Debris Flow Chronology and Potential Hazard along the Alaska Highway in Southwest Yukon Territory

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ABSTRACT

We studied 30 large debris fans along the Alaska Highway between the Alaska-Yukon boundary near Beaver Creek and the south end of Kluane Lake to document late Holocene and historic debris flow activity and to evaluate the hazard that debris flows pose to the highway and other infrastructure. We used dendrochronology and tephrochronology to date surfaces on the fans and to estimate debris flow recurrence. All of the fans are paraglacial landforms of largely latest Pleistocene and early Holocene age. Debris flows continued to occur, probably at a diminishing rate, during the middle and late Holocene, but have only left an irregular carapace of deposits on the early Holocene fans. The White River tephra, which is about 1,200 years old, occurs across the surface of most of the fans, indicating that few debris flows and floods have escaped existing channels of streams on the fans. We conclude that future debris flows, like those that have occurred on nine fans in the past few decades, will mostly be restricted to present stream crossings.

INTRODUCTION

The Alaska Highway connects Alaska and the continental United States and is a major transportation route. The part of the highway in Canada extends along the east margin of the St. Elias Mountains from the Yukon-Alaska boundary near Beaver Creek to Haines Junction and from there east to Whitehorse and south to Watson Lake (Figure 1). The highway crosses large individual and coalesced debris fans sourced in the Kluane Ranges along the west shore of Kluane Lake (Figure 2). The lower slopes and stream courses in the watersheds that feed these fans are mantled with colluvium. These sediments, as well as glacial deposits in the forefields of small glaciers in the headwaters of some of the catchments, are easily mobilized during storms, producing hyperconcentrated flows and debris flows that extend across the fans (Clague, 1981; Evans and Clague, 1989; Harris and McDermid, 1998; and Huscroft et al., 2004). Ground ice thaw during warm weather periods is a further triggering mechanism in areas underlain by permafrost (Harris and Gustafson, 1993; Huscroft et al., 2004). In the summer of 1967, after a period of intense rainfall, a debris flow occurred at the southeast corner of Kluane Lake and blocked the Alaska Highway (Evans and Clague, 1989). In July 1988, rain-induced debris flows occurred along several creeks in the study area (Evans and Clague, 1989). At that time, a major debris flow, 2 km west of the 1967 event, covered more than 500 m of highway, and two debris avalanches occurred in colluvium on slopes near Sheep Mountain on the southwest side of Kluane Lake, one of which blocked the highway. Farther north, toward Burwash Landing, the highway was severed by debris or hyperconcentrated flows in 1988 at six locations (Copper Joe, Lewis, Bocks, Mines/Nines, and Congdon creeks). Large amounts of coarse material were mobilized along the stream channels that cross the large debris fans in this area. Natural levees were eroded or overtopped, and artificial berms were breached at several locations (Evans and Clague, 1989). Frequent, but generally much smaller, flows have been described on the steep sides of the Slims River valley (Harris and McDermid, 1998) and Silver Creek valley

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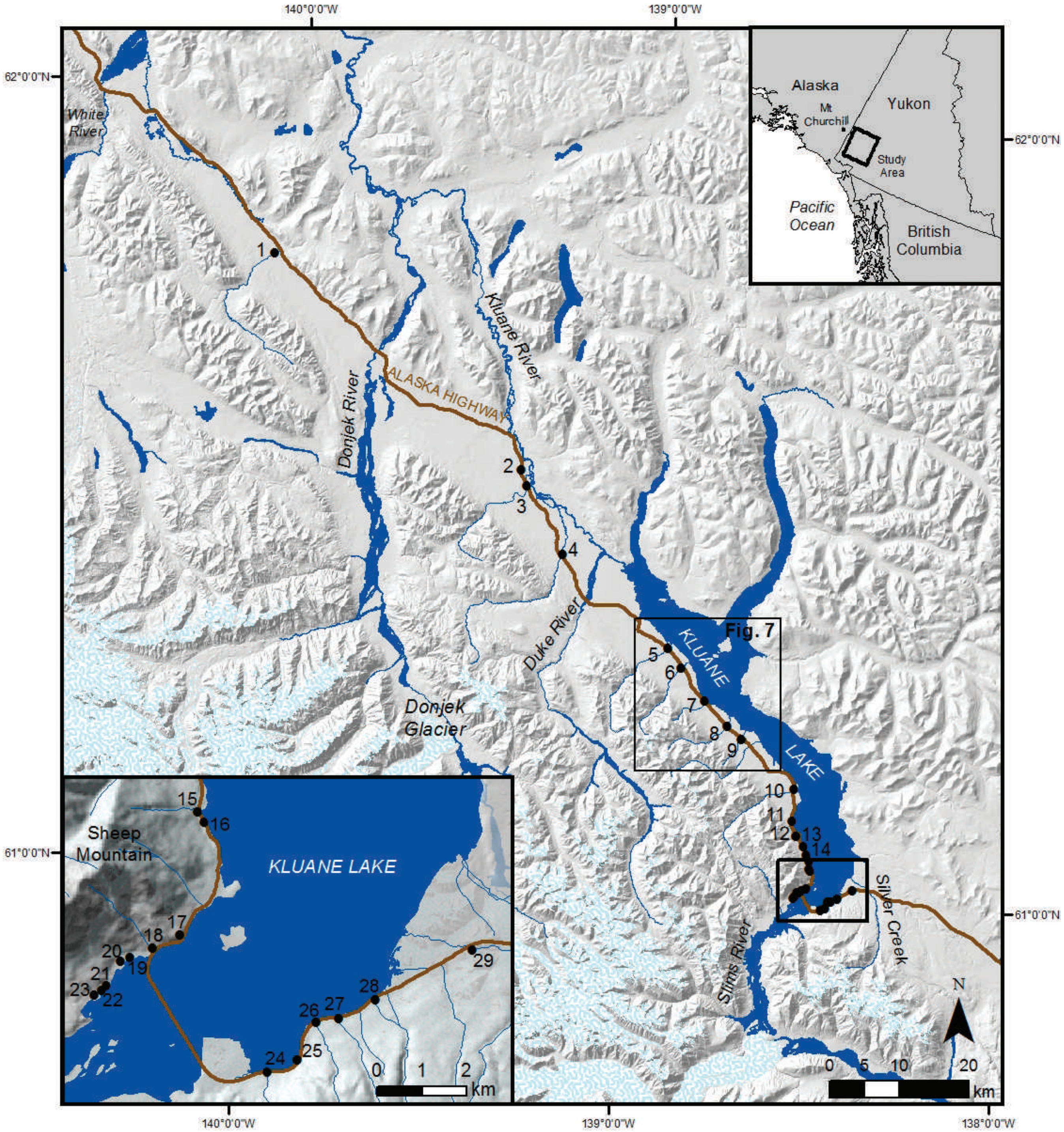

Figure 1. Study sites along the Alaska Highway. 1, Edith Creek; 2, Quill Creek; 3, Glacier Creek; 4, Burwash Creek; 5, Copper Joe Creek; 6, Lewis Creek; 7, Cluett Creek; 8, Bocks Creek; 9, Mines/Nines Creek; 10, Congdon Creek; 11, Sheep 1; 12, Sheep 2; 13, Sheep 3; 14, Sheep 4; 15, Sheep 5; 16, Sheep 6; 17, Sheep 7; 18, Sheep 8; 19, Sheep 9; 20, Sheep 10; 21, Sheep 11; 22, Sheep 12; 23, Sheep 13; 24, Slims-Silver 1; 25, Slims-Silver 2; 26, Slims-Silver 3; 27, Slims-Silver 4; 28, Slims-Silver 5; 29, Slims-Silver 6. Parts of Donjek, Duke, and Slims rivers appear as lakes because of their constantly shifting braided channels. Sites 17–24 are located along the southwest shoreline of Kluane Lake. The area shown in Figure 7 is indicated by a box.

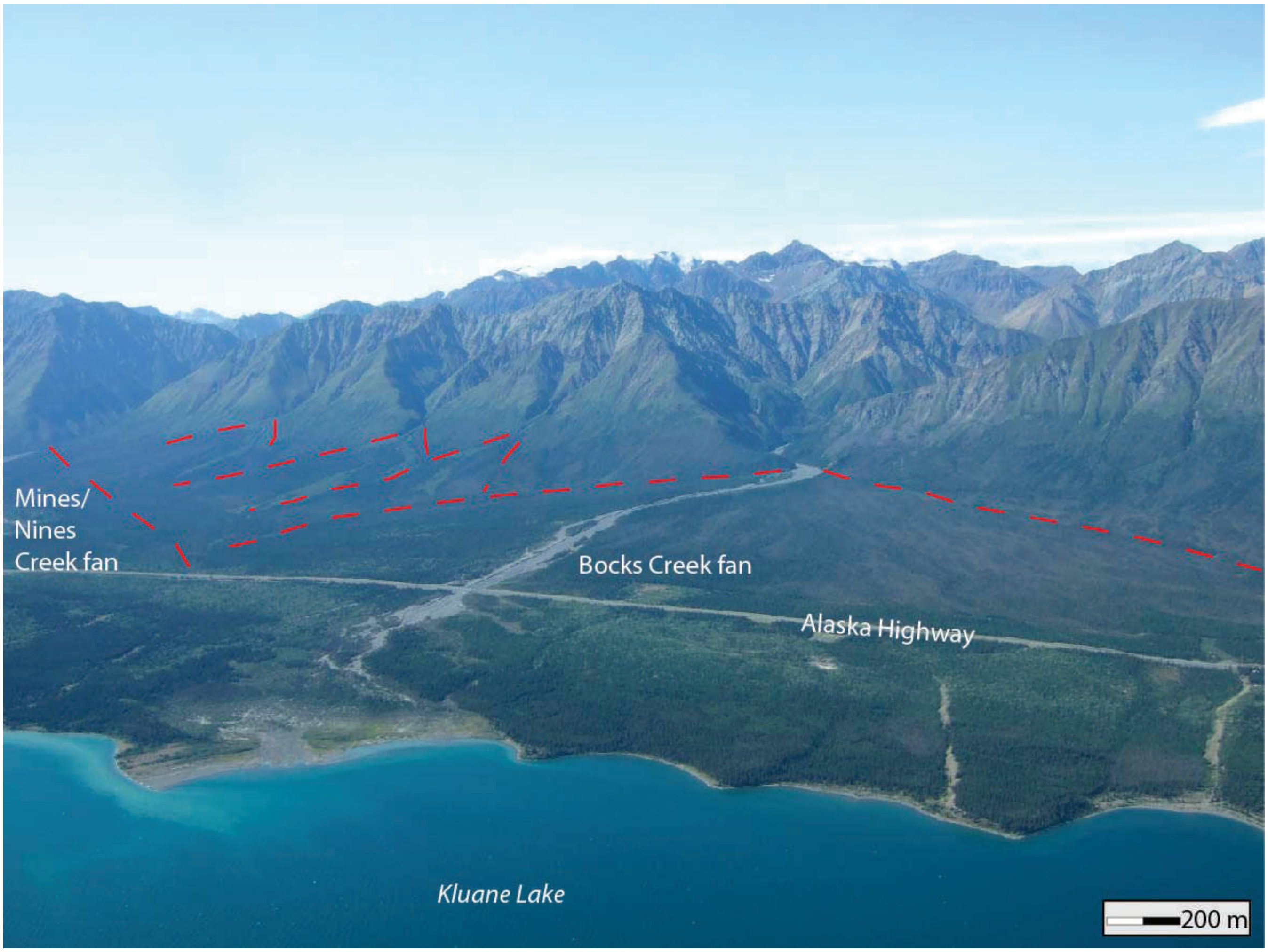

Figure 2. Debris fans along the west side of Kluane Lake south of Destruction Bay. View to the southwest.

(Huscroft et al., 2004), upstream of their intersection with the Alaska Highway. These debris fans extend out onto the floors of the main valleys, but are distant from the highway and, thus, pose no danger to it.

High-discharge flows in small steep watersheds in the Kluane Ranges involve mixtures of water and sediment in different proportions. The relative concentration of suspended sediment plays an important role in flow behavior and hazard; three basic types are recognized: (1) water flows, (2) hyperconcentrated flows, and (3) debris flows (Costa, 1988; Pierson, 2005). The amount of suspended sediment in water flows is insufficient to substantially affect how the flowing water behaves. Water may appear very muddy, but most of the suspended sediment is transported near the bed. However, bedload may include material up to boulder size. In hyperconcentrated flows, the amount of suspended sediment is sufficient to significantly change fluid properties and the sediment transport mechanism. Large volumes of sand are transported in suspension throughout the water column, although maintenance of high sediment loads depends on flow velocity and turbulence. Sediment at the base of a hyperconcentrated flow may move in a carpet rather than through sliding or saltation of individual clasts. These flows can be highly erosive. Debris flows are characterized by a slurry of sediment and water, in some cases similar to wet concrete. In steep confined canyons, such as are present in the Kluane Ranges, debris flows can achieve high velocities, transport large boulders, and cause catastrophic damage from impact or burial. In low-gradient channels and on fans, debris flows decelerate, but they can nevertheless rapidly infill channels, divert streams, and destroy infrastructure. These different flow types represent a continuum—boundaries between flow types are not sharp, and any one flow event can change from one flow type to another along the flow path and at different times during the same event. Similarly, the nature of a flow may be difficult to ascertain from its deposit (Costa, 1988; Pierson, 2005).

This study examines the potential hazard posed by debris flows to the Alaska Highway by establishing the chronology of the deposits west and south of Kluane Lake through tephrochronology, dendrochronology, and radiocarbon dating. It is part of a natural hazard assessment conducted along the corridor of a proposed pipeline to transport natural gas from the North Slope of Alaska to markets in the midwest United States.

STUDY AREA

The Kluane Ranges, the easternmost ranges of the St. Elias Mountains, have relief up to 1,800 m and are dissected by steep-sided valleys. Bedrock is a complex assemblage of Paleozoic slate, greywacke, limestone, dolomite, conglomerate, serpentinite, and greenstone (Wheeler, 1963). During the Late Wisconsin (Marine Isotope Stage 2) Kluane Glaciation, ice flowing eastward from the high ranges of the St. Elias Mountains deposited till to elevations of about 1,860 m a.s.l. (Denton and Stuiver, 1967). Outwash and glaciolacustrine sediments were deposited on the floors and lower walls of valleys during deglaciation, and silt deflated from active valley trains was deposited as loess on most surfaces (Borns and Goldthwait, 1966). Pleistocene sediments were weathered during a warm interval in the early Holocene to form the Slims Soil (Borns and Goldthwait, 1966). Most slopes are blanketed by till-derived stony Orthic Regosol-type soils (Soil Classification Working Group, 1998), which are poorly developed.

The study area has a subarctic continental climate with long cold winters, short mild summers, and relatively low precipitation east of the Kluane Ranges. Precipitation at the Arctic Institute of North America field station at the south end of Kluane Lake (468 mm/a, 1972–1980) falls primarily as rain in the summer (late May to August) and as limited snowfall in the fall and winter (Harris and Gustafson, 1993). Intense rainfall during thunderstorms in the summer can trigger debris flows, and small ones can be observed along highway embankments after some storms.

The portion of the study area from Beaver Creek to the north end of Kluane Lake is within the extensive discontinuous permafrost zone; it is bordered on the south by the sporadic discontinuous permafrost zone (Heginbottom et al., 1995). At higher elevation in the study area, however, permafrost is likely continuous.

The debris fans are covered by white spruce (*Picea glauca*) forest. The forest, which is periodically reset by wildfires and disease, is generally younger than 200 years old, thus living trees provide only minimum ages for the surfaces on which they are growing. White spruce is known to form adventitious roots when buried by a veneer of sediment and continues to live after burial (Jeffrey, 1959). Deciduous trees, including trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*), are largely restricted to current and recently abandoned stream courses and to areas disturbed by human activity and fire.

METHODS

Dendrochronology

Trees provide a minimum estimate of the age of the surface on which they are growing (Lawrence, 1946; Luckman, 1998; Koch, 2009). We sampled living trees on the debris fans we studied to constrain the ages of the land forms. Two increment cores were extracted from several trees on each fan using a 4.3-mm-diameter increment borer. Two cores allow data to be replicated and reduce the possibility of missing or false rings (Stokes and Smiley, 1996). We mounted and prepared cores for analysis by sanding with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Rings were measured with a precision of ±0.001 mm. Trees killed by a debris flow can be used to develop floating chronologies that can be cross-dated with living chronologies. The year of death then provides a precise age for the event.

We cut discs from dead trees found in stratigraphic sections and analyzed them in the same way as the cores. Trees that show multiple levels of adventitious roots were cored above, below, and at each root level to establish when the trees abandoned their previous root level and formed adventitious roots due to burial by debris.

We built a living tree-ring chronology from all sampled trees. The series was checked and verified using the International Tree-Ring Data Bank (ITRDB) software program COFECHA and cross-dated (50-year dated segments lagged by 25 years with a critical level of correlation [99 percent] set at 0.32), thus creating a master ring-width chronology (Holmes, 1983). We developed floating chronologies from trees killed by debris flows that we recovered along several streams. Where the floating chronologies proved too old to cross-date into living chronologies, we radiocarbon-dated outermost rings of one sample within each floating chronology, thus providing a limiting age for the associated event. AMS (Accelerator Mass Spectrometry) radiocarbon ages on outer rings were calibrated using the program

CALIB 6.0 (Stuiver et al., 2010). Calibrated ages, shown in brackets in this study, are the 1 σ range.

When living trees are used to date a surface, the ecesis interval must be added to the age of the oldest tree to obtain the minimum age of the surface (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993; Koch, 2009). The ecesis interval is the time from surface stabilization to successful seedling germination. The local ecesis interval was not established in this study, but has been previously estimated to be 10 years or more in this area (Luckman, unpublished data, reported in Clague et al., 2006). Furthermore, a correction must be made for the time required for trees to grow to sampling height (McCarthy et al., 1991; Koch, 2009). We cored trees with a downward angle as close to the ground as possible (<10 cm) and, therefore, made no correction for sampling height. Due to possible errors stemming from these two factors, we rounded off ages established from living trees to the nearest decade.

Tephrochronology

White River tephra is widespread in southern and central Yukon (Clague et al., 1995; Lerbekmo, 2008) and has been identified as far east as the Mackenzie Mountains in District of Mackenzie (Robinson, 2001) and south to central British Columbia (Lakeman et al., 2008). The source of the tephra is the Mt. Churchill area in the St. Elias Mountains near the Alaska-Yukon boundary (Figure 1). Two White River tephra layers are present in the study area: an older, finer-grained layer dating to *ca.* AD 300, which is restricted to the northern part of our study corridor, and a younger, coarser-grained layer dating to *ca.* AD 800, which is widespread and conspicuous throughout the study area.

The tephra consists mainly of pumiceous glass and is easily identified in the field from its white color. Within our study area, the younger tephra thins from up to 15 cm at Glacier Creek to less than 1 cm at the south end of Kluane Lake and at our northernmost site at Edith Creek. We dug five to 30 pits on each of the investigated fans to determine whether the younger White River tephra was present. Where present, it consistently was less than 50 cm below the fan surface (Figure 3).

RESULTS

The debris fans along the Alaska Highway between the Alaska-Yukon border and the south end of Kluane Lake (Figure 1) were constructed largely during and shortly after deglaciation and have only been modified to a small degree during the past 1,200 years, and in most cases during the past 5,000 years. White River tephra is present at or near the surface over most of the fans that we investigated. At some sites, however, debris and hyperconcentrated flows overtopped modern stream banks within the past 1,200 years and spread thin layers of sediment on the adjacent fan surface. White spruce growing on these surfaces are generally 150–200 years old, but the forest may not closely delimit the ages of the debris flows. No white spruce is present on some surfaces where the younger White River tephra was found at depths less than 50 cm. Many of these surfaces are wet sites, where successful germination of spruce may have been significantly delayed. White River tephra is absent in abandoned stream channels on the fans, which are conspicuous on aerial photographs because they support fewer and smaller spruce than the adjacent fan surface (Figure 4).

At several sites we found evidence for multiple debris flows in the form of gravel or diamicton layers separated by soils that in two cases included tree stems in growth position (Figure 5). We obtained radiocarbon ages on wood samples from soil layers overlain or underlain by debris flow deposits (Table 1). At some sites we found trees with up to two levels of adventitious roots (Figure 6). Trees with adventitious roots provide evidence that hyperconcentrated or debris flows deposited sediment around them at least once during their lifetime.

Debris Flow Chronology

Edith Creek

Edith Creek is the northernmost site that we investigated (Figure 1). Fan sediments exposed along the north bank of the stream south of the Alaska Highway comprise overbank flood or hyperconcentrated flow deposits that contain two horizons of detrital and *in situ* wood up to 30 cm in diameter, as well as reworked White River tephra (Figure 5). The sediments thus postdate the AD 800 eruption. The oldest tree growing on the fan surface had 226 rings at the time of sampling in 2009; assuming 10 years for ecesis, the surface thus is no younger than AD 1770. Although the wood at this site was too rotten to core or successfully cross-date, the two overbank events recorded at Edith Creek must have occurred between AD 800 and AD 1770. The areal extents of the two deposits are not fully known, but we found undisturbed White River tephra less than 10 m from the present stream channel, suggesting that the events were minor. We dug more than 10 pits across the fan, and all contained the younger White River tephra, indicating that the fan has been stable, and Edith Creek has been within its present channel, since AD 800.

Figure 3. White River tephra in a cutbank along Burwash Creek. Two tephras, both white, can be seen in this photograph. The lower, finer tephra is not widespread in the study area; it dates to about AD 300. The upper, coarser tephra, which dates to about AD 800, is a widespread stratigraphic marker.

Quill Creek

Although there has been historic placer mining in the upper reaches of Quill Creek, there is no evidence for recent debris flow activity. We found the younger White River tephra in pits adjacent to the channel and across the fan, indicating that Quill Creek has been contained within its channel since AD 800.

Glacier Creek

There is no evidence for recent debris flows along Glacier Creek. Pits dug adjacent to the stream channel expose the younger White River tephra less than 40 cm below ground level within surface peat or soil. Similarly, tephra is found at shallow depths in pits dug across the fan, indicating that Glacier Creek has been confined to its present channel since AD 800.

Burwash Creek

There are placer mining operations in the upper reaches of Burwash Creek, and the stream channel is disturbed on the fan. Just south of the Alaska Highway bridge, however, undisturbed strata are exposed along the stream bank. Both White River tephras are preserved in peat in the stream bank. Woody debris and *in situ* trees rooted in the peat are overlain by gravel. The *in situ* trees were successfully cross-dated with living trees in adjacent forest and show that the overlying gravel was deposited in the 20th century, likely in response to upstream mining activity. Aside from this mining-related sedimentation, Burwash Creek appears to have been contained within its channel since AD 300. Pits dug along a transect from the present channel to the west contain the younger White River tephra, further indicating a stable channel for at least 1,200 years.

Figure 4. The Congdon Creek alluvial fan, outlined by the white dashed lines. The black dashed lines indicate the portion of the fan that has been active since the White River eruption. The current and abandoned channels are evident from differences in vegetation. The thinner black line marks a levee constructed to deflect possible future high-flow events away from the highway. White circles are sites where White River tephra was observed, and black circles are sites where the tephra is absent.

Copper Joe Creek

Holocene sediments overlie Pleistocene drift in several sections along Copper Joe Creek near the Alaska Highway (Figure 7). There is no evidence for debris flows in these sections. Fine eolian sediments separate two soils; the lower soil contains the older White River tephra, and the upper soil contains the younger White River tephra. Similar sections are present in an old abandoned channel to the south (Figure 7). In the upper part of Copper Joe Creek, near the apex of its fan, several sections show late Pleistocene and Holocene sequences similar to the ones farther downstream. At one site near the apex, the younger White River tephra is overlain by coarse sediment, likely deposited by a debris flow or hyperconcentrated flow. About 400 m downstream, two coarse layers, which are likely debris flow deposits, are separated by fine sand and silt containing reworked White River tephra. The stratigraphy at these sites thus records two debris flow events at Copper Joe Creek during the Holocene: one prior to and the other after the younger White River eruption. Neither of the two debris flows, however, reached the distal part of the fan in the vicinity of the Alaska Highway. Cored trees near the apex of the fan indicate that the surface adjacent to the stream channel stabilized around AD 1810; thus, the younger event occurred between AD 800 and 1810. The younger White River tephra is found in peat less than 30 cm below the fan surface in several pits adjacent to the present channel, within abandoned

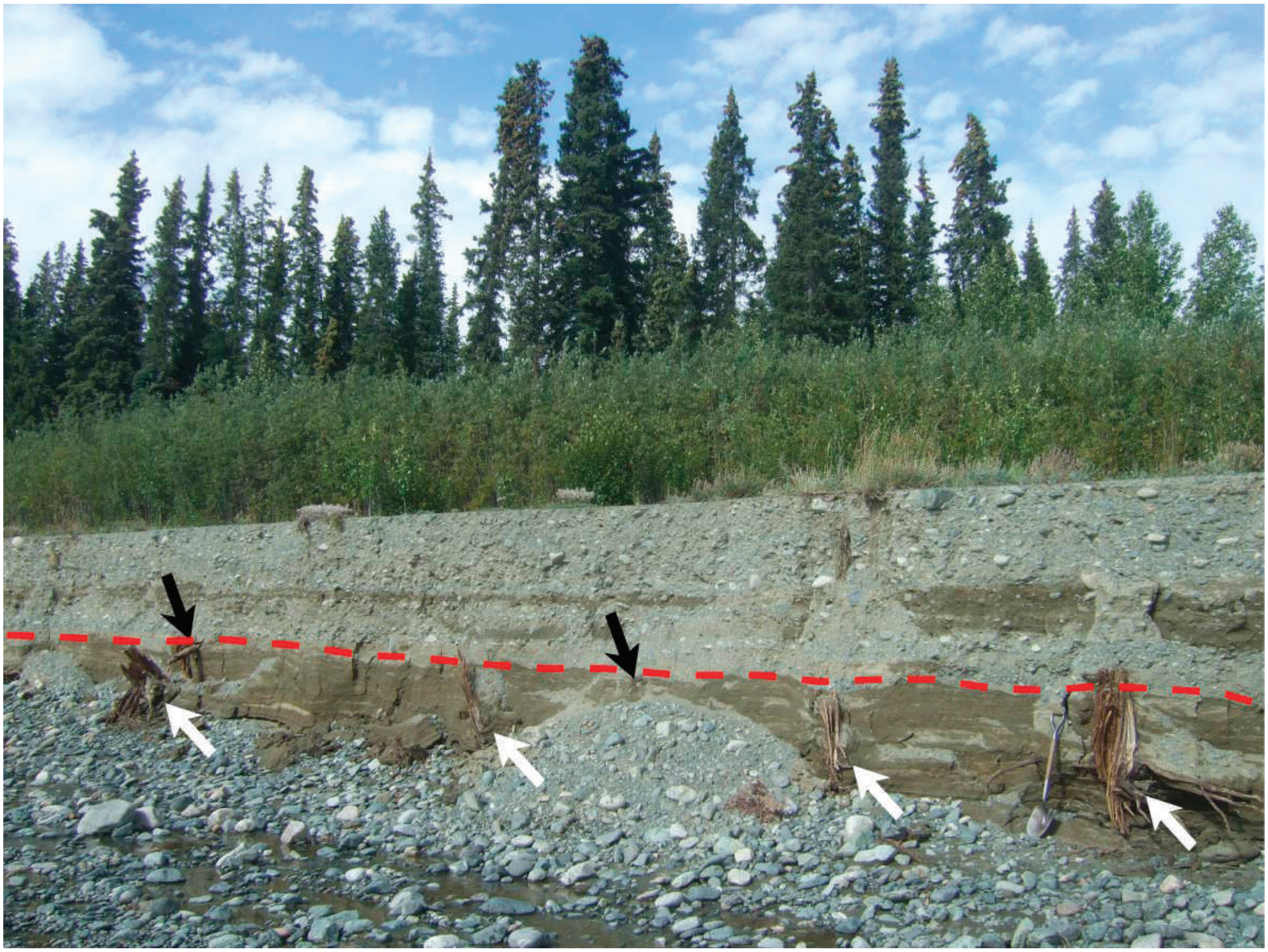

Figure 5. Cutbank along Edith Creek showing overbank flood deposits (upper limit indicated by red dashed line), which contain two horizons (black and white arrows) of detrital and *in situ* wood, as well as reworked White River tephra.

channels, and across the fan. This evidence suggests that the post-White River debris flow was a minor event.

Lewis Creek

Much of the channel of Lewis Creek (Figure 7) is protected by constructed levees, but several exposures in its upper reaches provide evidence for overbank flow events. At one site, the younger White River tephra is overlain successively by loess and a thin layer of coarse sediment deposited by a flood or debris flow. At another site, tephra rests directly on gravel that possibly was deposited by a debris flow. At a third site, late glacial sediments are overlain by a Holocene sequence that contains no evidence of debris flows. Pits adjacent to the current channel near those locations contain the younger White River tephra about 30 cm below the surface, indicating that the younger flood or debris flow event must have been small in size and extent.

Several *in situ* trees with two layers of adventitious roots were found near the apex of the Lewis Creek fan (Figure 6), indicating that sediments buried the roots of the trees twice. Two trees date to the AD 1780s. Cores from above, below, and at each root layer indicate that the two burial events occurred about 40 years and 25 years ago. The latter event is likely associated with a hyperconcentrated or debris flow event in 1988 (Evans and Clague, 1989). The older event may be associated with modification of the stream channel by humans.

Several abandoned channels of Lewis Creek (Figure 7) shed further light on its history. In one channel, no trees have yet become established and no tephra was found. Thus, this channel likely was active during the 1988 event (Evans and Clague, 1989). Another channel has 45 cm of peat, which grades down into silty fine sand and then gravel. The absence of tephra indicates that Lewis Creek occupied this channel some time after AD 800. Tephra is present in

Table 1. *Radiocarbon ages reported in this paper.*

Location	Laboratory No.	^{14}C Age (years BP)	Calibrated Age Range	Comment
Bocks	UCIAMS-72653	960 ± 15	AD 1025–1150	*In situ* stump, lowest soil
	UCIAMS-72654	120 ± 20	AD 1685–1885	*In situ* stump, second soil
	UCIAMS-72655	−2,075 ± 15	n/a	Roots, third soil
Sheep 8	UCIAMS-83756	1,920 ± 20	AD 60–125	Branch from top soil
	UCIAMS-83757	1,910 ± 20	AD 70–125	Roots(?) from second soil
	UCIAMS-83758	2,025 ± 20	1950–1995	Root from lowest soil
Sheep 9	UCIAMS-72651	3,535 ± 15	3730–3860	Roots from middle soil
	UCIAMS-72652	3,780 ± 15	4095–4225	Roots from lowest soil
Slims-Silver 1	UCIAMS-83759	4,515 ± 20	5065–5295	*In situ* stump; lowest soil
	UCIAMS-83760	4,440 ± 20	4975–5215	*In situ* stump; second soil
	UCIAMS-83761	3,270 ± 25	3450–3555	Detrital stem; top soil
	UCIAMS-83762	1,590 ± 20	AD 425–535	Organics from base

Note: Dated samples are outer perimeter wood. Radiocarbon samples were dated at the Keck Carbon Cycle AMS Facility. Calibrated age range is 1 σ, and ages are reported as cal years BP if older than 1,000 years and as AD if younger than 1,000 years. n/a = excess ^{14}C; therefore calibration not possible.

Figure 6. Recently killed trees that have been partially exhumed by high water flows along Lewis Creek. These trees have two levels of adventitious roots (red arrows).

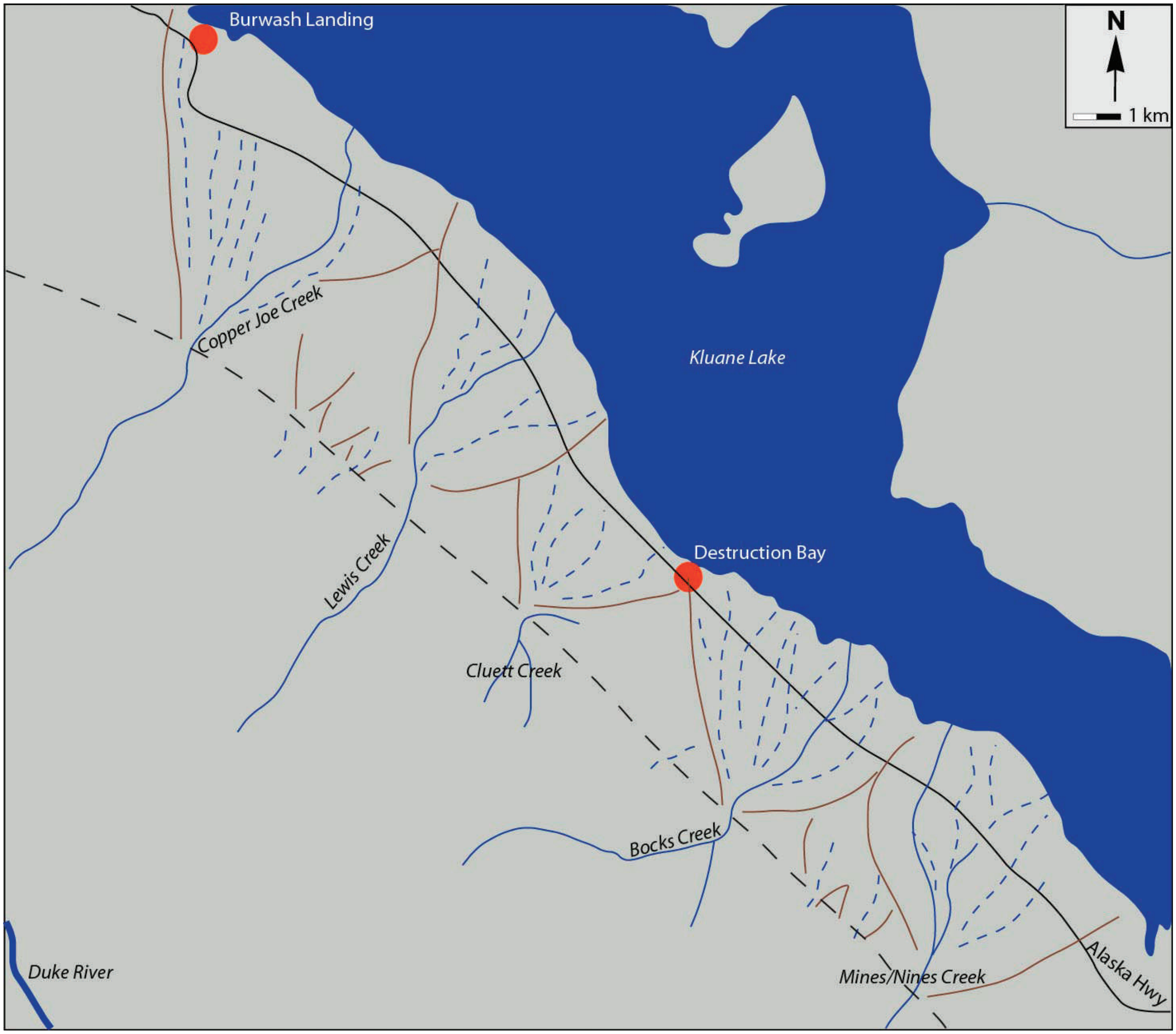

Figure 7. Detail of the fans west of the northern section of Kluane Lake. Brown lines indicate the margins of individual alluvial fans. Blue dashed lines show abandoned channels, and the black dashed line shows the boundary between the Kluane Ranges and Shakwak Valley. Red dots indicated locations of communities.

peat adjacent to the channel about 25 cm below the surface. Other pits dug across the fan indicate that Lewis Creek has been confined to its channels since AD 800, thus much of the fan surface is more than 1,200 years old.

Cluett Creek

The younger White River tephra was found 20–40 cm below the surface in pits dug in peat in the current channel and in several abandoned channels of Cluett Creek (Figure 7), indicating that no debris flows have occurred along these channels since AD 800. Similarly, tephra is present in pits dug across the fan. In the abandoned channel just south of the present active channel, silt including reworked tephra at 50 cm depth indicates possible overbank flow shortly after the younger White River eruption or, alternatively, that this channel was the main channel at that time. In two channels farther south, the younger White River tephra rests directly on gravel, and 100 m upstream in one of the two channels, the tephra was found 15 cm below the surface, but separated by about 40 cm of peat from the underlying gravel, indicating that this channel was active some time before the White River eruption. No tephra was found in two channels north of the present stream course; rather, boulders and gravel extend to the surface, indicating that Cluett Creek occupied these channels recently. It appears that Cluett Creek has occupied different channels in the recent past, but none of them shows clear evidence of debris flow events. We instead interpret the channels as having formed due to avulsion during periods of high stream flow, as is common on alluvial fans (Field, 2001).

Bocks Creek

There is evidence that recent debris flows overtopped the present-day channel of Bocks Creek (Figure 7). In a section near the apex of the Bocks Creek fan, a soil overlying a debris flow unit contains the younger White River tephra; the debris flow thus occurred before AD 800. This soil is overlain by sand that contains a few cobbles up to 20 cm in diameter. We interpret this layer to be a debris flow or flood deposit. It, in turn, is overlain successively by another soil containing fine eolian sediment and another fine-grained unit with cobbles up to 20 cm in diameter, which we also interpret to be a debris flow or flood deposit. In summary, a debris flow occurred at Bocks Creek prior to AD 800, and two small events, during which the stream escaped its present channel, occurred after AD 800. The oldest tree growing on the apex of the alluvial fan adjacent to the present channel had 177 rings at the time of sampling in 2009; adding 10 years for ecesis, we conclude that the surface has been stable at least since AD 1820. The extent of the two younger events is unknown, but White River tephra was found close to the present-day channel, which indicates that the flows were small. This conclusion is supported by the presence of two trees with adventitious roots. Both trees are rooted in the upper soil and are covered by a thin veneer of overbank deposits. Samples below, above, and at root level suggest that the overbank flow took place around AD 1798. Thus, the older overflow event is bracketed between AD 800 and AD 1798. Another section, about 200 m downstream, lacks evidence for both of these units, whereas a third section another 200 m downstream contains a thin unit of flood or hyperconcentrated flow sediments.

A 2-m-high section 300 m farther downstream along Bocks Creek contains four woody soil layers (Figure 8). The lowest soil overlies a gravel unit, is about 10 cm thick, and contains *in situ* trees. A sample of outermost wood from one of the trees yielded a radiocarbon age of 960 ± 15 ^{14}C years BP (AD 1025–1150). This soil is overlain by gravel (unit 2 in Figure 8), which we interpret to be a flood, hyperconcentrated flow, or debris flow deposit. This unit is capped by another soil, which also contains *in situ* trees. The outermost wood of one of these trees returned an age of 120 ± 20 ^{14}C years BP (AD 1685–1885). This soil, in turn, is overlain by a sand and gravel unit (unit 3) deposited by a flood, hyperconcentrated flow, or debris flow, which is capped by a third soil layer that contains woody debris. A sample of this woody debris returned a radiocarbon age with excess ^{14}C incorporated during the period of atmospheric thermonuclear weapons testing in the 1950s. Very fine silt directly above this soil as well as overlying gravel, a fourth soil, and the diamicton of the top layer must be younger than 60 years old. One of the two gravelly units is likely associated with the 1988 rainstorm (Evans and Clague, 1989).

The evidence presented above indicates that one debris flow occurred along Bocks Creek before the younger White River eruption, and at least three debris flows or hyperconcentrated flows occurred after the eruption. The oldest of the three post-White River events occurred sometime between AD 800 and AD 1100; the next younger event occurred between AD 1100 and AD 1798; and the last event happened around AD 1798. The presence of White River tephra in pits dug close to the present-day channel and across the fan indicates all three events were small.

Mines/Nines Creek

Mines and Nines creeks (Figure 7) are the same stream, but their channels have been extensively modified by humans. At several locations along the lower part of the channel, bedrock is overlain by a soil that contains the younger White River tephra and, therefore, lacks any evidence for debris flow events. Farther upstream, a layer of flood or debris flow deposits is bracketed by soils (Figure 9). The soil below the gravel unit (unit 1 in Figure 9) contains the older White River tephra, and the soil above it contains the younger tephra; therefore, the high-flow event that deposited the sediment occurred between AD 300 and AD 800. At another section closer to the apex of the fan, till is overlain by eolian sediments, which are capped by a soil that contains both tephras. Therefore, there is no evidence for debris flows in this section. In another section near the fan apex, however, till is overlain by three debris flow units. The three units are separated by thin soils, and the uppermost unit is overlain by eolian sediments and a soil that contains the younger White River tephra. This section thus provides evidence for three debris flow events older than AD 800. All pits dug adjacent to the present and recently abandoned channels contain White River tephra at depths of 25–30 cm below the surface, with no evidence for debris flows younger than AD 800. Similarly, pits dug across the fan contain the younger tephra, indicating a stable fan since AD 800.

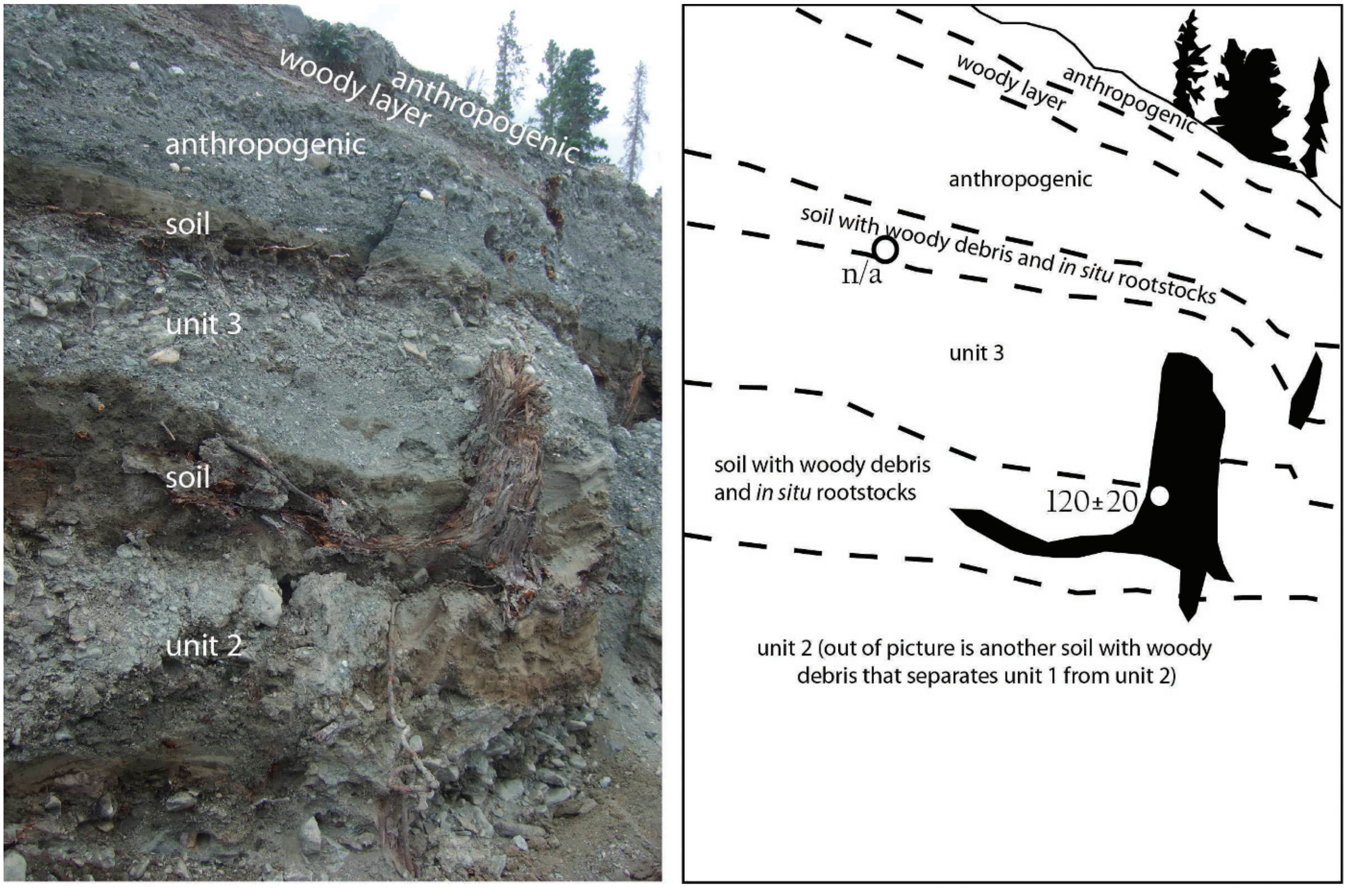

Figure 8. Cutbank along Bocks Creek with three layers of gravelly sediment separated by soil layers that include woody materials, some in growth position. Wood from an *in situ* tree separating units 2 and 3 yielded a radiocarbon age of 120 ± 20 ^{14}C years BP (AD 1685–1885). Wood from a soil layer directly above unit 3 contained excess ^{14}C, due to incorporation of carbon generated by mid-20th-century atmospheric thermonuclear weapons testing. This wood is probably less than 50 years old.

Congdon Creek

A 5-m-high section along Congdon Creek about 200 m upstream of the Alaska Highway (Figure 1) exposes about 1.5 m of Holocene sediment containing the early Holocene Slims Soil and the younger White River tephra, but lacks evidence for debris flows. A 1.4-m-high section of what we interpret to be a debris flow deposit is present another 100 m upstream. This deposit is overlain by overbank silt. No datable material was found in this section, thus the ages of the units are unknown. However, pits dug adjacent to the channel contain White River tephra in peat about 30 cm below the ground surface, indicating that either the debris flow pre-dates the tephra or was of minor extent and confined largely to the channel. Congdon Creek has been strongly modified by humans, thus it is possible that both the coarser and finer units are products of 20th-century channel disturbance. However, they also could be associated with the rainstorm in 1988.

Several sections upstream of flood and debris flow control structures (Figure 4) along Congdon Creek shed light on the history of the fan. In one section, coarse gravel (unit 1 in Figure 10) is capped by soil, which in turn is overlain by the younger White River tephra (Figure 10). The tephra is overlain by a 30-cm-thick eolian silt unit (unit 2), which is capped by 5–10-cm-thick pebbly gravel deposited by a flood or debris flow (unit 3). The gravel, in turn, is overlain by 25 cm of eolian silt (unit 4) and is capped by present-day soil. The upper eolian silt is reddish in color, indicating a substantial period of weathering. We infer that the gravel below the surface soil is closer in age to the White River tephra than to today. In another section, 200 m farther upstream, a thin organic layer containing tephra separates two gravelly debris flow units. A section at the apex of the Congdon Creek fan contains evidence for three debris flows. Till at the base of the section is overlain by a debris flow unit, which is capped by a thin soil. This soil is overlain by another gravelly debris flow unit that, in turn, is overlain by a soil containing the younger White River tephra. This soil is overlain by a third debris flow unit, on which the present-day soil

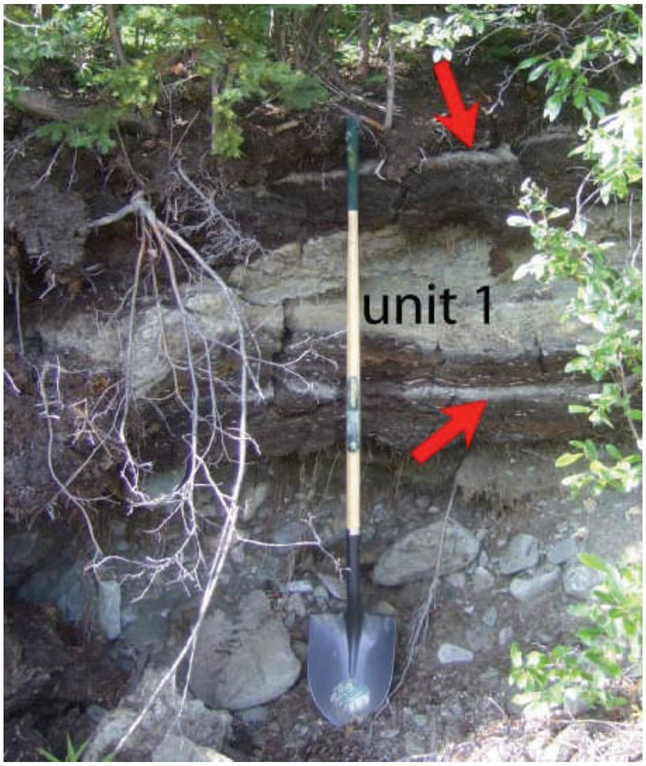

Figure 9. Section along Mines/Nines Creek with overbank flow deposits (unit 1) bracketed by organic silt. The lower soil contains the older White River tephra (lower arrow); the upper soil contains the younger White River tephra (upper arrow).

has developed. Two of the three debris flow events predate the younger White River tephra; the final event took place shortly after the younger tephra was deposited.

Several dead trees, some of which retain bark, stand in the middle of the Congdon Creek channel at the apex of the fan. The trees started growing at this site in the AD 1770s and appear to have been buried in debris up to 1.5 m thick in the mid-20th century. Thus, the last of the events mentioned above happened between AD 800 and AD 1770s. The event that buried the trees is most likely related to stream modification and not to the 1988 event. Pits dug across the fan indicate that the fan has been mostly stable since AD 800 (Figure 4).

Area between Congdon Creek and Silver Creek

There are numerous unnamed creeks between Congdon Creek and Silver Creek. We refer to the creeks and fans between Congdon Creek and Slims River and along the north side of Slims River up to the starting point of the Kaskawulsh Glacier trail as "Sheep" and number them from north to south (Figure 1). We refer to unnamed streams between Slims River and Silver Creek as "Slims-Silver" and number them from west to east (Figure 1).

Sheep 1—No tephra was found in pits dug on this steep fan, indicating that the surface is younger than AD 800. The oldest sampled tree contained 189 rings at the time of sampling in 2009; if 10 years are added for ecesis, the fan surface stabilized no later than AD 1810. Two debris flow units are separated by overbank sand in an exposure near the present-day channel. We found an *in situ* tree with adventitious roots in the overbank sediments. Tree-ring counts indicate that the second debris flow event occurred around AD 1836. The older event occurred between AD 800 and AD 1756 (the pith year of the tree).

Sheep 2–7—Tephra was found in most sections along the creeks and in the pits on these fans, indicating that the surfaces have been stable since AD 800. However, debris flow deposits cover the bases of some living spruce trees on the Sheep Creek fan and may be associated with the 1988 rainstorm. Thirteen cored trees up to 143 years old in 2009 show no scarring or tilting and, thus provide no evidence for this event during their lifetime. A section along the creek at Sheep 7 exposes White River tephra underlain by three probable debris flow units. No suitable material was found for dating at that site.

Sheep 8—The Alaska Highway provides a 200-m-long section through the Sheep Creek landslide (Figures 1 and 11; Clague, 1981). Blocky rock avalanche debris caps three debris flow units separated by weakly developed soils or silt layers containing woody debris. The lowest debris flow unit is clast-supported diamicton with subangular to subrounded clasts up to 1 m in diameter. This unit contains a thin sandy silt layer with some fine plant material. It is overlain by a weathered and oxidized silt layer with woody debris. A root from this horizon returned a radiocarbon age of 2,025 ± 20 ^{14}C years BP (1950–1995 calendar years BP). Above this soil is a second debris flow unit, similar to the first, but with mainly subrounded clasts. It is overlain by another oxidized silt layer with woody debris and *in situ* roots, one of which yielded a radiocarbon age of 1,910 ± 20 ^{14}C years BP (AD 70–125). Another clast-supported diamicton layer up to 3 m thick rests on this soil and is capped by a silt layer containing plant detritus. A branch from this soil returned a radiocarbon age of 1,920 ± 20 ^{14}C years BP (AD 60–125). On top of this soil is a blocky, clast-supported unit of the Sheep Mountain rock avalanche, which Clague (1981) dated to about 500–1,950 ^{14}C years BP (AD 50–1430).

We interpret this section to record a rock avalanche (top unit) and three debris flows. The oldest debris flow took place sometime before 1970 cal years BP.

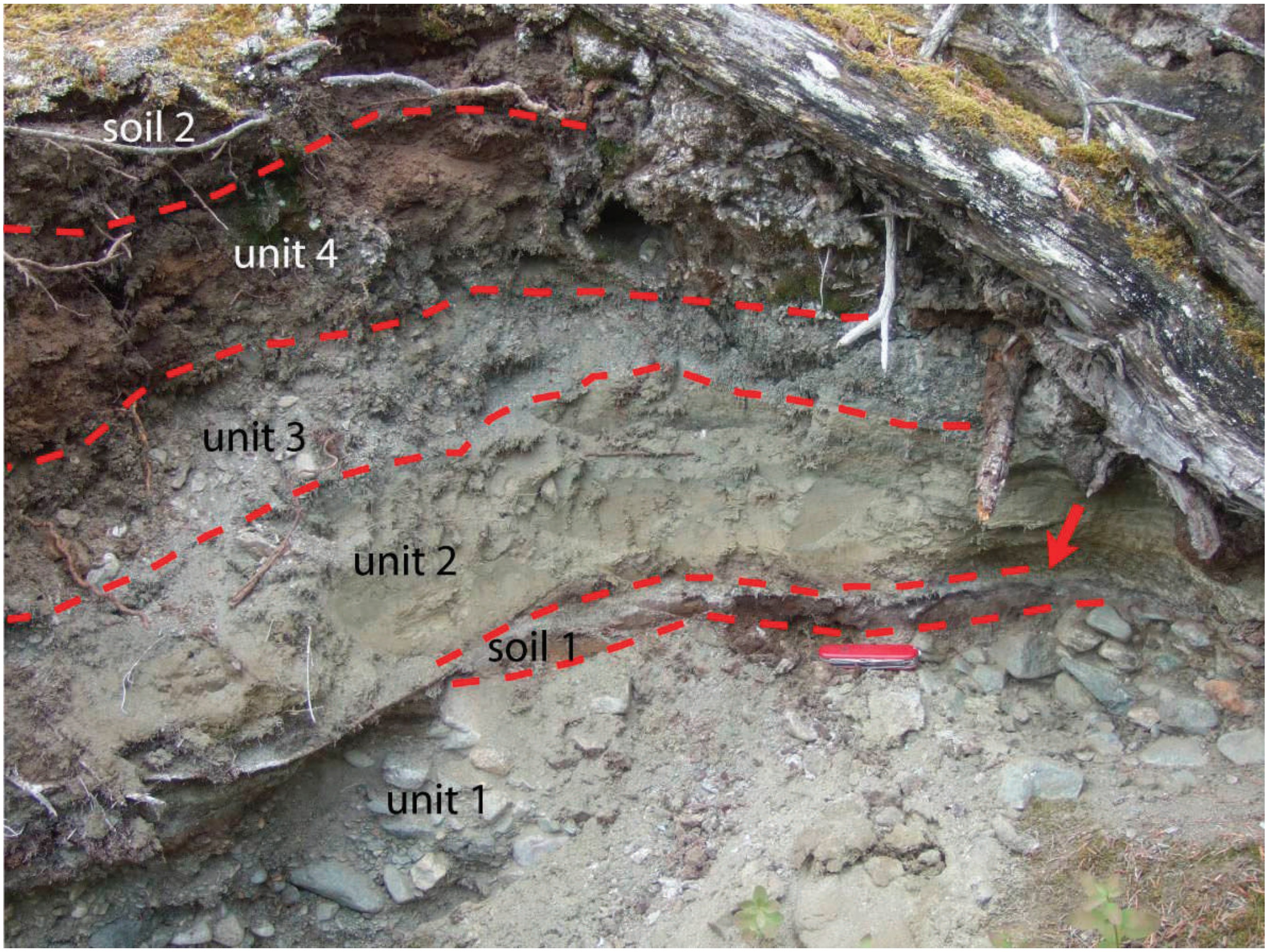

Figure 10. Section along Congdon Creek with coarse gravel (unit 1) overlain by soil 1 (red arrow) containing White River tephra. The soil is overlain by eolian silt (unit 2), pebbly gravel (unit 3), reddish eolian silt (unit 4), and the present-day soil (soil 2). Unit 3 was deposited by a flood or debris flow.

The next two debris flows occurred within about 100 years of each other, between AD 0 and AD 100.

Sheep 9—A prominent, steep, hummocky debris flow fan is present on the flank of Sheep Mountain just northwest of the Kluane National Park Visitor Centre (Clague, 1981). The fan comprises several matrix-supported diamicton units deposited by viscous debris flows and separated by reddened soils (Figure 12). The lowest soil contains small *in situ* roots and charcoal that yielded a radiocarbon age of 3,780 ± 15 ^{14}C years BP (4095–4225 cal years BP). A second soil, which also contains *in situ* roots and charcoal, returned a radiocarbon age of 3,535 ± 15 ^{14}C years BP (3730–3860 cal years BP). The third and uppermost soil contains the younger White River tephra. There is coarse sediment above this soil, but it was emplaced during road construction just above the site. At least three debris flows have occurred on this fan: one sometime before about 4200 cal years BP; another between 4200 and 3700 cal years BP; and a third between 3700 cal years BP and AD 800, but more likely closer to the older date than the younger one.

Sheep 10–14—These fans are located along the road that provides access to the Kaskawulsh Glacier trail in lowermost Slims River valley. Road cuts through the uppermost sediments of four of the fans reveal landslide debris overlain by an eolian sediment sequence that contains Slims Soil and White River tephra. Thus, the fans have been largely inactive throughout the Holocene. The Sheep 11 fan, however, has evidence of recent, localized debris flow activity. The fan is forested, but recently deposited lobes of gravel surround the base of trees growing on parts of the fan. Unfortunately, the rings of these trees provide no firm evidence for the age of this debris flow activity. The debris flows appear to have been small and slow-moving, because they did not scar the trees.

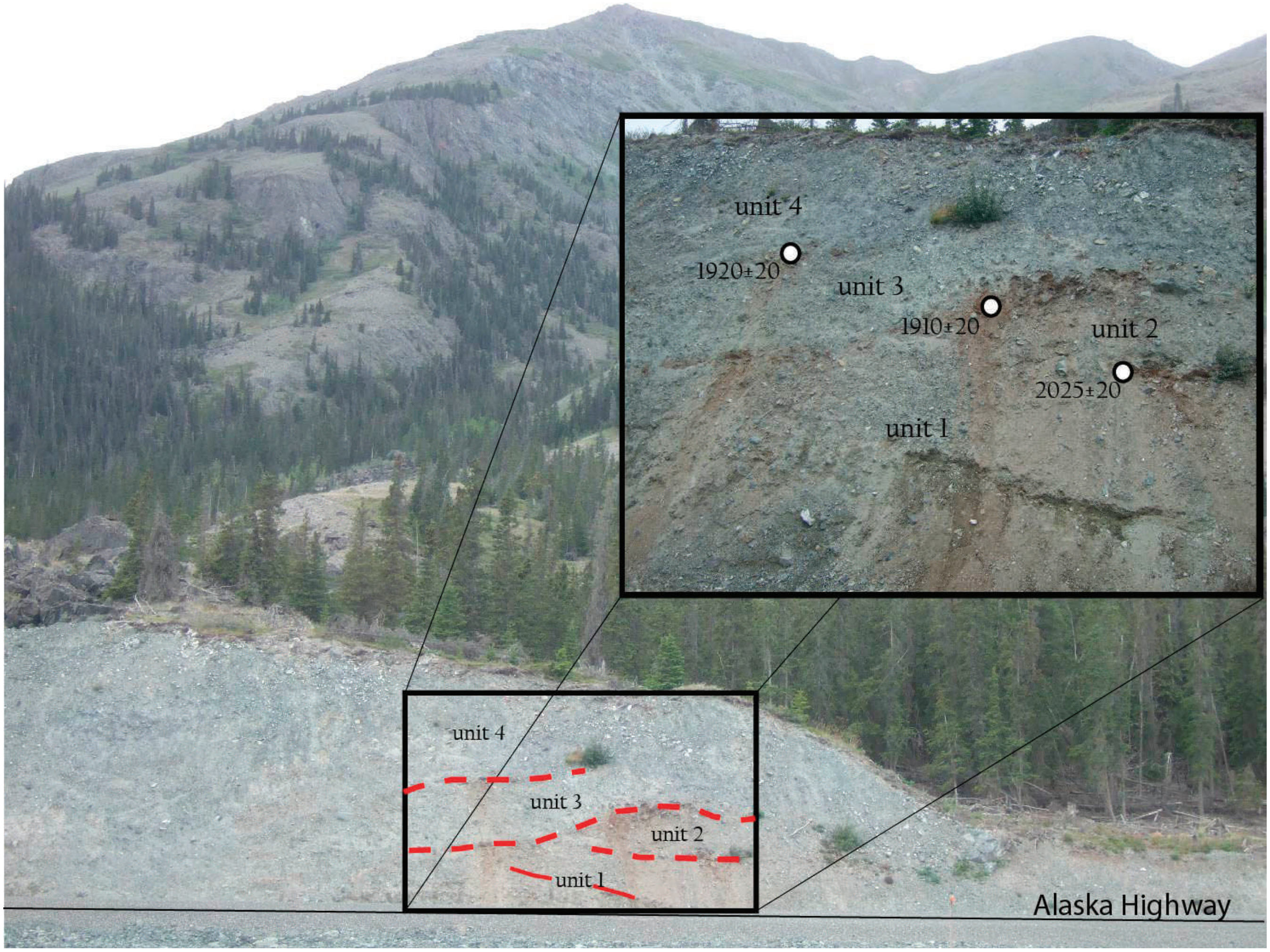

Figure 11. Section at the site of the Sheep Creek rock avalanche (locality Sheep 8). Blocky rock avalanche deposits (unit 4) cap a sequence comprising three debris flow units separated by thin soils or silt layers that contain woody debris. The sandy silt layer in unit 1 is indicated by the solid red line. The soil separating units 1 and 2 yielded a radiocarbon age of 2,025 ± 20 ^{14}C years BP (1950–1995 cal years BP); possible *in situ* roots in the soil separating units 2 and 3 yielded an age of 1,910 ± 20 ^{14}C years BP (AD 70–125); a branch in the soil separating units 3 and 4 returned an age of 1,920 ± 20 ^{14}C years BP (AD 60–125).

Slims-Silver 1—No tephra was found in pits dug on this fan, indicating that the surface is younger than AD 800. Slopewash locally overlies boulders that we interpret to have been deposited by debris flows. At one site, the boulders lie on a young vegetation layer. Based on the ages of trees growing on the fan surface, as well as ring data from trees that were overrun and killed by the debris flow, this event took place in the late 1980s and is associated with the rain-induced debris flows of 1988 that blocked the Alaska Highway at the time.

An approximately 100-m-long exposure along the Alaska Highway sheds light on the history of this fan. A matrix-supported diamicton with angular to sub-rounded clasts up to 0.7 m in diameter forms much of this section and is interpreted to be debris flow material. Three discontinuous wood layers were found within the section. The lowest one is about 4 m above the highway; the outermost rings of an *in situ* stump from this layer yielded a radiocarbon age of 4,515 ± 20 ^{14}C years BP (5065–5295 cal years BP). The outermost rings of an *in situ* stump in another wood layer about 2 m higher yielded an age of 4,440 ± 20 ^{14}C years BP (4975–5215 cal years BP). About 5 m below the top of the section is a third woody layer. No conclusive *in situ* material was identified in this layer, but a detrital stem returned an age of 3,270 ± 25 ^{14}C years BP (3450–3555 cal years BP). The section is capped by about 2 m of peat with organic-rich silt layers that are well exposed in a drainage ditch. The younger White River tephra is present near the bottom of the ditch. Plant detritus 2 cm above the base of the peat but below the tephra layer returned a radiocarbon age of 1,590 ± 20 ^{14}C years BP (AD

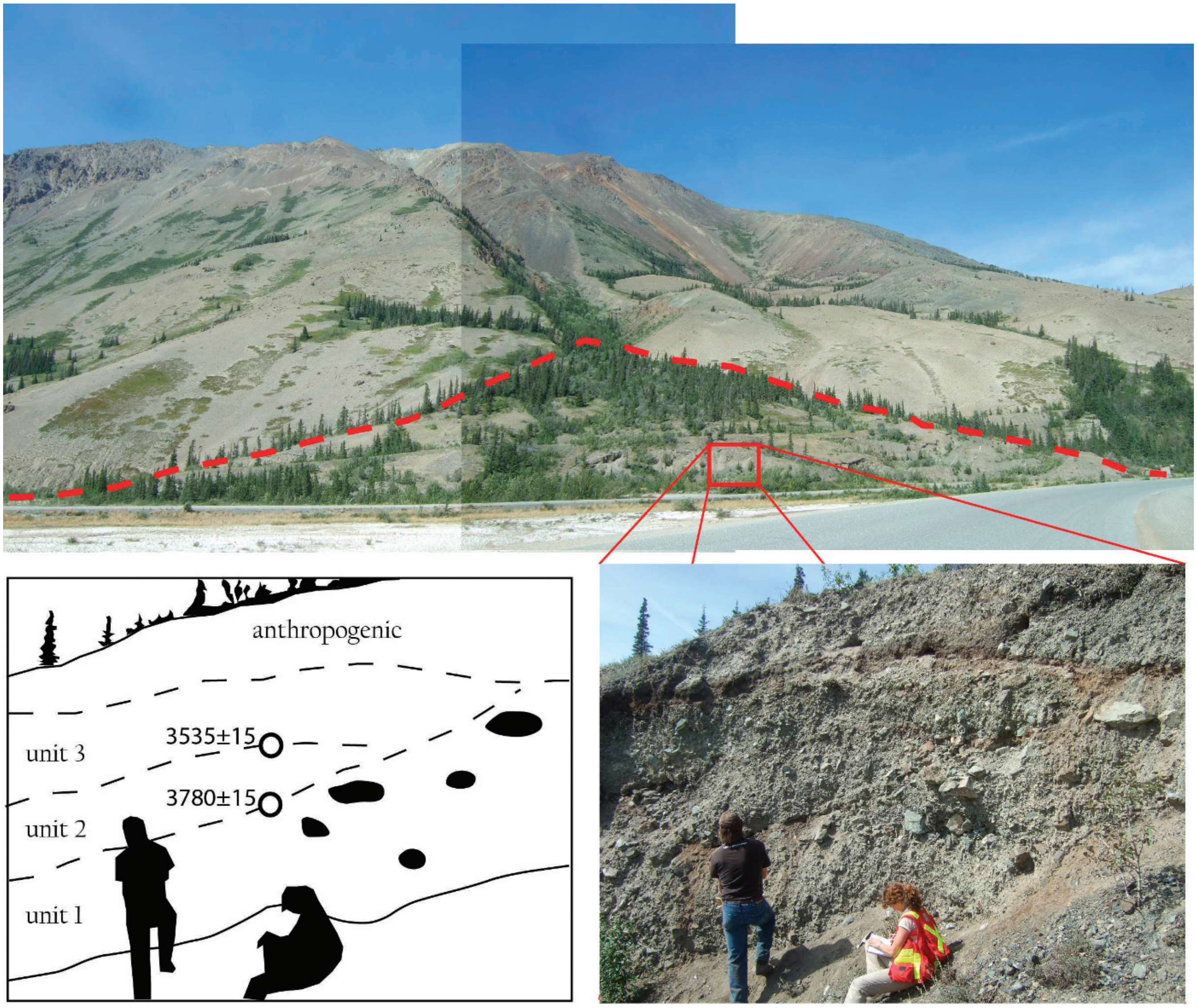

Figure 12. Debris cone at locality Sheep 9 at the south end of Kluane Lake. The fan comprises at least three debris flow units separated by thin soils that contain charcoal. Roots in the soil separating units 1 and 2 yielded a radiocarbon age of 3,780 ± 15 ^{14}C years BP (4095–4225 cal years BP), and roots in the soil separating units 2 and 3 returned an age of 3,535 ± 15 ^{14}C years BP (3730–3860 cal years BP). The soil separating unit 3 from the anthropogenic material contains the younger White River tephra.

425–535). We interpret this section to record at least three large debris flows: one before 5100 cal years BP, another about 5100 cal years BP, and a third about 3500 cal years BP.

Slims-Silver 2–5—Some of the pits dug on the fans and cones of these small unnamed creeks lack the younger White River tephra, suggesting activity since AD 800. The stratigraphy, however, suggests slopewash rather than debris flow activity. Other pits contain the younger White River tephra or show soil development, thus parts of each fan have been stable for more than 1,200 years.

Slims-Silver 6—This fan has been significantly modified by highway construction; it is crossed by both the present highway and its predecessor, located about 500 m farther upstream. The younger White River tephra was found in most pits dug on the fan, indicating stability since AD 800. However, tephra was not present in pits dug in several recent channels that lack full tree cover. It thus appears that debris flows have mostly been confined to several channels that cross the fan. Upstream of the old highway route, however, evidence of the 1967 debris flow is still visible.

Summary of Debris Flow Chronology

Figure 13 provides a summary of debris flow and hyperconcentrated flow activity in our study area.

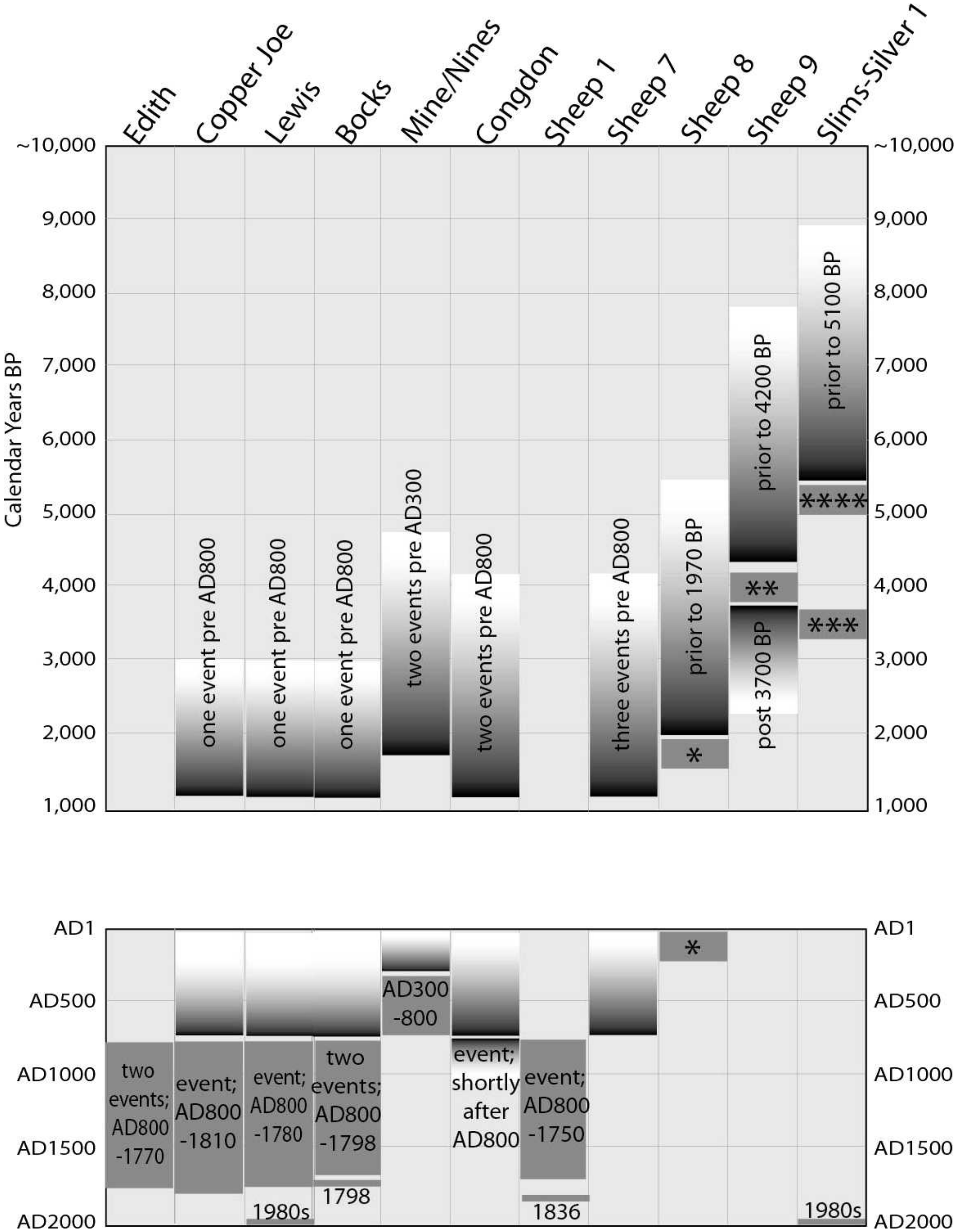

Figure 13. Inferred late Holocene debris flow chronology of 11 of the 30 alluvial fans along the Alaska Highway between Beaver Creek and the south end of Kluane Lake. * indicates two events at Sheep 8 between AD 0–100; ** indicates an event at Sheep 9 between 4200 and 3700 cal years BP; *** indicates an event at Slims-Silver 1 about 3500 cal years BP; **** indicates an event at Slims-Silver 1 about 5100 cal years BP.

The debris fan at Slims-Silver 1 provides evidence for debris flows prior to 5100 cal years BP, about 5100 cal years BP, and about 3500 cal years BP. At Sheep 9, debris flows occurred prior to 4200 cal years BP, between 4200 and 3700 cal years BP, and between 3700 cal years BP and AD 800. At Sheep 8, an event occurred prior to 1970 cal years BP and two events occurred between AD 0 and AD 100. Mines/Nines Creek is the only site where we found both White River tephras, which allows better temporal constraint of events. Two events here predate the AD 300 eruption, and a third event occurred between AD 300 and AD 800. We found evidence for at least one event older than AD 800 at Bocks, Copper Joe, and Lewis creeks; two events older than AD 800 at Congdon Creek; and three such older events at Sheep Creek 7. Edith, Copper Joe, and Lewis creeks show evidence for up to two minor events between AD 800 and AD 1770–1810. At Bocks Creek, two events date to between AD 800 and AD 1100 and around AD 1798. A debris flow occurred at Congdon Creek shortly after AD 800 (Figure 13). Much of the surface of the fan of Sheep 1 was overrun by debris flows between AD 800 and AD 1800. At least two events are recorded at one site; the older event dates to between AD 800 and AD 1750 and the younger event to about AD 1836. We found no evidence of debris flow activity outside the present-day channels of Burwash, Glacier, Cluett, and Mines/Nines creeks since AD 800. Cluett and Lewis creeks have avulsed since AD 800, but this instability does not necessarily relate to debris flow events. Sheep 6, Sheep 11, and Slims-Silver 2 through 5 provide evidence for recent activity, most likely within the past 50 years, but each of the events is localized, and some may only be slopewash. Recent activity at Slims-Silver 1 dates to the 1980s.

DISCUSSION

Results presented here indicate that the large debris fans along the west and south sides of Kluane Lake were constructed largely during and shortly after deglaciation and have only been slightly modified since then (Figure 13). No evidence was found for major debris flow activity in the 19th and 20th centuries on most of the fans. However, channels on some fans have been abandoned and new ones formed due to avulsion during this period. There is evidence for debris flows in the past few decades at nine sites, but all of the flows were relatively small.

Our study provides substantial support for a previous assessment (Evans and Clague, 1989) that fans south of Congdon Creek are relatively small, have steeper gradients, and are largely products of debris flows and hyperconcentrated flows, whereas fans north of and including Congdon Creek are much larger, have lower gradients, and appear to be dominated by fluvial processes. Furthermore, we also find support for the conclusion of Clague (1981, p. 969) that "a greater hazard to future development in the south Kluane Lake area is posed by debris torrents and debris flows on fans and aprons fronting the Kluane Ranges." However, this hazard is likely much lower than previously assumed. Several of the fans at the south end of Kluane Lake, as well as some of the more northern fans, are covered by Kluane loess and Slims Soil, indicating that they have not seen much activity outside their current streams since the early Holocene. Assuming a very basic calculation of volume for an inclined conic segment (Giles, 2010), and using Congdon Creek (Figure 4) as an example, we estimate a total volume of its alluvial fan (white dashed line in Figure 4) to be around 1×10^9 m^3, whereas the estimated volume of material deposited on the fan since deposition of the White River tephra (black dashed lines in Figure 4) is less than 2×10^6 m^3. We understand that these estimates have large potential errors, but they demonstrate that the alluvial fans in the study area are mostly paraglacial and, in this sense, relict. Drainage basins of the fans south of Congdon Creek are small with relatively low gradients and did not support valley glaciers, which would have supplied meltwater for their construction. Rather, they likely were constructed during deglaciation, when snowline was lower. The increased snow cover would have provided sufficient run-off during late spring and summer to entrain large amounts of glacial sediment for fan construction. The basins north of and including Congdon Creek supported valley glaciers during deglaciation, which most likely provided large amounts of meltwater and sediment required for fan construction.

The axial streams of all investigated fans have been significantly modified during the past several decades to lessen the likelihood of damage to the Alaska Highway from floods, hyperconcentrated flows, and debris flows. Much of this work was done after the rain-induced debris flows in July 1988 that severed the highway in many places in the study area (Evans and Clague, 1989). Channel works include large-diameter highway culverts, some of which are anchored with metal sheet piles to protect the highway from erosion. Levees and berms border most of the streams above the highway, some extending from the highway to near the apexes of the fans, whereas others are restricted to distances of 100–200 m above culverts. Stream banks, levees, and berms are armored with riprap near the highway. Transverse rows of steel stakes upstream of culverts span some stream beds to catch large woody debris and prevent plugging of culverts. Many of the berms and levees have been eroded during periods of high flow. We conclude that future debris or hyperconcentrated flows along the investigated reach of the Alaska Highway will mostly be restricted to present stream crossings because of mitigation measures that have been taken.

CONCLUSIONS

The large debris fans along the west and south sides of Kluane Lake were constructed largely during and shortly after deglaciation and have only been slightly modified since then. Debris flows or hyperconcentrated flows have occurred episodically on all fans during the late Holocene, but since AD 1200 streams have mainly been confined to their present channels. Rare storms, such as that in July 1988, have triggered numerous small debris flows in the study area. Future similar events may sever the highway, but at predictable locations. Mitigation following the 1988 rainstorm seems appropriate in light of the hazard and risk; future events are unlikely to deposit significant amounts of sediment on the lower parts of the fans outside current channels.

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