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SURFICIAL GEOLOGY OF THE ALASKA HIGHWAY CORRIDOR, DELTA JUNCTION TO DOT LAKE, ALASKA

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SURFICIAL GEOLOGY OF THE ALASKA HIGHWAY CORRIDOR, DELTA JUNCTION TO DOT LAKE, ALASKA

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Richard D. Reger[1], De Anne S. P. Stevens[2], and Diana N.Solie[2]

INTRODUCTION

The Alaska Highway corridor serves as the only land transportation route to interior Alaska and is likely to become the locus of increasing development, especially if the proposed natural gas pipeline or the proposed Alaska Railroad extension are constructed along this route. During 2006 and 2007, the Alaska Division of Geological & Geophysical Surveys conducted reconnaissance mapping of surficial geology in the initial segment of the proposed corridor through the upper Tanana River valley, beginning in the vicinity of Delta Junction in the Big Delta Quadrangle and ending at the eastern limit of the Mt. Hayes Quadrangle east of Dot Lake Village (Combellick, 2006; Solie and Burns, 2007) (fig. 1). Following a preliminary field reconnaissance in 2006, surficial geology was initially mapped in the corridor segment by interpreting 1:65,000-scale, false-color, infrared aerial photographs and plotting unit boundaries on acetate overlays. Special attention was given to identifying geologic processes and conditions that potentially might negatively impact future development in the corridor, including faults, permafrost, and mass-movement features, as well as areas prone to flooding and earthquake-induced liquefaction. Potential sources of construction materials were also identified.

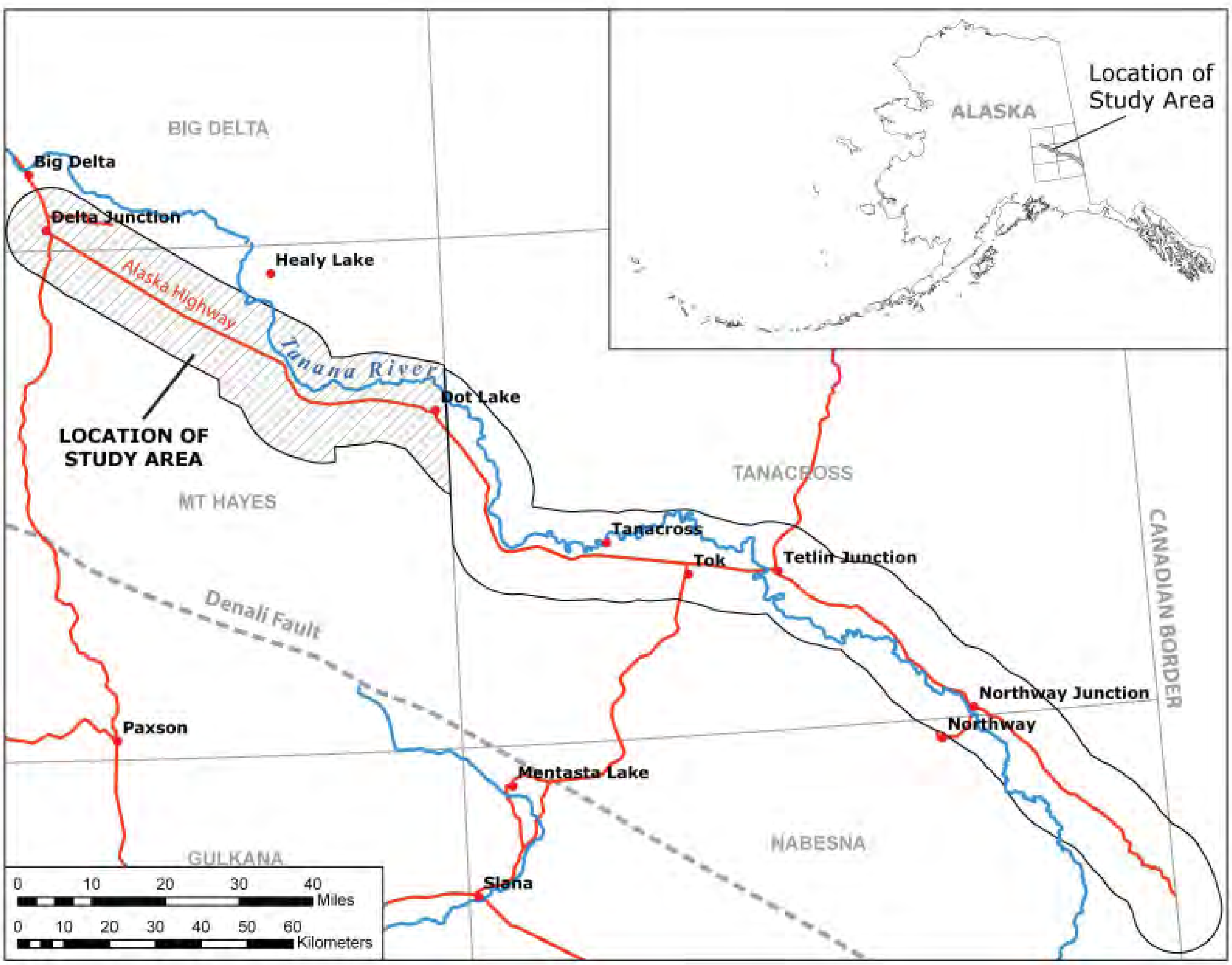

Figure 1. Location of map area in the Big Delta and Mt. Hayes quadrangles, Alaska.

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Information from previous geologic reports was incorporated during the interpretation process. Verification of photo mapping was accomplished during the 2007 field season, when map units were described and samples collected for analyses. Following orthorectification of the aerial photographs and attached acetate overlays, unit boundaries were digitized onscreen into ArcGIS and the surficial geology map was prepared (sheets 1 and 2).

PHYSIOGRAPHY AND SURFICIAL GEOLOGY

The Alaska Highway corridor extends through the Tanana Lowland along the northern flank of the eastern Alaska Range (Wahrhaftig, 1965a). The main axial stream in this reach is the Tanana River, a large, turbid, braided, anastomosing, and meandering stream nourished primarily by meltwater supplied by glaciers in the Alaska Range to the south (Anderson, 1970). From the Alaska Range, several large, braided, meltwater streams flow northward to the Tanana River, including the Delta, Gerstle, and Johnson rivers (Dingman and others, 1971; Nelson, 1995). In the past, lobes of glacial ice occupied these and other alpine valleys in the central and eastern Alaska Range and spread into the Tanana Lowland. From terminal moraines, broad piedmont fans and aprons of coarse outwash alluvium spread northward toward the Tanana River (Péwé and Holmes, 1964; Holmes and Péwé, 1965; Péwé and Reger, 1983a; Reger and Péwé, 2002). These large, permeable gravel bodies are important aquifers that supply large volumes of groundwater to the Tanana River (Wilcox, 1980). According to Péwé (1965) and Wahrhaftig (1965a), the present course of the Tanana River along the southern margin of the Yukon–Tanana Upland is a direct consequence of the northward growth of piedmont fans from the Alaska Range.

Between Dry Creek and Chief Creek, an unglaciated, stream-dissected plateau rises between 800 and 1,800 ft (240 and 545 m) above and south of the Tanana River trough. This granitic terrane is deeply weathered and dissected, and granitic tors stand high above ridge crests and upper slopes where the surrounding grüs has been differentially stripped by periglacial slope processes (fig. 2). Unglaciated dendritic tributary stream valleys contain frozen fills of sandy grüs wash mixed with lowland loess. Coarse fills in drainages entered by ice during past glaciations, like Berry Creek, are composed of outwash related to moraines in upper valleys. Lower slopes of the planar northern flank of the dissected plateau are covered by aprons of blocky granitic rubble formed by downslope displacement of the frost-rived, coarsely jointed bedrock.

The braided, anastomosing, and meandering floodplain of the Tanana River through the corridor ranges in width from 0.5 to 4 mi (0.8 to 6.4 km) and features active channels with numerous sand and silt bars, inactive and abandoned floodplain surfaces, and low river terraces. The Delta, Gerstle, and Johnson rivers dump tremendous volumes of sediment into the Tanana River, enough to change the stream morphology from meandering to braided

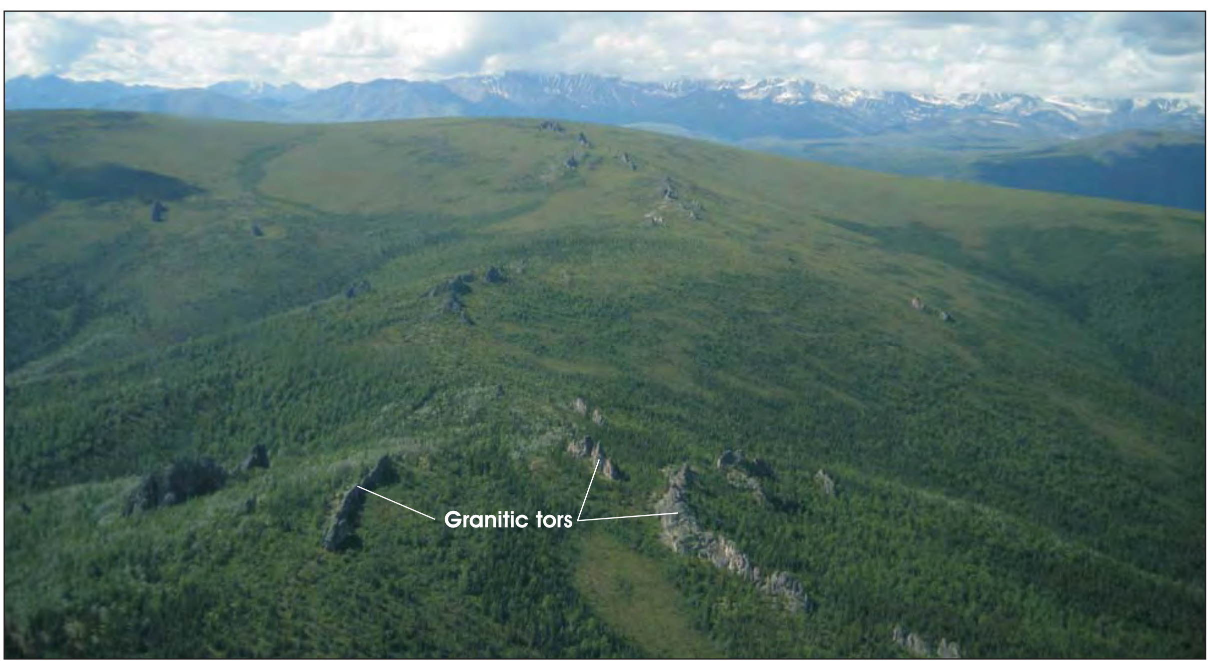

Figure 2. Aerial view south of granitic tors in Knob Ridge area, central Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 7/13/07.

anastomosing. Several large clearwater lakes are impounded in reeentrants of the Yukon–Tanana Upland by Tanana River alluvium (Péwé and Reger, 1983b), including Twelvemile, Black, Moosehead, and Sand lakes, and Lake George. These lakes principally receive water from clearwater streams draining the southern Yukon–Tanana Upland, including the Healy River and George, Sand, and Billy creeks. However, during flooding of the Tanana River, flows in streams draining some lowland-marginal lakes reverse, and turbid Tanana River waters enter some lakes, like Black Lake and Sand Lake, building complex deltas.

The unglaciated, stream-dissected topography of the southern Yukon–Tanana Upland has a maximum local relief of ~1,500 ft (~457 m). Higher bedrock hills and ridges are veneered by frost-rived bedrock and colluvium thinly covered by a blanket of loess. Scattered bedrock tors stand above ridge crests and upper side slopes. Extensive, perennially frozen, ice-rich retransported silt and lowland loess up to 173 ft (53 m) thick cover colluvium and stream deposits on lower valley walls and fill valley bottoms (Kreig and Reger, 1982, plates 10 and 11; Reger and Solie, 2008).

Strong surface winds sweep the Tanana and Delta river valleys (Mitchell, 1956; Péwé and Holmes, 1964) and have been active for millennia. These winds strip sand and silt from unvegetated stream bars and carry them to depositional sites downwind (Péwé, 1951, 1955). In the past, eolian sand built dunes on outwash fans and floodplain terraces along the Tanana River west of the Gerstle River and blanketed other near-source surfaces (Kreig and Reger, 1982; Reger and Péwé, 2002). Surprisingly, little loess of late Pleistocene age has been recognized across central Alaska north of the Alaska Range, probably because strong katabatic winds and lack of forest vegetation during the last major glaciation did not favor deposition and preservation of loess (Busacca and others, 2004). High-velocity katabatic winds apparently deflated loess from exposed slopes and carried the silt across broad depositional areas downwind, particularly during past glaciations (Thorson and Bender, 1985; Muhs and others, 2003). However, during Holocene time lower-velocity, variable, local winds deposited thick, sandy loess on moraines and bedrock near high-volume sources of silt and sand, like the active, braided river floodplains of the Delta, Gerstle, and Johnson rivers (Péwé and Holmes, 1964; Péwé and Reger, 1983a). These thick loess accumulations are identified by areas of subdued topographic relief and, on lower north-facing slopes, by concentrations of shallow, parallel rills that are remnants of partially eroded loess mixed with retransported silt that is typically frozen and ice rich (Reger and Solie, 2008). Silt fans and aprons on gully floors and valley bottoms indicate the presence or former presence of significant loess on the slopes above. Paleosols in loess represent intervals of slower loess deposition during which soil-forming processes were not overwhelmed by surface sedimentation and had sufficient time to alter near-surface sediments. Compared to unaltered loess layers, paleosols have higher percentages of fine silt and clay (Busacca and others, 2004, p. 288), implying deposition by lower velocity winds when soil formation was dominant.

Compositionally, loess along the Tanana River is made up of mineral grains derived from igneous and metamorphic rocks (Péwé, 1955; Muhs and others, 2003). Although Muhs and others (2003) reported that calcite and other carbonate minerals are noticeably rare along the Tanana River, local loess with significant carbonate content is reported (Péwé, 1968). The presence of calcareous rinds on the lower surfaces of quartz ventifacts buried by thin loess and eolian sand on a bedrock ridge crest adjacent to the Tanana River near the mouth of Shaw Creek (Péwé and Reger, 1983b) indicates that, at least locally, loess may have significant carbonate content.

Most loess adjacent to the Tanana River north of Delta Junction is latest Wisconsinan to Holocene in age (Hamilton and Goebel, 1999; Potter and others, in press) as is loess at the Gerstle River archaeological site (Potter, 2005). Basal sections of loess in the Delta River area contain a thin bed of white tephra that correlates with layer G of the Hayes tephra and dates close to 3,660 ± 125 radiocarbon (RC) yr B.P. (Begét and others, 1991; Reger and Péwé, 2002). Farther east in the second corridor segment, a thin, white tephra found at shallow depths in loess sections probably correlates with the northern lobe of the White River Ash, which dates ~1,890 RC yr B.P. (Péwé, 1975a; Schaefer, 2002).

GLACIAL HISTORY

Surface evidence of multiple glaciations as old as the late Tertiary is preserved in this western segment of the corridor. Differences in relative glacial extents and the morphologies and weathering properties of deposits, particularly paleosols, are the bases for identifying deposits of these ice advances. Our reconnaissance field descriptions are not backed up by chemical analyses that would demonstrate the intensity of soil development during soil-forming intervals (Muhs and others, 2000, 2001, 2003). The most useful soil properties for distinguishing between different glacial deposits in the field are solum depth; color of B horizon; frequency, color, and thickness of clay skins; intensity of soil alteration; and presence of cryogenic features (Tarnocai and others, 1985). With caution, the presence and degree of development of ventifacts can also be used to differentiate deposits of late Pleistocene glaciations in the corridor (Péwé and Holmes, 1964; Péwé and Reger, 1983b).

LATE TERTIARY GLACIATION

Carter (1980) described numerous, angular to rounded boulders as large as 7 ft (2.1 m) diameter in tilted conglomerate beds of probable tillite in the upper Nenana Gravel at ~2,900 ft (~885 m) elevation along a bedrock ridge that is part of the steep northeastern front of the Granite Mountain block west of the Gerstle River (fig. 3). The boulders, which are enclosed in fluvial gravels, range from fresh to “rotten” and include lithologies that are not present in the Gerstle River drainage today. The large sizes, shapes, and variable compositions of the boulders may be evidence for a glacial genesis, including deposition by jökulhlaups. The stratigraphic context indicates that this early glaciation occurred during the Pliocene Epoch.

EARLY GLACIATION(S)

Evidence for three glaciations attributed to the Pleistocene Epoch has been identified in that part of the eastern Alaska Range crossed by the corridor. One or more early glaciations may be included in the poorly documented Darling Creek glaciation, which Péwé (1975b) assigned a pre-Illinoian age. Possibly correlative glaciations include pre-Healy glaciations in the Nenana River valley to the west (Thorson, 1986) and pre-Reid glaciations in the Yukon Territory to the east (Hughes, 1989).

GLACIAL FEATURES

The walls and floors of cirques and valleys assigned to the earliest glacial advance(s) in the northern corner of the Granite Mountain block are greatly modified by frost weathering, the accumulation of extensive colluvial deposits, and postglacial stream erosion. Till of this age is deeply weathered and is preserved as discontinuous blankets surrounding numerous low bedrock knobs arranged roughly in a lobate pattern beyond terminal moraines assigned to the next younger Delta glaciation (compare plate 1 with Holmes and Péwé, 1965). We hypothesize

Figure 3. Tilted tillite? in upper Nenana Gravel of Pliocene age at ~2,900 ft elevation, northeastern Mt. Hayes C-3 Quadrangle, Alaska. Photograph taken 6/78.

that the lobate distribution of bedrock knobs mimics the arcuate pattern of the former pre-Delta moraines, which initially protected the underlying bedrock from weathering and erosion. Eventually, surface weathering processes dissected and removed the morainal arc and began attacking the underlying bedrock, leaving the knobs as residual bedrock remnants. Morainal morphology no longer exists. Angular to rounded tillstones in a sandy matrix are dominated by lithologies, like quartz and quartzites, that resist weathering. In general, granitic clasts are crumbly or have weathered to grüs fragments and contributed to the sandy matrix.

An isolated remnant of pre-Delta moraine is preserved as a cluster of subangular to subrounded granitic erratics up to 215 ft (65 m) above the highest level of the early Delta (oxygen-isotope stage 6) (OIS 6) terminal moraine at the mouth of upper Dry Creek valley (sheet 2). To the northeast ~1.5 mi (~2.4 km) at the mouth of the canyon of the east fork of Dry Creek is an isolated knob of pre-Delta moraine or perhaps an outwash fan produced by pre-Delta ice that entered the head of the east fork of Dry Creek. Subrounded granitic boulders up to 5 ft (1.5 m) diameter are scattered in sandy surface debris on this knob and down the slope toward the Tanana River. The morphology of the original landform, whether moraine ridge or outwash fan, is greatly modified by slope processes. Local surface relief is ~1 ft (~0.3 m), and debris from upslope has partially overridden the knob. A well-developed weathering profile extends through the thin surface loess and >2 ft (>0.6 m) into the underlying diamicton. Granitic clasts in the diamicton are well weathered but still coherent; surfaces are rough and deeply pitted with shallow depressions where mafic minerals and feldspar crystals were altered and removed, and weathered feldspar laths stand several millimeters in relief. Most cobbles are split. In the coarse to very coarse sand matrix, biotite crystals have a golden sheen and appear to be expanded by hydration. Many pebbles are crumbly with very rough surfaces. Other than fragments of former aplite dikes and a few quartz clasts, all clasts are granitic.

In the southern corridor between upper Dry Creek and upper Berry Creek, possible deposits of pre-Delta glaciation(s) outside the limits of moraines of the Delta glaciation form a discontinuous surface lag in small valleys and on upper slopes of rounded ridges of granitic bedrock (sheet 2). Holmes and Foster (1968) mapped these deposits as rock rubble. The blanket deposits retain no morainal morphology and are reworked into microrelief features, including stone stripes and steps, by periglacial mass-movement processes. No original glacier-scoured bedrock surfaces are preserved, but a reddish-brown paleosol associated with this surface is exposed in the east wall of upper Dry Creek valley, and small bedrock knobs crop out along ridge crests. At the head of the east fork of Dry Creek beyond the Delta moraine, the well-dissected valley floor is broadly U-shaped in cross profile, which contrasts with the V-shaped cross profiles of other tributary valleys cut into the weathered granitic terrane there. This U-shaped cross profile probably resulted from glaciation of this valley prior to the Delta glaciation before the valley was deeply eroded. Small ridge-crest tors are evidence of the stripping of debris by mass-movement processes from around more resistant bedrock masses, a process that eventually resulted in the emergence of massive granitic tors 9 mi (14.5 km) to the east (fig. 2, sheet 2). Studies in northeastern Baffin Island (Briner and others, 2006) and northern Finland (Darmody and others, 2008) have demonstrated that small tors have survived several inundations by cold-based glaciers, so mapping the distribution of former glaciers based on upland tor distribution is risky. However, the prominent tors on Knob Ridge (fig. 2) represent a very long interval of stripping by periglacial slope processes, and the limit of possible pre-Delta glaciation is tentatively placed close to the spectacular granite tors on Knob Ridge, well within the limits of the granitic pluton (sheet 2) (Holmes and Foster, 1968).

PALEOSOL EVIDENCE

Canadian pedologists and geologists recognize a suite of paleosols, termed the Wounded Moose paleosols, that is thought to have formed during as many as four warm, moist, Pliocene to middle Pleistocene interglaciations (table 1). These paleosols are present on drifts of pre-Reid glaciations in the western Yukon Territory (Tarnocai and Schweger, 1991). Included in the suite of paleosols are strong brunisols and weak to strong luvisols in both surface and buried contexts. Brunisolic representatives show evidence of intense soil weathering, like strong chromas and red hues in B horizons relative to horizons beneath, indicating that significant down-profile translocation of iron oxides occurred during the soil forming process (Canada Department of Agriculture, 1974). Luvisolic representatives have argillic Bt horizons made of illuvial silicate clays, indicating that strong illuviation occurred during the soil-forming process, and may show strong reddening (rubification) of the B horizon. Colors of Bt horizons vary from 5YR on outwash to 7.5 YR on tills (Smith and others, 1986). In general, luvisolic paleosols range in solum depth from 1.7 to 7 ft (0.5 to 2.1 m) and exhibit strongly leached, rubified paleoargillic Bt horizons with thick clay skins on ped and pebble surfaces and as bridges between sand grains. Maximum pedogenic hematite, which imparts the red coloration in paleoargillic horizons, is concentrated in discrete zones in the clay matrix (Smith and others, 1987). Luvisols display evidence of strong cryoturbation subsequent to soil development in the form of disrupted, deformed, and displaced soil horizons as well as oriented and split stones. Sand wedges and involutions

Table 1. Summary of Quaternary glacial chronologies in western Yukon Territory, eastern Alaska Range, and Yukon–Tanana Upland

Cordilleran Ice Sheet, western Yukon Territory	**Eastern Alaska Range**	**Yukon–Tanana Upland**
Smith and others (1986), Hughes (1989), Tarnocai (1989), Tarnocai and others (1985), Tarnocai and Schweger (1991)	Péwé and Holmes (1964), Holmes (1965), Holmes and Péwé (1965), Holmes and Foster (1968), Péwé and Reger (1983a), Duk-Rodkin and others (2004), Hamilton (unpublished)	Weber (1986), Duk-Rodkin and others (2004), Briner and others (2005)
Holocene glaciation[a]	Holocene glaciation [a,b]	Unknown[c]
Stewart soil	Post-Donnelly soil	Immature soil formation
McConnell glaciation	Donnelly glaciation	Ramshorn advances Salcha glaciation
Diversion Creek paleosol	Post-Delta paleosol	Variable soil formation
Reid glaciation[d,e]	Delta glaciation [d,e]	Eagle glaciation Mt. Harper glaciation
Wounded Moose paleosols	Pre-Delta paleosol(s)[f]	Deep soil formation
Pre-Reid glaciations	Darling Creek glaciation(s)	Charley River glaciation

[a]Northern lobe of White River Ash was deposited ~1.9 RC ka (Lerbekmo and others, 1975).
[b]Bed G of Hayes tephra set H was deposited ~3.7 RC ka (Begét and others, 1991; Riehle, 1994; Reger and Péwé, 2002).
[c]Previously named Ramshorn I and II advances (Weber, 1986), but later dated late Wisconsin by Briner and others (2005).
[d]Sheep Creek tephras CC, C, K, and A, which were previously thought to date ~190 ka (Berger and others, 1996; Schaefer, 2002), are now thought to date ~80 ka, based on optically stimulated luminescence ages, and postdate the Reid and Delta glaciations (Westgate and others, 2008). Sheep Creek tephra F, which is stratigraphically beneath the Old Crow tephra in the Fairbanks area, is still thought to date ~200 ka (Westgate and others, 2008).
[e]Old Crow tephra is dated at ~140 ka (Preece and others, 1999; Schaefer, 2002) and is thought to postdate the Reid and Delta glaciations (Hughes, 1989; Begét and Keskinen, 2003).
[f]Includes the Gerstle River paleosol of Duk-Rodkin and others (2004).

are typically present, and ventifacts, which may have formed prior to soil development, are common on paleosol surfaces. As a result of frost action after soil development, clay skins and bridges are typically fragmented and dispersed in upper B horizons.

Paleosols thought to be equivalent to the Wounded Moose paleosols have been identified at two localities in this western segment of the corridor. A mature rubified luvisol >3.3 ft (>l m) thick in extremely weathered till at ~2,280 ft (695 m) elevation on the west wall of the Gerstle River valley was recognized and sampled for paleomagnetic signature by Duk-Rodkin and others (2004). Their sample, which had normal polarity, was tentatively assigned to the Gauss Chron (2.6 to 2.9 Ma), the Olduvai Subchron (1.77 to 1.95 MA), or perhaps the Jaramillo Chron (0.99 to 1.07 Ma) on the basis of >90 percent weathered clasts and the presence of the red luvisol to a depth of >3.3 ft (1 m) (similar to the Wounded Moose paleosols). A second possible example is the paleosol exposed in granitic bedrock along the top of the east wall of upper Dry Creek valley, although this paleosol may be related to Tertiary weathering on this tectonically uplifted surface (Gary Carver, 7/8/07 oral commun.).

DELTA GLACIATION

GLACIAL FEATURES

In the Delta Junction area, the type terminal moraine of the Delta glaciation consists of a relatively high and narrow, arcuate, outer morainal ridge and a relatively broad and low, inner arcuate moraine, perhaps indicating a two-stage event (Péwé and Holmes, 1964; Reger and Péwé, 2002) (sheet 1). These features were deposited by a large tongue of ice that originated on the south side of the central Alaska Range and flowed through the range down the Delta River valley (Péwé and Reger, 1983a). Topographic relief of Delta-age moraines in this area is locally more subdued than local relief on the younger type-Donnelly terminal moraine nearby, especially west of the Delta River, where a surface blanket of eolian sediments derived from the Delta River is thick (Reger and Péwé, 2002). The density of kettle lakes on the type Delta moraine is less than on the type Donnelly moraine because of in-filling by slopewash sediments and lowland loess (Péwé and Reger, 1983a, table 3). Proximal outwash of Delta age extends from the outer moraine northward toward the Tanana River and is abruptly truncated by the Clearwater Lake escarpment (fig. 4). The average depth of the surface weathering profile on moraines of Delta age in the type area ranges from 5 to 7 ft (1.5 to 2.1 m) (Péwé and Reger, 1983a, table 3). Stones in the type moraines and associated outwash are composed of bedrock lithologies in the Delta River valley to the south, in contrast to lithologies found in Delta moraines and outwash in other valleys along the north flank of the eastern Alaska Range. Beneath a discontinuous blanket of medium to coarse eolian sand on moraines and proximal outwash of Delta age, surface clasts, particularly those of uniform lithologies, are shaped and polished into well-formed ventifacts (Reger and Péwé, 2002). On nonuniform lithologies with variable hardness, shallow vortex-etched pits and short grooves are well developed and resistant inclusions and mineral crystals stand a few tens of inches (millimeters) in relief. Delta-age ventifacts typically bear continuous to discontinuous calcareous coatings and rinds on bottom and lower surfaces. These objects are typical components in eolian-sand casts of former ice wedges, which are common in landforms of Delta age in the type area and are up to 3.3 ft (1 m) across.

During the Delta glaciation, an extensive ice cap developed on the northern Granite Mountain upland between ~4,600 and ~5,600 ft (~1,400 and ~1,700 m) elevation at the heads of Granite Creek, Rhoads Creek, and Sawmill Creek. This ice-accumulation center supplied considerable ice to those three drainages, and their glaciers were much more extensive than coeval glaciers in small, snow-impoverished valleys at ~3,200 ft (~975 m) elevation along the mountain front (sheet 1). Overlapping relations indicate that advances of Delta ice out of Delta River valley and Granite Mountain sources were not simultaneous. The terminal moraine and outwash of the Jarvis Creek–Granite Creek lobe overlap the earlier east lateral moraine of the Delta River lobe. Outwash of Delta age east of the type terminal moraine has a fairly thick cover of eolian sand and lowland loess so that former braided stream channels

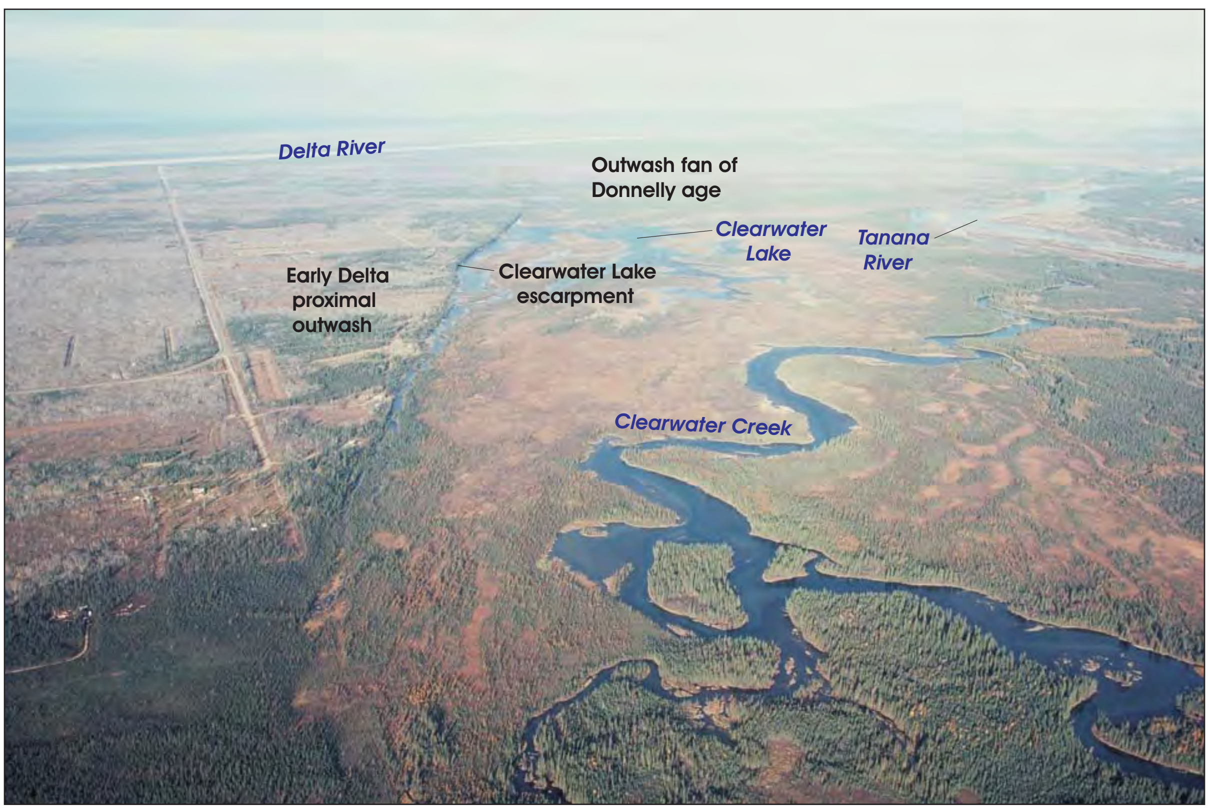

Figure 4. Aerial view west of Clearwater Lake escarpment truncating proximal outwash of Delta glaciation, east-central Big Delta A-4 Quadrangle, Alaska. Photograph taken 9/76.

are not visible on the surface, and, where eolian-cover deposits are frozen, small thaw ponds pock the surface (Reger and Solie, 2008). Sources of outwash alluvium in that area can be differentiated by lateral tracing and by clast lithology. Outwash from the Jarvis Creek area and from north of Granite Mountain contains a higher percent of rounded quartz pebbles and numerous granitic and foliated metamorphic lithologies, and outwash from the Delta River valley contains a conspicuously higher percent of greenstone and amphibolite clasts. Well-formed ventifacts along the unconformity at the base of eolian cover sediments seem to be reliable indicators of Delta outwash.

Delta-age terminal moraines of the Gerstle River and Little Gerstle River lobes are nearly obscured by the extensive outwash of Donnelly age (sheet 1 and 2). Cross-cutting relations between Delta lateral moraines indicate that ice advanced out of the Little Gerstle River valley after the Delta advance in the larger Gerstle River valley (Hamilton, unpublished manuscript). Elevations of lateral moraines in the Little Gerstle River valley indicate that ice of Delta age was ~400 ft (~120 m) thicker than ice of the later Donnelly advance. Sections exposed in test pits indicate that the loess cover on terminal moraines of Delta age is 4 to 8 in (10–20 cm) thick, and the loess varies in color from light olive brown (2.5Y5/6) to pale yellow (5Y7/3) (SP-1, fig. 5)[3]. Where there have been frequent wildfires, the color of the loess ranges from pinkish gray (7.5YR6/2) to red (2.5R4/6), imparting a pinkish color to drift sheets of Delta age. Solum depth is >3.3 ft (>l m) and silt caps are generally ≤0.3 in. (≤7.6 mm) thick. Platy metamorphic rocks are typically shattered by frost action, particularly in the upper part of the till.

The Macomb Plateau–Horn Mountain upland apparently supported a broad ice cap during the Delta glaciation (Holmes and Foster, 1968) and probably was nourished by ice from sources in the higher Alaska Range to the south. Outlet glaciers, which lacked cirques, extended down the valley of Dry Creek, entered upper Sears Creek and upper Berry Creek, and apparently fed into the Johnson River–Little Gerstle River system (shhet 2). Former limits of Delta ice advances down the east fork of Dry Creek and down Sears Creek are indicated by the abrupt

[3]Locations of logged soil pits are shown on sheets 1 and 2.

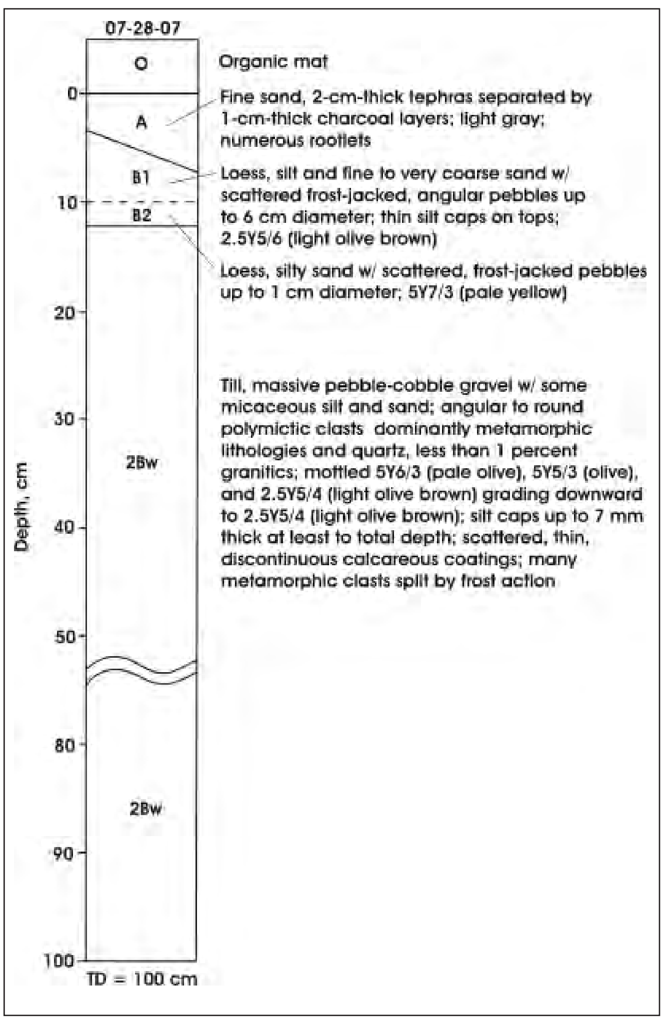

Figure 5. Soil profile (SP-1) at 63°46'48.5"N, 145°04'38.3"W in Gerstle River terminal moraine of Delta glaciation, southeastern Mt. Hayes D-3 Quadrangle. Elevation 1,700 ft.

narrowing of canyons and the upvalley limits of significant valley fills and terraces, which are probably outwash of Delta age that is now buried by younger fans and related slope debris. No morainal form is preserved on Macomb Plateau, where slopes are smooth and rounded (fig. 6). Deposits on the upland surface are composed of at least 7 ft (2.1 m) of perennially frozen, ice-rich organic silt with some sand and scattered pebbles, cobbles, and boulders derived from reworking of former till, primarily by gelifluction (Reger and Solie, 2008). A few large granitic erratics are widely scattered across the plateau. Tors and frost-shattered rubble indicate that bedrock is exposed or thinly buried around the margins of the upland. On streamlined, ice-scoured bedrock knobs near the northern edge of the plateau at the head of Dry Creek valley, large, angular blocks of granitic bedrock were displaced upward as much as ~3.3 ft (~1 m) after the Delta glaciation by the growth of ice in subhorizontal joints (Yardley, 1951), disrupting the former glaciated surfaces. Surfaces of displaced blocks are no longer polished or striated, and many are pitted where ferromagnesian minerals (principally biotite and hornblende) have been removed by weathering, although plagioclase feldspar crystals appear little weathered. Slopes around the glacier-scoured outcrops have aprons of grüs and are littered with angular blocky, frost-rived rubble (fig. 7).

Talus forms are widespread and well developed on the lower walls of upper Dry Creek valley, including large debris-flow fans at the mouths of tributary valleys in the west valley wall. A stubby, blocky rock glacier has developed along the base of the west valley wall at the head of the valley. An obvious blunt end moraine of late Delta age at the mouth of upper Dry Creek valley is massive, 100–120 ft (30–36.6 m) thick, has fairly high relief in contrast to other moraines of Delta age (fig. 8), and was assigned to the Donnelly glaciation by Holmes and Foster (1968), who postulated the source was a plateau glacier of Donnelly age on Macomb Plateau at the head of the valley. The abrupt, square terminus of this moraine encourages one to suggest that the moraine is offset by faulting, but no unambiguous evidence of faulting was observed. The moraine is covered by numerous granitic

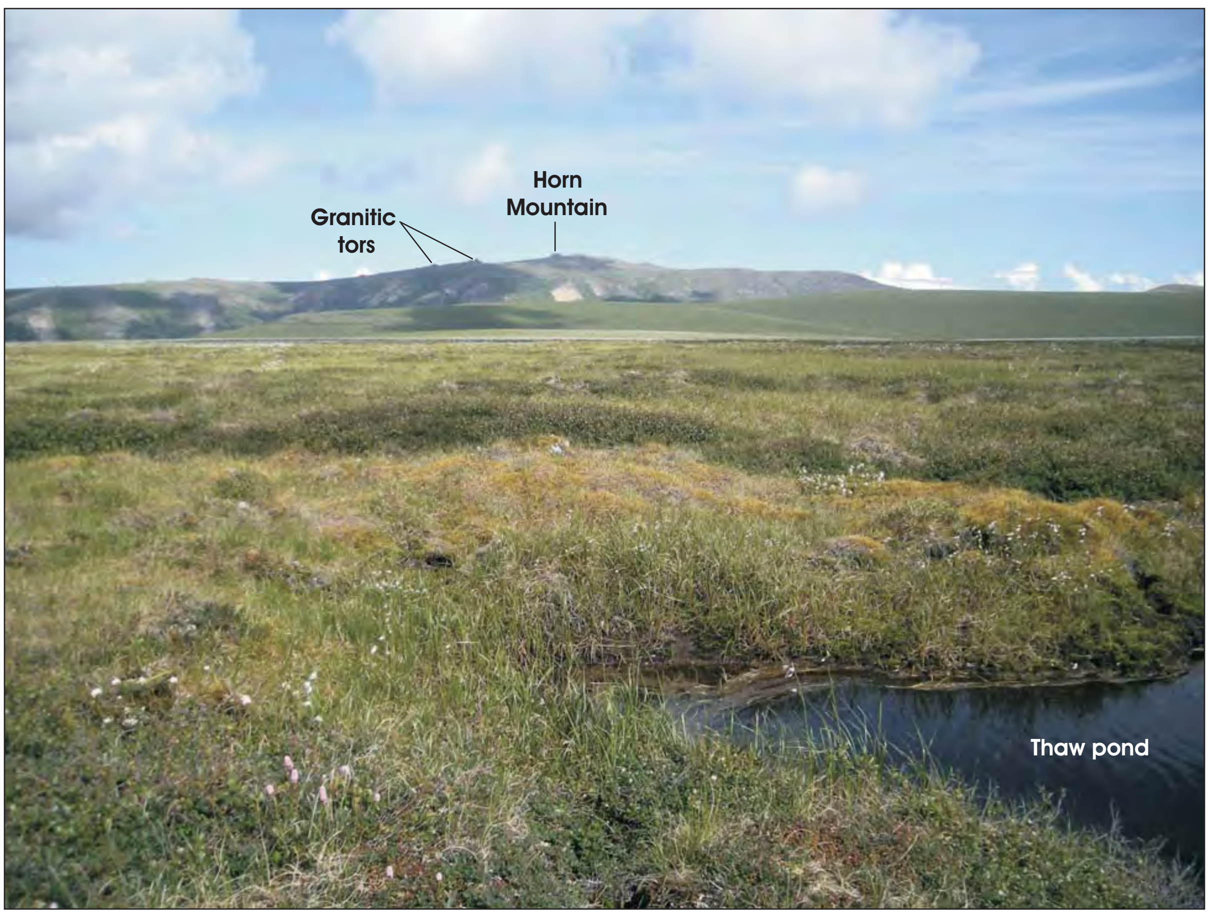

Figure 6. Alpine tundra at ~4,350 ft elevation on Macomb Plateau, central Mt. Hayes C-2 Quadrangle, Alaska. Granitic tors along skyline near Horn Mountain are residual bedrock eminences left after differential stripping by near-surface periglacial slope processes. Photograph taken 7/9/07.

Figure 7. Granitic knobs scoured by glacial ice during Delta glaciation of Macomb Plateau at head of Dry Creek valley, east-central Mt. Hayes C-2 Quadrangle, Alaska. Irregular knob surfaces formed by periglacial frost-jacking of joint blocks in granitic bedrock during Donnelly glaciation. Photograph taken 7/9/07.

blocks up to 7 ft (2.1 m) in diameter, and exposed surfaces of granitic erratics, particularly on upvalley sides, are roughened by granular disintegration and blasting by wind-driven winter snow. Contrasts in lichen cover on upvalley and downvalley surfaces of large erratics indicate that winter winds have been an important surface-weathering agent. Small aplite dikes and mafic inclusions stand up to 1.2 in (3 cm) in relief on upvalley surfaces. A test pit in the moraine exposed a pre-Donnelly inceptisol profile that is >2.6 ft (>0.8 m) deep and in which thick silt caps are present on the upper surfaces of clasts to at least that depth. Large broken feldspar crystals form a granular surface lag, indicating that smaller components have been removed by surface winds. Surface microrelief features indicate that the surface lag is being displaced downslope by frost creep. Beyond the end moraine on the steep northern slope of the plateau is a well-preserved terminal moraine of probable early Delta age (fig. 8). A test pit dug along the rounded moraine crest indicates that the solum on this feature is >2 ft (0.6 m) deep.

Mapping of moraines in valleys cut into the northern margin of Macomb Plateau near Horn Mountain demonstrates that valley glaciers developed there during both Delta and Donnelly glaciations, probably in response to winter winds sweeping snow from Macomb Plateau into leeward valleys (sheet 2). Valleys that supported glaciers only during the Delta glaciation have headwalls and floors that are extensively modified by the accumulation of colluvium, including massive, multi-generational debris flows, and associated outwash that is now deeply notched by postglacial stream erosion (fig. 9). In contrast, valleys that were reoccupied during the Donnelly glaciation retain steep headwalls with extensive, bold rock outcrops and valley walls are cut by shallow, linear couloirs formed by snow avalanching. Colluvium is generally limited to lower slopes. The nature of the colluvium in these valleys is a function of the properties of the bedrock upslope. Coarsely jointed granitic bedrock produces blocky colluvium. Schists and bedded quartzites yield fine-textured debris.

The lack of a terminal moraine and associated outwash of Delta age for the Johnson River lobe is anomalous. However, the log of a water well drilled in 2001 for the Dry Creek community indicates that till of Delta age may

Figure 8. Aerial view southeast of early (OIS 6?) and late (OIS 4?) end moraines of Delta glaciation, upper Dry Creek valley, east-central Mt. Hayes C-2 Quadrangle, Alaska. Photograph taken 7/13/07.

be present beneath ~100 ft (~30 m) of proximal outwash of Donnelly age (Steve Squires, unpublished data). No glacial erratics or deposits have been found on densely forested bedrock ridges north of the Tanana River in that area. Later, we speculate that the lack of a terminal moraine of Delta age and the lack of erratics north of the Tanana River may be the result of periodic massive flooding down the Tanana River.

PALEOSOL EVIDENCE

In the Yukon Territory, Diversion Creek weathering profiles include both surface and buried paleosols in the form of moderate brunisols and weak luvisols developed on till and outwash of the Reid glaciation, which is correlated with the Delta glaciation (Hughes, 1989) (table 1). These paleosols developed during the Sangamon Interglaciation in climatic conditions similar to the modern boreal forest in southern Canada. Evidence of moderate weathering is the slight to moderate development of melanic (Bm) horizons (equivalent to cambic color horizon of United States soil terminology) (Soil Survey Staff, 1975) with some evidence of moderate oxidation and dissolving of calcium carbonate to produce porous rock fragments (Canada Department of Agriculture, 1974). Typical color hues of B horizons are 7.5YR in outwash of Reid age and 10YR in till of Reid age. There is weak to moderate development of Bt horizons in luvisols, and clay skins are thin to very thin and scattered. Rubification is slight. Periglacial features (sand wedges, involutions, and other cryogenic structures) are present in ≤20 percent of profiles (Tarnocai, 1989). Weakly developed Diversion Creek profiles are ~3.3 to 5 ft (~1 to 1.5 m) thick on deposits of the Reid glaciation.

In general, soils in the upper Tanana River valley are inceptisols produced by weak to moderate chemical weathering compared to areas such as south-central Alaska, where there is greater precipitation and spodosols are produced (Muhs and others, 2000, 2001, 2003). In the type area of the Delta glaciation, the average depth of the

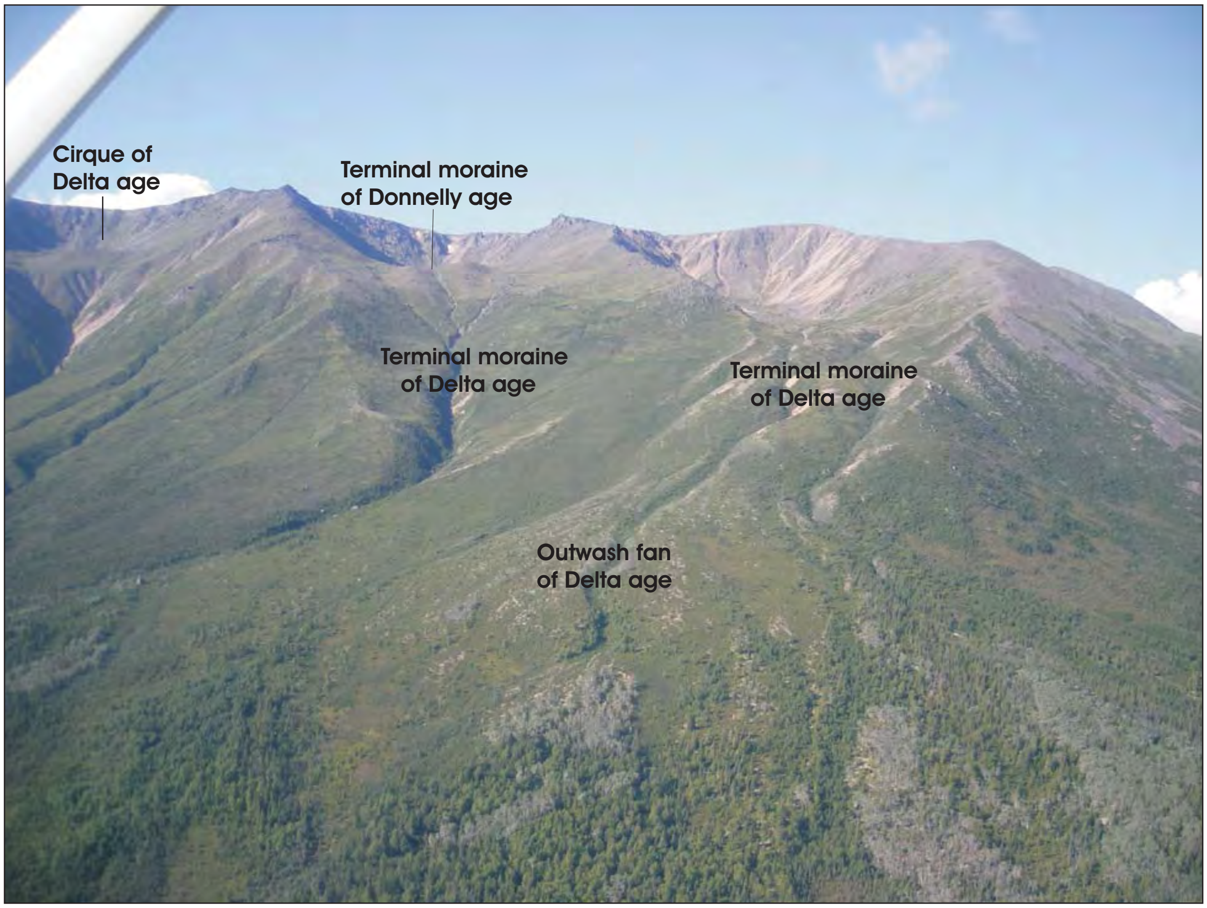

Figure 9. Cirques of Delta and Donnelly glaciations cut into northern margin of Macomb Plateau in the vicinity of Horn Mountain, central Mt. Hayes C-2 Quadrangle, Alaska. Photograph taken 7/13/07.

surface weathering profile ranges from 5 to 7 ft (1.5 to 2.1 m), and the content of schist fragments in weathered zone varies from 1 to 10 percent (Péwé and Reger, 1983a, table 3). On equivalent moraines farther east in the corridor, Holmes (1965, p. H10) and Holmes and Foster (1968, p. 28) reported that depths of iron staining exceed 10 ft (3 m). On related outwash, gravel clasts are iron stained to depths of 3.5 ft (1.1 m) and disintegrated rock fragments are present to depths >12 ft (3.6 m). In hand-dug test pits on Delta-age moraines, we documented inceptisols to depths of >3.5 ft (>1.1 m) and silt caps up to 0.3 in (7.6 mm) thick to depths of >2.6 ft (>0.8 m). Limited sampling indicates that Bw horizons in till of Delta age generally have an olive brown (2.5Y5/4) color.

AGE

The age of the Delta glaciation has long been controversial (Reger and Péwé, 2002). The minimum age of the Delta glaciation in east-central Alaska is based on relations between Delta deposits and tephras of known age (Westgate and others, 2001). However, there is disagreement among workers about the age and stratigraphic positions of dated tephras. In general, the widespread and distinctive Old Crow tephra is considered to be ~140 ka old on the basis of values obtained on glass by the isothermal-plateau fission-track method (Preese and others, 1999) (table 1). Yet, mean values derived by this method range widely from 120 ± 20 ka to 160 ± 30 ka for samples from the Halfway House section and 150 ± 20 ka for two samples from the Holitna Lowland (Muhs and others, 2003). In comparison, Berger and others (1994) reported partial-bleach thermoluminescence ages of loess samples above and below the Old Crow tephra in the Halfway House section at 110 ± 32 ka and ≥140 ± 30 ka, respectively, and Berger and others (1996) reported ages of loess samples in equivalent position at Birch Hill at 128 ± 22 ka and 144 ± 22 ka, respectively. Péwé and others (1997, fig. 25) reported a thermoluminescence age of 136 ± 20 ka for loess between the Old Crow tephra and the overlying Eva Creek Forest Bed in the upper Eva Creek section. Of course, loess stratigraphy is everywhere very complex, and Muhs and others (2003) disputed the stratigraphic location at

Eva Creek reported by Péwé and others (1997); they contended (p. 1953) that Old Crow tephra is located in, not beneath the Eva Creek Forest Bed. So, based on available information, estimates of the age of the Old Crow tephra range from ~120 to ~160 ka, although an age of 140 ka is generally accepted. Begét and Keskinen (2003) reported Old Crow tephra overlying outwash of Delta age in a terrace at Moose Creek near Fairbanks, implying that the Delta glaciation is older than 140 ± 20 ka, and they assigned the Delta glaciation to OIS 6, which according to the GRIP ice core from Greenland began ~180 ka, peaked ~ 160 ka, and ended ~ 140 ka (Benn and Evans, 1998).

Stratigraphically ~10 ft (~3 m) beneath the Old Crow tephra in the upper Eva Creek section near Fairbanks is the Sheep Creek tephra (Preese and others, 1999), a distinctive white, glassy distal tephra that was reworked in upper alluvium attributed to the Delta glaciation in the Canyon Creek section (Weber and others, 1981; Begét and Keskinen, 2003). Hughes (1989) reported Sheep Creek tephra overlies outwash of the Reid glaciation in the central Yukon Territory. Westgate and others (2001) reported Sheep Creek tephra overlies deposits attributed to the Reid glaciation at Ash Bend along the Stewart River in the central Yukon. Various attempts to date the Sheep Creek tephra have produced mixed results. Hamilton and Bischoff (1984) attempted to provide uranium-series ages of bones apparently closely associated with Sheep Creek tephra in the Canyon Creek section, and, after rejecting clearly spurious younger ages, settled on a range of ~72 to ~89 ka. However, questions remain about uranium-series ages in an open geochemical system, particularly when there is evidence of reworking. A widely accepted age of 190 ± 20 ka for Sheep Creek tephra was provided by Berger and others (1996), who used partial- and total-bleach thermoluminescence methods. After reassessment of western Yukon sections containing the Sheep Creek tephra, using optically stimulated luminescence (OSL) dates, Westgate and others (2008) now assign the Reid glaciation (equivalent to Delta glaciation) to OIS 6 (table 1).

Recent investigations in the Yukon Territory and east-central Alaska provide stable-isotope and cosmogenic evidence that indicates an early Wisconsin (OIS 4) glaciation occurred there (Briner and others, 2005; Lacelle and others, 2007; Young and others, 2007; Ward and others, 2007). Briner and others (2005) collected four samples for cosmogenic-exposure age determination from boulders on the terminal moraine of the Eagle glaciation in the valley of Ramshorn Creek in the Yukon–Tanana Upland. Weber (1986) assigned the Eagle advance to the early Wisconsin glaciation. Exposure ages uncorrected for erosion range from 25.1 ± 1.0 to 61.4 ± 3.9 ka without obvious outliers, which is typical of pre–late Wisconsin moraines, supporting assignment of the Eagle advance to the early Wisconsin glaciation (OIS 4). To evaluate the age of the Delta glaciation in the type area, Young and others (2007) made five collections of 25 to 30 quartzose pebbles from the type Delta medial moraine near Donnelly Dome south of the map area. Exposed boulders were not sampled. An early Wisconsin (OIS 4) age of 53.5 ± 11.0 ka was obtained for these samples after eliminating a 24.7 ± 0.6 ka outlier.

Duk-Rodkin and others (2004) used the mapping of Weber (1986) and paleomagnetic evidence for their regional survey of Pliocene–Pleistocene glaciations in east-central Alaska. Weber (1986) identified five pre-Holocene glaciations in the Yukon–Tanana Upland (table 1). She also identified a two-stage Holocene glaciation, which she designated the Ramshorn glaciation. Duk-Rodkin and others (2004) correlated the Mount Harper and Reid glaciations, based on similar degrees of weathering and preservation of glacial features. They also correlated the Black Hills glaciation of Fernald (1965) in the upper Tanana River valley with the Reid glaciation, based on similar relative extents and appearances of moraines. Cosmogenic-exposure measurements by Briner and others (2005) indicate that the Ramshorn and Salcha glaciations are late Wisconsinan in age and the Eagle glaciation is early Wisconsinan in age. Measurements of samples collected from erratics of the Mount Harper glaciation yielded a range of ages from ~60 to ~170 ka, which is consistent with a two-stage (Illinoian and early Wisconsin) Delta glaciation. Because serious questions remain about the suitability of paleomagnetic samples collected by Duk-Rodkin and others (2004) and about the accuracy of cosmogenic-exposure dating of moraines (Putkonen and Swanson, 2003), correlations of glaciations in the Yukon–Tanana Upland with glaciations in the Alaska Range remain tenuous.

So, many questions clearly remain regarding the paleomagnetic evidence, and the soil evidence does not seem to offer any significant breakthroughs. However, the post-Delta position of the ~140 ka Old Crow tephra seems clear (Begét and Keskinen, 2003), and redating of sections containing Sheep Creek tephra in the western Yukon using OSL ages indicates that the Reid glaciation (equivalent to the Delta glaciation) is OIS 6 in age (Westgate and others, 2008), not OIS 8 as previously believed (Westgate and others, 2001). Cosmogenic-exposure ages have apparently identified OIS 4 (early Wisconsin) moraines in the Yukon Territory (Lacelle and others, 2007; Ward and others, 2007) and east-central Alaska (Briner and others, 2005; Young and others, 2007), but questions remain about the use of cosmogenic-exposure ages for dating moraines, particularly using pebble collections that are subject to repeated burial and exposure by frost action. We have identified two sets of Delta moraines in the map area. Early and late Delta moraines in the type area and in Dry Creek valley may well be OIS 6 and OIS 4 in age, respectively (fig. 8). For now, the most reasonable approach is probably to consider the term ‘Delta glaciation’ to be an umbrella term for more than one glaciation, ranging in age from Illinoian (OIS 6) (early Delta) to early Wisconsinan (OIS 4) (late Delta).

DONNELLY GLACIATION

GLACIAL FEATURES

The type terminal moraine of the Donnelly glaciation was deposited west of Donnelly Dome just outside the map area south of Delta Junction by the Delta River glacial lobe (Péwé and Holmes, 1964). Solum depths on Donnelly moraines in the type area range from 1.7 to 2.6 ft (0.5 to 0.8 m), and the content of schistose clasts in weathered till is conspicuously higher than in weathered till of Delta age (Péwé and Reger, 1983a, table 3). Kettles are several times more abundant on moraines of Donnelly age than on moraines of Delta age. However, outside areas of rapid sand or loess deposition, surface relief is similar on both Delta and Donnelly moraines (Reger and Péwé, 2002).

From the type Donnelly terminal moraine, an extensive outwash fan was built northward down the Delta River through a gap eroded in the outer type Delta terminal moraine and associated outwash. This fan pins the Tanana River against bedrock hills of the southern Yukon–Tanana Upland (Reger and Péwé, 2002) and is contiguous with Donnelly outwash that underlies the Shaw Creek flats to the north (fig. 10). Unpublished radiocarbon dates for the upper outwash gravels range from ~18,000 to ~19,800 RC yr B.P. (Alyeska Pipeline Service Company, 1976). Southeast of the type Delta terminal moraine and associated proximal outwash, a broad apron of outwash of Donnelly age spreads northward toward the Tanana River from the terminal moraine of the Granite Creek lobe of the Granite Mountain ice cap and terminal moraines of independent glaciers in other alpine valleys along the northwestern and northeastern fronts of the Granite Mountain block (Holmes and Péwé, 1965). This apron is truncated by a post-Donnelly scarp, the Gerstle–Clearwater escarpment, that trends northwestward from the Gerstle River to the Clearwater Lake escarpment (sheets 1 and 2). Details of small, braided channels on the outwash are generally visible through thin cover sands and lowland loess, but downwind of sources of abundant sand, thick blankets of eolian sand obscure braided channels. Areas of frozen sand and loess in the eolian blanket are indicated by concentrations of small thaw ponds (Reger and Solie, 2008). In general, ventifacts are not well formed on Donnelly outwash surfaces and are generally uncommon there. However, the degree of ventifact development depends on local conditions. Where surface conditions of low relief, frequent strong surface winds, local sources

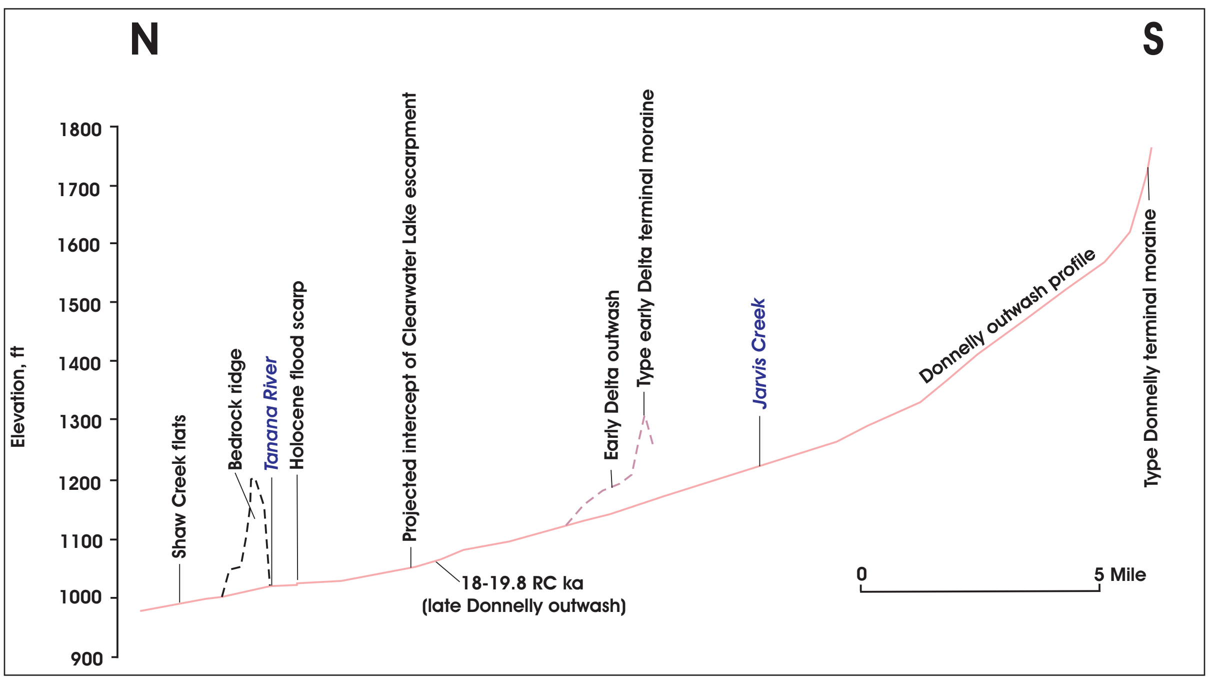

Figure 10. Profile of outwash surface from type Donnelly terminal moraine in Mt.Hayes D-4 Quadrangle along Richardson Highway to Shaw Creek flats in Big Delta A-4 Quadrangle compared to dashed profiles of nearby early Delta terminal moraine and proximal outwash and bedrock of southern Yukon–Tanana Upland. Radiocarbon ages from Alyeska Pipeline Service Company (1976). Vertical exaggeration ~62.

of adequate but not overabundant sand for cutting (but not burial), and little or no vegetation existed in post-Donnelly time, locally abundant ventifacts developed with weak surface polish, shallow pitting and grooving, and no facets or keels.

As previously noted, glacial advances, including those of Donnelly age, were much more extensive along the flanks of the Granite Mountain block in alpine valleys that received ice from the Granite Mountain ice cap, like Hajdukovich Creek (sheet 1), than in isolated valleys (Holmes and Péwé, 1965). The Donnelly moraine of Hajdukovich Creek, which extends barely beyond the mountain front, is sandy and is dominated by granitic erratics. The loess cover is thin and discontinuous, and the weathering profile is ~1.6 ft (~0.5 m) thick (SP-2, fig. 11). Silt caps are rare or absent in the weathered zone.

Ice of Donnelly age barely entered the map area in the Gerstle River drainage and joined with more expansive ice that advanced down the western arm of the Little Gerstle River–Johnson River system (sheets 1 and 2). Hamilton (unpublished manuscript) measured sections along the bluffs of the Gerstle River and documented two drift sheets of Donnelly age, indicating that at least one readvance occurred during the Donnelly glaciation. He collected wood from fluvial deposits between Delta-age till near the base of the bluffs and the older of two tills of Donnelly age higher in the bluff and dated the wood at 25,300 ± 950 RC yr B.P. (GX-2179) (table 2). The discontinuous blanket of eolian sand and loess on the Donnelly moraine along the river measured as thick as 20 ft (6 m). Outwash of Donnelly age forms a broad apron that joins with Donnelly outwash to the northwest (sheets 1 and 2). Williams (1970) documented 80 ft (24 m) of Donnelly outwash gravel overlying probable drift of the Delta glaciation in a water well ~1 mi (~1.6 km) beyond the Delta terminal moraine of the Gerstle River lobe, and Hamilton (unpublished manuscript) measured 12 to 18 ft (3.6 to 5.5 m) of Donnelly outwash gravel in river sections north of the moraine. An extensive blanket of eolian sand covers the outwash apron northwest of the Donnelly terminal moraine (sheet 1).

The Donnelly-age glacier that flowed down the upper Johnson River valley bifurcated into two terminal branches, and the Little Gerstle River glacier was diverted down the relatively wide western branch (sheet 2). Physiographic evidence encouraged Hamilton (unpublished manuscript) to postulate that at least three significant fluctuations occurred in the lower Little Gerstle River glacier during the Donnelly glaciation. He measured several sections along the bluffs of the Little Gerstle River, and, from the base of a 10-ft-thick (3-m-thick) alluvial sand and gravel

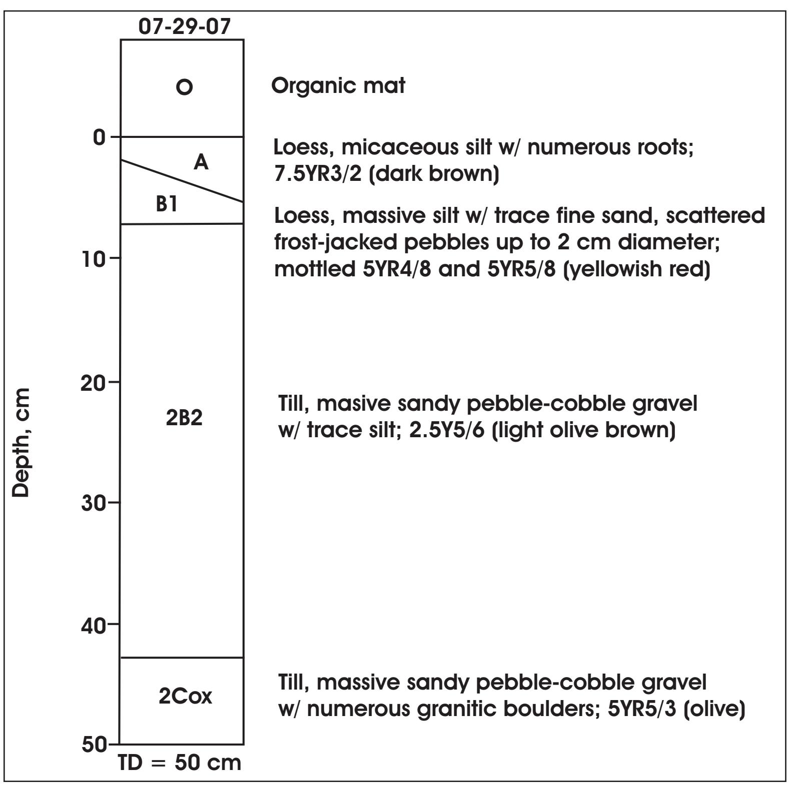

Figure 11. Soil profile (SP-2) at 63°49’49.6”N, 145°20’22.6”W in Hajdukovich Creek terminal moraine of Donnelly glaciation, southwestern Mt. Hayes D-3 Quadrangle, Alaska. Elevation 2,200 ft.

Table 2. Summary of radiocarbon dates associated with late Quaternary deposits in the upper Tanana River corridor

Map locality[a]	Material dated and stratigraphic context	Chronological significance	Laboratory number	Radiocarbon age (RC yr B.P.)	Source
RC-1	Wood from fluvial sand and gravel between Delta and Donnelly tills	Maximum age for Donnelly advance in Gerstle River valley	GX-2179	25,300 ± 950	Hamilton (Unpublished, section E4, table 4)
RC-2	Wood from base of 15-ft- (4.6-m-) thick fluvial sand overlying till of Donnelly age	Minimum age for Donnelly advance in Little Gerstle River valley	GX-2177	14,800 ± 650	Hamilton (Unpublished, section E5, table 5)
RC-3	Organics from base of eolian sand overlying fluvial sand above till of Donnelly age	Minimum age for Donnelly advance in Johnson River valley	GX-2178	9,830 ± 320	Hamilton (Unpublished, section E2, table 6)

[a]Sample localities shown on sheets 1 and 2.

overlying till of Donnelly age, he collected a sample of wood that dated 14,800 ± 650 RC yr B.P. (GX-2177) (table 2). The sandy surface peat in those sections measured 2 ft (0.6 m) in thickness and the eolian sand and loess cover deposits measured 3 to 7 ft (0.9 to 2.1 m) thick.

During the Donnelly glaciation, ice flowing down the relatively narrow eastern branch of the combined Little Gerstle River–Johnson River system deposited a massive terminal bulb in the Tanana Lowland (sheet 1). In contrast to other nearby terminal moraines of Donnelly age, most of the Johnson River terminal moraine is composed of ice-stagnation deposits, indicating that the fairly narrow lower valley of the Johnson River limited the supply of glacier ice into the terminal zone. Because the bluff exposures along the lower Johnson River are uncomplicated, Hamilton (unpublished manuscript) noted that the Johnson River glacier behaved in a simple manner compared to the more complicated, fluctuating behavior of the Little Gerstle River glacier, even though both glaciers were part of the same compound ice system. Huge reserves of sand and gravel aggregate are represented by extensive esker-kame complexes in the terminal lobe on both sides of the Johnson River (sheet 2) (Reger and Solie, in press).

East of the Johnson River, a pit dug at 1,500 ft (455 m) elevation in the terminal moraine of Donnelly age revealed a solum depth of 19 in. (48 cm) (SP-3, fig. 12). Between the Alaska Highway and the mouth of the Johnson River, Donnelly-age till, which measures 36 to 40 ft (11 to 12.2 m) thick in bluff exposures, is sandwiched between two layers of outwash. The upper (recessional) outwash is a pebble–cobble gravel with scattered boulders and sand lenses, and pebbles and cobbles have discontinuous calcareous rinds and coatings. A lag of boulders up to 1.6 ft (0.5 m) in diameter separates the upper gravel from the till beneath (fig.13). The deeply weathered loess capping the section is ~3.3 ft (~1 m) thick. An extensive, thick eolian-sand and silty sand blanket on the southern, upvalley (inner) side of the Donnelly terminal moraine of the Johnson River lobe obscures morainal topography and was derived from the adjacent, active braided floodplain (sheet 2). Organic material collected by Hamilton (unpublished manuscript) from the base of the 3- to 12-ft-thick (0.9- to 3.7-m-thick) eolian sand dated 9,830 ± 320 RC yr B.P. (GX-2178) (table 2).

A pit dug at 3,850 ft (1,170 m) elevation on a Donnelly moraine in the valley north of Horn Mountain exposed a weakly differentiated A/B horizon in a 6.5- to 10-in.-thick (16- to 25-cm-thick) loess overlying a 6- to 7-in.-thick (15- to 18-cm-thick) 2Bw horizon developed in till (SP-4, fig. 14). Solum depth is 13 to 16 in. (33 to 41 cm), which is typical of post-Donnelly weathering profiles.

A conspicuous terminal moraine of Donnelly age laps against the subtle terminal moraine of Delta age in the upper drainage of Berry Creek (sheet 2). A pit dug into the younger moraine near Plateau Lake displayed a fairly thin weathering profile featuring a discontinuous elluvial E horizon up to 2.4 in (6 cm) thick that is frost disturbed

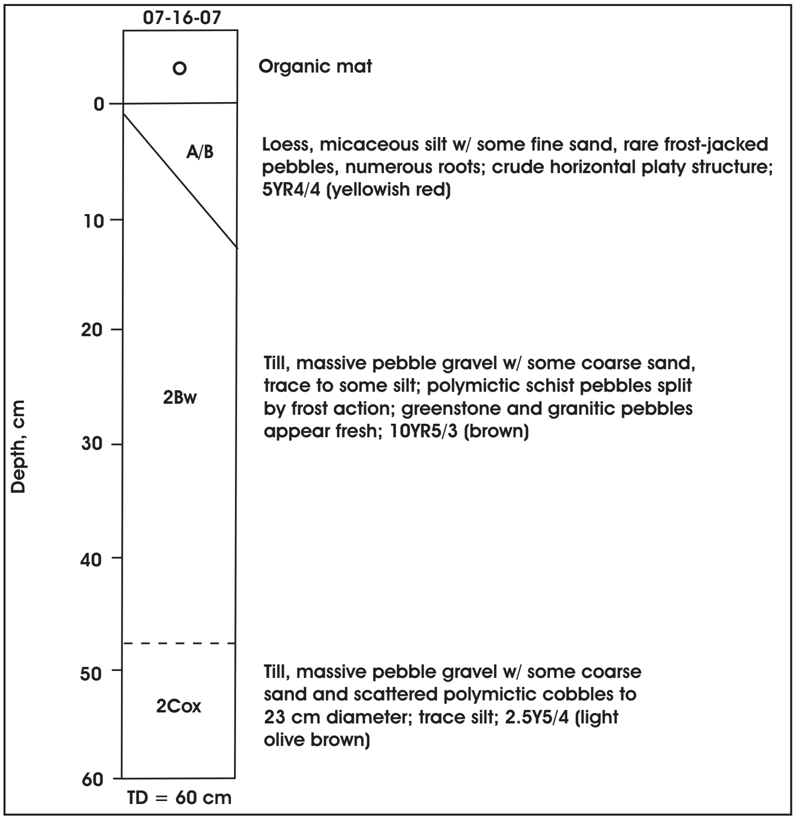

Figure 12 (left). Soil profile (SP-3) at 63°40'50.7"N, 144°40'36.5"W in Johnson River terminal moraine of Donnelly glaciation, northeastern Mt. Hayes C-2 Quadrangle, Alaska. Elevation 1,500 ft.

Figure 13 (below). Bluff exposure of deposits of Donnelly glaciation along lower Johnson River, northeastern Mt. Hayes C-2 Quadrangle, Alaska. Person indicated by red arrow near center provides scale. Photograph taken 9/9/06.

(SP-5, fig. 15). Sandy silt caps on cobbles are up to 0.4 in. (1 cm) thick on upper surfaces, but under surfaces are clean, although lightly stained and weakly pitted. Rubification of the loess is almost certainly due to oxidation during local wildfires. We speculate that the shallow depth of the solum at this location may be a function of repeated wildfires, which prevented the development of thick vegetation to produce humic acids. Valley-train deposits of late Donnelly age extend from the terminal moraine down Berry Creek to the remnant of the outwash terrace at the highway bridge (sheet 2). At the Berry Creek crossing of the Alaska Highway, the roadcut exposes ~7 ft (~2 m) of outwash gravel overlying frost-shattered granitic bedrock (fig. 16). Gneiss and quartzite clasts in the outwash gravel indicate that their source ultimately is the metamorphic terrane south of the map area (Holmes and Foster, 1968). Approximately 36 ft (11 m) of lowering of base level since late Donnelly time is demonstrated by the incision of lower Berry Creek at the highway bridge, but the ultimate cause of the downcutting, whether tectonic or climatic, remains obscure.

PALEOSOL EVIDENCE

Comparison of soil profiles indicate that surface soils formed during the Holocene on drift of the McConnell glaciation in the western Yukon Territory are very similar to soils developed on Donnelly moraines in the map area (table 1). In both areas, soils are ~1.3 to 2 ft (0.4 to 0.6 m) deep on moraines of the last major glaciation and represent the most weakly developed soil profiles among the suite of Tertiary–Pleistocene weathering profiles. The prominent horizon in Stewart soils in the Yukon Territory is a melanic (Bm) horizon, which is characterized primarily by removal of carbonates to produce local Cca horizons (Smith and others, 1986). These layers may also be derived by leaching of calcareous loess. Very little illuviated clay, in the form of scattered thin skins, is present, representing ~2 percent in outwash profiles and ~12 percent in till profiles (Smith and others, 1986). The dominant color of weakly developed B horizons is 10YR. There is some development of silt caps in the lower solum. Cryogenic or periglacial features are generally not present.

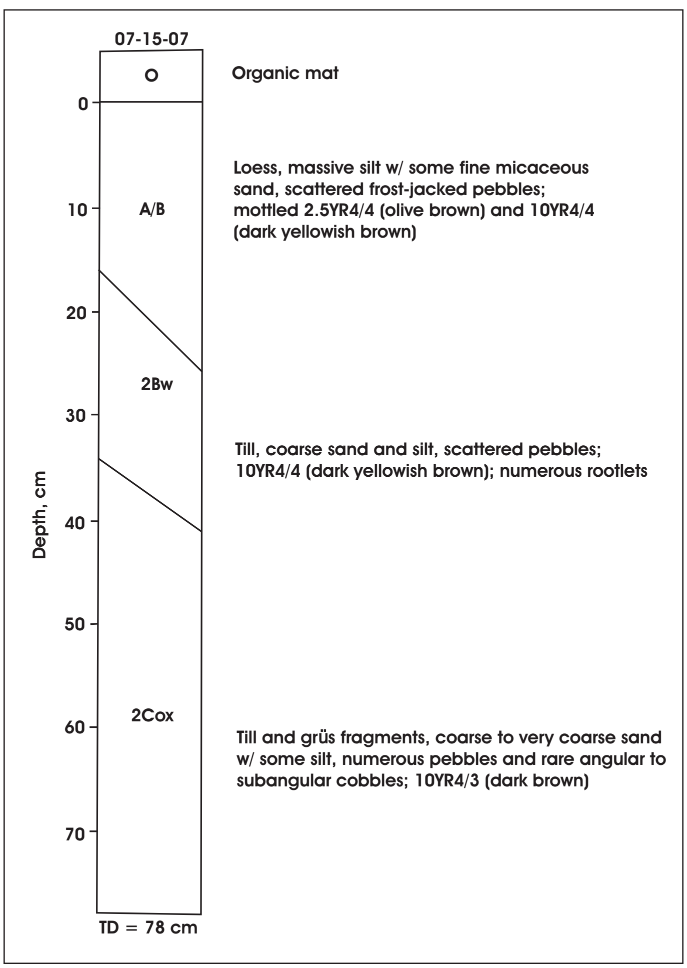

Figure 14. Soil profile (SP-4) at 63°38'59.6"N, 144°43'55.8"W in terminal moraine of Donnelly glaciation in cirque ~1 mi north of Horn Mountain, central Mt. Hayes C-2 Quadrangle, Alaska. Elevation 3,850 ft.

On moraines in the type area of the Donnelly glaciation, the average depth of the surface weathering profile ranges from 1.5 to 2.5 ft (0.5 to 0.8 m) and surviving schist fragments are much more common than in weathering profiles of Delta age (Péwé and Reger, 1983a, table 3). On moraines of Donnelly age farther east in the corridor, weathered zones are 1 to 1.5 ft (0.3 to 0.5 m) thick as defined by stained and frost-split metamorphic and granitic clasts; gravel clasts in related outwash deposits are stained to depths of 2–3 ft (0.6–0.9 m), and the content of disintegrated schist fragments is significantly less than in weathering profiles of Delta age (Holmes, 1965, p. H11; Holmes and Foster, 1968, p. 32). In our test pits, solum depth ranged from 1.1 to 2.6 ft (0.3 to 0.8 m) and silt caps

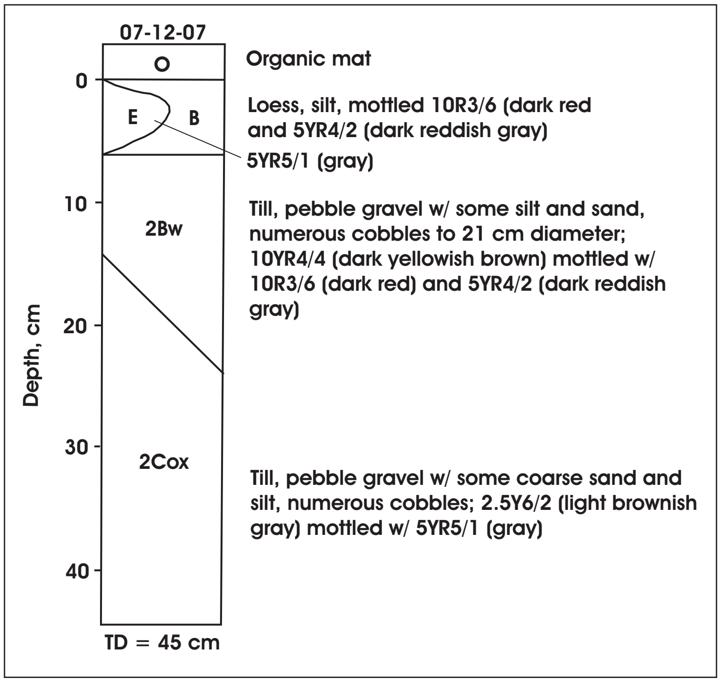

Figure 15. Soil profile (SP-5) at 63°37'24"N, 144°26'20.2"W near Plateau Lake in upper Berry Creek terminal moraine of Donnelly glaciation, west-central Mt. Hayes C-1 Quadrangle, Alaska. Elevation 2,240 ft.

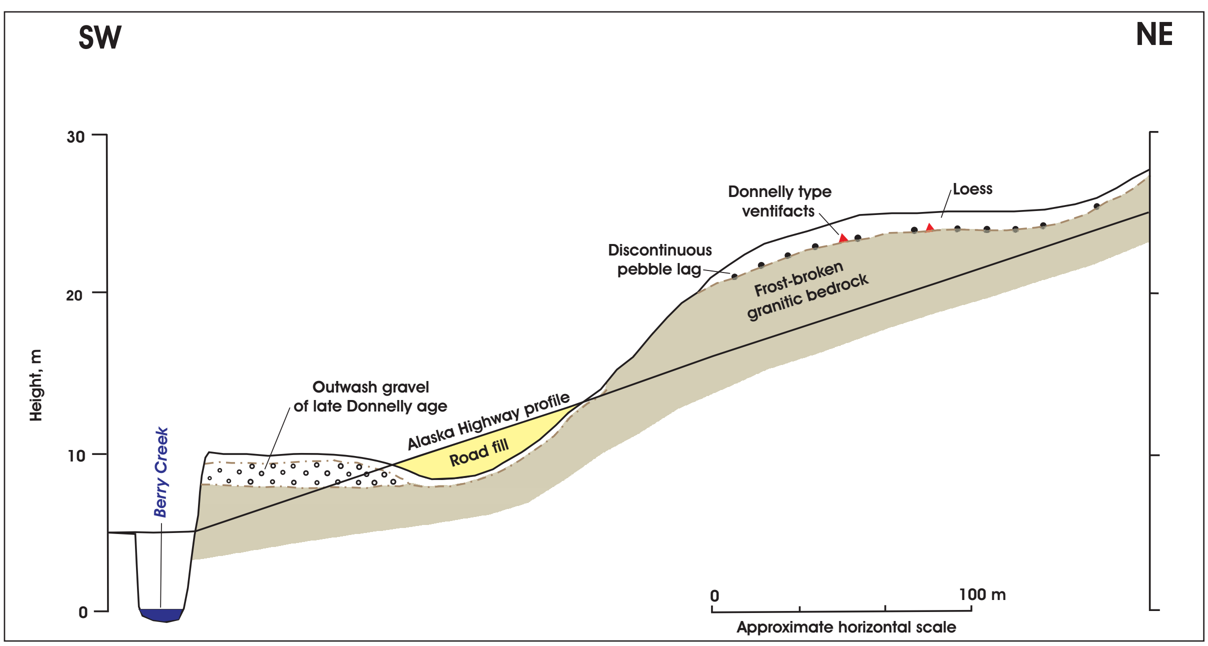

Figure 16. Profile sketch of physiographic and geologic relations along Alaska Highway at crossing of Berry Creek, northwestern Mt. Hayes C-1 Quadrangle, Alaska. Vertical exaggeration ~6.

were generally thin and rare, except in SP-5, where the silt caps were as thick as 0.4 in (1 cm). We documented weakly developed inceptisols characterized by light staining and weak pitting of clasts in several hand-dug test pits. In three soil pits dug in till of Donnelly age, B horizons ranged in color from light olive brown (2.5Y5/6) to brown (10YR5/3) to dark yellowish brown (10YR4/3). Cox horizons generally varied in color from olive (5YR5/3) to light olive brown (2.5Y5/4) to dark yellowish brown (10YR4/3).

A late Holocene soil profile developed on sandy natural levee deposits near Sand Lake has weak horizon differentiation, and the B horizon is grayish brown (10YR5/2) in color. Mason and Begét (1991) documented similar colors in sandy flood deposits downriver just west of Fairbanks.

AGE

Based on the radiocarbon evidence, most workers agree that the Donnelly glaciation is late Wisconsin (OIS 2) in age (Hamilton, 1994), although opinions have differed in the past (Reger and Péwé, 2002). Maximum-limiting dates for the climax of the last major glaciation in or near the corridor are represented by two radiocarbon ages. Hamilton's unpublished age of 25,300 ± 950 RC yr B.P. (GX-2179) (table 2) for wood below the oldest Donnelly till of the Gerstle River lobe is very close to an age of 24,900 ± 200 RC yr B.P. (QL-1369) obtained just west of the map area by Ten Brink and Waythomas (1985) for soil organics beneath outwash related to the early Donnelly terminal moraine in the Little Delta River valley. A minimum-limiting date for the peak of the Donnelly glaciation in the corridor is 14,800 ± 650 RC yr B.P. (GX-2178) for wood from the base of a 15-ft-thick (4.6-m-thick) fluvial sand overlying till of Donnelly age in the Little Gerstle River drainage (Hamilton, unpublished manuscript) (table 2).

Cosmogenic-exposure ages provide supporting evidence. North of the corridor in the Yukon–Tanana Upland, a combination of ^{10}Be and ^{26}Al cosmogenic-exposure ages of four granitic boulders on the crest of a lateral moraine of the Salcha glaciation in Ramshorn Creek valley indicate that this late Wisconsin equivalent of the Donnelly glaciation (Weber, 1986) has uncorrected cosmogenic-exposure ages that range from 16.4 ± 1.1 to 28.7 ± 1.3 ka (Briner and others, 2005). Recalculations after accounting for boulder surface erosion average from 21.2 ± 5.9 to 22.8 ± 6.9 ka. After eliminating the oldest outlier, the exposure ages range from ~21 to ~23 ka. Four boulders on the younger Ramshorn end moraine nearby, to which Weber (1986) assigned a late Holocene age, have uncorrected cosmogenic-exposure ages that range from ~16 to 28.4 ± 1.1 ka but cluster into two groups, ~26–29 ka

Table 3. Dimensions of granitic flood boulders on late Donnelly strath terrace, Sears Creek–Berry Creek area, and calculations for triangular shape plot (fig. 28)

Map locality[a]	Latitude	Longitude	Maximum diameter (cm)	Intermediate[b] Diameter (cm)	Minimum[b] diameter (cm)	Minimum[b] / Maximum	Maximum–Intermediate[b] / Maximum–Minimum
1	N63°41'26.0"	W144°24'22.3"	130	130	60	0.46	0
			230	150	50+	0.22	0.44
			210	140	100+	0.48	0.64
			170	110	50+	0.29	0.50
			150	110	80+	0.53	0.57
			140	130	80+	0.57	0.17
2	N63°41'23.4"	W144°24'31.9"	130	50	20+	0.15	0.73
			110	80+	20+	0.18	0.33
3	N63°41'24.4"	W144°24'48.4"	220	180	30+	0.14	0.21
			150	90	70	0.47	0.75
			145	135	80	0.55	0.15
			160	120	90	0.56	0.57
			200	110	80	0.40	0.75
			190	140+	40	0.21	0.33
4	N63°41'20.6"	W144°26'10.0"	230	180	70+	0.30	0.31
5	N63°41'16.2"	W144°27'46.1"	270	160	100	0.37	0.65

[a]Sample localities shown in figure 26.
[b]Subintermediate and subminimum dimensions of partially buried boulders, which are indicated by +, are used as intermediate and minimum dimensions in the calculations.

and ~16–18 ka, complicating corrections for isotopic inheritance (Briner and others, 2005). Excluding the older pair of ages because the Ramshorn moraine is clearly younger than the downvalley Salcha moraine indicates that the Ramshorn advance occurred ~18 to ~19 ka ago (OIS 2), not during the late Holocene as speculated by Weber (1986) (table 1).

^{10}Be ages of four collections of 25 to 30 quartzose pebbles from the type Donnelly terminal moraine south of the map area average 13.2 ± 2.0 ka after excluding one clearly aberrant, much older age (65.3 ± 2.1 ka) that probably results from isotopic inheritance (Young and others, 2007). Closer to the proposed map area, cosmogenic ^{10}Be exposure ages of four boulders on the crest of the north lateral moraine of Donnelly age along the northern tributary of upper Bear Creek near Fish Lake range from 15.6 ± 1.5 to 15.9 ± 1.5 ka, excluding two younger ages (9.0 ± 0.9 and 8.8 ± 0.9 ka) and an older age (21.3 ± 2.0 ka) (Young and others, 2007). All of these results clearly place the Donnelly glaciation in late Wisconsin time (OIS 2), but questions remain about the effects of changing snow cover through the Holocene and the effects of frost action, including multiple cycles of exposure and reburial, on cosmogenic-exposure ages of pebble collections.

These ages do not constrain the beginning and end of the Donnelly glaciation as a paleoclimatic event but represent a period of time when the combination of low temperatures and increased snowfall was conducive to the growth and maintenance of a greatly expanded glacier system in the eastern Alaska Range. According to fossil pollen and fossil vertebrate records in eastern Beringia, this climatic event began between 30,000 and 40,000 RC yr B.P. at the end of the Boutellier nonglacial interval (Schweger and others, 1982). Models based on fossil pollen and changes in lake levels predict a full-glacial climate in the Interior at 12,000 RC yr B.P., but 3,000 years later conditions had become much warmer and drier (Edwards and others, 2001). Today, most Pleistocene scientists agree that the Younger Dryas pollen interval of cold, dry climate ended ~11,500 cal. yr ago and marks the end of the late Wisconsin glaciation.

EVIDENCE OF MULTIPLE PALEOFLOODS

Although evidence of Pleistocene outburst flooding has been documented along the Yukon River and its tributaries, the Porcupine and Charley rivers (Thorson and Dixon, 1983; Thorson, 1989; Froese and others, 2003), this report first documents evidence of such major flood events in the Tanana River drainage.

Péwé (1965, p. 38; 1975b, p. 68) proposed a simple model of widespread, alternating cycles of aggradation and erosion in the Tanana River valley related to cycles of glaciation and interglaciation, respectively, in the Alaska Range. He suggested that ‘great alluviation’ occurred in the Tanana River valley during the penultimate (Delta or Illinoian) glaciation, and several clearwater lakes, including Harding, Birch, and Quartz lakes, were impounded behind the resulting massive alluvial fill at the mouths of reentrants along the margin of the southern Yukon–Tanana Upland. During the subsequent (Sangamon) interglaciation, the alluvial valley fill was dissected, cutting prominent terrace scarps up to 100 ft (30 m) high along the Tanana River upstream from Fairbanks and across the huge Wood River fan south of the Tanana River (Péwé and others, 1966). During the last major (Donnelly) glaciation, aggradation was renewed and was followed by local Holocene dissection. Péwé (1965, p. 38) and Wahrhaftig (1965a, p. 29) suggested that the northward spread of fluvial and glaciofluvial sediments derived from the rising Alaska Range pushed the Tanana River northward against the Yukon–Tanana Upland. However, this model does not consider possible effects of jökulhlaups in the upper Tanana River valley.

Although they expected outburst flooding in the upper Tanana River valley during late Pleistocene glaciations, Hamilton and Thorson (1983, p. 49) cited communications with Hank Schmoll and Dave Carter claiming that they found little evidence for outburst floods in Mentasta Pass or along the Tok River during their mapping in the uppermost Tanana River drainge. Later, Schmoll (1984) postulated that Glacial Lake Atna in the Copper River Basin drained subglacially through Mentasta Pass. Such subglacial drainage would have dumped considerable meltwater into the upper Tanana River across the unusually broad and low-gradient Tok alluvial fan. During our investigations in and near the western segment of the corridor, we have identified numerous features that indicate several episodes of massive flooding down the upper Tanana River during the late Pleistocene. The following discussion does not consider evidence upstream in the Tanana River valley.

DOT LAKE VILLAGE AREA

Our attention was first drawn to two large, aligned and streamlined terraces with sharp ends pointed downstream along the Tanana River at the eastern boundary of the Mt. Hayes Quadrangle (fig. 17) because streamlined landforms of this type typically form during massive flooding (Baker and others, 1987). The upstream terrace is rock defended (fig. 18) and was mapped and described by Holmes (1965) as being composed mostly of silt and sand (Qts). He mapped and described the downstream terrace as being composed of gravel from local sources (Qg). Carter and Galloway (1978) mapped both terraces as questionable till of the Delta glaciation (Qmo?). Our examination of the 110-ft-high (33-m-high) southeastern face of the downstream terrace revealed that the upper 10 ft (3 m) of the bluff is composed of coarse, clean, massive pebbly sand with numerous cobbles up to 8 in (20 cm) diameter and rare, subangular to subrounded granitic boulders up to 3.6 ft (1.1 m) in diameter (fig. 19). This relatively coarse sandy unit is underlain by at least 20 ft (6 m) of clean, coarse to very coarse sand with numerous pebbles. Massive sands like these deposits represent suspended loads laid down during floods by hyperconcentrated flows (Costa, 1988). On the opposite (southwest) side of the same high terrace, in the lowland near the base of the high escarpment scoured during one or more massive floods, sits an exceptionally large (9-ft-long [2.7-m-long]) subrounded granitic boulder (fig. 18), perhaps indicating that other very large, flood-transported monoliths are buried deep in the terrace.

To the north near the mouth of Billy Creek, a small but obvious expansion fan associated with a small slack-water basin spreads northward away from the Tanana River (fig. 18). Fans of this type are deposited where flood waters pass an obstruction, like the nearby bedrock ridge, and spread into a local hydraulic basin, like a tributary valley (Baker, 1973). Although we have not dug test pits in the slackwater basins because they are generally frozen (Reger and Solie, 2008), fine-grained slackwater deposits, including rhythmites, are typically deposited in these marginal backwater basins from the suspended loads carried by jökulhlaups (Waitt, 1980, 1984, 1985; Smith, 1993; Baker and others, 2004).

The broad, flood-scoured lowland north of Dot Lake Village is bounded by extensive scarps cut during former massive flooding (fig. 18). The ages of these features and their associated deposits are indicated by landform interrelations. At Dot Lake Village, the 15-ft-high (4.5-m-high), linear flood escarpment is cut into clean pebbly sands with scattered, rounded to subrounded cobbles, which Holmes (1965) mapped as gravel from local sources (Qg). These sandy deposits grade southeastward into very coarse proximal outwash of the Donnelly glaciation in the Robertson River drainage, which is also cut by the Dot Lake Village escarpment (fig. 18; sheet 2). Clearly, the flood event(s) that scoured the lowland north of Dot Lake Village and cut the Dot Lake Village escarpment occurred late in or postdated the Donnelly glaciation. Along the same scarp near the eastern limit of the map area,

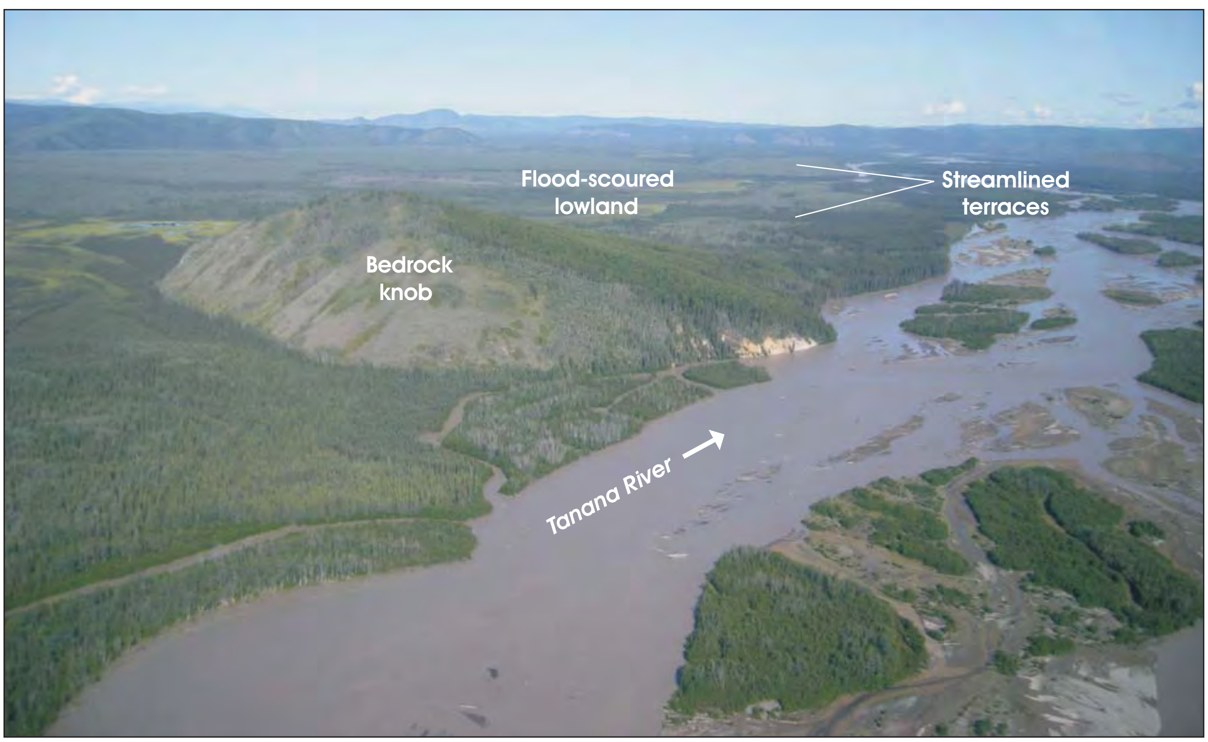

Figure 17. Aerial view northwest of bedrock-defended, streamlined terraces of Donnelly age, east-central Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 7/13/07.

further evidence of this age is the large Holocene alluvial fan of the Bear Creek–Chief Creek drainage, which was built into the trough excavated by the former large-magnitude flood(s) and obscures the flood scarp. The lengthy flood scarp along the north side of the Dot Lake lowland must be equivalent to the lengthy scarp in the Dot Lake Village area, and so must also be late Donnelly or early Holocene in age. By inference, the sandy deposits of the high, streamlined terrace cut by the escarpment are probably the same (Donnelly) age as the proximal outwash south of the Dot Lake Village lowland.

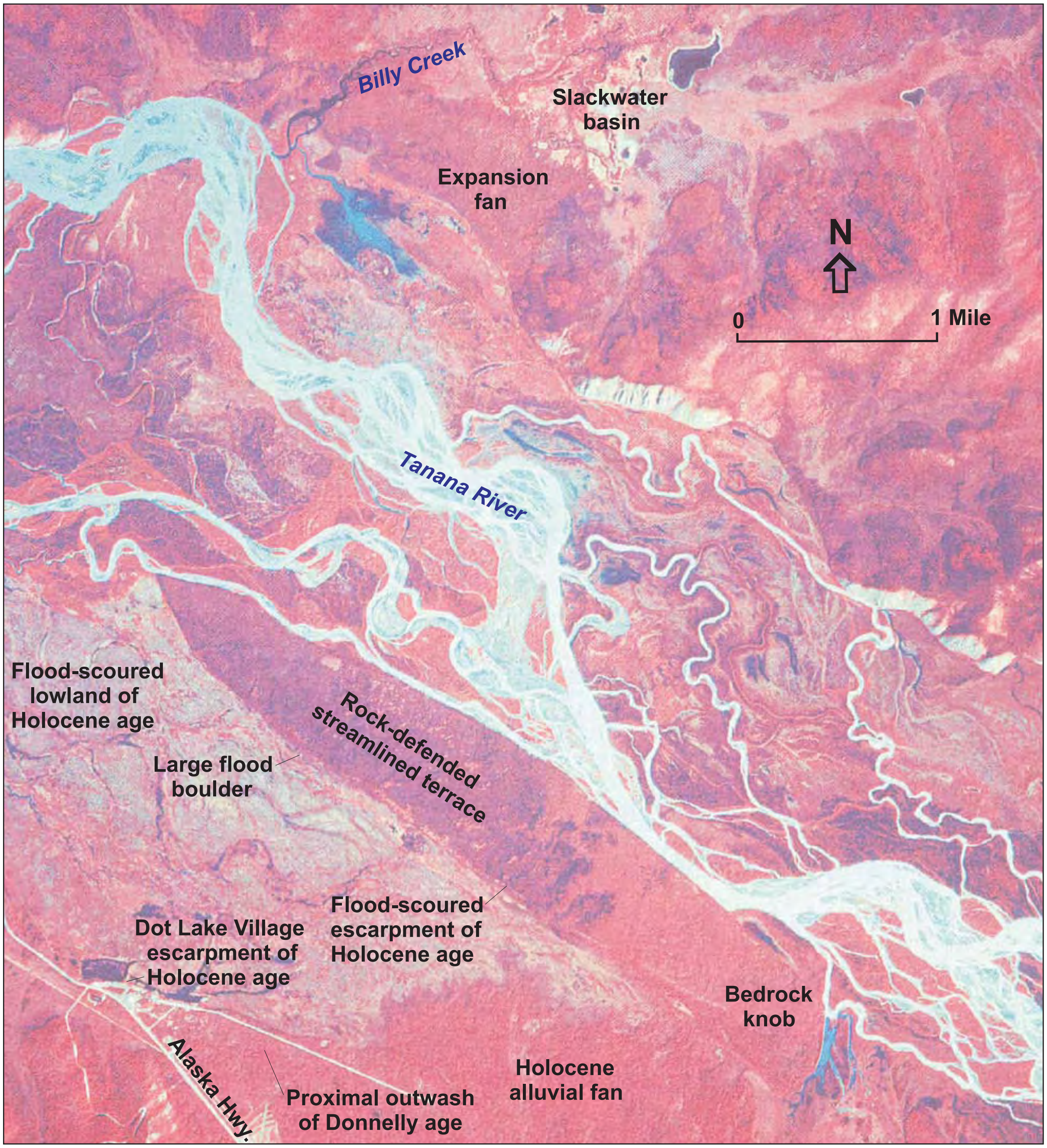

Figure 18. Landforms related to large-magnitude flooding of upper Tanana River near Dot Lake Village, northeastern Mt. Hayes C-1 Quadrangle, Alaska.

Figure 19. River-bluff exposure of pebbly sand flood deposits, northeastern Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 7/13/07.

SAM CREEK AREA

West of Dot Lake Village, for ~4.5 mi (~7.2 km) the Alaska Highway traverses a terrace tread that is crossed by the upper, intermittent course of Sam Creek (fig. 20). This surface is bounded to the north by an 18-ft-high (5.5-m-high), flood-scoured scarp that slopes 30–34°N. Near the west end of the terrace, two west-trending scarps were also probably cut by flooding, although they may have a fault origin (Carver and others, 2008a and b). Hand-level surveys along upper Sam Creek indicate that this terrace surface is tilted southward because the thalweg of Sam Creek is nearly horizontal (Carver and others, 2008a and b). The location on the concave southern side of Tanana River valley indicates that this terrace, which has a streamlined form and is pointed at both upvalley and downvalley ends, is a longitudinal bar deposited along the margin of a massive flood (O'Connor, 1993). The feature was previously mapped as questioned drift of the Delta glaciation (Qmo?) (Carter and Galloway, 1978).

Near-surface deposits on the longitudinal bar are dominantly well-drained, polymictic sandy pebble gravels with scattered cobbles and boulders that are at least 29 ft (8.8 m) thick and are sporadically frozen to depths >26.5 ft (>8 m) (Brazo, 1988; Reger and Solie, 2008). Examination of the walls of several gravel pits indicates that subrounded to rounded granitic boulders reach a maximum diameter of ~3.6 ft (1.1 m). Among several cobble lithologies are distinctive rock types that indicate deposition by the Tanana River, including vesicular volcanics and micaceous gabbro. These gravels are generally lightly stained by iron oxides to a depth of at least 4.6 ft (1.4 m), perhaps by near-surface groundwater rich in tannins when permafrost was more extensive. However, clasts have thin (<.04 in [<l mm]), discontinuous coatings of calcite to depths ≥3.3 ft (≥1 m), indicating that more extensive coatings and rinds were partially dissolved by acidic groundwater or that groundwater was alkaline at times, perhaps when permafrost thawed. An open geochemical system is indicated. A single, small ice-wedge cast was found in the terrace gravel (fig. 20). This feature, which measures 11 in. (28 cm) across the top and 4 ft (1.2 m) deep, has a filling composed of sandy gravel with some silt. Most pebbles in the wedge fill are oriented subparallel to parallel with

the wedge axis, likely as a result of in-filling during melting of the ice wedge (fig. 21). Overlying loess, which is 1 ft (0.3 m) thick, also collapsed into the shallow trough that formed when the near-surface ice wedge melted. The size and composition of this ice-wedge cast are typical of ice-wedge casts formed during Holocene time in Donnelly outwash north of Delta Junction (Alyeska Pipeline Service Company, 1976). The thin loess cap bears a weakly developed post-Donnelly soil profile. Clasts along the unconformity at the base of the loess are slightly modified to crude ventifacts with surface features, like weak to moderate polish, shallow pitting, and lack of facets or keels, that are typical of ventifacts preserved on surfaces of Donnelly age. Thin (≤0.02 in [≤0.5 mm]) silt caps are present to a depth of ~4 ft (~1.2 m), but no clay skins or bridges were observed. In the upper 30 in (0.8 m) of the terrace gravels, many schistose and granitic clasts are split or crumbly, respectively, due to frost weathering in the active zone. Typically, this zone of weathered clasts is much thicker in gravels of Delta age.

Evidence of flooding of the longitudinal bar is the widespread presence of waves composed of coarse to very coarse sand with trace to some silt, numerous subrounded to rounded pebbles, and scattered cobbles. Waves similar to these are typically associated with extensive flood bars in the Channeled Scabland of east-central Washington state (Baker, 1973, 1978). Several of these wave forms are sectioned by road cuts (fig. 22). Both wave complexes and single waves are present, and nine long axes trend 185° to 240° azimuth, averaging ~216° azimuth, roughly normal to the trend of the longitudinal bar (fig. 22). Wave heights vary from 2 to 9 ft (0.6 to 2.7 m), averaging ~1.6 ft (~0.5 m). Median diameters of the largest cobbles range from 2.8 to 4 in. (7 to 10 cm) and average ~3.1 to 3.5 in. (~8 to 9 cm). The coarse texture of these deposits indicates that the waves were deposited by water, not wind. The suite of pebbles and cobbles includes lithologies, like a 5.5-in (14-cm) vesicular basalt cobble, that are diagnostic of deposition by the Tanana River. Wave orientation indicates that former flood waters flowed west–northwest in this reach of the Tanana River valley.

A series of auger samples taken generally perpendicular to the trend of the longitudinal bar near upper Sam Creek (fig. 23) indicates that 4 to 12 in (10 to 30 cm) of nonsticky, nonplastic silty Holocene loess with scattered to numerous frost-jacked pebbles overlies ≤3.3 ft (≤1 m) of sticky, semiplastic clayey silt with trace to some medium-to-coarse fluvial sand and scattered polymictic pebbles. Underlying the sticky, sandy silt are at least 2 ft (0.6 m) of clean to slightly silty, friable, medium-to-very-coarse fluvial sand of latest Donnelly–early Holocene age (Carver and others, 2008a and b) with numerous subangular to subrounded, polymictic pebbles. Represented in the pebble collections are muscovite schist, several intermediate dike rocks, quartz, and several granitic lithologies. Many pebbles exhibit shallow surface pitting of mineral grains and weak to moderate surface polish, perhaps

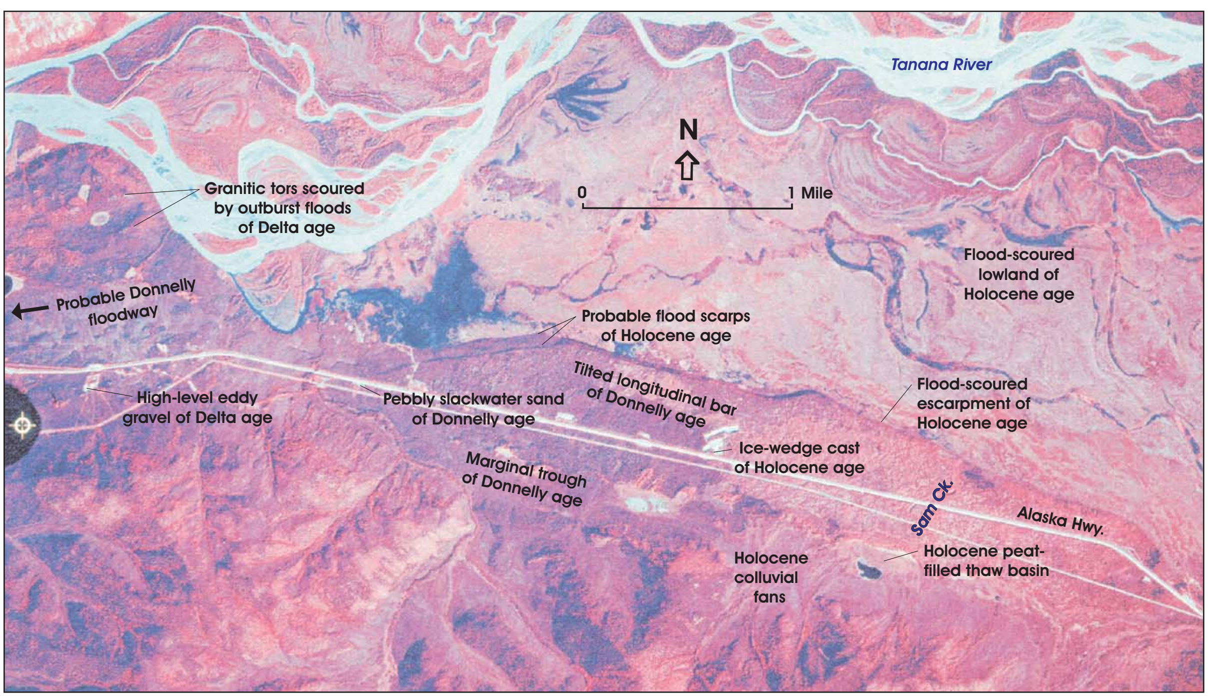

Figure 20. Landforms related to large-magnitude flooding of upper Tanana River in upper Sam Creek area, north-central Mt. Hayes C-1 Quadrangle, Alaska.

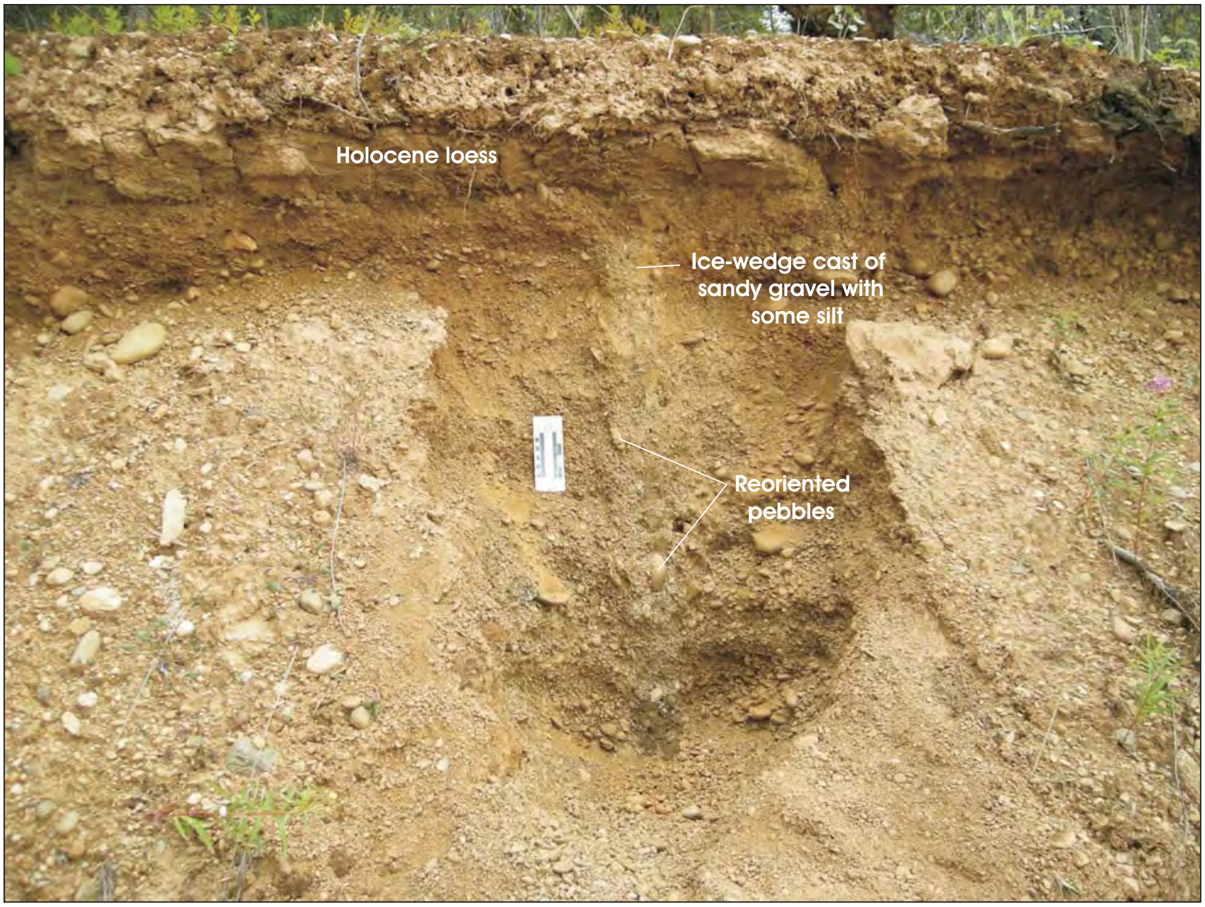

Figure 21. Ice-wedge cast in pebble–cobble gravel of Donnelly age on tilted longitudinal flood bar (fig. 18), north-central Mt. Hayes C-1 Quadrangle, Alaska. Scale in inches and centimeters. Photograph taken 7/10/07.

produced by contact with flowing silt- and sand-laden waters. No ventifacts were found. The origin of the clay fraction in the silt is uncertain, but a pedogenic origin cannot be ruled out. The clayey silt was not encountered in several other test holes in the vicinity of the Alaska Highway. Limitation of the clayey unit to the southern half of the tilted longitudinal bar in the vicinity of a possible floodway through the marginal trough typically associated with longitudinal bars (O'Connor, 1993) raises the possibility that flooding could have deposited a thin clay–silt drape that subsequently filtered into the underlying sediments. The presence of the clayey unit beneath the Holocene loess may be evidence that late Donnelly–early Holocene flooding occurred in the marginal trough when the scarps on both sides of the broad lowland north of the longitudinal bar were scoured. Because of the proximity of the clayey deposits to upper Sam Creek, another viable scenario is deposition of clays flushed from the weathered granitic upland to the south during early Holocene flooding of Sam Creek.

From the bedrock upland south of the possible marginal floodway, colluvial fans have extended into and across the marginal channel, indicating that the channel has some antiquity. The floor of the trough there is locally occupied by thaw basins that are partially filled with frozen peat of unknown thickness (Reger and Solie, 2008), again indicating some antiquity. Elsewhere in the channel, auger borings encountered unfrozen, clean, coarse-to-very-coarse, polymictic fluvial sand with numerous pebbles beneath 10–12 in (25–30 cm) of micaceous Holocene loess. This sand is very similar to sand exposed in a road cut at the west end of the longitudinal bar (fig. 20). There, a massive, clean, very well sorted, coarse-to-very-coarse polymictic fluvial sand with angular grains contains numerous granules and scattered subangular, polymictic pebbles up to 2.7 in (7 cm) diameter. Present in the pebble collection is vesicular andesite, which indicates a Tanana River origin. The lower surfaces of most pebbles have a discontinuous thin coating of calcium carbonate, and discontinuous thin silt caps are present on pebbles, suggesting a Donnelly age for the deposit. The massive character of the sand indicates that the sand was deposited rapidly in quiet water conditions, perhaps as a delta along the margin of a former lake impounded by the Donnelly advance of Johnson Glacier downstream to the west or perhaps along the margin of an outburst flood of Donnelly age.

Figure 22. Road cuts along Alaska Highway expose cross sections of pebbly sand waves on tilted longitudinal flood bar, north-central Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 7/21/07.

Evidence of probable large-scale flooding in the upper Tanana River valley during the Delta glaciation is preserved on 200-ft-high (60-m-high) granitic knobs between ~1,400 and ~1,600 ft (427 and 488 m) elevation 0.8 mi (1.3 km) north of the Alaska Highway (fig. 20). Large, asymmetric granitic tors there are separated by deep depressions, and lower slopes are covered by loess-capped sand dunes bearing Donnelly-age soil profiles. Bedrock surfaces on the tors are rough, and feldspar grains stand up to 2.8 in. (7.1 cm) in relief. However, loess, not grüs, is generally found between the blocks. Upriver bedrock surfaces on the eastern tors slope 15° to 20° northeast parallel to sheet joints and are fairly planar. Downriver bedrock surfaces slope 40 ° to 45° southwest and consist of a jumble of very large, angular to subangular granitic blocks up to 30 ft (9.1 m) long and 7 ft (2.1 m) thick, which impart jagged slope profiles. Carter and Galloway (1984, p. 67) interpreted these granitic outcrops as being scoured by glacial ice in this relatively narrow reach of the Tanana River valley. However, contrasting slope morphologies are consistent with inundation by major outburst floods down the Tanana River but are the reverse of the asymmetrical profiles one would expect if the bedrock knobs were scoured by ice flowing eastward up the Tanana River valley, as suggested by Carter and Galloway. The lack of grüs, the presence of loess between the weathered granitic blocks, the cover of eolian sand with post-Donnelly soil profiles, the asymmetrical tor profiles, and the association of the tors with deep bedrock depressions probably resulted from inundation and quarrying of these tors by massive jökulhlaups during the Delta glaciation. The evidence indicates that these voluminous inundations were >200 ft (>60 m) deep in this 2-mi-wide (3.2-km-wide) reach of Tanana River valley.

Fresh granitic knobs are present in the lowland between the granitic upland described above and the Alaska Highway (Larry Freeman, 7/28/07 oral commun.). These unweathered granitic knobs, which are below the level of the highway, and the presence of numerous large, granitic flood boulders downstream in the Sears Creek–Berry Creek area are evidence that this lowland was probably a channel for jökulhlaups of Donnelly age (figs. 20 and 26).

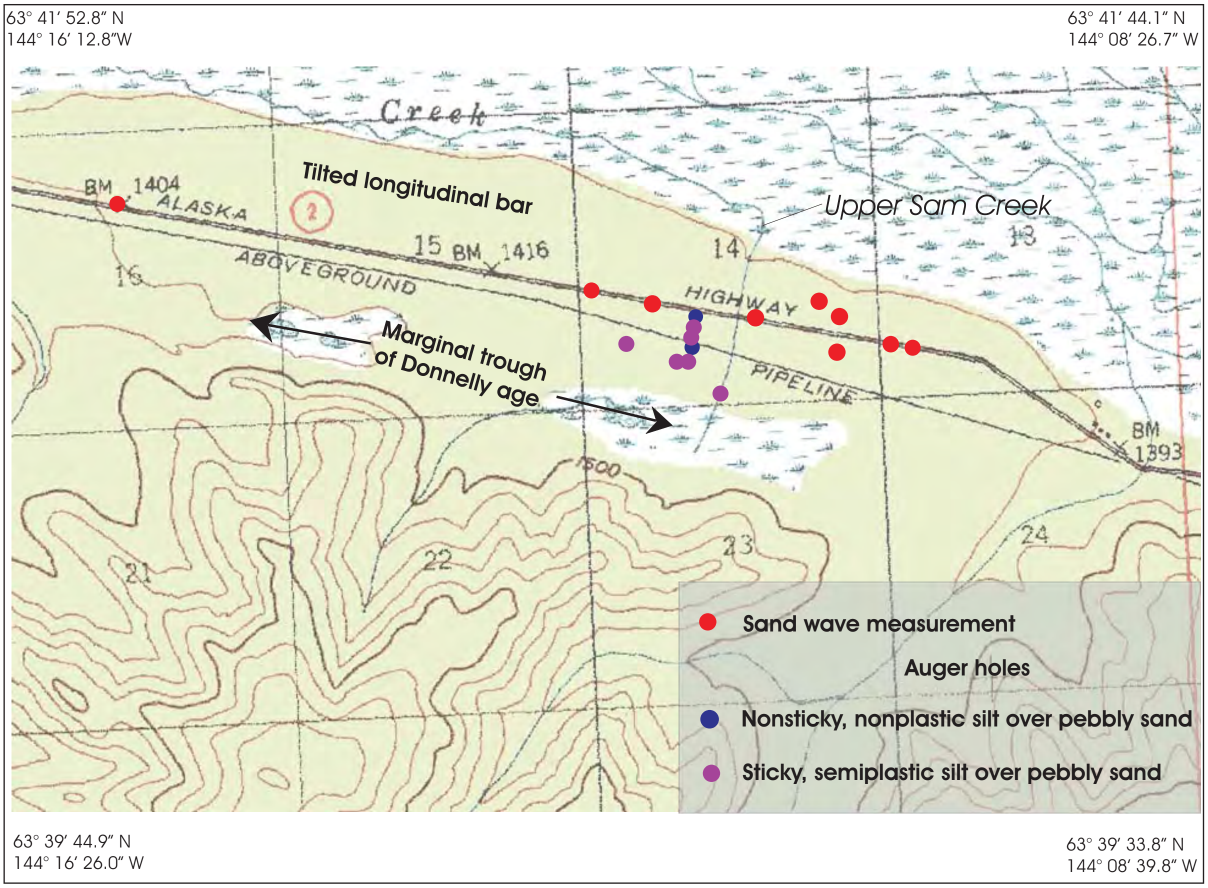

Figure 23. Measurement and sampling localities in vicinity of upper Sam Creek, north-central Mt. Hayes C-1 Quadrangle, Alaska.

Evidence of large-magnitude flooding during Delta and Donnelly glaciations is also present in an area of small granitic bedrock knobs at the west end of the Sam Creek area (fig. 20). Both north and south of the Alaska Highway is a swarm of low, streamlined granitic bedrock knobs below ~1,460 ft (~445 m) elevation. These knobs are oriented roughly parallel to the 225° azimuth, or ~45° from the general east–west orientation of the Tanana River valley in this reach. In contrast to granitic knobs at or above ~1,500 ft (~455 m) elevation to the south, these 8- to 10-ft-high (2.4- to 3-m-high) knobs have little grüs debris surrounding them, although there are shallow weathering pans on upper surfaces, and small knobs and mafic inclusions 3 to 4 in (8 to 10 cm) across stand 0.6 to 2 in (1.5 to 5 cm) above the surface. These features indicate that grüs was formerly present. Smooth lower slopes appear to be fresher than upper surfaces of the granitic knobs. In roadside exposures, the granitic bedrock is split into platy blocks ~1 ft (~0.3 m) thick, but there is no evidence of grüs. The lack of grüs on and around these knobs and their streamlined morphologies may be evidence of their inundation by jökulhlaups during the Donnelly glaciation and may establish an elevation limit for these colossal floods. Although these streamlined, aligned granitic knobs look much like roches moutonnées scoured by glacial ice, their locations close to the south wall of the Tanana River valley do not allow room for scour by glacial ice flowing from the west at an angle to the nearby valley wall, and there is no clear evidence for eastward expansion of Johnson River glacier or westward expansion of Robertson River glacier beyond their Donnelly limits.

Nearby, in an abandoned gravel pit at ~1,500 ft (~455 m) elevation along the southern margin of the cluster of aligned granitic knobs is a high-level deposit of massive to crudely cross-bedded pebble gravel with some very coarse sand and numerous subangular to rounded cobbles as large as 15 in. (38 cm) in diameter. Cross bedding generally dips toward the 32° azimuth, up the Tanana River, indicating that these gravels were deposited as high-level eddy deposits (O'Connor, 1993). Clast lithologies, including vesicular volcanics, indicate deposition by the Tanana River. Many rounded granitic clasts are "rotten" or have weathering rinds up to 2.4 in (6 cm) thick, indicating in-situ weathering after deposition, but others appear fairly fresh. Calcareous coatings on lower surfaces of pebbles and cobbles are discontinuous and thin and extend to depths >28 in (>70 cm). The color of the sandy matrix is 10YR4/4 (dark yellowish brown), which indicates a moderate degree of weathering. The gravel is >7 ft (2 m) thick and formerly buried knobs of weathered granitic bedrock up to 8 ft (2.4 m) high and 5.6 ft (1.7 m) across (fig. 24). However, there is no grüs associated with the weathered bedrock there, although nearby slightly higher knobs of granitic bedrock, which stand ~10 ft (~3 m) above nearby gravels, are surrounded and covered by up to 7 ft (2 m) of grüs; rounded core stones are also present. Either any easily erodible grüs was stripped off the granitic bedrock when the Tanana River deposited these high-level gravels, or grüssification occurred on nearby bedrock surfaces after gravel deposition. Depending on the susceptibility of the granitic bedrock to hydration, which is a function of the type and amount of biotite present (Isherwood and Street, 1976), the presence of grüssified bedrock may be evidence for 10^4 to 10^6 years of postflood weathering (Wahrhaftig, 1965b). The moderate state of weathering and the location >83 ft (>25 m) above the highest elevation of the tilted longitudinal bar of Donnelly age to the east and ~106 ft (~32 m) above the late Donnelly outwash terrace along Berry Creek to the west indicate that this gravel is probably Delta in age. The lack of rubification and lack of clay skins and bridges in the soil profile argues against a pre-Delta age.

SAND LAKE AREA

Sand Lake occupies the mouth of Sand Creek valley, which was formerly blocked by flood deposits along the northern margin of the Tanana River valley (sheet 2). The margin of the associated former slackwater basin with its fill of fine-grained sediments is still visible (fig. 25). Subsequently, the alluvial barrier that formerly dammed the valley was partially removed, and the Tanana River is currently building a complex delta into Sand Lake during flood stages. During lower river stages Sand Lake drains into the Tanana River through the flood channel. At the other end of the lake a much larger delta has been built into Sand Lake by Sand Creek, and the tortuous, lower

Figure 24. High-level, polymictic pebble–cobble gravel of probable Delta age deposited by Tanana River around granitic bedrock knobs without grüs, northwestern Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 8/2/07.

course of the creek is constrained across the delta by natural levees. This feature was formerly extensively frozen and ice rich (Reger and Solie, 2008), but under modern climatic conditions is thawing, as indicated by the complex of actively growing thaw lakes and ponds pocking the delta surface.

A test pit dug near Sand Lake into a natural-levee deposit at the top of an 8.6-ft-high (2.6-m-high) river scarp penetrated 3.2 in (8.1 cm) of organic mat and 18 in (45.7 cm) of silty loess that grades downward into probable fluvial silt with trace very fine sand and rare pebbles. Weak horizon differentiation and the grayish brown (10YR5/2) color of the B horizon in the 12.5-in-deep (32-cm-deep) solum indicate that this natural levee is late Holocene in age. Fine sand with numerous platy to rounded small pebbles was encountered at depths of 19 to 25 in (48 to 64 cm). The lowest sediment in our 29-in-deep (73.7-cm-deep) test pit is clean, coarse sand with numerous platy to rounded polymictic pebbles. No large cobbles or boulders were found in these Holocene flood deposits, indicating that the flood bedload is not represented.

SEARS CREEK–BERRY CREEK AREA

As previously discussed, the presence of fresh, streamlined granitic knobs indicate that the lowland between the granitic tors in the northwestern corner of figure 26 and the Alaska Highway was probably scoured by large

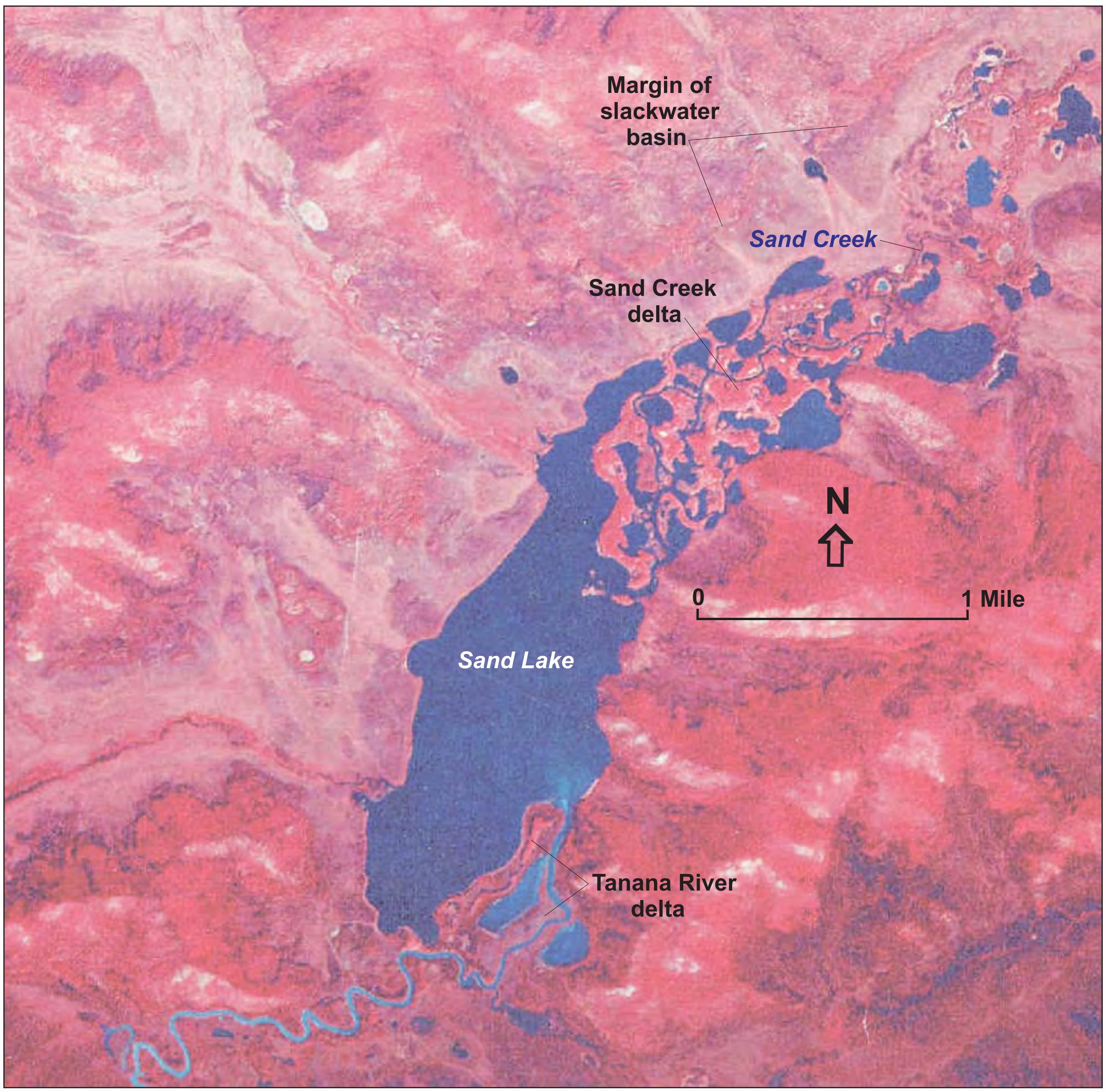

Figure 25. Deltas and slackwater basin limit in Sand Lake area, north-central Mt. Hayes C-1 Quadrangle, Alaska.

floods during the Donnelly glaciation. This floodway was subsequently transected by a late Donnelly or post-Donnelly flood that produced a northeast-trending scarp along the Tanana River (fig. 26). Cross-cutting relations demonstrate that the linear flood-cut scarp along the northwestern flank of the granitic upland postdates the probable floodway of Donnelly age through the lowland south of the granitic upland and north of the Alaska Highway and predates the Holocene alluvial fan (fig. 26). The late Donnelly outwash terrace along lower Berry Creek may have been tectonically uplifted because it has been incised ~36 ft (~11 m) (fig. 16), and the stream subsequently built a Holocene alluvial fan onto the margin of the Tanana River floodplain (fig. 26, sheet 2). GPS readings indicate that the outwash terrace remnant is ~106 ft (~32 m) below the Tanana River gravels of probable Delta age ~1.1 mi (~1.8 km) to the east (fig. 24).

Except in very coarse proximal outwash deposits or deep in alluvial deposits exposed in gravel pits, few boulders are found in Tanana River terrace deposits in the map area. A notable exception is on the strath terrace in the Sears Creek–Berry Creek area, where numerous exceptionally large, near-surface granitic boulders, almost certainly deposited by paleofloods, were excavated during highway construction from the clean, near-surface sandy pebble–cobble gravels that generally buried them at ~1,330 ft (~405 m) elevation (fig. 27). At only one locality were these large boulders found in situ in pebble–cobble terrace gravels with lithologies indicating deposition by the Tanana River. Apparently because of the concentration of large granitic boulders in this reach, Carter and

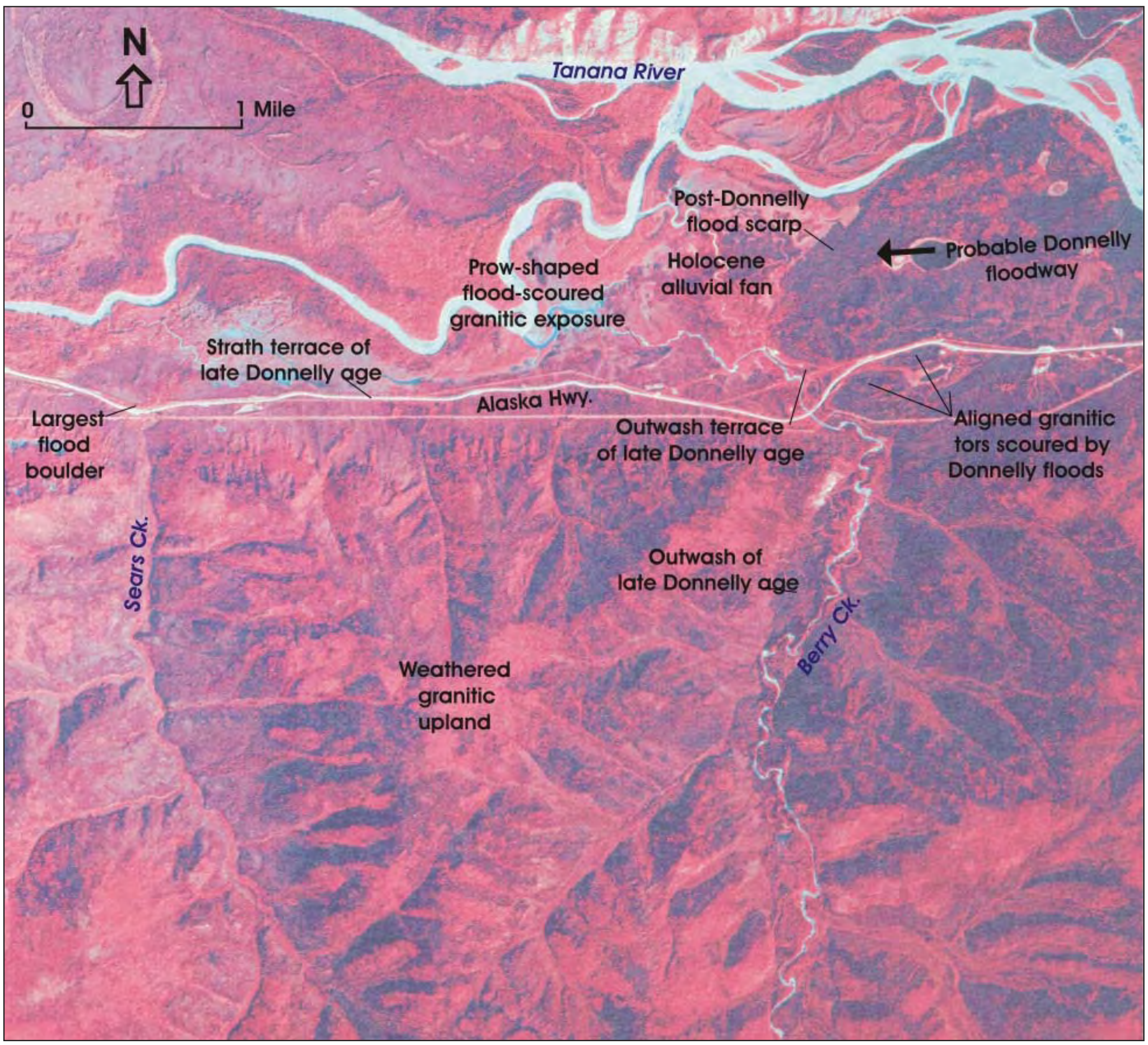

Figure 26. Landforms related to large-magnitude flooding in Sears Creek–Berry Creek area, northwestern Mt. Hayes C-1 Quadrangle, Alaska.

Galloway (1978) mapped this strath terrace along the base of the fairly linear, dissected high scarp at the northern edge of a weathered granitic upland as questioned till of the Delta glaciation (Qmo?). The late Donnelly age of these deposits is indicated by the interfingering of strath terrace gravels and the outwash of late Donnelly age along Berry Creek to the east (fig. 26). The largest and westernmost flood boulder known to be associated with the strath terrace in the Sears Creek–Berry Creek area measures 9 ft by 5.3 ft by 3.3 ft (2.7 m by 1.6 m by 1.0 m) (fig. 28, table 3).

To evaluate variations of boulder shape in a small (n = 16) sample of exposed and partially exposed granitic flood boulders in gravels of the late Donnelly strath terrace, minimum boulder dimensions were divided by maximum boulder dimensions and plotted against maximum minus intermediate dimensions divided by maximum minus minimum dimensions using a classification developed by Sneed and Folk (1958) for the shapes of large particle sizes (fig. 29). This plot indicates that flood boulders on the late Donnelly strath terrace are rather evenly distributed among several shape classes and show little significant preference (table 4), although very platy forms are well represented compared to the other two corners of the triangular plot (fig. 29). We speculate that the size and shape of the granitic flood boulders are functions of the size and spacing of joints in the granitic bedrock from which the boulders were derived.

The large sizes of these granitic rocks and their subrounded to rounded corners indicate that they were rolled downstream by powerful currents in flood channels as part of the traction bedload. During high-regime flows, downstream rolling movements of large boulders are initiated by scouring beneath the boulders. On the strath terrace, gray granitic flood boulders are commonly mixed with angular to subangular, tabular, brownish blocks and boulders of granitic bedrock that were probably plucked from nearby bedrock by flood waters and incorporated into the bedload (fig. 28). North of the Alaska Highway along the margin of the Tanana River floodplain ~0.6 mi

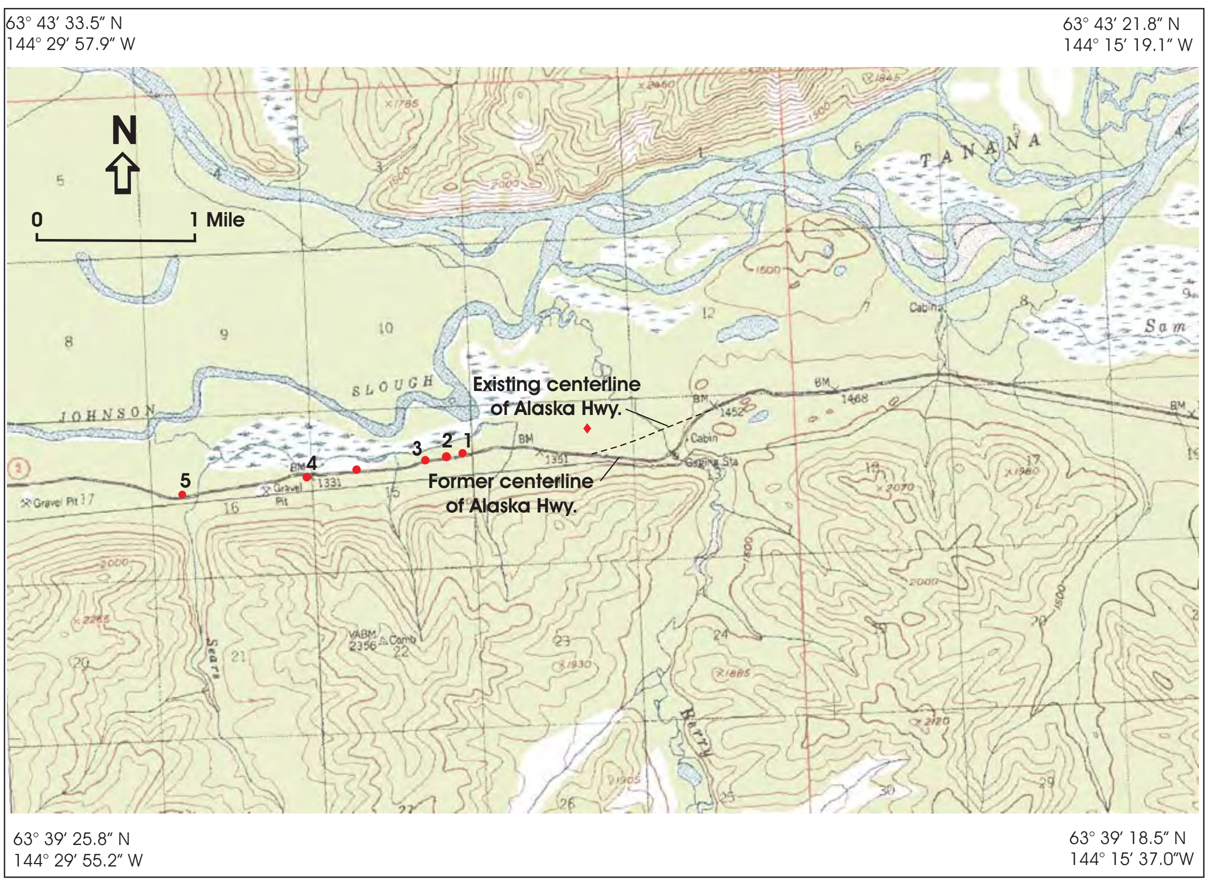

Figure 27. Locations of large granitic flood boulders (red dots) and probable local source of flood boulders (red diamond) associated with strath terrace of late Donnelly age in Sears Creek–Berry Creek area, northwestern Mt. Hayes C-1 Quadrangle, Alaska. Numbers refer to localities cited in table 3.

Figure 28. Largest granitic flood boulder found along Alaska Highway (locality 5 in figure 26) in Sears Creek–Berry Creek area, northwestern Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 8/1/07.

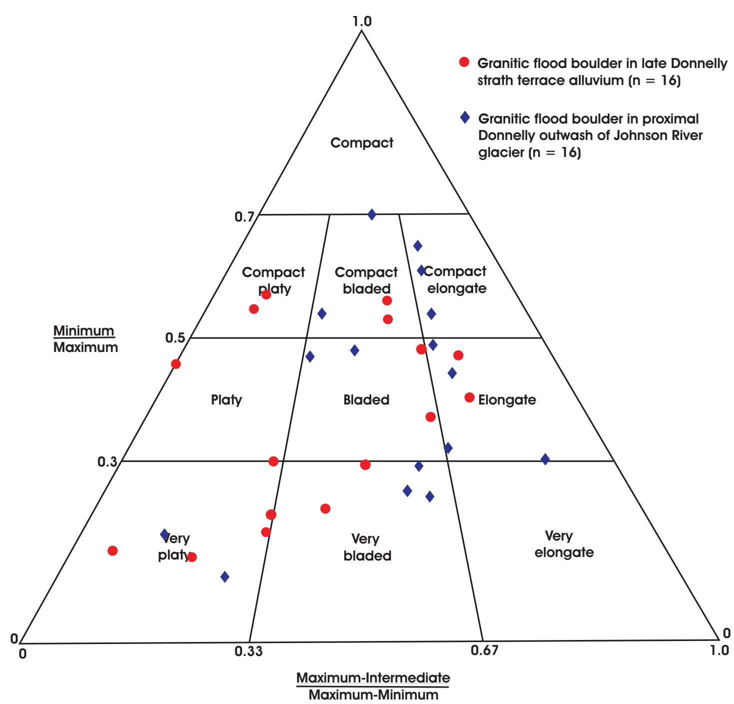

Figure 29. Shape classes of granitic flood boulders in strath-terrace alluvium of late Donnelly age (red dots) and proximal-outwash alluvium of Donnelly age (blue diamonds), based on boulder dimensions (classification of Sneed and Folk, 1958).

Table 4. Distribution of flood boulders in 10 classes of triangular shape plot developed by Sneed and Folk (1958) (fig. 28). Red numbers represent flood boulders in late Donnelly strath terrace (n = 16); blue numbers represent flood boulders in proximal Donnelly outwash of Johnson River glacier (n = 16).

Shape class	Number of samples (n)	Percent represented
Compact	0 0	0 0
Compact platy	2 0	12.5 0
Compact bladed	2 2	12.5 12.5
Compact elongate	0 3	0 18.8
Platy	2 0	12.5 0
Bladed	2 2	12.5 12.5
Elongate	2 4	12.5 25.0
Very platy	4 2	25.0 12.5
Very bladed	2 3	12.5 18.8
Very elongate	0 0	0 0
Total	16 16	100.0 100.1

(~1 km) east-northeast of the known eastern limit of the large granitic flood boulders, an unusual chaotic jumble of large angular to subangular, tabular, granitic blocks of the local bedrock probably is the source of local boulders mixed with gray flood boulders on the strath terrace (figs. 28 and 30). Contrasting appearances indicate that the gray flood boulders traveled farther than the local, brownish granitic blocks. As previously mentioned, a likely source of the gray boulders is the fresh-looking granitic knobs in the lowland north of the Alaska Highway ~1.7 mi (~2.7 km) east-northeast of the easternmost gray flood boulder in this reach.

Because the widths of the Tanana River valley in this reach and the Snake River canyon are similar, comparison with the curve of velocity at depositional sites during the huge Bonneville flood down the Snake River (O'Connor, 1993, fig. 78b) provides a rough estimate of velocities during late Donnelly floods in this reach of the Tanana River valley (fig. 31). Our five largest boulders measured 5 to 6 ft (1.5 to 1.8 m) along their intermediate axes, implying that paleoflood velocities were roughly 18.5 to 22 ft/sec (5.6 to 6.7 m/sec), averaging ~20 ft/sec (~6.1 m/sec), when the boulders ceased moving. Current velocities that initiated their movement were much faster, perhaps as much as twice as fast (O'Connor, 1993, p. 57).

JOHNSON RIVER AREA

Several large (≤3.3 ft or 1 m), subrounded to rounded granitic boulders are exposed in sandy pebble–cobble proximal outwash of Donnelly age cut by the Alaska Highway east of the Johnson River bridge (sheet 2). Nearby, along the margin of an associated 13-ft-deep (4-m-deep), flat-floored, wide, outwash channel, there are numerous large (≤7 ft or 2.1 m), subrounded to rounded granitic boulders (fig. 32) that are also partially buried in proximal outwash. These boulders indicate that particularly coarse debris was transported by episodic outburst floods during the Donnelly glaciation and contributed to the proximal outwash deposit. To evaluate form variation in a small collection (n = 16) of granitic flood boulders in this proximal outwash, we again used the classification of Folk and Sneed (1958) (table 5) and compared the plots with those of flood boulders in the Sears Creek–Berry Creek area (fig. 29). The outwash boulders display a similar uniform distribution in morphology with only slightly greater representations in compact elongate, elongate, and very bladed classes (table 4).

Figure 30. Large granitic blocks probably jumbled chaotically during large-magnitude flooding of the upper Tanana River, northwestern Mt. Hayes C-1 Quadrangle, Alaska. Photograph taken 8/1/07.

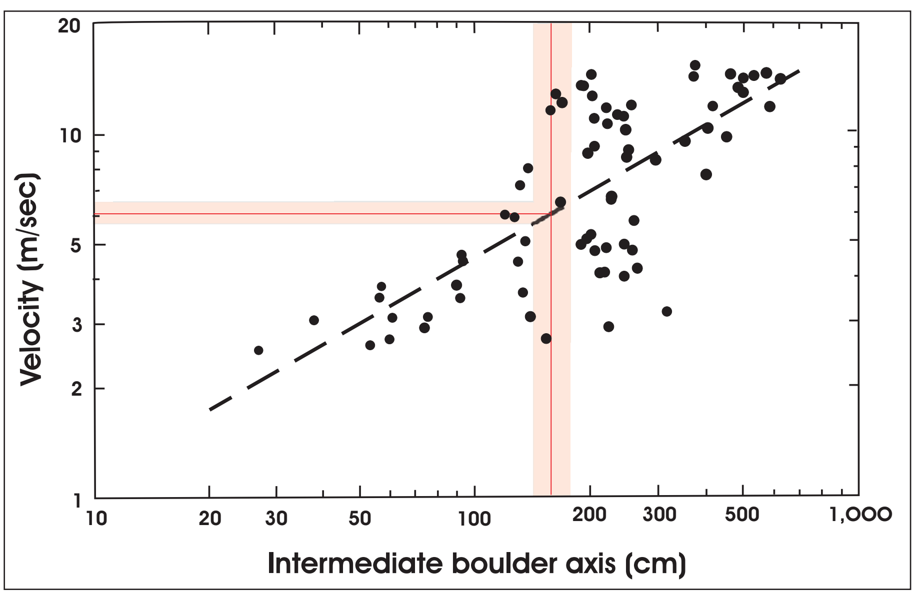

Figure 31. Comparison of intermediate axes of flood boulders and inferred velocity at depositional sites during the Bonneville flood (in black) (O'Connor, 1993, fig. 68b) with the range of intermediate axes of the five largest boulders on the Sears Creek–Berry Creek strath terrace and the inferred range of paleoflood velocities (in red). The O'Connor curve is based on the average intermediate axes of the five largest boulders measured at 75 sites.

In a nearby, deep gravel pit in proximal outwash emanating from the nearby terminal moraine of Donnelly age, 26 ft (7.9 m) of pebble–cobble gravel outwash with numerous large, rounded, granitic flood boulders overlies a unique, very fine to medium sand with trace silt that is >10 ft (>3 m) thick (fig. 32) (Birch, 1976). The sand, which is brownish gray (10YR6/2) in color, is massive to very fine bedded with silt partings along bedding planes. Climbing ripples indicate that stream flow during sand deposition was to the southwest, toward the source of the overlying proximal outwash. We believe that the sand was deposited in slackwater conditions along the margin of a flood of the Tanana River, probably early in the Donnelly glaciation before the proximal outwash reached this site.

Figure 32. Features related to large-magnitude flooding in lower Johnson River area, northeastern Mt. Hayes C-1 Quadrangle, Alaska.

Table 5. Dimensions of granitic flood boulders in Donnelly proximal outwash of Johnson River glacier, and calculations for triangular shape plot (fig. 28)

Latitude	Longitude	Maximum diameter (cm)	Intermediate[a] diameter (cm)	Minimum[a] diameter (cm)	Minimum[a] / Maximum	Maximum–Intermediate[a] / Maximum–Minimum
N63°41'59.2"	W144°37'41.6"	91	80	16+	0.18	0.15
		107	81	12+	0.11	0.27
		79	57	48+	0.61	0.71
N63°42'00.2"	W144°37'19.5"	108	65	48+	0.44	0.72
N63°42'00"	W144°37'22.4"	147	80	47+	0.32	0.67
N63°41'58.7"	W144°37'29.2"	126+	68	36	0.29	0.64
N63°41'59.8'	W144°37'39.4"	200	130	98+	0.49	0.69
		170	115	92+	0.54	0.71
		112	93	60+	0.54	0.37
		118	46	36	0.31	0.88
N63°41'40.9"	W144°36'14.7"	112	85	54+	0.48	0.47
N63°41'35.5"	W144°36'01.6"	170	127	110	0.65	0.72
		115	96	80	0.70	0.54
N63°41'34.7"	W144°35'54.6"	128	104	60+	0.47	0.35
		120	68	30+	0.25	0.58
		100	53	24+	0.24	0.62

[a]Submaximum, subintermediate, and subminimum dimensions of partially buried boulders, which are indicated by +, are used as maximum, intermediate, and minimum dimensions in the calculations.

We propose that the apparent lack of glacial deposits on the bedrock hills north of the Tanana River beyond the limit of the Donnelly glaciation and the mysteriously missing terminal moraine and associated proximal outwash of Delta age (sheet 2) are evidence of large-magnitude floods of pre-Donnelly age in the Johnson River area. The log of a water well dug for the Dry Creek community in 2001 (fig. 32) encountered boulders in silt at a depth of 100 ft (30 m) beneath thick sand and gravel (Steve Squires, unpublished data). We suggest that the boulders and silt are till of Delta age that is buried by thick outwash of Donnelly age and may indicate that the Johnson River glacier was more extensive during the Delta glaciation than during the Donnelly glaciation, making the lack of a terminal moraine and associated outwash even more anomalous. We propose that, if large-magnitude floods down the upper Tanana River were sufficiently frequent during the Delta glaciation, perhaps the terminus of the Johnson River glacier was periodically trimmed back before the glacier could impinge against the bedrock wall on the north side of the Tanana River opposite the mouth of the Johnson River. Subsequently, outwash of the Donnelly advance likely buried any remnants of Delta drift left in the terminal area.

During an early major flood, perhaps a massive jökulhlaup of Delta age, a large, high-level expansion fan spread north of the bedrock ridge east of the Tanana River and impounded several lakes against the Yukon–Tanana Upland, including Moosehead Lake, Lake George, and Black Lake (fig. 33, sheet 2). Excavations in similar fans associated with lowland-marginal lakes down the Tanana River exposed thick gravel deposits (Péwé and Reger, 1983b), which are evidence of large-magnitude floods. The large expansion fan of Delta? age that impounds Moosehead Lake and Lake George is separated by a scarp from the lower flood-expansion fan of late Donnelly age (fig. 43), as are other, similar terrace sets in the Tanana River drainage (Péwé and Reger, 1983b). In this area, the late Donnelly expansion fan spread from the Tanana River northward behind the bedrock knob. Closer to the Tanana River, a large natural levee associated with a crevasse-splay complex was deposited on the post-Donnelly expansion fan east of the Tanana River (fig. 32).

BLACK LAKE AREA

Black Lake has an unusual outline formed by nearly complete filling of the lake basin by flood deposits of late Donnelly and Holocene ages (fig. 33). During Holocene floods of the Tanana River, rising waters flowed east-northeast up flood channels and entered the dumbbell-shaped lake basin at both ends, building flood fans. The two lake basins are nearly pinched off by a growing Holocene flood fan. A 23-in-deep (58-cm-deep) test pit dug into Holocene flood deposits near the channel between the lake basins initially encountered a thin (3-in or 7.6-cm) surface loess capping 9 in (23 cm) of micaceous fluvial silt representing waning flood deposits. The fluvial silt is underlain by 6 in (15 cm) of pebbly silty sand that overlies clean sandy pebble gravel with numerous cobbles, which almost certainly represents material carried in the bedload during Holocene floods. Subangular to well rounded cobbles measure up to 6.3 in (16 cm) diameter and generally are concentrated in layers (channel lags or fills). Larger cobbles and boulders prevented deeper excavation. This pit confirmed the Holocene age of the deposits and demonstrated that larger bedload material is buried by later suspended material. This relationship was exaggerated during large-magnitude jökulhlaups that transported large granitic flood boulders as traction bedload and later buried them in pebble–cobble gravels representing smaller components of the same bedload. Lack of grüs associated with the nearby, 50-ft-high (15-m-high) tip of a granitic ridge may indicate repeated scouring during episodic large-magnitude paleofloods (fig. 34).

West of the Tanana River, a pendant bar of late Donnelly age formed where the flooding Tanana River spread after passing the Donnelly terminal moraine. This feature is equivalent in elevation and age to the lower expansion fan east of the river (fig. 33). The very coarse upper flood gravel in this pendant bar is exposed beneath Holocene loess 60 ft (18 m) above the Tanana River in a roadcut leading from the Alaska Highway to a boat landing at the

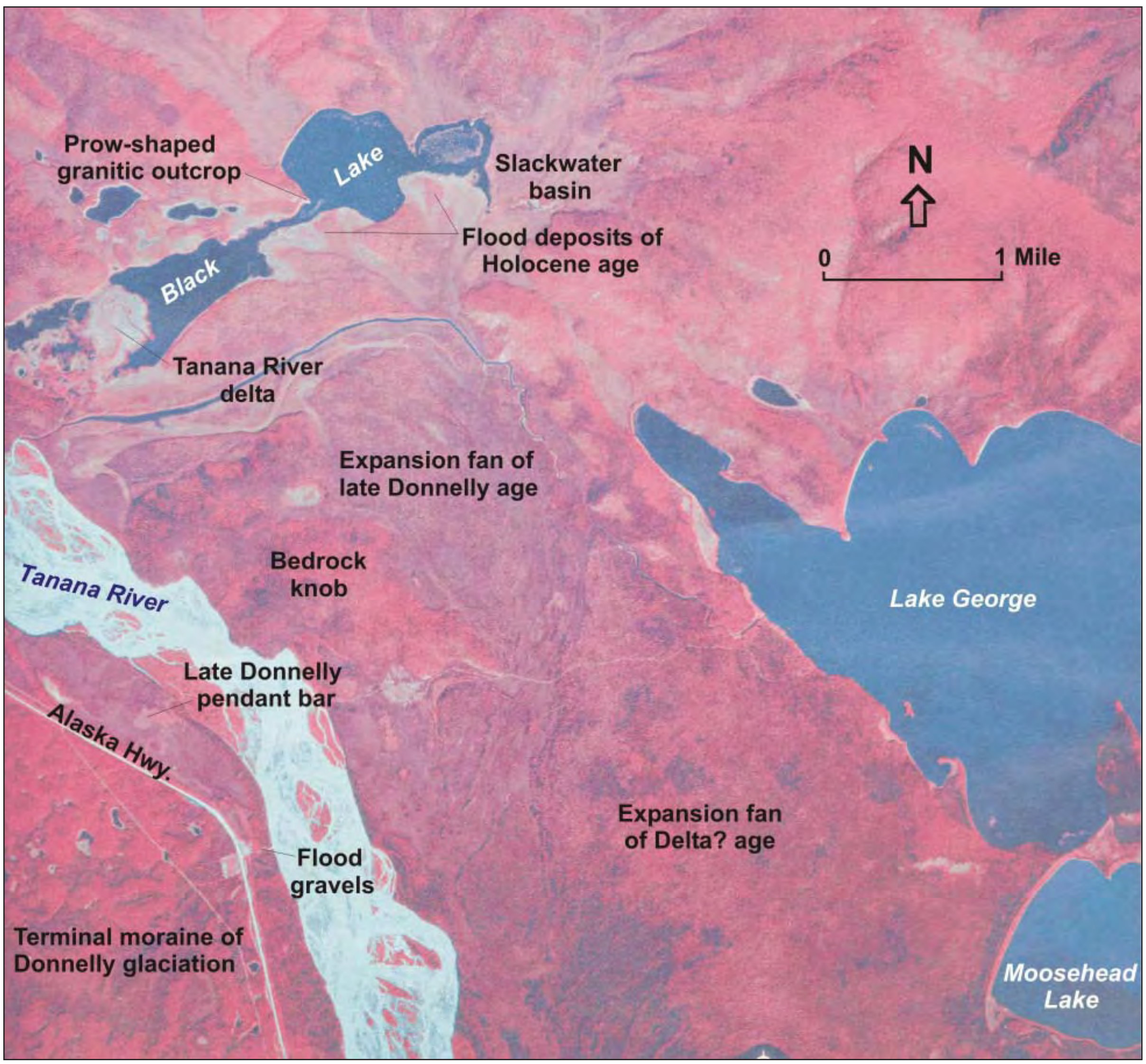

Figure 33. Features related to large-magnitude flooding of the upper Tanana River in the Black Lake area, southeastern Mt. Hayes D-2 Quadrangle, Alaska.

Figure 34. Prow-shaped granitic bedrock exposures washed by numerous large-magnitude paleofloods in the Black Lake area, southeastern Mt. Hayes D-2 Quadrangle, Alaska. Photograph taken 7/23/07.

river (fig. 33). There, flood gravel is composed of numerous subrounded to rounded polymictic cobbles and granitic boulders up to 3.6 ft (1.1 m) in diameter, grain sizes typically found in pendant bars in the Channeled Scabland of east-central Washington State (Baker, 1973, 1978). Many of the cobbles and boulders have thick calcareous encrustations, particularly on lower surfaces.

The $^{230}Th/^{234}U$ contents of dense, laminar, translucent, calcareous, pedogenic rinds in coarse outwash gravels were analyzed to establish minimum ages of outwash of the Pinedale and Bull Lake glaciations in the Wind River basin of northwestern Wyoming (Sharp and others, 2003). Features, like unconformities and bleaching, that indicate open geochemical systems were identified in microscopic sections prior to sampling and avoided. We believe that this approach is not suitable for dating the flood gravels in the pendant bar because the calcareous rinds were almost certainly deposited from groundwater percolating through the gravels before the pendant bar was incised and the modern terrace formed. Evidence supporting this conclusion is the pervasive nature of calcite weathering of gravel clasts (fig. 35). Many clasts in the upper 3 ft (1 m) of the deposit are so altered by the growth of calcite that many foliose schist clasts are totally disaggregated and granitic clasts crumble readily even though this deposit is late Donnelly in age. Clearly, these clasts were not transported in these conditions during flooding. The intensity of the salt weathering there leads the observer to initially overestimate the age of the flood deposit. We suggest that the weathering was accomplished by bicarbonate-saturated groundwater in a fluctuating vadose zone near the surface of the pendant bar and is not related to soil-forming processes. According to Anderson (1970, sheet 4) the waters in the upper Tanana River basin contain considerable bicarbonate. The source of the bicarbonate has not been evaluated, but Dashevsky and others (2003) identified several units with calcareous components in their Jarvis Belt, including local carbonate interbeds, sandy limestones, quartz–carbonate veins, and siderite alteration. We note that many cobbles bearing partial calcareous rinds are present in numerous gravel pits in the corridor. Obviously, the calcareous rinds have been partially dissolved by acidic groundwater, so the geochemical system was clearly not closed, and the clast rinds in the pendant bar are not suitable candidates for dating by the $^{230}Th/^{234}U$ method.

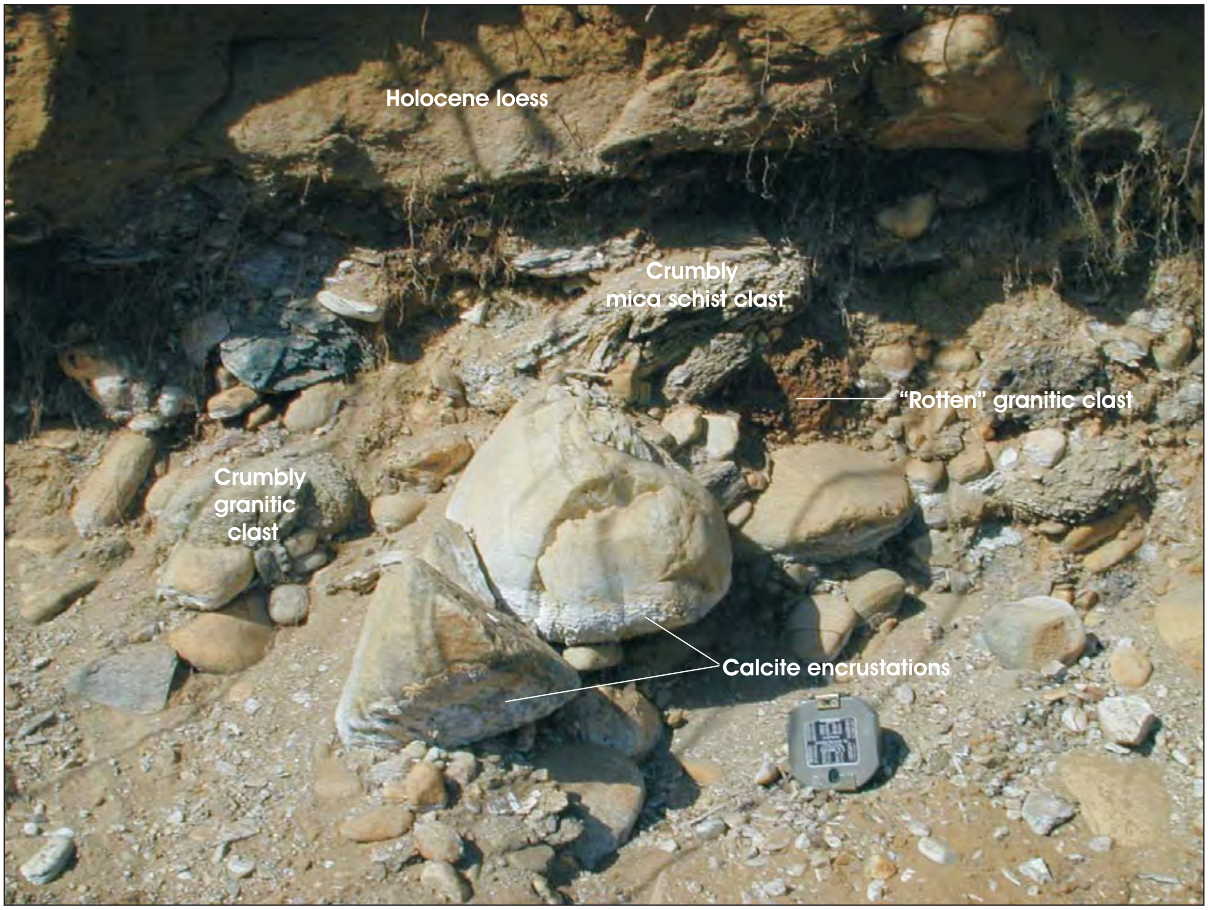

Figure 35. Near-surface cobble–boulder gravel in pendant bar of late Donnelly age, southeastern Mt. Hayes D-2 Quadrangle, Alaska. Brunton compass is 2.8 in. (7 cm) wide. Photograph taken 9/10/06.

LITTLE GERSTLE RIVER–GERSTLE RIVER AREA

Delta terminal moraines of the Little Gerstle and Gerstle River lobes are nearly buried by moraines and outwash of Donnelly age, and little evidence of paleoflooding is apparent there. However, ~4 mi (~6.5 km) downstream from the mouth of Little Gerstle River, a pair of terraces probably formed during outburst floods of Donnelly age (sheet 2). East of the Tanana River north of a bedrock ridge, the eastern terrace forms an expansion fan that impounds Twelvemile Lake and two smaller lakes near the edge of the map area. West of the Tanana River, the equivalent surface is partially defended by two bedrock hills and is covered in part by Holocene sand dunes. Post-Donnelly flooding has cut a channel along the southwestern margin of the Donnelly terrace there, and this floodway still channels floodwaters from the Tanana River into the Gerstle River.

A prominent, generally linear scarp cuts Donnelly outwash for ~21 mi (~34 km) northwest from the Gerstle River to the vicinity of Clearwater Ranch at the edge of the map area (sheets 1 and 2). This Gerstle-Clearwater escarpment clearly is Holocene in age, and a broad, abandoned floodplain occupies the lowland from the base of the scarp for several miles northeastward beyond the limit of the map area toward the Tanana River. Near Clearwater Ranch the Holocene Gerstle-Clearwater escarpment intersects the much older Clearwater Lake escarpment.

CLEARWATER LAKE AREA

The west–northwest-trending Clearwater Lake escarpment cuts proximal outwash from the type early Delta terminal moraine and is in turn buried by outwash from the type Donnelly moraine (fig. 36, sheet 1) (Reger and Péwé, 2002). This prominent linear feature was initially suspected to be a fault scarp by Weber (1971) and Carter and Galloway (1978), but intensive examination of trench exposures and geophysical surveys across the feature found no evidence of faulting (Alyeska Pipeline Service Company, 1976). Lindholm and others (1959) had previously concluded that the Clearwater Lake escarpment was cut by the braided Tanana River. Related high scarps, some attributed to unconfirmed faults, extend discontinuously for several miles down the Tanana River (Péwé and others, 1966), suggesting the regional scale of the escarpment (fig. 37). High-volume springs emerging along the base of the Clearwater Lake escarpment supply high-quality water for Clearwater Lake and Clearwater Creek, which are important fish-wintering habitats. The ultimate source of these waters is the deep aquifer confined beneath till of Delta age and supplied by infiltration of water from the Delta River southwest of Fort Greely (Williams, 1970, p. 44).

Physiographic relations in the Delta Junction area clearly demonstrate that the Clearwater Lake escarpment postdates the early Delta glaciation and predates the Donnelly glaciation. Intuitively, the regional scale of this feature, which extends across the southern Tanana River valley for ~110 mi (~177 km) (fig. 37), implies that regional-scale processes are responsible for cutting the scarp. Considering the many flood-related features in the upper Tanana River valley and their ages from Delta to Holocene time, we propose that a series of large-magnitude outburst floods cut the Clearwater Lake escarpment after the deposition of the early Delta outwash and before the deposition of the Donnelly outwash fan in late Wisconsinan (OIS 2) time. If the outer (older) type Delta moraine is OIS 6 in age, perhaps the erosion of the associated proximal outwash to produce the Clearwater Lake escarpment was accomplished by numerous jökulhlaups during an early Wisconsin (OIS 4) glaciation that is now considered to be late Delta in age.

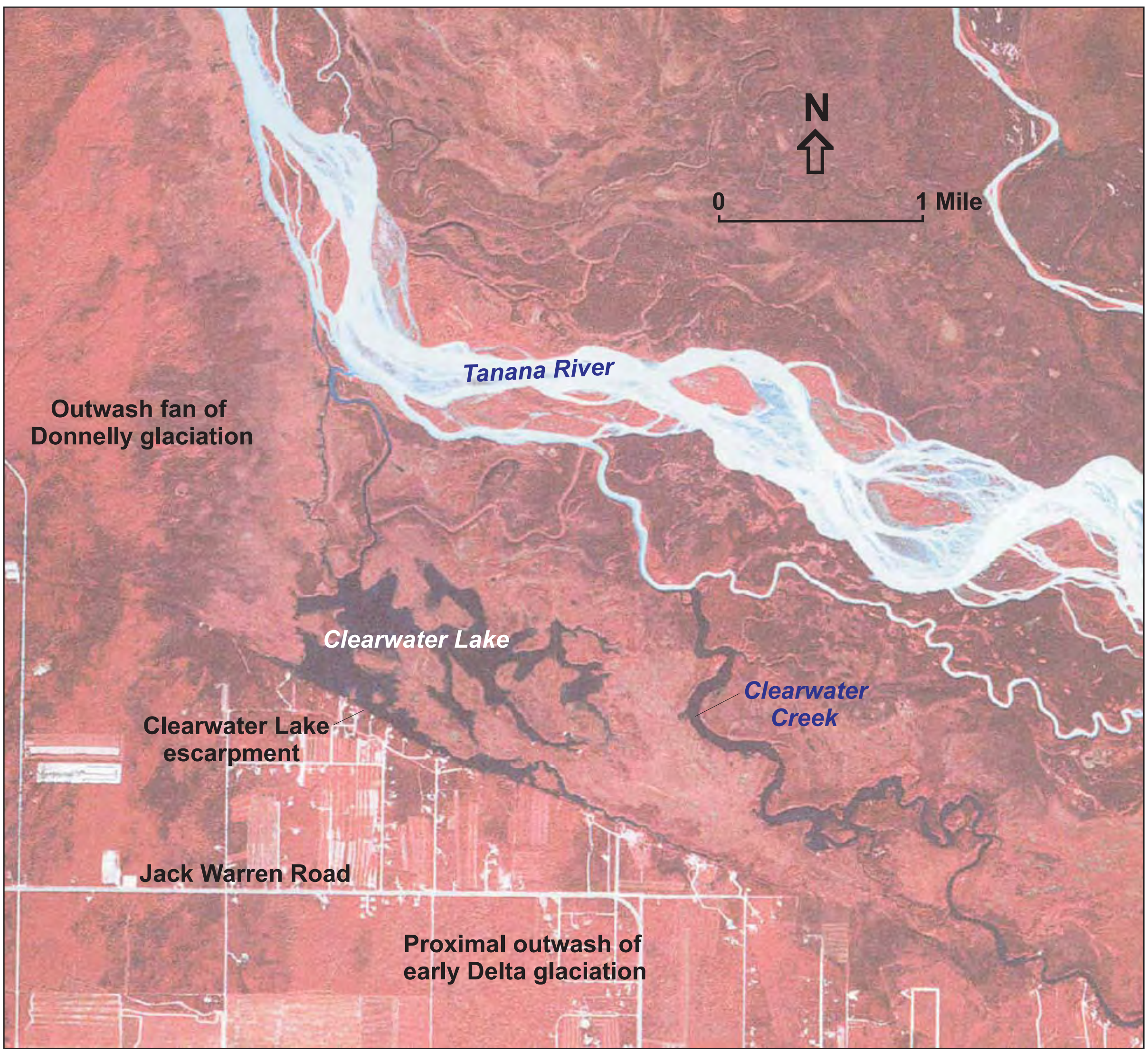

Figure 36. Landforms associated with Clearwater Lake escarpment, east-central Big Delta A-4 Quadrangle, Alaska.

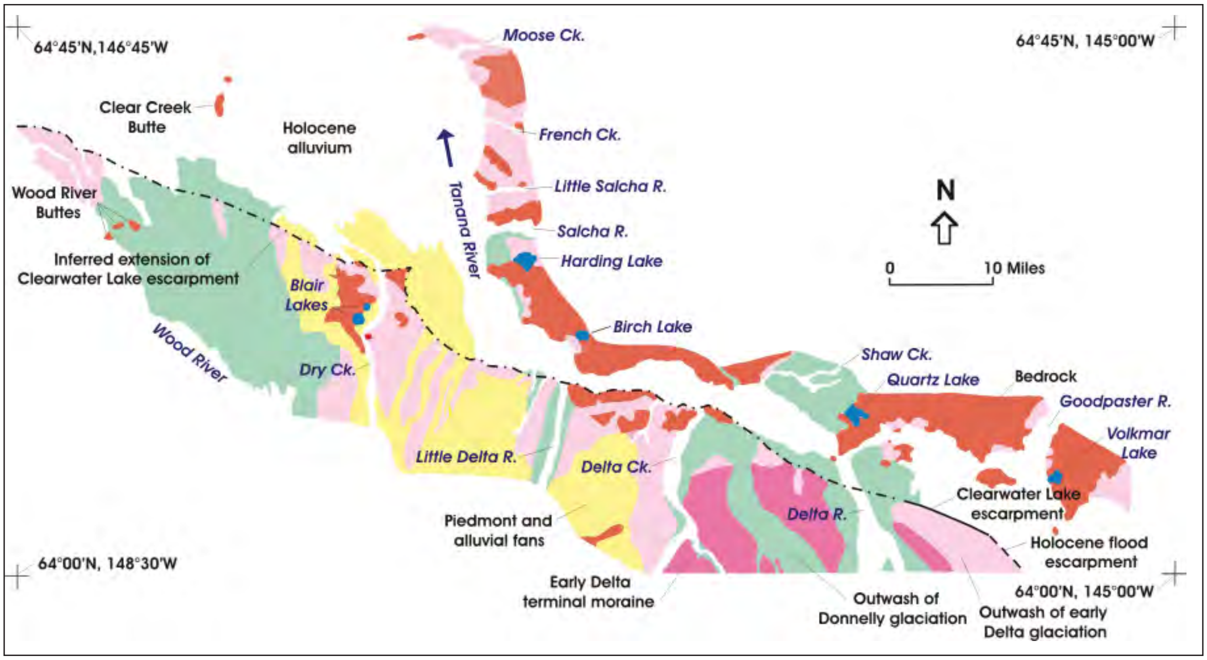

Figure 37. Inferred westward extension of Clearwater Lake escarpment across southern Tanana River valley. Holocene alluvium includes active-floodplain, inactive-floodplain, and abandoned-floodplain deposits as well as low fluvial–terrace deposits.

RAMIFICATIONS

Numerous physiographic and stratigraphic features demonstrate that many large-magnitude paleofloods have occurred in the upper Tanana River valley. These events range in age from probable early Delta (OIS 6) through the Holocene. Although heavy vegetation and a paucity of extensive exposures seriously limited our observations, we conclude that, in general, flood sediments of late Pleistocene age are much more coarsely textured than sediments of Holocene floods and suggest that Tanana River valley floods flowed much faster, deeper, and wider during past glaciations. As a corollary, we also suggest that the largest floods of the Tanana River were jökulhlaups. This is a worldwide phenomenon (O'Connor and Costa, 2004), and the geologic ramifications are significant, although jökulhlaups of the magnitudes described in this report clearly do not currently occur in the Tanana River valley. Suddenly, the genesis of many physiographic features in the Tanana River valley is becoming clearer, allowing us to develop better models to be tested in the field. These models will allow us to better understand the complex events that ultimately produced the terraces of the Tanana River valley and their associated alluvium-dammed clearwater lakes. For example, we can postulate huge jökulhlaups breaking past glacial dams in the upper Tanana River valley (perhaps during the late Delta or early Wisconsin glaciation [OIS 4]), slicing off the proximal outwash apron of the type Delta terminal moraine to form the Clearwater Lake escarpment, and scouring a wide trough between the escarpment and the margin of the southern Yukon–Tanana Upland. Because the Delta River is graded to the Tanana River, the presence of this trough would initiate a cycle of downcutting in the lower Delta River and its tributaries. Locally, the Delta River would have eroded downward as it passed through the Delta terminal moraine and the lower Delta River valley would become incised. Tributaries, like Jarvis Creek, would also erode downward and headward, incising and extending their lower valleys. With the advance of ice in the Delta River valley during the subsequent Donnelly glaciation, outwash spread from the type Donnelly terminal moraine down the incised lower Delta River valley, partially filling the valley and building a huge fan that spread through the gap in the Delta terminal moraine into the flood-scoured trough, and eventually pinned the Tanana River against the Yukon–Tanana Upland (fig. 10). Because of the rise in local base level caused by the deposition of Donnelly outwash in the lower Delta River valley, tributary streams, like Jarvis Creek, consequently began to rapidly deposit alluvium in their incised lower valleys. Now we can begin to understand the complex events that produced at least 18 ft (5.5 m) of inset gravel fill under Delta Junction during the past 3,400 RC yr in the middle of a terrace of late Wisconsin age (Péwé and Reger, 1983a).

On a regional scale, this complex process almost certainly occurred, probably at different times during the late Pleistocene, all along the discontinuous scarp system eroded across huge piedmont fans almost to Nenana. In this model, we can appreciate the complex ramifications of flood-scoured troughs associated with flood-cut escarpments and their potential role in focusing post-flood deposition in the Tanana River valley.

MODERN HAZARDS

Our evaluation of the map area documents evidence for multiple past glaciations and for several huge outburst floods associated with former expanded glacial systems. However, these powerful geologic agents no longer directly threaten the upper Tanana River valley because glaciers have retreated to upper valleys outside the map area and flooding is associated with seasonal cyclonic storm cycles and the annual buildup of stream icings, not major outburst floods. Cold-weather flooding in the Delta Junction area results from damming of the braided Jarvis Creek floodplain by the buildup of stream icings (Reger and Péwé, 2002), and thick stream icings develop each winter on the broad, braided floodplains of the Gerstle River and the Johnson River. Seasonal flooding across the broad alluvial apron southeast of Delta Junction, which potentially threatens local agricultural developments, is managed by flood-control structures. From short, steep drainages on the flanks of mountainous uplands along the southern margin of the map area, cobble- and boulder-rich debris flows periodically clog small drainages, damage bridges, and inundate low sites along the Alaska Highway.

Widespread, shallow, and locally ice-rich permafrost presents a more insidious natural hazard on abandoned floodplains and low terraces of the Tanana River and in valleys in the southern Yukon–Tanana Upland (Reger and Solie, 2008). Elsewhere, perennially frozen ground is generally deep and is present in isolated masses that do not constrain surface developments.

Mapping and paleoseismic investigations of potential active faults in and near the western segment of the Alaska Highway corridor have documented evidence of multiple late Pleistocene and Holocene surface-faulting events on five faults (Carver and others, 2008a and b).The principal active fault in the corridor is the Dot "T" Johnson fault, a generally east-west-trending, south-dipping thrust fault that represents a major eastward extension of the Northern Foothills Fold and Thrust Belt (NFFTB) (Bemis and Wallace, 2007). Previously, the eastern-most recognized extension of the NFFTB was the Donnelly Dome fault. The west end of the Dot "T" Johnson fault is connected to the Donnelly Dome fault by the northeast-trending, left-oblique-slip Granite Mountain and Panoramic faults. In the western half of the corridor, the Dot "T" Johnson thrust fault consists of two left-stepping segments, the Granite Mountain segment (sheet 1) and the Dot Lake segment (sheet 2). The two segments are separated by the northeast-trending, left-oblique-slip Canteen fault. The Dot "T" Johnson fault structurally defines the tectonically active northern margin of the Alaska Range foothills in the upper Tanana River valley.

Trenches across the Dot "T" Johnson thrust and the Canteen fault exposed evidence of repeated surface ruptures during the latest Pleistocene and Holocene (Carver and others, 2008a and b). The paleoseismic evidence shows the Dot "T" Johnson fault is a previously unrecognized source of large earthquakes in close proximity to the corridor. The fault constitutes a potential surface-faulting hazard and has the potential to generate strong shaking in the corridor (Carver and others, 2008a). Such earthquakes would likely trigger slope failures in the mountains and along river bluffs and cause significant liquefaction in susceptible sediments. Liquefaction is likely to be particularly widespread and severe in the upper Tanana River valley because of proximity to the fault and the abundance of liquefiable sediments (Reger and Solie, in press).

Several moderate to large bedrock failures were identified in mountainous terrain in the map area, but these instabilities generally do not threaten lowlands that are likely to be developed.

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