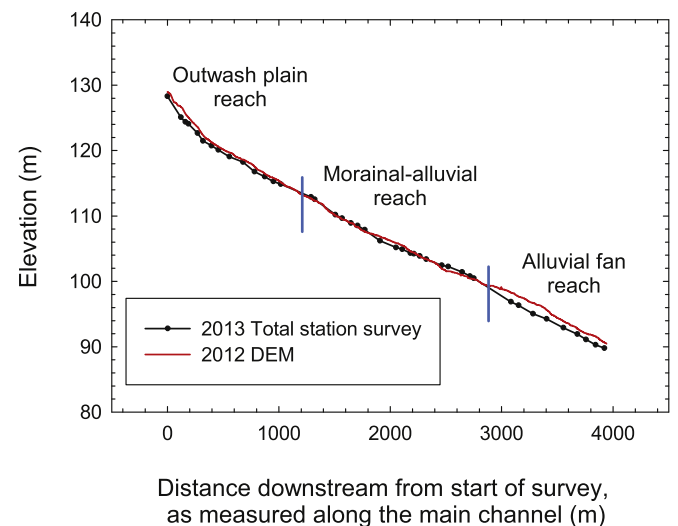


Fig. 10. Longitudinal profile of Exit Creek. Total station survey data are available as Supplementary data.

Facilities Resurrection River Bridge Inspection Reports that no change in hydraulic cross section of the Resurrection River, a braided river pinned against the valley wall by the Exit Creek fan, had occurred since road bridge construction in the mid-1980s. Comparison of a 1986 aerial photo of the confluence (Barber, 2003) to the 2012 orthophoto shows a 75-m shift in the path of Exit Creek away from the bridge but reveals only minor channel adjustments to Resurrection River itself. Field observations during 2012–2014 showed Resurrection River effects to be limited to minor trimlines along the Exit Creek fan and deposition of surficial sand drapes, likely slackwater deposits, no farther upstream than the lower 100 m of the Exit Creek fan.

Subaerial sediment availability in the Exit Creek basin is relatively low, and most of the sediment within the fluvial system is probably derived directly from glacial outwash. Exit Creek contains numerous prominent moraines on the valley floor that provide potential sources of sediment to Exit Creek. The persistence of these moraines, however, suggests that fluvial reworking of these features within the low gradient foreland has generally been minimal, with the Exit Glacier outflow stream more commonly occupying favorable channel positions between moraines. Substantial erosion of the moraines probably occurred only episodically, during the uncommon creation of moraine breaches. Outside of the valley floor, the steep slopes surrounding Exit Glacier are generally composed of visible bedrock covered by only a thin,

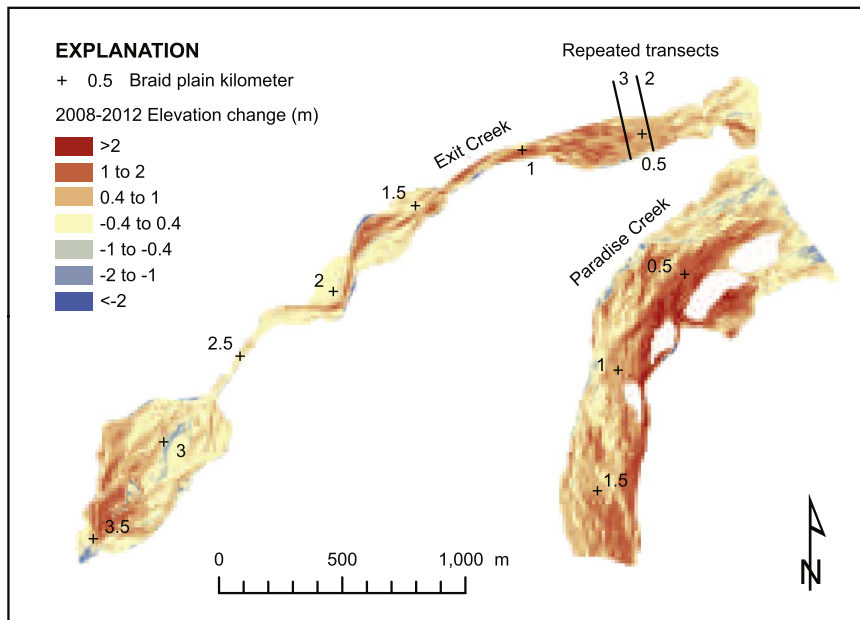


Fig. 11. Topographic change in Exit Creek and the lower 1.5 km of Paradise Creek calculated from 2008 LiDAR data and 2012 photogrammetry data. Positive numbers and warm colors indicate aggradation. Transect survey data are available as Supplementary data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

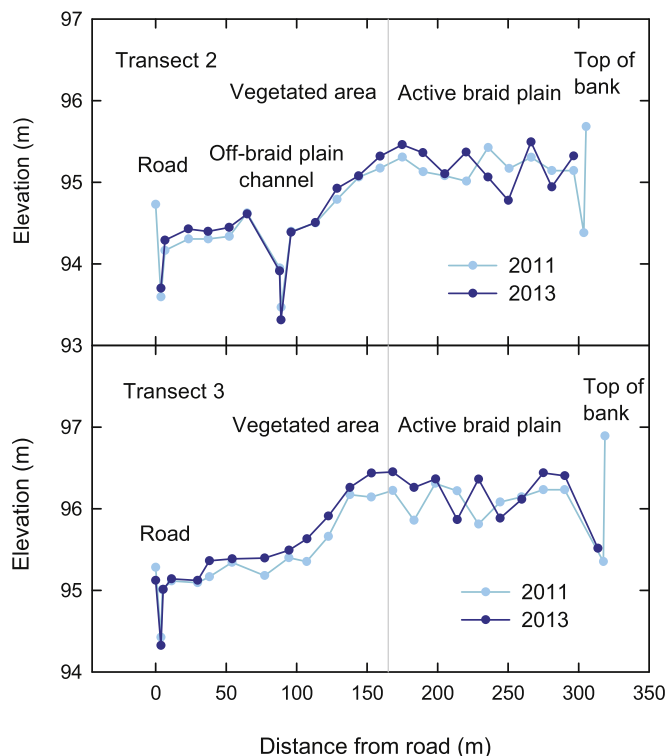


Fig. 12. Elevation change at two surveyed transects of Exit Creek 2011–2013. Transect positions are shown in Figs. 4 and 11.

discontinuous veneer of sediment. In contrast, the presence of an actively braiding outwash plain at the terminus of Exit Glacier suggests that glacier erosion is consistently delivering a relatively high sediment load to the stream, an assumption supported by the observed aggradation from 2008 to 2012 (Fig. 11).

Paradise Creek basin has substantially greater sediment availability within portions of its generally steeper foreland and appears to transport more material than Exit Creek. In the lower 2 km of Paradise Creek, median particle sizes ranged from gravel to cobbles, and boulders occurred frequently; the 2012 DEM longitudinal profile showed an average slope of 0.02, or about twice that of Exit Creek.

Moraines on the Paradise Glacier valley floor are small and limited to the upper reaches of the unnamed western fork of Paradise Creek. This may partly be an artifact of more restricted moraine production, but we infer it to largely be a function of the valley topography favoring subsequent moraine erosion. Within the glacier foreland, both forks of Paradise Creek valley are narrower and steeper than the Exit Creek foreland, predisposing them to post-depositional reworking (Fig. 1). Within and outside the foreland, Paradise is framed by steep valley walls that provide substantial colluvial inputs to the stream itself. Available aerial photos show evidence of frequent debris-rich winter avalanches (and possibly summer landslides) from steep slopes above the western fork directly into (and on one occasion burying) the stream. Alluvial fans at the mouths of small tributaries to Paradise Creek are trimmed and scalloped, suggesting that Paradise Creek is actively reworking or has at some point in the past reworked these features. Paradise Creek aggraded even more rapidly, while transporting generally larger material, than Exit Creek between 2008 and 2012 (Fig. 11); we infer that aggradation to be at least partly caused by the enhanced subaerial availability of transportable sediment.

4. Discussion

This project was motivated by a desire to understand the causes of Exit Creek's recent, recurrent flooding of Herman Leirer Road, which was uncommon in the decades before 2009 but became a multi-annual occurrence between 2009 and 2014. Increased flooding can be associated with increased streamflow or sedimentation-driven channel aggradation in a stable channel location or with channel migration or avulsion. Because enhanced streamflow and sediment supply are expected during a period of glacial retreat, we first ask whether recent changes in one or both of these drivers can explain recent road flooding. We then consider consequences of Exit Creek's periodic capture of neighboring Paradise Creek. Finally, Exit Creek is examined from the broader perspective of paraglacial sedimentation, in which Exit Glacier's advance and retreat have conditioned Exit Creek's behavior over the course of the LIA, including specifically the timing and locations of channel aggradation and alluvial fan production.

4.1. Streamflow and sediment load of Exit Creek

The available stage data for Exit Creek reveal no gross anomalies that would suggest major changes in peak streamflow. That record is

incomplete, however, and has a speculative relationship to actual streamflow. In contrast, the timing of road flooding compared to primary processes driving streamflow (Fig. 7; Table A2) provides a convincing argument against recent increases in snowmelt, glacier melt-water runoff, or rainfall as the primary cause of road flooding. Given evidence for warming summer temperatures (Bieniek et al., 2014) and glacier retreat (Kurtz and Baker, 2016), we do not argue that runoff from spring snowmelt and summer glacier melt have not increased—only that we find little evidence linking those likely increases to post-2009 road floods. Importantly, although rainfall was associated with all but one road flood, some periods of high rainfall did not generate road floods. The lack of consistent correlation of road floods with high stage, or with climate variables likely to generate high streamflow, suggests that the observed increase in road flooding appears to depend on factors other than simply high streamflow.

The sediment load carried by Exit Creek in the past few decades is even less well documented than its streamflow, but the braid plain elevation differential between 2008 and 2012 (Fig. 11) documents at least recently active sediment transport. The nearly ubiquitous presence of aggradation along the Exit Creek braid plain, even upstream of the isolated bank incision, suggests that the primary sediment source is subglacial erosion. We cannot quantify the variability of direct glacial erosion over the period of LIA expansion and retreat but generally expect that erosion scaled with glacier size. The notable lack of the steep, sediment-rich hillsides we identify as a major sediment source in the adjacent Paradise basin, or for example at Mt. Rainier (Czuba et al., 2012), limits colluvial contributions to Exit Creek, such that recent glacier retreat has not exposed a voluminous, readily accessible sediment supply. At the head of the outwash plain, documented 2008–2012 aggradation, steeper slopes, and coarser bar particle sizes demarcate the start of a transitional geomorphic setting between the steep bedrock valley headwall and the lower-angle foreland. Because recent evidence is limited for transient remobilization of sediments stored subaerially in the foreland and also because recent (DEM comparison) evidence for aggradation within the Exit Glacier foreland is consistent with historical (alluvial fans of varying ages) evidence for aggradation, we suggest that changes in sediment supply in recent decades have not been sudden or substantial.

We must consider recent changes in streamflow and sediment load of Exit Creek in context of the potentially significant impact of an intermittent influx of water and sediment from Paradise Creek. Transbasin flow was substantial as recently as the 1940s when Exit Glacier, and subsequently Exit Creek, cut into the Paradise Creek fan and captured some or all of Paradise Creek upstream of the LIA moraines. Paradise Creek has comparable streamflow and probably greater sediment transport capacity than Exit Creek, so it is likely that Exit Creek had higher streamflow and greater sediment load during the period of stream capture. We cannot confidently reconstruct the immediate impacts of that transbasin flow, which depended among other factors on what fractions of stream flow and sediment load were captured; but Exit Creek's adjustment to this external perturbation could have been substantial. The subsequent shift of Paradise Creek away from the transbasin flow path, completed by 1950, therefore began a period in which lower Exit Creek adjusted to a decrease in these inputs. Any recent (post-2009) increases in streamflow or sediment load have, in comparison with the intermittent changes incurred by historic stream capture, been very small.

4.2. Glacial conditioning of stream position

Channel adjustments during the post-LIA retreat of Exit Glacier have been substantial and have largely occurred in response to the evolving positions of Exit Glacier's terminus, the moraines it left behind, and breaches in those moraines. During the LIA maximum advance of Exit Glacier, most flow probably occurred on alluvial fans along the glacier margin, north and south of the terminus. These were abandoned

sometime later, probably abruptly, when Exit Creek breached the LIA moraines. Since then, the lowermost 1 km of the creek has consistently discharged from the center of the LIA moraines, depositing a new alluvial fan downstream of that breach with no evident opportunity for Exit Creek flows to return to the older fans. Upstream of the LIA moraines, this process has repeated itself at progressively upvalley locations. Proglacial streams discharging from the margins of the glacier have been free to migrate broadly within the new valley floor exposed by glacier retreat, but only until confined to topographically favored locations near the valley center by breaches in successive terminal moraines (Fig. 5). This pattern is common in glacier forelands (e.g., Glasser and Hambrey, 2003) and, in the absence of renewed glacier advance, typically is irreversible. These changes in stream position are a common characteristic of paraglacial environments and are important to distinguish from more typical braid plain migration because of the implications for flood hazard.

Glacier retreat continues to impact fluvial processes during a paraglacial period within which 'glacially conditioned sediment stores are either exhausted or attain stability' (Ballantyne, 2002). Implicit in this definition is a primary expectation of the paraglacial period: that abundant glacial deposits in the recently deglaciated proglacial environment will for some period of time be readily transported by enhanced fluvial discharge from a shrinking ice mass. This pattern explains the classic manifestation of paraglacial activity—enhanced downstream sediment yields (Slaymaker, 2011)—but it also predicts localized incision near the glacier front where glacial streams cut down through moraines, debris fans, and fluvial terraces (Maizels, 1983). The modern aggradation of the Exit Creek channel does not, at least superficially, conform to the prediction of localized incision near the glacier front. This is partly because much of that incision has already occurred: the terminal moraine loops, for example, were breached decades ago. The consistent longitudinal gradient we measured along most of Exit Creek, excepting the youngest terrain of the outwash plain reach near the modern glacier margin, also suggests that there has been enough time since deglaciation for the creek to cut and/or fill any knickpoints or inflections imposed by these glacial landforms (Fig. 10). These findings conform to conclusions of Welch (1970) that most of the erosion of recessional moraines occurs within the first 10 years of emplacement, and of Ballantyne (2002) that most paraglacial modification of landforms within a low-relief glacier foreland occurs quite rapidly, usually within a few decades of deglaciation. From the 1951 moraine downstream to the confluence with Resurrection River, we infer that the paraglacial period, including glacier-conditioned changes in stream position, is largely complete.

This finding has implications for future channel migration. One is that substantial sections of the Exit Glacier foreland, including the portion of the Herman Leirer Road between the LIA moraines and the visitor center, are largely protected—by stream incision into the valley center—from ready access by Exit Creek (Fig. 13A). We do not, in other words, take the presence of former channels in these locations as indicative of likely future occupation. Downstream of the stable central breach in the LIA moraines (Fig. 13B), however, Exit Creek flows onto a broad alluvial fan where it is unconfined by post-glacial landforms (Fig. 13C and D). In that setting, the implication is that the stream position is governed by fan-building and braiding processes that are long-lived and largely independent of recent Exit Glacier retreat except for its general contributions to streamflow and sediment load.

Viewed through the filter of largely completed paraglacial adjustment, recent aggradation along much of Exit Creek (Fig. 11) is less a transient paraglacial phenomenon than an expected response to the geography of the basin. The general topographic expression of a merged fan across the lowest parts of the Exit-Paradise glacier forelands leads us to infer that the pre-LIA maximum foreland was already a depositional environment. The distinct shapes of the older Exit Creek fan north of the LIA moraines, the historical Exit Creek fan, and the lower Paradise Creek fan (Fig. 4) merge about 0.5 km from the Resurrection River to



Fig. 13. Photographs of glacially conditioned controls on channel position in Exit Creek (A and B) and fluvial processes active on the Exit Creek alluvial fan (C and D). (A) Paraglacial incision left former fluvial surfaces such as this terrace at a campground in the morainal-alluvial reach inaccessible to the modern channel. (B) The 1894 moraine forms a resistant bank at the breach of the suite of Little Ice Age moraines, BPK 1.4. (C) View upstream, taken from the alluvial fan at BPK 1.0 at low flow in May 2014, showing stranded woody debris and coarse bank deposits from recent overtopping of a low bank. Exit Glacier is in the background. (D) View downstream, taken from the margin of the active braid plain on the alluvial fan at BPK 0.8 in September 2014, showing fresh gravel deposits trapped by large woody debris along an area of negative bank heights.

form a single river-parallel contour. The specific nature of this likely pre-LIA fan is obscured by subsequent reworking and fan-building, but the presence of a fan here is expected. The tongues of Exit and Paradise glaciers drop steeply from the high, bedrock-supported margins of the Harding Icefield to the relatively low-angle valley floor, and the strong inflection generated by this transition is a natural setting for stream sediment deposition. Streams in similarly strong inflections near Seward have a documented history of sedimentation-related flooding and channel migration issues (Northwest Hydraulic Consultants, 2007; U.S. Army Corps of Engineers, 2008).

Ongoing migration of the suite of channels downstream of the LIA moraines evident in historic photos as far back as 1950 (Fig. 6) is a normal fan-building process, fundamentally different from the glacially conditioned and largely irreversible changes in stream position described earlier. Downstream of the confining influence of the LIA moraines, Exit Creek began building a modern alluvial fan sometime prior to 1950 in an area that encompasses the active braid plain, transitional braid plain, and inactive braid plain of Fig. 6. Aggradation across the width of that fan is evident in the modern topography (Fig. 6A), vegetation patterns suggest a considerable portion of the fan was occupied in the decades prior to 1950 (Fig. 6B), and channel migration has continued since that time (Fig. 5). The stratigraphy and dynamics of proglacial fans have been described elsewhere (Zielinski and Van Loon, 2000), and their similarities to braided rivers debated (Blair and McPherson, 1994). We interchange fan and braid plain terminology here but focus on the dynamics of channel migration or

avulsion, here meaning substantial movement of the active braid plain, which in either environment have the important characteristic of being reversible: in the absence of significant changes in boundary conditions, former channel positions within a braid plain are generally considered accessible to future fluvial reoccupation. Avulsion adjusts for imbalances during the development of alluvial fans and braided rivers on historical and longer timescales (e.g., Godaie and Kimbrel, 2015, on the Olympic Peninsula of Washington State) and can occur more swiftly in aggradational settings. Notably, Gran et al. (2015) found an at least temporarily stabilizing influence of vegetation on a braided river on an alluvial fan that concentrated flow and hence aggradation in unvegetated areas but further observed from flume experiments that this ultimately unstable condition results in eventual avulsion. In forested regions where these laterally perched areas of the braid plain exist, avulsion can be accomplished through local triggers such as large woody debris (Mt. Rainier; Chiao, 2016). Over the course of the LIA, Exit Glacier retreat has clearly altered the boundary conditions for fan deposition through episodic, large-scale changes in the position and size of the Exit Creek braid plain, but the available evidence suggests that such changes are to a large extent complete, at least for this downstream reach of the river. Recent and ongoing changes in channel position have been confined within a well-defined alluvial fan, and we recognize no process that would prevent further migration and avulsion within that fan, importantly including the zone of recent flooding on Herman Leirer Road.

5. Conclusions

Despite variations in glacier size and position, streamflow and sediment supply from glacier meltwater runoff, and transbasin flow from adjacent Paradise Creek, the general depositional character of Exit Creek has not changed since at least the LIA. Abundant sediment production by glacier erosion, combined with an abrupt slope decrease at the foreland, has produced a long-term pattern of fan building throughout the period of glacier advance and retreat. Within this framework, though, glacial conditioning has dictated frequent and abrupt changes in channel position juxtaposed with periods of channel confinement, typically at moraine breaches. Throughout the paraglacial period, these glacier-directed or moraine-dictated concentrations of flow have also redirected the flux of sediment to new locations, serving as nozzles to establish the apices of alluvial fan construction. This clearly holds for the now-abandoned moraine breach that built the older Exit Creek fan to the north and for the present central breach that locks in place the apex of the modern Exit Creek alluvial fan.

The glacier's capacity to direct flowpaths diminishes with time and distance from the retreating terminus, however, explaining the contrast between rapid channel changes near the glacier margin and relatively permanent channel positions at more distal locations. In a clear example, glacier-directed outwash paths around moraine fragments in the glacier foreland eventually become terraces inaccessible by the present fluvial processes except over very long timescales. More importantly for the road flooding issue, we infer that the current and formerly fluvial area downstream of the central LIA moraine breach — an alluvial fan with an apex that has likely been fixed for more than a century — is now a relatively permanent feature. Road construction placed Herman Leirer Road along the centerline of what in 1950 was clearly a pre-existing fan and capitalized on a period when the active braid plain was relatively compact, occupying only a portion of the fan. The full retreat of Exit Glacier from the foreland makes it increasingly likely that the fan upon which the road was built will stay active for the foreseeable future because the geomorphic conditions for abandonment of the moraine breach at its apex are glacially conditioned and not recoverable.

Although glacially conditioned controls restrict the modern channel, in particular at moraine breaches and post-paraglacial bank-confined reaches (Fig. 13), channel migration within these confines is reversible by normal fluvial process. The topographic perching of the active braid plain above the road, the relatively rapid recent accumulation of sediment there, the lack of confinement provided by low or indistinct banks, and the expectation that the stream will continue to aggrade set the stage for an eventual shift to adjacent, lower elevation areas — namely, the formerly occupied parts of the fan that now hold the road. Consistent with this conclusion, we interpret the road flooding observed from 2009 to 2014 as incipient channel migration across the alluvial fan and expect that the presently forested area adjacent to the road will at some point in the future be reoccupied by Exit Creek channels. On the basis of available evidence, peak streamflows are not a necessary or sufficient condition for spillage from the active braid plain and do not explain the specific timing of individual road flooding events. Unlike in single thread channels, where flooding necessarily correlates to high streamflow, flooding from a braided stream extends beyond the active braid plain whenever a flow split between braids overwhelms the capacity of a braid plain-marginal channel. Following from this perspective of braiding and fan-building, changes in streamflow and/or sediment transport associated with ongoing glacier retreat, though possibly substantial, are not in this instance the primary drivers of road flooding. Similarly, future changes in glacier melt or renewed transbasin flow may impact rates of aggradation or channel migration, but the expectation of an active fan downstream from the LIA moraine breach, where channels are free to shift across not only the currently active braid plain but also the vegetated formerly active areas, remains.

Appreciating external controls on the fluvial system — in this case,

glacially conditioned channel positions and transbasin flow — helps identify the bounds on fluvial process, in particular channel migration. Even in a system with little streamflow or sediment data, topographic data and aerial photographs, coupled with temperature and precipitation records, can provide the context required to unravel these controls, a critical component to managing lands along braided rivers.

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Appendix A. Supplementary data

Supplementary material associated with this article can be found in the online version, at doi: <http://dx.doi.org/10.1016/j.geomorph.2017.06.004>. Additional data is available at <http://dx.doi.org/10.5066/F75T3HJZ> (a USGS data release published simultaneously). The supplementary material includes data sources used, road flood dates, and particle size information. The additional data include survey data, particle size data, modern and historical channel extents, braid plain kilometer designation, drainage area boundaries, Little Ice Age glacier extents, and a 2012 digital elevation model and orthophoto used in this article.

References

- Ahlstrand, G.M., 1983. Dendrochronological Evidence of the Recent History of Exit Glacier. Unpublished National Park Service Mimeo (10 pp).
- Ballantyne, C.K., 2002. Paraglacial geomorphology. *Quat. Sci. Rev.* 21 (18), 1935–2017.
- Barber, W.F., 2003. Field Review of Exit Glacier Area Near Seward, Alaska. 13 pp.
- Barclay, D.J., Wiles, G.C., Calkin, P.E., 2009. Holocene glacier fluctuations in Alaska. *Quat. Sci. Rev.* 28 (21–22), 2034–2048.
- Bieniek, P.A., Walsh, J.E., Thoman, R.L., Bhatt, U.S., 2014. Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. *J. Clim.* 27, 2800–2818. <http://dx.doi.org/10.1175/JCLI-D-13-00342.1>.
- Blair, T.C., McPherson, J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *J. Sediment. Res.* A64 (3), 450–489.
- Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology* 53 (3–4), 299–316.
- Burgess, E.W., Forster, R.R., Larsen, C.F., 2013. Flow velocities of Alaskan glaciers. *Nat. Commun.* 4. <http://dx.doi.org/10.1038/ncomms3146>.
- Chiao, C., 2016. The role of large woody debris and riparian forest in channel avulsion in the Carbon River, Mount Rainier National Park, Washington. M.S. (Thesis, Univ. of Washington Earth and Space Sciences Applied Geosciences Technical Report 37, 51 pp).
- Church, M., Ryder, J.M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geol. Soc. Am. Bull.* 83 (10), 3059–3072.
- Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Moller, M., Nicholson, L., Zemp, M., 2011. Glossary of glacier mass balance and related terms. In: IHP-VII Technical Documents in Hydrology 86. UNESCO-IHP, Paris.
- Collins, D.N., 2008. Climatic warming, glacier recession and runoff from alpine basins after the Little Ice Age maximum. *Ann. Glaciol.* 48 (1), 19–24.
- Curran, J.H., 2012. Streamflow Record Extension for Selected Streams in the Susitna River Basin, Alaska. U.S. Geological Survey Scientific Investigations Report 2012–5210. (36 pp).
- Curran, J.H., McTeague, M.L., 2011. Geomorphology and Bank Erosion of the Matanuska River, Southcentral Alaska. U.S. Geological Survey Scientific Investigations Report 2011–5214. (52 p).

- Cusick, J.A., 2001. Foliar Nutrients in Black Cottonwood and Sitka Alder Along a Soil Chronosequence at Exit Glacier, Kenai Fjords National Park, Alaska. Master's thesis University of Alaska, Anchorage (183 pp).
- Czuba, J.A., Magirl, C.S., Czuba, C.R., Curran, C.A., Johnson, K.H., Olsen, T.D., Kimball, H.K., Gish, C.C., 2012. Geomorphic Analysis of the River Response to Sedimentation Downstream of Mount Rainier, Washington. U.S. Geological Survey Open-File Report 2012-1242. (134pp).
- Fountain, A.G., Tangborn, W.V., 1985. The effect of glaciers on streamflow variations. *Water Resour. Res.* 21 (4), 579–586.
- Gibson, W., 2009a. Mean Minimum Temperature for Alaska 1971–2000. Geospatial Dataset-2170519. National Park Service Alaska Regional Office.
- Gibson, W., 2009b. Mean Maximum Temperature for Alaska 1971–2000. Geospatial Dataset-2170512. National Park Service Alaska Regional Office.
- Gibson, W., 2009c. Mean Precipitation for Alaska 1971–2000. Geospatial Dataset-2170508. National Park Service Alaska Regional Office.
- Glasser, N., Hambrey, M., 2003. Ice-marginal terrestrial landsystems: Svalbard polythermal glaciers. In: Evans, D., Gooster, L. (Eds.), *Glacial Landsystems*. Arnold, pp. 65–68.
- Godaire, J.E., Kimbrel, S., 2015. Finley Creek alluvial fan geomorphic and hydraulic analyses and implications for restoration. In: Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), April 19–23, 2015, Reno, Nevada, pp. 941–952.
- Gran, K.B., Tal, M., Wartman, E.D., 2015. Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system, Mount Pinatubo, Philippines. *Earth Surf. Process. Landf.* 40 (8), 1101–1115.
- Gray, M., 2003. 2003 Exit Glacier Area Hydrological Evaluation. Unpublished National Park Service (document, 5 pp).
- Gurnell, A.M., Edwards, P.J., Petts, G.E., Ward, J.V., 2000. A conceptual model for alpine proglacial river channel evolution under changing climatic conditions. *Catena* 38 (3), 223–242.
- Helm, D.J., Allen, E.B., 1995. Vegetation chronosequence near Exit Glacier, Kenai Fjords National Park, Alaska. *Arct. Alp. Res.* 27 (3), 246–257.
- Kurtz, D., Baker, E., 2016. Two Hundred Years of Terminus Retreat at Exit Glacier: 1815–2015. National Park Service Natural Resource Report NPS/KEFJ/NRR-2016/1341. (29 pp).
- Leonard, E.M., 1986. Varve studies at Hector Lake, Alberta, Canada, and the relationship between glacial activity and sedimentation. *Quat. Res.* 25 (2), 199–214.
- Maizels, J.K., 1983. Proglacial channel systems: change and thresholds for change over long, intermediate, and short time-scales. In: Collinson, J.D., Lewin, J. (Eds.), *Modern and Ancient Fluvial Systems*. Blackwell Publishing Ltd., pp. 251–266.
- Marren, P.M., Toomath, S.C., 2013. Fluvial adjustments in response to glacier retreat: Skaftafellsjökull, Iceland. *Boreas* 42 (1), 57–70.
- Martin, M., 2006. Floodplain Reconnaissance at Exit Glacier and Other Areas. (KEFJ. National Park Service Memorandum, 10 pp).
- Martin, G.C., Johnson, B.L., Grant, U.S., 1915. Geology and Mineral Resources of Kenai Peninsula, Alaska. U.S. Geological Survey Bulletin 587. (scale 1:250,000).
- van der Nat, D., Schmidt, A.P., Tockner, K., Edwards, P.J., Ward, J.V., 2002. Inundation dynamics in braided floodplains: Tagliamento River, Northeast Italy. *Ecosystems* 5 (7), 636–647.
- National Weather Service, 2014. Alaska-Pacific River Forecast Center River Observation Database. accessed online at: http://aprfc.arh.noaa.gov/php/rivobs/get_chart.php (on March 20, 2014).
- Northwest Hydraulic Consultants, Inc., 2007. Long-term Sedimentation Trends on Seward, Alaska Valley Streams. Northwest Hydraulic Consultants, Inc., Seattle, Washington (18 pp).
- Ohmura, A., 2001. Physical basis for the temperature-based melt-index method. *J. Appl. Meteorol.* 40 (4), 753–761.
- Perica, S., Kane, D., Dietz, S., Maitaria, K., Martin, D., Pavlovic, S., Roy, I., Stuefer, S., Tidwell, A., Trypaluk, C., Unruh, D., Yekta, M., Betts, E., Bonnin, G., Heim, S., Hiner, L., Lilly, E., Narayanan, J., Fenglin, Y., Zhao, T., 2012. Precipitation-frequency atlas of the United States, Alaska. National Oceanic and Atmospheric Administration Atlas 7(2). National Weather Service, Silver Spring, Maryland accessed online at: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_ak.html (on March 24, 2014).
- Pfeffer, W.T., Arendt, A.A., Bliss, A., Bolch, T., Cogley, J.G., Gardner, A.S., Hagen, J.-O., Hock, R., Kaser, G., Kienholz, C., Miles, E.S., Moholdt, G., Mölg, N., Paul, F., Radic, V., Rastner, P., Raup, B.H., Rich, J., Sharp, M.J., The Randolph Consortium, 2014. The Randolph Glacier Inventory: a globally complete inventory of glaciers. *J. Glaciol.* 60, 537–552. <http://dx.doi.org/10.3189/2014JoG13J176>.
- Rampton, R., 2015. Obama: Shrinking Exit Glacier a Powerful Sign of Warming Climate. Reuters accessed online at: <http://www.reuters.com/article/us-usa-obama-alaska-glacier-idUSKCN0R14U120150902> (on March 14, 2016).
- Shreve, R., 1972. Movement of water in glaciers. *J. Glaciol.* 11, 205–214.
- Slaymaker, O., 2011. Criteria to distinguish between periglacial, proglacial, and para-glacial environments. *Quaestiones Geographicae* 30 (1), 85–94.
- Sloan, C.E., 1985. Water Resources and Hydrologic Hazards of the Exit Glacier Area Near Seward, Alaska. U.S. Geological Survey Water Resources Investigations Report 85-4247. (8 pp).
- Stark, K.J., Allen, K., Nadeau, A.J., Sopcak, J., Danielson, L., Komp, M.R., Drazkowski, B., 2015. Kenai Fjords National Park: natural resource condition assessment. In: Natural Resource Report NPS/KEFJ/NRR—2015/900. National Park Service, Fort Collins, Colorado.
- Tetreau, M., 1993. Hydrology Survey – Exit Creek Delta and Beaver Pond Area: Unpublished National Park Service Document. (6 pp).
- Tysdal, R.G., Case, J.E., 1979. Geologic map of the Seward and Blying Sound quadrangles, Alaska. U.S. Geological Survey Miscellaneous Investigations Series Map 1150. (12 pp., 1 sheet, scale 1:250,000).
- United States Army Corps of Engineers, 2008. Alaska Baseline Erosion Assessment, Erosion Information Paper – Seward, Alaska. United States Army Corps of Engineers, Anchorage, Alaska (6 pp).
- Viereck, L.A., Dyrness, C.T., Batten, A.R., Wenzlick, K.J., 1992. The Alaska Vegetation Classification. U.S. Forest Service General Technical Report PNW-GTR-286.
- Welch, D.M., 1970. Substitution of space for time in a study of slope development. *J. Geol.* 78, 234–239.
- Western Regional Climate Center, 2014. Station Daily Time Series, Station: Harding Icefield, Alaska. Western Regional Climate Center accessed online at: <http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?akAHAR> (on December 17, 2014).
- Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surf. Process. Landf.* 35 (2), 136–156.
- Wiles, G.C., Calkin, P.E., 1994. Late Holocene, high-resolution glacial chronologies and climate, Kenai Mountains, Alaska. *Geol. Soc. Am. Bull.* 106 (2), 281–303.
- Wiley, J.B., Curran, J.H., 2003. Estimating Annual High-flow Statistics and Monthly and Seasonal Low-flow Statistics for Ungaged Sites on Streams in Alaska and Conterminous Basins in Canada. U.S. Geological Survey Water-Resources Investigations Report 03-4114. (61 pp).
- Williams, H., 2014. 20th Century Evolution of Paradise Creek, and Potential Impacts on Exit Creek in Kenai Fjords National Park, AK. Senior Project. Alaska Pacific University, Anchorage, Alaska (32 pp).
- Zielinski, T., Van Loon, A.J., 2000. Subaerial terminoglaciated fans III: overview of sedimentary characteristics and depositional model. *Geol. Mijnb.* 79, 93–108.