SURFICIAL GEOLOGY OF MOUNT MOOSILAUKE 7.5-MINUTE QUADRANGLE, GRAFTON COUNTY, NEW HAMPSHIRE

by

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INTRODUCTION

This report describes the surficial geology and Quaternary history of the Mount Moosilauke 7.5-minute quadrangle in the White Mountains of northern New Hampshire. Surficial deposits include unconsolidated glacial and non-glacial sediments, such as clay, silt, sand, gravel (pebbles to boulders). Nearly all these sediments were deposited during and after the late Wisconsinan glaciation, which began about 25,000 years ago. Surficial sediments cover bedrock over much of the quadrangle, especially on valley floors where the deposits have various land uses, including aggregate extraction, groundwater supply and protection, waste disposal, building sites, and agriculture. The field work and map compilation for this study were carried out by the authors in support of the STATEMAP cooperative between the New Hampshire Geological Survey and the U.S. Geological Survey (USGS). The geologic map accompanying this report shows the distribution, age, composition, and origin of sedimentary units. This map, along with mapping and research done by others in the White Mountains, provides the basis for the discussion of glacial and postglacial geologic history described below. Maps and map pamphlets can be accessed at the New Hampshire Geological Survey (www.des.nh.gov/land/geology).

Geographic setting. The Mount Moosilauke 7.5-minute quadrangle is in the western White Mountains. The map area extends in latitude from 44º00'00" to 44º07'30" N, and in longitude from 71º45'00" to 71º52'30" W. The quadrangle encompasses parts of the towns of Lincoln, Easton, Landaff, Woodstock, and Benton. Most of the quadrangle lies within the White Mountain National Forest, with a small area in the south-central part on Mount Moosilauke owned by Dartmouth College. Limited residential development is mainly in the upper part of the Wild Ammonoosuc River drainage area.

The quadrangle lies entirely in the Connecticut River and the Pemigewasset River drainage basins. Three major drainage divides from north to south occur between Ham Branch and Mud Pond "North" at about 1320 feet above sea level (a.s.l.), the Wild Ammonoosuc and Lost River at about 1870 feet a.s.l., and between Tunnel Brook and Slide Brook at about 2290 feet a.s.l. Tributary streams going counterclockwise in the map area include: 1) in the northeast Ham Branch and Reel Brook drain to the north and join Gale River that flows to the Connecticut River; 2) in the northwest Bowen Brook, Dearth Brook, Davis Brook, and an unnamed brook that originates at Mud Pond "North" all drain into the Wild Ammonoosuc River, which flows west to the Connecticut River; 3) in the west Little Tunnel Brook joins Tunnel Brook, which originates at Mud Pond "South" and drains to the north into the upper Wild Ammonoosuc River; 4) in the southwest, Jeffers Brook and Still Brook drain into Slide Brook, which in turn makes it way to the Connecticut River via Oliverian Brook; 5) in the south-central Gorge Brook joins the

Baker River, which originates in Jobildunk Ravine and flows south and southeast to the Pemigewasset River; 6) in the southeast Walker Brook joins Lost River, which originates in Kinsman Notch and flows east to the Pemigewasset River; 7) in the east Gordon Pond Brook flows east to the Pemigewasset River; and 8) in the east-central Beaver Brook, Stark Falls Brook, Olesons Brook, Stony Brook, Underhill Brook, Clay Brook, and Black Brook flow into the upper Wild Ammonoosuc River. Other than the two Mud Ponds, there are only two other small ponds in the quadrangle, Beaver Pond, a dammed water body in a former beaver meadow in Kinsman Notch, and Gordon Pond along the east-central border high on Kinsman ridge.

The topography of the Mount Moosilauke quadrangle is hilly to mountainous, with Mount Moosilauke in the south-central part of the area the most dominant landform. At 4802 ft, Mount Moosilauke is the 10th tallest and 3rd most prominent peak (behind only Mount Washington and Mount Lafayette) in New Hampshire. The lowest elevation in the quadrangle lies between 980 and 1000 feet on the upper Wild Ammonoosuc River in Landaff along the western border. The Appalachian Trail traverses the quadrangle from the southwest to the northeast, passing over Mount Moosilauke, dropping down to Kinsman Notch at 1870 feet (the fourth most prominent glacial U-shaped valley in the White Mountains), and climbing along Kinsman Ridge over Mount Wolf between 3480 and 3520 ft. One of the most exciting tourist attractions in the White Mountains is the Lost River Reservation in Kinsman Notch, which owes its popularity to glacial meltwater stream-carved underground caverns and potholes now made accessible by boardwalks and ladders. Above lie the steep Dilly Cliffs, made more unstable since ravaged by a wildfire in late 2017.

Bedrock geology. Bedrock includes a complex assortment of metasedimentary and metavolcanic rocks of Ordovician to Devonian age, intrusive igneous rocks of the Ordovician Oliverian Plutonic Suite, and the Devonian New Hampshire Plutonic Suite (Lyons et al., 1997). Quaternary sediments cover much of the bedrock at lower elevations in the Mount Moosilauke quadrangle except in larger stream beds and along road cuts on Routes 112 and 116. Outcrops are scarce to absent on much of Mount Moosilauke, except along ridgelines, eroded trails, deeper brook valleys, local slides, and in southeast-facing ledges and cliffs. Many of the smaller brooks, and even Baker River southeast of the mountain, are filled with boulders derived from the glacial till. Outcrops are also absent in much of the northwestern portion of the quadrangle, in a streamlined area of thick till that extends southeastward across the Wild Ammonoosuc River valley. New bedrock mapping of the Moosilauke quadrangle was done by Thompson (2022), which can be accessed at the New Hampshire Geological Survey (www.des.nh.gov/land/geology).

PREVIOUS WORK

Very little large-scale or detailed surficial geologic mapping has been conducted previously in Mount Moosilauke quadrangle other than broad-scale surficial mapping of the Connecticut River watershed (Lougee, 1939) and the entire state (Goldthwait et al., 1951). Haselton (1975) and Davis (1999) characterized four cirques on Mount Moosilauke, Spear (1989) radiocarbon-dated and constructed a post-glacial pollen diagram from a sediment core recovered at Deer Lake bog on Mount Moosilauke, and Sturtevant (2014) and Geier (2021) used LiDAR and GIS tools to map contour-parallel benches flanking the east side of Mount Moosilauke. A regional aquifer study by Flanagan (1996) provides helpful information on the sand and gravel deposits. Information on glacial and postglacial geomorphology was also derived from Google Earth and LiDAR imagery supplied by the New Hampshire Geological Survey (NHGS).

Detailed surficial mapping of adjacent areas has been carried out by Hildreth (2013) in the Woodstock quadrangle to the southeast, by Fowler (2013a) in the Franconia quadrangle to the northeast, by Fowler (1913b) in the Lincoln quadrangle to the east, and by Thompson (2014) in the Sugar Hill quadrangle to the north. Surficial mapping in nearby areas of the White Mountains to the northeast has been useful for comparison: Nelson and Thompson (1998) in the Littleton quadrangle, Hildreth (2002) in the South Twin quadrangle, Fowler (2010) in the Mount Washington quadrangle, Fowler (2012) in the Carter Dome quadrangle, Fowler and Barker (2015) in the Mount Dartmouth quadrangle, and Thompson (2016) in the Mount Jefferson quadrangle. Also, much has been written about the moraines and glacial-lake deposits of the Ammonoosuc River basin in the Littleton-Bethlehem area, which have been studied by many workers since the mid-1800s (Thompson, 1999; Thompson et al., 1999).

DESCRIPTION OF GEOLOGIC MAP UNITS

Classification of surficial deposits represented on the geologic map are based on their age and origin. Map units are designated by letter symbol (such as "Qt”), with the first letter indicating the age of the unit (i.e., "Q" for the Quaternary, which encompasses both the Pleistocene and Holocene epochs), and the second letter indicating the type of sediment in the unit (i.e., “t” for till). Surficial map units in the Mount Moosilauke quadrangle are described below. These unit descriptions are expanded and modified from those used by Woodrow Thompson for the adjacent Sugar Hill 7.5-minute quadrangle to the north.

Artificial fill (unit af)

Areas of constructed fills, burrow excavations, debris dumps, and railroad embankments related to historic logging activities, with most too small to be individually mapped.

Stream alluvium (unit Qal)

Unit Qal consists of alluvial gravel, sand, silt, and organic material deposited by late-glacial to modern streams. Sediment textures vary widely depending on the local depositional environment.

Alluvial fan deposits (units Qf, Qfo)

Alluvial fans (Qf) commonly form in mountainous areas where steep upland streams discharge into more gently sloped, larger valleys. The abrupt decrease in stream gradient at the mouths of these streams causes at least the coarsest part of their sediment loads to be deposited. Fans typically consist of very coarse gravel, although diamicts may also be present locally from the deposition of debris flows. Fans commonly overlap with one another as base levels dropped over time. The unit Qfo is used for older alluvial fans. Extreme precipitation events likely caused fans to begin forming immediately after deglaciation before vegetation took hold to become a stabilizing influence on steep slopes. There is also evidence in many areas of the quadrangle that fan growth continues to the present, especially in places with active debris flows that replenish the fans, such as in Tunnel Brook valley.

Wetland deposits (unit Qw)

Unit Qw consists of fine-grained and organic-rich sediments deposited in low, flat, poorly drained areas located along streams and several upland areas, such as Gordon Pond near the eastern boundary. Wetland deposits may overlie stream alluvium, stream terraces, alluvial fans, and till. Many wetlands occupy the floor of Tunnel Brook valley, and a large wetland overlies the Tunnel Brook fan near the confluence of Wild Ammonoosuc River, all of which are not differentiated from their underlying units to emphasize the subsurface geology. Additional wetlands adjacent to Wild Ammonoosuc River were consolidated within the stream alluvium unit (Qal). Several large upland wetlands occur between Bowen Brook and Rte 116, one of which is enclosed by a till ridge currently interpreted as a moraine. Wetlands were modified from the LiDAR-derived National Wetland Inventory Plus (NWIPlus), which remains the authoritative source for wetlands.

Landslide deposits (Qls)

Landslide is a generic term (Varnes, 1978) covering a wide variety of mass movement landforms and processes involving moderately rapid to rapid downslope transport by means of gravity. The unit consists of slide blocks, slumps, debris flow tracks, and minor rockfall deposits composed of poorly sorted diamicton, rock fragments, and colluvium that may still be subject to downslope movement, soil creep, or mass wasting. Most landslides in the White Mountains are debris flows triggered by extreme precipitation events upon already oversaturated soils and rock debris on slopes. Debris tracks commonly consist of a scarp, trough, and levees on the sides of the trough, and fans and debris-flow toe lobes in the runout zone. Many debris flow tracks are sites of recurring events, which in a few locations may be radiocarbon-dated from clastic lenses identified in lake sediment cores at the base of the tracks, such as at Profile Lake in Franconia Notch (Davis et al., 2019). Some slopes in the Mount Moosilauke quadrangle consist of many debris flow tracks in places overlapping with one another so that mapping the tracks individually is difficult. For example, on the north-facing slope of Gorge Brook ravine in the southwestern part of the quadrangle debris flows are lumped together as broad units of Qls. Historical photographic records show that many debris flow tracks have remained active to the present day. Rockfall is included at the most rapid end of the landslide spectrum (Varnes, 1978) and typically forms talus slopes at the base of cliffs, which in the Mount Moosilauke quadrangle are mapped as Qc (colluvium).

Colluvium (unit Qc)

Colluvium in the Mount Moosilauke quadrangle is reserved for loose, heterogeneous, incoherent angular blocks deposited by mass wasting at the base of bedrock cliffs. These features are also known as talus slopes and the most prominent example in the Mount Moosilauke quadrangle occurs at the foot of the Dilly Cliffs in Kinsman Notch.

Stream terrace deposits (unit Qst)

Stream terraces in the Mount Moosilauke quadrangle are remnants of past flood plains that have been left perched on valley sides at various levels as streams eroded down to their modern levels. These flat-topped deposits consist mostly of sand and gravel that was reworked from older glacial sediments. Prominent stream terraces occur along the upper Wild Ammonoosuc River and its tributaries, including Tunnel Brook.

Ice-contact stratified deposits (Qic)

Sand and gravel ice-contact deposits include a wide variety of landforms, including eskers, kame terraces, kettles, glacial lake sediments, and ice-contact deltas. These sediments were laid down by glacial meltwater streams between the valley walls and receding ice tongues in valleys. Ice-contact sediments are better sorted and stratified than till, and the particles are more rounded than particles found in till. Because of their unique topographic character, eskers and glacial lakes are broken out from Qic and mapped separately as units Qge and Ql.

Esker deposits (unit Qge)

The classic definition of an esker is a long, narrow, sinuous ridge composed of well-sorted and well-stratified sand and gravel deposited in ice-walled tunnels at the base of a glacier. In the Mount Moosilauke quadrangle, eskers are limited to segments, such as a prominent ridge about 0.5 mi long and 50 feet high just northeast of the junction of Rte 112 and Rte 116 in which a sand and gravel pit was active until recently. The subglacial stream that formed this esker segment presumably flowed southward along the valley, toward where the ice margin stood. This esker originally was likely much longer, with parts of it having been removed by postglacial erosion. Other esker segments occur just south of Mud Pond "North" near Rte 116 and just north of Mud Pond "South" in Tunnel Brook valley.

Glacial-lake deposits (unit Ql)

Other than glacial Lake Franconia in the north, large glacial lakes did not extend into the Mount Moosilauke quadrangle. However, laminated clay sediments at ~2000-ft elevation in Little Tunnel Brook ravine and at ~1500 ft near the north end of Tunnel Brook valley required ponding of a small bodies of water by receding continental ice in the upper Wild Ammonoosuc valley. These elevations correlate to other ice contact deposits elsewhere in the area. Another small glaciolacustrine area is mapped on a flat bench at 1180-ft elevation near the confluence of Bowen Brook and the Wild Ammonoosuc River. Sediments there are composed of well-sorted fine sand and silt to ~1.4 m depth with rare cobbles. There may be other small areas in the quadrangle where glacial-lake deposits lie buried underneath overlying sediments.

Block Fields (Felsenmeer) (unit Qbf)

Also known as felsenmeer (Rapp, 1960), block fields are a continuous veneer of large angular to subangular blocks of rock derived from underlying bedrock by intensive frost action in flat or gently sloping areas. Two prominent black fields occur at about 4250-ft elevation on the south side of the Glencliff Trail below the south summit of Mount Moosilauke and between about 4400-ft and 4600-ft elevation on the northwest side of Mount Moosilauke between the summit and tree line.

Till (map units Qt and Qtt)

Till is a diamicton commonly described as non-stratified sediment carried or deposited by a glacier. Till is usually unsorted with grain sizes ranging from clay and silt to sand and gravel to cobbles and boulders. Till is mapped as Qt and is the most widespread surficial deposit in the Mount Moosilauke quadrangle and blankets hills and sides of large mountains in the quadrangle. The geologic map indicates areas where bedrock outcrops are common and/or the till thickness is inferred to be less than 10 feet (3 m) with the unit Qtt, typically on mountain tops. Water well logs in the quadrangle show that till commonly lies beneath younger water-laid sediments in valleys.

Exposures of till in the Mount Moosilauke quadrangle include shallow cuts created along roadways and logging roads and deeper cuts from slumped banks along streams triggered during extreme precipitation events, such as those in late August 2011 and late October 2015. In a few places, borrow pits and excavations along logging roads have revealed up to 20 feet (6 m) of till, and the buried thickness may be much greater beneath some of the lower valley sides. Till in the Mount Moosilauke quadrangle has a dominantly sandy or silty-sandy matrix because it was derived from coarse-grained crystalline bedrock. In some exposed sections, till is interbedded with discontinuous sorted and stratified sediments deposited by meltwater.

Much of the till observed in the Mount Moosilauke area is ablation till, which is formed during the melting of glacier ice in unstable sedimentary environments where slumping and meltwater flow are common. Ablation till includes many subtypes including flow till (Hartshorn, 1958). Ablation till is typically loosely textured with intercalated lenses of water-laid sediment common, but rarely clay-size particles. In contrast, lodgment till is compact with a fissile structure and is difficult to excavate because it was compressed at the base of a thick ice sheet. Lodgment till is present at depth in the quadrangle and was found in a few deep cutbanks along streams, including in Tunnel Brook and Reel Brook valleys.

Stones are abundant in till, with faceted and striated clasts being the diagnostic indication of deposition directly from ice. Faceted and striated clasts are primarily found within lodgment till exposures in the quadrangle. Many till stones are composed of rock types that require long-distant transport, therefore are considered erratics and evidence for deposition by glacial ice. Examples of erratics include rounded cobbles of the Clough Quartzite and large boulders of Bethlehem Gneiss and Kinsman Granodiorite.

Ablation till and lodgment till should not be confused with the “upper till” and “lower till” as described in many parts of New England, as these two terms refer to glacial deposits of different age (Koteff and Pessl, 1985; Thompson and Borns, 1985; Weddle et al., 1989). The “upper till” was deposited during the late Wisconsinan glaciation of the Laurentide Ice Sheet about 25,000 to 13,000 years ago, also known as Marine Isotope Stage 2 (MIS-2). The “lower till” was deposited earlier, presumably during the Illinoian glaciation over 130,000 years ago (MIS-6). The “upper till” is not as oxidized and as compact as the “lower till,” which has been taken to indicate the relative age difference. Although the “upper till” is ubiquitous in the Mount Moosilauke quadrangle, some of the exposures of lodgment till in deep stream cuts cannot be ruled out as “lower till.”

Moraines (unit Qm)

Unlike the till benches that are described above and are ubiquitous on the flanks of Mount Moosilauke, moraines are rare in the Mount Moosilauke quadrangle. Although moraines are not found in any of the cirques on Mount Moosilauke, several moraine segments that lie in the northwestern part of the quadrangle likely represent a stillstand or a slight readvance of the receding continental ice margin. Notable examples of moraines lie across Rte 116 north, south, and west of Mud Pond "North," with one segment in particular being the steepest-sloped, most sharply-crested, and highest-relief moraine that the authors have seen anywhere in the White Mountains.

GLACIAL AND POSTGLACIAL GEOLOGIC HISTORY

The following reconstruction of the Quaternary history of the Mount Moosilauke quadrangle is based on the authors' interpretations of surficial earth materials described in this report, as well as topographic features in the study area, and the sequence and chronology of deglaciation recorded in neighboring quadrangles to the north and east. The co-authors do not agree on all interpretations.

The most recent (late Wisconsinan) glaciation began about 25,000 years ago, when the Laurentide Ice Sheet in Canada spread southward across New England (Stone and Borns, 1986). The late Wisconsinan continental ice sheet covered the highest summits in the White Mountains, including Mount Washington (Antevs, 1932; J.W. Goldthwait, 1925; R.P. Goldthwait, 1938, 1940; Bierman et al., 2015; Koester et al., 2021) and Mount Moosilauke. The ice sheet produced the stony till deposits that blanket large areas of the quadrangle. Rocks pried loose from the hills were scattered in the direction of glacial transport.

Abrasion by rock debris dragged at the base of the glacier polished and striated the bedrock surface. In many places striae are not evident because they are either concealed beneath surficial sediments or have been destroyed by bedrock weathering. The geologic map shows sites in the quadrangle where striae trends have been recorded. Most striae data came from bedrock surfaces recently exposed by erosion on hiking trails, along stream cuts, on ledges along roadsides, and on landslide scars. Glacial striations and grooves also can be seen more easily on wet surfaces soaked by recent rain or even bottled water.

Striae data from the Mount Moosilauke quadrangle usually indicate glacial flow toward the south-southeast, such as seen near the summit of Mount Moosilauke (Fig. 1). This ice flow primarily occurred during the maximum phase of late Wisconsinan glaciation, when glacially streamlined hills in the area were sculpted with the same orientation. Within the continental ice sheet, faster moving ice streams were likely responsible for a large part of the erosion of U-shaped valleys, known as "notches" in the White Mountains (Eusden et al., 2013; Fame et al., 2019). Kinsman Notch is the most prominent U-shaped valley in the Mount Moosilauke quadrangle and exhibits a glacial erosional form known as a roche moutonnée on its floor as seen protruding above the water line in Beaver Pond (Fig. 2). Tunnel Brook valley is also a classic U-shaped glacial valley and not accessible by motorized vehicles. Sites were not found with multiple striae directions that might indicate a shift in ice flow from a glacial readvance such as seen in the Sugar Hill quadrangle to the north (Thompson, 2014).

The time of glacial recession from the Mount Moosilauke quadrangle can be estimated from ^{14}C dating, ^{10}Be exposure dating, and correlation of sequences of annual clay layers (varves) deposited in glacial Lake Hitchcock in the Connecticut River valley (Antevs, 1922; Ridge et al., 2012). The recession of the Laurentide Ice Sheet would have simultaneously produced ice surface lowering and recession of its margin as mountains became nunataks. In the rugged terrain of the White Mountains, the configuration of the ice margin probably was very irregular, with tongues of still-active ice in some of the valleys when nearby mountain peaks had already emerged from the ice sheet. Block fields (felsenmeer, Fig. 3) began to form on flat areas and gentle slopes adjacent to the ice as the margin lowered downslope. A radiocarbon age of 13,000 +/-400 yr BP (15,514 cal yr BP, median probability, Calib v.8.2, Reimer et al. 2020) was obtained from the 4.63-4.88 m depth of a sediment core recovered from Deer Lake bog (44º 02' N, 71º 19' W, 4350 ft elevation) in the col between Mount Moosilauke and Mount Blue (Spear, 1989). The Deer Lake bog ^{14}C age accords with the North American Varve Chronology (Ridge et al., 2012), which shows that continental ice receded from the study area shortly before 14,000 years ago. The Deer Lake bog ^{14}C age also fits with rapid regional lowering of the continental ice surface centered about 14,300 years ago as determined by ^{10}Be exposure dating of glacial boulders and bedrock surfaces along elevational transects (glacial dipsticks) in the northern New England area (Corbett et al., 2019; Koester et al., 2021; Halsted et al., in press). Although crystalline erratic boulders are abundant on Mount Moosilauke (Fig. 4), the massif was unfortunately not targeted as a glacial dipstick location for ^{10}Be exposure dating.

The paucity of end moraines in the Mount Moosilauke quadrangle hinders detailed reconstruction of the pattern of continental deglaciation, although a spectacular example of a high-relief moraine ridge occurs just southeast of Mud Pond "North" (Fig. 5). The lack of moraines in the cirques on Mount Moosilauke, such as Jobildunk Ravine (Fig. 6), strongly suggests that the cirques were carved before the last overriding of the Laurentide ice sheet and were not sites of local glaciers following deglaciation of the ice sheet (Haselton, 1975; Davis, 1999), which accords with a rapid rise in equilibrium-line altitudes as climate warmed and the ice sheet surface rapidly lowered. The identification of Little Tunnel Brook ravine as a cirque by Haselton (1975) and Davis (1999) has been rejected for this map because its schrund elevation would be implausibly too low paleoclimatically.

Glacial Lake Franconia

During deglaciation, Lake Franconia filled behind the Mud Lake "North" spillway and Mud Pond moraine and backed up into the Sugar Hill quadrangle to the north (Thompson, 2014). The spillway is interpreted to have been initiated subglacially (pers. comm. W.B. Thompson, 2022), which is corroborated by the esker within the lake's interpreted extent. Subglacial drainage continued to the west down the Wild Ammonoosuc River, which must have accumulated to a significant discharge by the time the flow reached the western edge of the quadrangle where a large meandering meltwater channel widens beyond what the Wild Ammonoosuc River can competently fill.

Ice-contact Deposits

As continental ice continued to recede from higher elevations, glacial meltwater deposited stratified and well-sorted sand and gravel sediments. In the upper Wild Ammonoosuc and its tributaries, as well as Reel Brook in the northeastern part of the quadrangle, ice-contact sediments are found in several locations between 1180-ft and 2350-feet elevation, with most occurring between 1870-ft and 2050-ft elevation. The most prominent ice-contact kame terraces at 1870-ft elevation appear in Tunnel Brook, Clay Brook, Reel Brook, and the headwaters of the Wild Ammonoosuc River. On the north side of Kinsman Notch, at 1870-ft elevation and higher, is an elongated stretch of boulder-free benches composed of well-sorted sand and gravel that are interpreted to be a kame terrace. The correlation of disparate deposits across current watersheds at the 1870-ft elevation suggests that ice ponded on the northwestern side of Kinsman Notch around the location of Beaver Pond and formed a relatively flat ice surface in the upper Wild Ammonoosuc valley and tributaries as well as into the Reel Brook drainage.

Ice-contact deposits at the 2000-ft to 2050-ft elevations are represented by both Qic and Ql units in Tunnel Brook, Little Tunnel Brook, and Reel Brook valleys. An outlying cluster of down-stepping ice-contact deltas that occur immediately west of Slide Brook are the highest, from 2350-ft to 2050-ft elevation. These kettled deposits mark marginal positions as the continental ice surface lowered in the area.

Many of the ice-contact deposits on hillslopes between 1870-ft and 1640-ft elevations on the flanks of Moosilauke and in the Reel Brook drainage are flat-topped kame terraces composed of fine-grained immature sand. These deposits then grade downslope into esker-like landforms suggestive of subglacial deposition adjacent to the kame in an area of increased meltwater flow. Many of these hillslope ice-contact sediments are sourced primarily from the underlying bedrock, suggested by an overabundance of grains composed of dark gray schist and volcanic rocks derived from the Littleton Formation.

At the mouth of Tunnel Brook, at 1460-ft and at 1380-1320-ft elevations, near the apex of an alluvial fan, are stratified drift deposits that mark at least two down-stepping ice margins. The thickest exposed section of these sediments (25 vertical feet) is along the west side of Tunnel Brook, recently exposed by bank failure due to Tropical Storm Irene during late August 2011. At this site, the 25-foot-thick unit of ice-contact stratified sands and gravels overlies a 50-foot-thick section of till, which includes intercalated flow till that appears to have some stratification (Fig. 7). The deposit here at the 1320-ft elevation is the same elevation as the Mud Pond “North” spillway, which raises a question of timing. If the ice level was somewhat horizontal as it lowered, then ice may have persisted in Wild Ammonoosuc River valley when the lake drained, causing meltwater to flow back under the ice and run subglacially down Wild Ammonoosuc River valley. In support of abundant subglacial meltwater is a large, westerly-widening, meandering meltwater channel with 236 feet of relief on the western edge of the quadrangle where the Wild Ammonoosuc River still flows.

The lowest ice contact elevation (1190 ft) is represented by ice-contact glaciolacustrine sediments (Ql) adjacent to Bowen Brook, near the confluence of the Wild Ammonoosuc River. It is unclear whether the large meandering meltwater channel in the nearby Wild Ammonoosuc River formed before or after “glacial Lake Bowen.”

Correlation of some of these deposits at similar elevations across valleys and watersheds suggests deposition occurred in contact with a waning remnant of the continental ice sheet. The stepwise nature of the deposits suggests the ice sheet was lowered during punctuated episodes that were ubiquitous across the map area.

Synglacial Meltwater Channels

As the continental ice surface continued to lower, subglacial meltwater deeply eroded bedrock in the upper Wild Ammonoosuc valley and the upper Lost River valley, where the latter hosts a popular tourist attraction with subterranean caverns and potholes. Subglacial meltwater also deposited sand and gravel sediments in the form of eskers, with remnants occurring near the junction of Rte 112 and Rte 116, just south of Mud Pond "North," and in Tunnel Brook valley, just north of Mud Pond "South" (Fig. 8). A few areas in the quadrangle reveal locations and slopes of meltwater channels carved on hillsides by glacial streams that generally support a northward recession of the ice margin.

Meltwater channels eroded into till are abundant across the quadrangle and are exhibited by wide-banked channels, dry or wet, that often have concave-up channel bottoms that lack the typical floodplain and stream terrace morphology that modern streams have. Many have been occupied by current streams, which may or may not have deposited alluvial sediments. Most channels are perpendicular to contours and flowed downslope during deglaciation. A few noteworthy meltwater channels carved slope-parallel channels near ice contact deposits. Some appear as segments, appearing and disappearing across the till surface. Between 1800-ft and 1900-ft elevations, high above the western bank of Tunnel Brook and immediately west of the Little Tunnel Brook fan, are two slope-parallel meltwater channels that end at apexes of ice-contact deltas. The channels are short and appear seemingly out of nowhere, turn abruptly, deposit ice-contact material, then disappear. These features have been called in-and-out channels by Mannerfelt (1945) and Syverson and Mickelson (2009) and are interpreted to have formed from meltwater that flowed off the glacier to erode the till surface then flowed back onto or into the glacier. These in-and-out-channels along with their associated ice-contact deposits mark temporary ice margins as shown on the map. The other occurrence of ice-marginal slope-parallel channels is in the very southwest corner of the map on both sides of Still Brook. In this area, an ice-marginal channel was carved into till grading from 1800-ft to 1900-ft elevation. Then the channel was dissected by younger meltwater and modern stream flow to leave abandoned segments. A series of down-stepping ice marginal channels parallel to this one continues to the southwest in the East Haverhill, Warren, and Mount Kineo quadrangles to the west, southwest, and south, respectively.

Till Benches

Two main styles of till benches are found in the map area, with both following contours with little elevation change across drainages for thousands of feet.

The first style of till bench is best represented on nearly all flanks of Mount Moosilauke, where LiDAR reveals dozens of subparallel, curvilinear, step-like, and commonly flat-topped topographic features that contour slopes (Fig. 9). About 50 to 60 benches extend from near the summit down to about 2200-ft elevation, well below Ravine Lodge in the Mount Kineo quadrangle. The benches range in height from 2 to 35 ft with an average spacing of 212 linear feet (n = 60). Many segments of these till benches are parallel to contours and the segments can be traced for thousands of feet with little elevation change across drainages and even across the floor and walls of Jobildunk Ravine, the best developed cirque on the mountain. However, some benches cut across contours and overlap other benches, with lobes falling and rising with elevation differences of up to 50 feet.

The authors field-verified that the benches on Mount Moosilauke are more-or-less flat-surfaced, rather than ridge forms with backslopes. Thus, these till benches were not created by rotational slumps or glacial readvances against the mountainsides. Growing on the benches are approximately 100-year-old trees that show bowed trunks in the downslope direction, indicating that these features show a present-day mass wasting component (Figs. 10-11). The bowing of the tree trunks is likely the result of soil creep and appears to increase toward the lower parts of the benches that are commonly over-steepened by logging skid paths, which took advantage of the relatively flat surfaces on the bench tops.

On Mount Mansfield in northern Vermont, similar bench-like features have been mapped as recessional moraines by Wright (2018, 2019) and were proposed to be formed annually as the rapidly lowering ice sheet readvanced slightly during winter (Wright, 2019; Corbett et al., 2019). The first author of this report was a co-author on the Corbett et al. (2019) paper but does not think that there is enough supporting evidence that these features on Mount Mansfield are moraines, although is open to the possibility for the features being formed annually. Besides Mount Mansfield, LiDAR reveals similar contour-parallel features on other mountain slopes in northern New England. The formation of these till benches likely occurred throughout the White Mountains as the ice sheet surface lowered and broadened summit areas as enlarging nunataks.

Following LiDAR analysis of Mount Moosilauke, Sturtevant (2014) initially interpreted these bench features as De Geer moraines (Bouvier et al., 2015; Sinclair et al., 2018), but then later in a thesis addendum concluded that the features are best defined as gelifluction lobes, created by a type of soil creep in persistent frozen conditions, or permafrost. Geier (2021), after similar LiDAR analysis, concluded that the till benches on Mount Moosilauke are solifluction lobes, produced in temperate climates by freeze-thaw action. The second and third co-authors of this report agree that the few lobate benches that do not form flat-topped surfaces may have been formed in part by solifluction. The first author believes that these looped bench segments seen on LiDAR are the result of differential slumping against the ice margin, which likely receded unevenly at times. All authors interpret that soil creep has modified the surfaces of the benches. The authors plan to examine some of the looped bench segments in the field together sometime, although all are cognizant of the difficulties with field interpretations on the heavily forested slopes.

Based on an extensive literature review (Washburn, 1956, 1973, 1980; Rapp, 1960, Hamelin and Cook 1967; Benedict, 1970, 1976, Embleton and King), the first author does not agree with Sturtevant (2014), Geier (2021) that the till benches are characteristic of solifluction. Nearly all the till benches parallel the slopes on contour and are linear in extent rather than lobate. Typical solifluction lobes described with diagrams and photographs in the literature are elongated upslope and have an order of magnitude less width than the even the shortest segments of the till benches on Mount Moosilauke. Solifluction lobes also have been described as having frontal ridges and central depressions (Verpaelst et al., 2017), which are absent on the benches on Mount Moosilauke.

If solifluction is not the primary process involved with formation of the till benches, an alternative depositional model is required for their formation. Slope materials were no doubt initially unstable as the ice sheet margin lowered, and till deposited earlier on slopes above the receding margin was likely mobile and readily transported downslope by meteoric water to bank up against the ice and infill troughs. Concurrently glacial debris likely sloughed off the ice surface and was transported by meltwater to mix with the till already there to provide additional fill to the troughs and form flat-topped or slightly sloping surfaces down slope. The sediments filling the troughs and forming these benches can be called flow till, as described by Hartshorn (1958). As the ice margin rapidly lowered, the till benches dewatered via breaches separating the linear segments that quickly became stabilized for the most part, except for a few places where LiDAR reveals bench surfaces that appear to overlap, which the first author believes represent translational debris slides or slumps (Varnes, 1978).

The second style of till bench is best exhibited by the unique benches near Clay and Black brooks in the Wildwood area. The upper bench at 1525-ft elevation between Clay and Black brooks is a subglacially formed bench formed by the ice sheet shearing off material, based on streamlined till on that surface. Immediately below this level is a bench between 1410-ft and 1475-ft elevations that persists for about 3000 feet distance. The bench follows the somewhat dendritic pattern of the nearby incised Clay and Black brooks and unnamed streams in the area, making the full length of the bench nearly 2 miles. These streams are interpreted to have initiated as subglacial channels due to their outsized extent compared the streamflow currently there, concave-up valley shape, and larger meander wavelength compared to the shorter meander wavelengths shown in Holocene alluvium (unmapped). It is interpreted that this bench represents an ice margin during a stillstand in deglaciation when ice remained at the 1410-ft and 1475-ft elevations for enough time to allow meltwater erosion to carve out the bench. The resulting half-pipe of a meltwater channel is asymmetrical because the other side was eroded into ice.

Mapping, Sampling, and Analyses

Routine geologic mapping was conducted across the quadrangle with the use of long-handle shovels, augers, and sharpshooter spades. The authors used hand-held GPS as well as GPS-aided iPads equipped with high-resolution LiDAR and aerial imagery. Data were collected using traditional field books and/or with the Field Maps mobile software from ESRI. The Thin Till map unit, composed of till less than 10-15ft thick, was delineated in large part by LiDAR visualization of landform texture and aided by a predictive model for bedrock outcrops and shallow soil by Fraser et al. (2020). Local ground truthing subsequently refined the map unit contacts.

The authors sampled with Jack Ridge an exposed 6-meter vertical section of silt/clay laminations separated by partings of fine sand on an east-facing, 30-degree slope at about 2000 feet elevation in Little Tunnel Brook (LTB) ravine (Fig. 12) that have similarities to varves (annual couplets of sediments deposited in glacial lakes). Similar exposures were excavated near the sampled location, and the combined occurrences suggest the laminated clay section is up to 80 feet thick. Preliminary paleomagnetic analyses of the oriented sediment samples by Ridge at his Tufts University laboratory are inconsistent in that some declination measurements suggest pre-late Wisconsinan deposition, whereas other measurements suggest deglacial deposition and some measurements appear to indicate post-depositional disturbance. Further paleomagnetic measurements are planned for the laminated clay section in LTB ravine to determine whether the sediments might have been deposited during MIS-3 as opposed to during late Wisconsinan deglaciation, as the latter should be correlative with the North American Varve Chronology (NAVC). Ridge does not think that the laminations at the LTB ravine site were deposited annually as were the rhythmites in glacial Lake Hitchcock that make up a large part of the NAVC (Ridge et al., 2012). However, the laminations in LTB ravine require ponded water that necessitates the presence of a receding ice mass in the upper Wild Ammonoosuc River drainage. Stream cutbanks along Tunnel Brook exposed by Tropical Storm Irene also reveal compact laminated clays and lodgment till at about 1500 feet elevation, which would be worthy of palemagnetic measurements to determine whether the sediments might date to the Illinoian glaciation (MIS-6).

Radiocarbon-dated wood from lake sediments in northern Maine (Anderson et al., 1988), OSL- and IRSL-dated cave sediments in northern Vermont (Munroe et al., 2016), and surface exposure dating with paired cosmogenic isotopes (^{10}Be and in situ ^{14}C) from the summit area of Mount Washington (Koester et al., 2020) together indicate that northern New England was free of continental ice between about 32,000 and 68,000 years ago (Davis et al., 2022), which is supported by radiocarbon-dated mollusks indicating that the St. Lawrence Lowlands were also free of ice about 34,000 years ago (Parent and Dubé-Loubert, 2017).

The authors have not yet been successful in locating a potential corroborating section of laminated sediments from 1840-ft to 1880-ft elevations in the Reel Brook valley observed by Brian Fowler while he was working for the New Hampshire Department of Transportation. Staff from New Hampshire Geological Survey scoured the southern banks of Reel Brook and the till hillside between 1700-ft and 2000-ft elevations and found compact clay-rich dark gray till with striated stones and gravel. However, taken together the till benches found primarily on the flanks of Mount Moosilauke, the clay laminations in Little Tunnel Brook ravine, the ice-contact deltas identified in many areas of the quadrangle, and the ice-contact sand and gravel deposits found in the upper Wild Ammonoosuc reveal a consistent pattern of deglaciation of the Mount Moosilauke quadrangle.

During and after deglaciation of the Moosilauke quadrangle, nonglacial streams began to establish their modern drainage patterns. As soon as the ice receded from the sides of these mountains, the freshly deposited glacial sediments were very susceptible to erosion until a vegetation cover was established. Much of the alluvial gravel and sand in the fan deposits probably formed at this time, along with the early stream alluvium. Older alluvium forms prominent terraces (Qst) that stand higher than the present-day flood plain along the upper Wild Ammonoosuc and its tributaries.

The most prominent post-glacial landforms in the Mount Moosilauke quadrangle are the extensive landslide tracks and deposits (Qls) that occur on steeper slopes. The landslide deposits were primarily the result of debris flows from extreme precipitation events as evidenced by the extensive levees parallel to the landslide tracks. Many landslide tracks have remained active with debris flows through the 1900s into the early 2000s as evidenced by historical photographs (pers. comm., Steven D. Smith) and Google Earth images. The most extensive post-glacial debris flow activity has occurred on the east-facing slope of Mount Clough above Tunnel Brook valley (Fig. 13) and on the north-facing slope in Gorge Brook ravine. However, debris flow tracks also remain active in Slide Ravine, Tunnel Brook ravine, and Little Tunnel Brook ravine on the west flanks of Mount Moosilauke.

Deposits of recent flood-plain alluvium (unit Qal) continue to accumulate along modern streams in the Mount Moosilauke quadrangle, and organic-rich sediments (unit Qw) are being deposited in small wetlands. Most of the alluvial sand and gravel transport along streams in the area presumably occurs when water levels are high during spring runoff or during floods caused by extreme precipitation events. The largest talus slope (Qc) lies at the base of the Dilly cliffs, along the north side of Rte 112 on the east side of Kinsman Notch (Fig. 14).

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Sand and gravel resources are found mainly in valley areas of the quadrangle, where they have been concentrated by glacial and postglacial deposition. Small pit operations occur in eskers formed in tributary valleys to the upper Wild Ammonoosuc River in the north-central part of the map area. Much of the sandy till with its silty-sandy matrix compacts well in applications where fill is needed in the quadrangle although has not been much exploited.

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FIGURES

Figure 1. Photograph looking northwest at glacial striae oriented N15W preserved in exposed metamorphic bedrock along the Gorge Brook Trail (4622-ft elevation, 44º 01.1402’ N, 71º 49.6205’ W).

Figure 2. Photograph looking east at roche moutonnée with up-ice, gentle slope facing N10W at Beaver Pond in Kinsman Notch (1858-ft elevation, 44^o 02.6000' N, 71^o 47.5891' W). Co-author for scale.

Figure 3. Photograph looking southeast across block field on south side of Glencliff Trail (4250-ft elevation, 44^{o} 00.7294' N, 71^{o} 50.5223' W).

Fig. 4. Large erratic crystalline boulders on the floor of Tunnel Brook valley just east of Mud Pond "South" (2320-ft elevation, 44º 1.1466' N, 71º 51.5770' W).

Fig. 5. Moraine ridge crest just southeast of Mud Pond "North" (1440-ft elevation, 44^o 6.66294' N, 71^o 48.7071' W).

Figure 6. Photograph looking northwest across the elongated floor to the headwall of Jobildunk ravine, the most prominent of three cirques on Mount Moosilauke.

Figure 7. Photograph looking west across Tunnel Brook along U.S. Forest Service Road 162 at 75-foot vertical exposed section of ice-contact stratified sand and gravel interbedded with till on the right and a large block of compact laminated clays at the left that indicates glaciofluvial transport from up valley (1255-ft elevation, 44º 5.10984’ N, 71º 49.95804’ W).

Figure 8. Photograph looking north with esker ridge on left and beaver swamp on right side of trail that was a former carriage road just north of Mud Pond "South" in Tunnel Brook valley (2265-ft elevation, 44^{o} 1.39452 N, 71^{o} 51.71322 W).

Figure 9. Photograph looking north along the top surface of one of dozens of sub-parallel, step-like, till benches that flank the east slopes of Mount Moosilauke. These benches are far more obvious on LiDAR images than they are on the ground, but loggers in the 1940s made good use of them for locating their skid paths, which also can be seen on LiDAR.

Figure 10. Photograph of a gently-front-sided till bench with tree trunks showing rotation at their bases due to active movement (creep) of the soil layer. Note that tree bowing appears more pronounced closer to the lower part of the bench.

Figure 11. Photograph, co-author for scale, of a steeply-front-sided till bench with tree trunks showing rotation at their bases due to active movement (creep) of the soil layer. Note that tree bowing appears more pronounced at the lower part of the bench that was undercut by construction of a skid path for logging in the 1940s.

Figure 12. Photograph looking west at exposed section of laminated clays with silt and sand partings in Little Tunnel Brook ravine (2000-ft elevation, 44º 03.3314' N, 71º 50.1438' W).

Figure 13. Photograph looking west from Slide Ravine toward the east-facing slopes of Mount Clough where at least nine separate historic debris flow tracks have been documented by Steven D. Smith (pers. comm., 2022).

Figure 14. Photograph looking northwest at the Dilly cliffs and talus slope along the north side of Rte 112 on the east side of Kinsman Notch.

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GLOSSARY OF TERMS

(updated and expanded from glossary originally compiled by John Gosse and Woodrow Thompson for the Maine Geological Survey mapping program)

Ablation till: till formed by release of sedimentary debris from melting glacial ice, accompanied by variable amounts of slumping and meltwater action. May be loose and stony, and contains lenses of washed sand and gravel.

Alluvial: refers to sediments or processes resulting from the action of running water, such as the alluvium found on river flood plains.

Alluvial fan: an accumulation of sediment typically deposited where a relatively steep upland stream enters a valley and the sudden decrease in stream gradient causes much of its load to be deposited. Often develops a fan-shaped outline as it spreads into the valley. Usually has a noticeable (gentle to moderately steep) surface slope and coarse gravelly sediments.

Block field: a continuous veneer of large angular to subangular blocks of rock derived from underlying bedrock by intensive frost action in flat or gently sloping areas (also known as felsenmeer).

Clast: pebble-, cobble-, or boulder-size fragment of rock or other material in a finer-grained matrix. Often refers to stones in glacial till or gravel.

Clast-supported: refers to sediment that consists mostly or entirely of clasts, generally with more than 40% clasts. Usually, the clasts are in contact with each other. For example, a well-sorted cobble gravel.

Colluvium: sedimentary debris on the lower slopes of hills and mountains. Results from slow downslope movement due to gravity, freeze-thaw action, etc., acting upon preexisting surficial sediments (derived from till in many cases, from which it may be hard to distinguish).

Delta: a body of sand and gravel deposited where a stream enters a lake or ocean and drops its sediment load. Glacially deposited deltas in New England usually consist of two parts: (1) coarse, horizontal, often gravelly topset beds deposited in stream channels on the flat delta top, and (2) underlying, finer-grained, inclined foreset beds deposited on the advancing delta front

Deposit: general term for any accumulation of sediment, rocks, or other earth materials.

Diamicton: any poorly-sorted sediment, containing a wide range of particle sizes (e.g., glacial till).

Drumlin: an elongate oval-shaped hill, often composed of glacial sediments, that has been shaped by the flow of glacial ice, such that its long axis is parallel to the direction of ice flow.

End moraine: a ridge of sediment deposited at the margin of a glacier. Usually consists of till and/or sand and gravel in various proportions and commonly simply called a “moraine.”

Englacial: occurring or formed within glacial ice.

Eolian: formed by wind action, such as a sand dune.

Esker: a ridge of sand and gravel deposited at least partly by meltwater flowing in a tunnel within or beneath glacial ice. Many ridges mapped as eskers include variable amounts of sediment deposited in narrow open channels or at the mouths of ice tunnels.

Fluvial: Formed by running water, for example by meltwater streams discharging from a glacier.

Glaciolacustrine / glacial-lacustrine: refers to sediments or processes involving a lake which received meltwater from glacial ice.

Glaciomarine / glacial-marine: refers to sediments and processes related to environments where marine water and glacial ice were in contact.

Head of outwash: same as outwash head.

Holocene: term for the period from 12,000 years ago to the present, commonly used synonymously with "postglacial" because most of New England has been free of glacial ice since that time.

Ice age: see Pleistocene.

Ice-contact: refers to any sedimentary deposit or other feature that formed adjacent to glacial ice. Many such deposits show irregular topography due to melting of the ice against which they were laid down and resulting collapse.

Ice-marginal bench: refers to sedimentary deposits like moraines but without a ridge form including a back slope and composed of till rather sand and gravel as would be a kame terrace.

***Kame terrace*:** a terrace-like ridge composed of stratified sand and gravel deposited by a meltwater stream between a melting glacier or ice lobe and higher valley wall and left standing after disappearance of the ice.

Kettle: a depression on the ground surface, ranging in outline from circular to very irregular, left by the melting of a mass of glacial ice that had been surrounded by glacial sediments. Many kettles now contain ponds or wetlands.

Kettle hole: same as kettle.

Lacustrine: pertaining to a lake.

Late-glacial: refers to the time when the most recent glacial ice sheet was receding from New England, approximately 20,000-12,000 years ago.

Laurentide ice sheet: the most recent continental ice sheet that covered New England, during Late Wisconsinan time.

Late Wisconsinan: the most recent part of Pleistocene time, during which the latest continental ice sheet covered New England (approximately 25,000-12,000 years ago).

Lodgment till: very dense variety of till, deposited beneath flowing glacial ice. May be known locally as "hardpan."

Matrix: the fine-grained material, generally silt and sand, which comprises the bulk of many sediments and may contain clasts.

Matrix-supported: refers to any sediment that consists mostly or entirely of a fine-grained component such as silt or sand. Usually contains less than 20-30% clasts, which are not in contact with one another. For example, fine sand with scattered pebbles.

Moraine: general term for glacially deposited sediment, but often used as short form of “end moraine.”

Nunatak: an isolated hill, ridge, or peak of bedrock that projects prominently above the surface of a glacier and is surrounded by glacier ice.

Outwash: sediment derived from melting glacial ice and deposited by meltwater streams in front of a glacier.

Outwash head: the end of an outwash deposit that was closest to the glacier margin from which it originated. Ice-contact outwash heads typically show steep slopes, kettles, and hummocks, and/or boulders dumped off the ice. These features help define former positions of a receding glacier margin, especially where end moraines are absent.

Pleistocene: term for the period between 2.6 million years ago and 12,000 years ago, during which there were several glaciations. Also called the "Ice Age."

Postglacial: time following late Wisconsinan deglaciation, which may may overlap with the Pleistocene/Holocene boundary.

Proglacial: occurring or formed in front of a glacier.

Quaternary: term for the era between 2.6 million years ago and the present; includes both the Pleistocene and Holocene.

Solifluction lobe: isolated tongue-shaped feature, up to 25 m wide and 150 m long, formed by slow, viscous, downslope flow of waterlogged soil and other unsorted surficial material typically at high elevation in regions underlain by frozen ground.

Sorting: the degree to which the rock or mineral particles in a sediment are all the same or similar in size. For example, many glacial tills contain a mixture of rock debris ranging from clay-size to boulders, and thus are very poorly sorted.

Striation: a narrow scratch on bedrock or a stone, produced by the abrasive action of debris-laden glacial ice. Plural form sometimes given as “striae.”

Subaqueous fan: a somewhat fan-shaped deposit of sand and gravel that was formed by meltwater streams entering a lake or ocean at the margin of a glacier, like a delta but was not built up to the water surface.

Subglacial: occurring or formed beneath a glacier.

Talus: a pile of rocks at the bottom of a bedrock cliff, formed by falling and sliding of blocks of rock that detached from the cliff.

Till: a heterogeneous, usually non-stratified sediment deposited directly from glacial ice. Particle size may range from clay through silt, sand, and gravel to large boulders.

Topset/foreset contact: the more-or-less horizontal boundary between topset and foreset beds in a delta. This boundary closely approximates the water level of the lake or ocean into which the delta was built.