Surficial geologic map of the Keene 30’ x 60’ quadrangle, New Hampshire, 2023

Digital compilation by

Joshua A. Keeley, Jean A. Schwab, and Michael W. Howley

Field checked by

Joshua A. Keeley and Jean A. Schwab

2023

New Hampshire Department of Environmental Services
New Hampshire Geological Survey
29 Hazen Drive, P.O. Box 95
Concord, NH 03302-0095

COMPANION DOCUMENT

Surficial Geologic Map Series GEO-100-024000-SMAP
Map and companion documents can be found at https://www.des.nh.gov/land/geology

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program (STATEMAP), Award #G21AC10863

"*The rocks which you walk over are often not only worn smooth and slippery, but grooved out, as if with some huge rounded tool, or they are much oftener convex*." – Henry David Thoreau on Monadnock Mountain, ca. 1860 (Thompson, 2013)

Abstract

This report describes the surficial geology and Quaternary history of the New Hampshire portion of the Keene 30x60-minute quadrangle, located in the southwestern part of New Hampshire. Surficial earth materials include unconsolidated sediments (till, sand, gravel, etc.) of glacial and nonglacial origin. Most of these deposits formed during and after the last glacial maximum (LGM). In the northeastern U.S., the LGM is constrained to 26,000–24,000 years ago based on pre-LGM radiocarbon dates (Sirkin and Stuckenrath, 1980) and the calibrated varve chronology (Stanford et al., 2021). Surficial sediments cover the bedrock over hillsides and valley bottoms in the quadrangle and are subject to various land-use considerations. These include sand and gravel extraction, development and protection of ground-water resources, siting of waste disposal facilities, selection of building sites, siting and construction of roads, 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 of surficial geologic units, and indicates their age, composition, and known or inferred origin. It also includes information on the geologic history of the quadrangle, such as features indicating the flow direction of glacial ice. This map provides the basis for the discussion of glacial and postglacial history presented here.

Introduction

The Keene 30' x 60' quadrangle covers parts of Massachusetts, New Hampshire, and Vermont, and includes several geological sites of regional significance. Sediments deposited by the Laurentide Ice Sheet, its meltwater streams, and glacial lakes have been a large focus of geologists for nearly 200 years (Jackson 1844). Monadnock Mountain, New Hampshire, lies in the northeastern part of the quad and has been a focal point for geologists and recreationalists alike. Writer and naturalist, Henry David Thoreau, spent time studying the features there between 1844 and 1860. The glacial striations atop Monadnock Mountain were studied at length by Keene native and conservationist, George Wheelock (Wheelock, 1873). Later, investigations of the varves of glacial Lake Hitchcock by Antevs (1922) provided invaluable insights into the style and duration of Pleistocene glaciation. One of Monadnock Mountain's most spectacular features, the Billings fold, was featured in Marland Billings' "Structural Geology" textbook in 1942, making the summit an iconic destination for geologists across the world.

This 1:100,000-scale 30x60' surficial geologic map is a compilation of 14 previously mapped 1:24,000-scale 7.5' surficial geologic maps, of which 13 were published by the New Hampshire Geological Survey and one was published by the United States Geological Survey (USGS) (Campbell and Hartshorn, 1980) (Fig. 1). The original mapping was done between 1980 and 2019 by a variety of geologists (Table 1). This compilation project was recommended and approved by the New Hampshire Geologic Resources

Advisory Committee in 2020 to satisfy stakeholders' needs for seamless geologic map data. The map is provided as a high-resolution PDF as well as in ESRI geodatabase format following USGS's data standard, Geologic Map Schema (GeMS). The deliverables include open-source-readable files such as GIS shape files, Microsoft Excel spreadsheets, and text files for all users. Maps, map pamphlets, and GIS data may be requested from the New Hampshire Geological Survey via geology@des.nh.gov.

Methods

Previously published and digitized 1:24,000-scale map unit GIS polygons were merged and consolidated into 20 surficial units using depositional environment and age categories defined by the original mapper in an effort to remain consistent with the original data and field relationships. In order to achieve an internally consistent map without redundancies and ambiguities, several slight modifications were made. For example, bedrock polygons originally mapped as "br" were too small and few in number to map at this scale, so they were consolidated into the thin till unit (Ptt), which consists of both thin till and abundant bedrock outcrops. This is also true for eskers, which were consolidated into glaciofluvial units. Ice margins were left off the final map due to their inconsistency across the 14 original maps, but the data are available in GIS. Gravel pits and field stations were also left off the map and are available in GIS.

The original 7.5-minute map publications were in various levels of cartographic completion and not all followed the same standard format. Preparing new publication-ready PDFs for each original 7.5' map was outside of the scope of the project. However, because the authors realize and encourage that map users may compare this compilation to the original publications, the GIS data include a crosswalk between original map units and their new designations in this compilation. That information is stored in the field "Original_MapUnit" in the feature class or shapefile "MapUnitPolys". The depositional environment information is on the map and stored in the field "DepEnv" in the "DescriptionOfMapUnits" table.

The map unit symbols/labels follow a consistent naming scheme. Geologic map unit symbols begin with a capitol letter for age distinction (H, P, or Q for Holocene, Pleistocene, and Quaternary, respectively). Lower case letters stand for depositional environment (Depositional environment categories include alluvial, palustrine (wetland), eolian, glaciolacustrine, glaciofluvial, and glacial (for till units). Subcategories of alluvium include active alluvium (Ha), stream terraces (Qst), and river terraces (Qrt), the lattermost being a designation reserved for the Connecticut River. Subcategories of glaciolacustrine include lake bottom sediments (l), and deltaic (d). Ice-contact deposits with local glacial lake sediments are undifferentiated into glaciofluvial/glaciolacustrine (fl) units. Map units involved in large glacial lake systems, such as glacial Lake Hitchcock, glacial Lake Ashuelot, and glacial Lake Contoocook contain additional characters, "h", "a" and "c", respectively.

Many of these maps were published prior to the availability of statewide 1-meter LiDAR and were mapped on 1:24,000-scale topographic basemaps. The statewide Water Well Inventory, maintained by the New Hampshire Department of Environmental Services, was used to update the thin till layer systematically across the map. Steps were taken during the compilation process to assess the accuracy of these geologic map units in comparison to the LiDAR. However, due to the scope of this project, limited steps were taken to align the GIS to the LiDAR. The accuracy of the map unit polygons is generally less than 100 feet, although higher inaccuracies may occur.

The compilation authors identified edge-matching discrepancies in the existing GIS data and resolved them with site-specific field work. Field work was done in late May and early June 2022, and mainly consisted of edge-matching the textural overlay polygons (OverlayPolys).

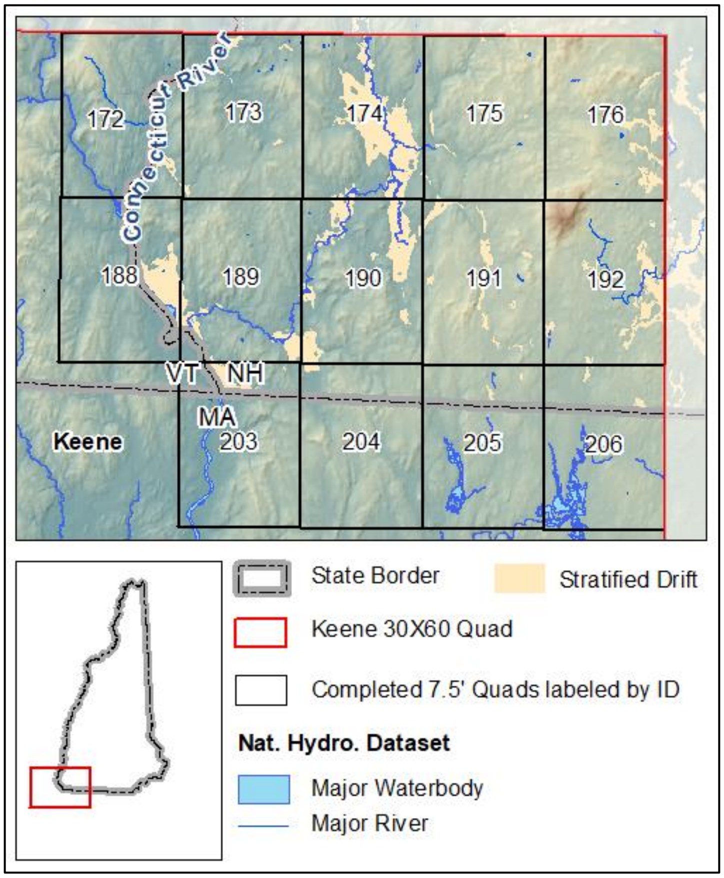

Figure 1. Index map of compiled 1:24,000-scale geologic surficial maps

Table 1. Summary of compiled 1:24,000-scale geologic surficial maps

Keene 30x60-minute quadrangle			
Quad ID	**7.5-minute quadrangle**	**Year published**	**Author**
172	Putney	1997	Koteff/Larsen
173	Spofford	1999	Larsen
174	Keene	1997	Larsen/Koteff
175	Marlborough	1999	Pendleton
176	Dublin	2000	Nelson/Nelson
188	Brattleboro East	1999	Pendleton
189	Hinsdale	1998	Hildreth/Pendleton
190	West Swansey	1997	Pendleton
191	Troy	1996	Hildreth
192	Monadnock Mountain, NH	1995	Hildreth
203	Northfield, MA	1980	Campbell/Hartshorn
204	Mount Grace	2019	Prentice
205	Royalston	2019	Prentice
206	Winchendon	2021	Prentice

Surficial geologic history of the Keene 30' x 60' quadrangle, New Hampshire

Surficial deposits include unconsolidated to weakly consolidated deposits overlying bedrock. In the Keene quadrangle, bedrock includes metaigneous and metasedimentary rocks of Paleozoic age. Throughout New England, glacial sediments were deposited in direct contact with, adjacent to, or distal (far from) glacial ice of the Laurentide Ice Sheet since the LGM around 26,000-24,000 years ago (26-24 ka) (Halstead et al., 2022; Stanford et al., 2021). Surficial deposits also include post-glacial sediments consisting of stream alluvium, lacustrine sediments, various wetland classifications of organic-rich sediment overlying poorly drained substrate, and mass wasting deposits such as colluvium, landslides, and debris flows. In Keene, at the 1:100,000-scale, small wetlands were not mapped, and colluvium was not differentiated from steep till-covered hillsides potentially undergoing soil creep. No landslides were mapped across the area.

Ice recession at the MA, VT, NH border within the Connecticut River valley has been estimated at 15,500 years ago (calibrated to present-day calendar) (Ridge, 2012) (Fig. 2).

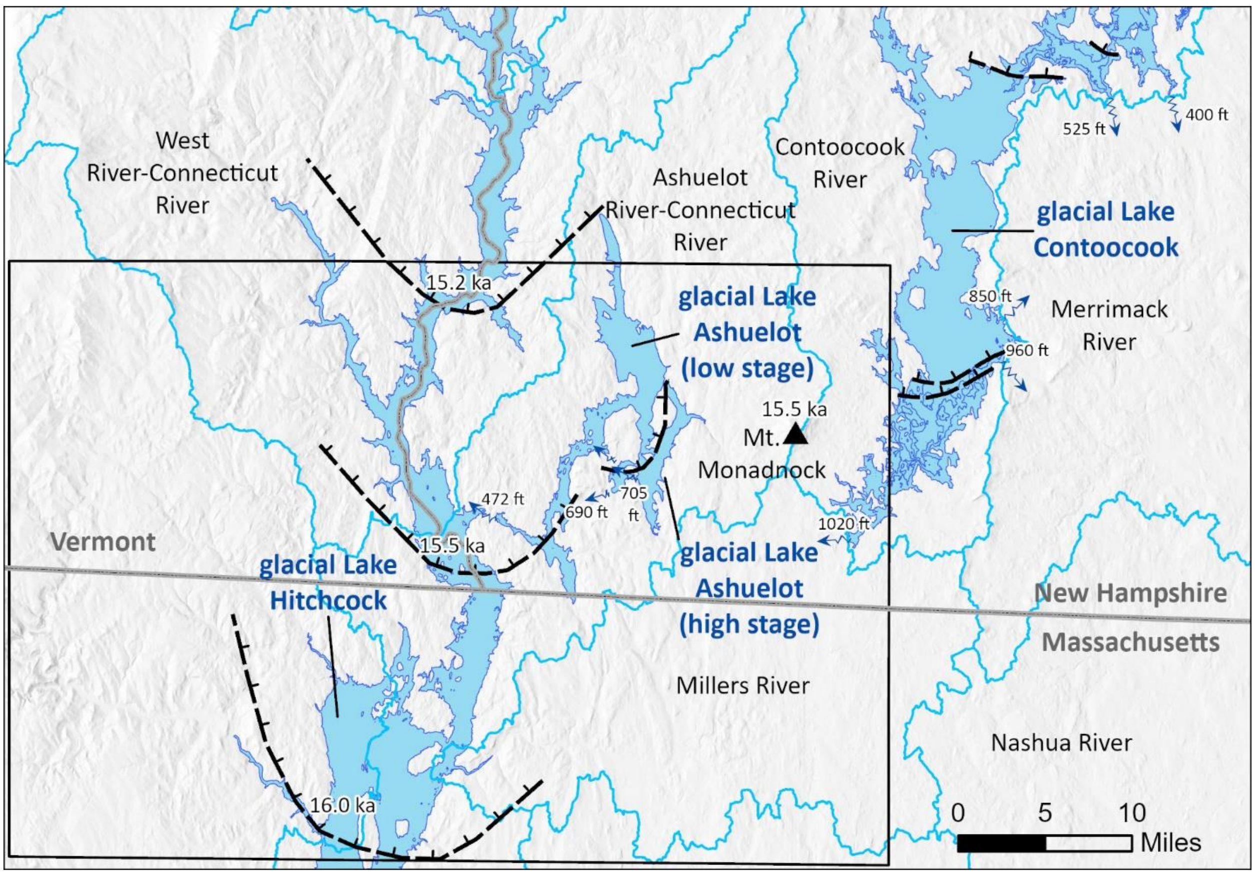

Figure 2. Regional figure showing ice margins and maximum extents of glacial lakes in southwestern New Hampshire, southeastern Vermont, and north-central Massachusetts. The Keene 30x60 quadrangle is shown by the black inset rectangle. Ice margins are shown by dashed black lines with ticks indicating the up-ice direction. Ice margins in the Connecticut River valley are labeled by age in thousands of years before present (ka) and based on the varve chronology of Ridge et al. (2012). Major hydrologic watersheds shown by light blue lines and black labels. The age of 15.5 ka at Monadnock Mountain shows good relationship with the ice margin at 15.5 ka in the Connecticut River valley. Major lake spillways shown by blue arrows and labeled by elevation in feet.

At this location, an ice lobe occupying the Connecticut River valley deposited ice-contact deltas at the southwestern corner of the map and into Massachusetts. At this time, the southeastern portion of the quadrangle in New Hampshire was probably already ice free, which left space at the higher elevations of the Contoocook River basin to accommodate glacial Lake Contoocook. Glacial Lake Contoocook filled to various elevations upstream of various ice and earthen dams, which are well documented by Hildreth and Moore (1996) from their 1993 Friends of the Pleistocene fieldtrip. The first two lakes that ponded between hillsides and the ice sheet were small and are on the Lowell 30' x 60' sheet (Barker, 2020). The lake extent shown by the green line on the map corresponds to stage 3 of Hildreth and Moore (1993), the sediments of which graded to two spillways near present-day Pool Pond at about 1,020 feet elevation. The next-lower lake level corresponds to stage 4 of Hildreth and Moore (1993), which had a spillway at about 960 feet elevation in the Lowell 30x60 quadrangle. Only the line segments east and northeast of Dublin Pond correspond to the 960-foot elevation spillway. As ice receded approximately to the northwest, these natural dams either melted or collapsed, thereby releasing water from glacial Lake Contoocook through progressively lower spillways to the northeast. While ice occupied lower elevations in the northern Contoocook Valley, glacial Lake Contoocook spilled towards the south. Once the ice in the northeastern Contoocook Valley melted, discharge from glacial Lake Contoocook flowed northeast along the course of the present-day Contoocook River.

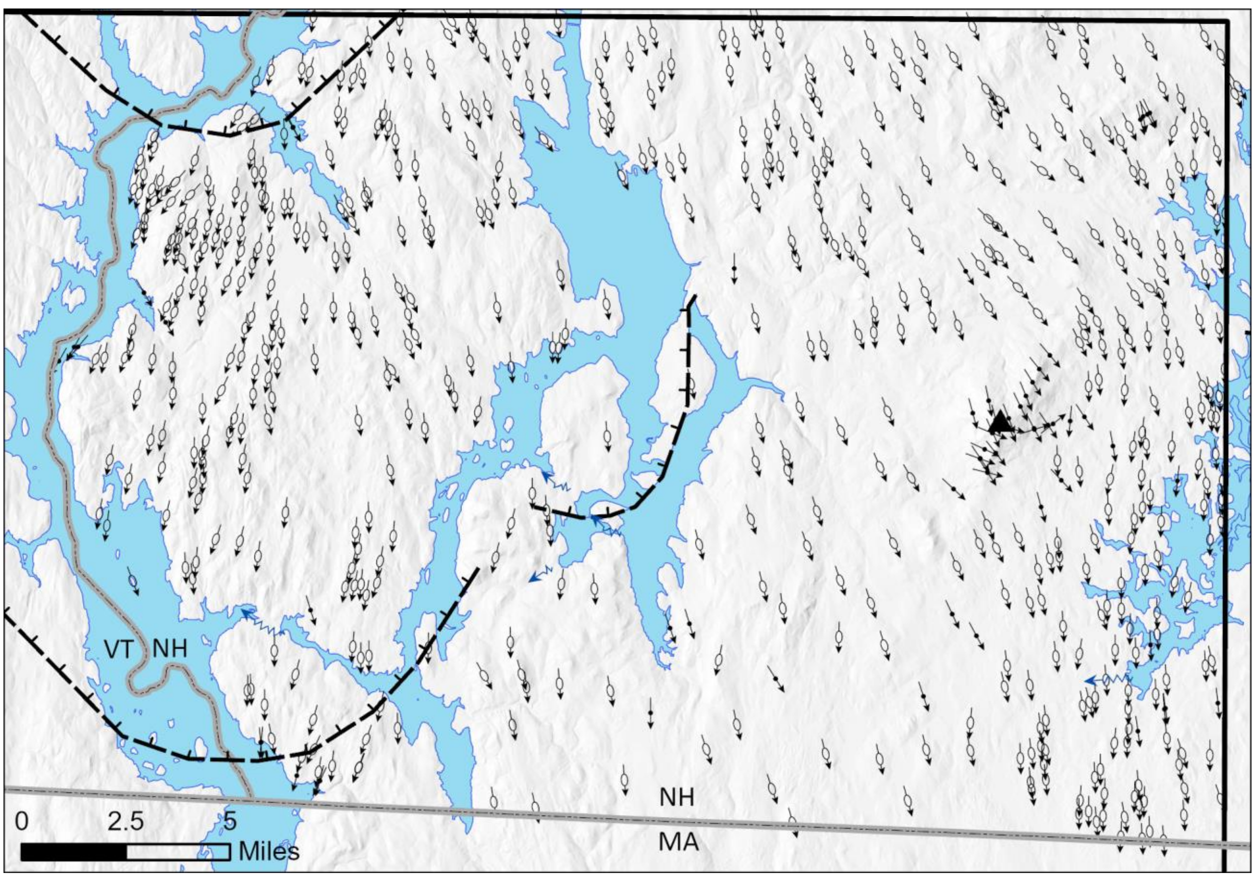

Figure 3. Glacial movement indicators across the New Hampshire portion of the Keene 30x60 quadrangle. Note glacial lakes and ice margins for reference. Monadnock Mountain is shown by the black triangle. Glacial striations are shown by the arrow with a closed dot. Drumlins, streamlined hills, and flutes are shown by the arrow with an open oval.

As ice continued to retreat and melt, the elevation of the ice lowered, exposing nunataks, or islands of hilltops sticking up through the ice sheet. At some point, Monadnock Mountain become a nunatak, exposing the bedrock at its peak to cosmogenic nuclides. The isotope, beryllium 10 (^{10}Be), is a cosmogenic nuclide that begins to accumulate in the rock when earth materials become free from ice cover. ^{10}Be ages obtained along an elevation profile of the mountain are in good agreement with the 15.5 ka ice margin estimated independently by the varve chronology in glacial Lake Hitchcock (Hodgdon, 2016; Halsted et al., 2022). After 15.5 ka, Halsted et al., (2022) document rapid thinning of the Laurentide Ice Sheet in the northeastern U.S. between 15-13 ka based on ^{10}Be exposure dating throughout the region. Coincident with this interpretation, due to the limited number of mapped moraines in southern New Hampshire, many workers have hypothesized that ice melted rapidly in place, in a style that failed to deposit end moraines along a stable ice margin. However, several small end moraines have been mapped in the Keene 30x60 quadrangle, and more may be apparent with the high-resolution LiDAR data now available. As a result of lidar analysis, dynamically flowing ice at the thinning edge of the ice sheet has recently been documented elsewhere in New Hampshire (Tinkham et al., 2022). Ice movement indicators like glacial striations, drumlins, streamlined hills and glacial flutes are shown on the map and on Figure 3. The majority point south to south-southeast, but local topographic controls on ice movement are also apparent. Ice flow indicators suggest ice converged into areas of open topography such as the wide valleys of Connecticut, Ashuelot, and Contoocook rivers, whereas ice diverged around higher topographic features like ridges and peaks such as Monadnock Mountain. Dynamic ice in the Keene 100K quadrangle is evident from multiple cross-cutting glacial striation directions on Monadnock Mountain, where striations higher on the mountain point southeast, whereas striations on the lower flanks point east and northeast. Likewise, in the Connecticut River valley, most striations in New Hampshire point south and southwest on the higher hillsides, but the lower elevations show ice was topographically constrained by the valley walls as ice thinned over time.

Till (diamicton), a glacially deposited poorly sorted mixture of sediment composed of grain sizes from clay to boulders, was deposited ubiquitously across the map. Depending on the specific glacial depositional environment, different types of till were deposited. Subglacial deposition, especially on the up-ice (stoss) side of hillsides, led to the deposition of very dense compact tills, which are usually an unoxidized olive green to gray color. Sandier and less compact tills likely experienced some winnowing of clay and silt by meltwater and possibly redeposition. Tills that originated from material that was carried on top of or within the ice may occur as redeposited diamicton in water-saturated debris flows.

Once the Ashuelot River basin became ice free, glacial meltwater flowing under, within, and from the surface of the melting ice sheet discharged from the ice and deposited sandy deltas in contact with the ice. Fine-grained silty and clayey lake-bottom sediments were deposited in a large pro-glacial lake in the Ashuelot Valley, now occupied by Keene and surrounding towns. The high stage of glacial Lake Ashuelot formed between high hillsides upstream of the Franconia Mountain Range and Hewes Hill at an elevation of 705 feet. When the Franconia Mountain Range and Hewes Hill spillway was active, ice still occupied the Ashuelot Valley north of Hewes Hill, blocking lower spillways. After ice receded enough to expose the valley constriction through Rabbit Hollow Road, meltwater was controlled by an outlet at 690 feet. Once ice receded north of the drainage divide between Indian Brook and Perry Brook, meltwater carved a sinuous gorge and had an outlet at 525 feet. This gave way to the main stage of glacial Lake Ashuelot, which was controlled by a spillway at 470 feet elevation immediately south of the current course of the Ashuelot River in Winchester near the Hinsdale town border.

During the main stage of glacial Lake Ashuelot, meltwater continued to pour into the lake, depositing glaciolacustrine sediments along the shoreline and into the basin. Grain sizes from the shoreline to deep-water settings change from sandy to silty and clayey, respectively, which reflect changes in flow strength and sediment supply. Lake bottom sediments of glacial Lake Ashuelot include varves, which are clay/silt and silt/sand couplets deposited annually. The finer grained sediments were deposited in the sediment-poor winter and the sandier layer was deposited during the summer, when meltwater and sediment supply would have been greater. Ernst Antevs included these Ashuelot varves in his New England Varve Chronology, in which he established the first direct dating method of glacial sediments and correlated them across several lakes in New England including glacial Lakes Hitchcock and Ashuelot (Antevs, 1922). Expansion of Antevs' work has provided numerical ages of the deglaciation of parts of New England (Ridge et al., 2012; Fig. 4).

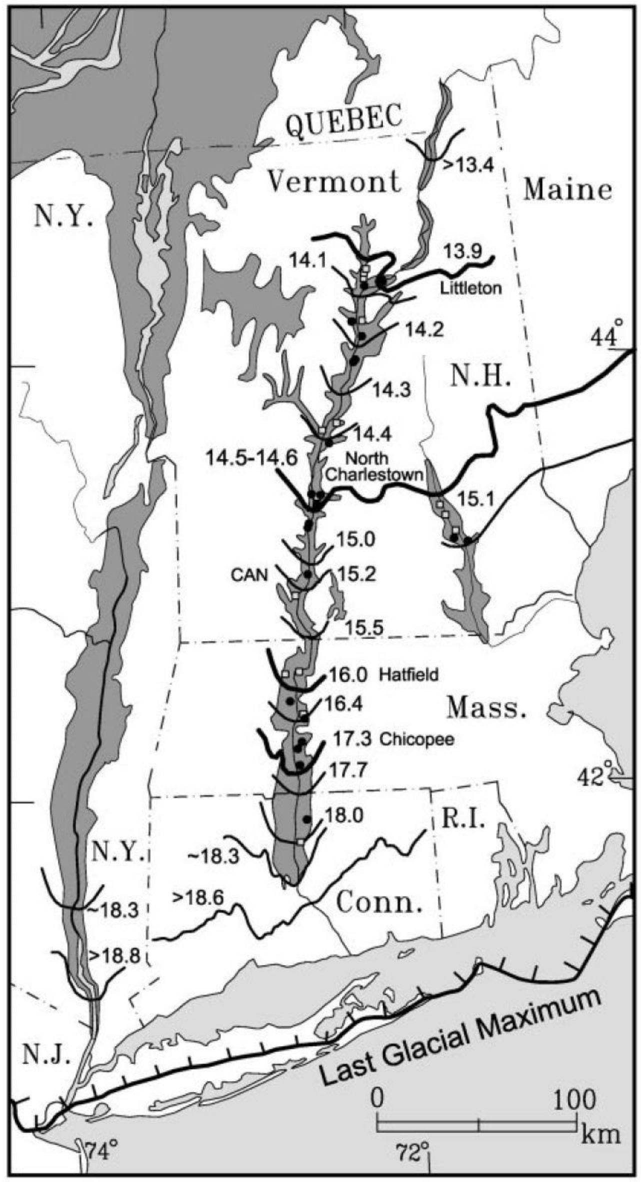

Figure 4. Approximate reconstructed ice recession positions of the last deglaciation in western New England. Ages in calibrated calendar years before 2000 AD. From Ridge et al., (2012).

By the time the 470-foot-elevation spillway in Winchester failed and began discharging floodwaters from glacial Lake Ashuelot, ice was likely free from the portion of the Connecticut River valley at the confluence of the Ashuelot River. In its place was glacial Lake Hitchcock. The projected level for glacial Lake Hitchcock is immediately west of the Winchester spillway and it is likely that the floodwaters of glacial Lake Ashuelot poured into glacial Lake Hitchcock. The floodwaters carved broad and deep channels into the till and sediment from Lake Ashuelot was reworked resulting in a large sediment load that was eventually deposited into glacial Lake Hitchcock as one of the largest deltas in the quadrangle.

As ice continued retreating northward in the Connecticut River valley, its meltwater discharge deposited a series of ice-contact deltas with progressively higher elevations. Work by Koteff and Larsen (1989) documented a linear trend of approximately 0.9 meters per kilometer when plotting the elevations of foreset/topset contacts of these deltas from their distance from the New Britain Spillway in Connecticut. Koteff and Larsen (1989) concluded that because the deltas created a titled plane, that glacial Lake Hitchcock existed as one continuous lake from the New Britain Spillway in Connecticut all the way to ice-contact deltas in northern New England as a result of delayed isostatic rebound. Hooke and Ridge (2016) provided an alternative to explain the straight water plane and concluded that ice-contact deltas within the Connecticut River valley of New Hampshire and Vermont were deposited within local short-lived ice-contact lakes in the mouths of tributaries and not a main valley lake that was lower than elevations of Koteff and Larsen (1989).

The ice sheet continued receding, making space for new ice-contact deltas, kames, and glaciofluvial systems across the quad. Post-glacial sedimentation included wind-blown (eolian) sand deposited as dunes in the Connecticut River valley and variously across the quad in subordinate amounts. The transition from late Pleistocene to early Holocene was characterized by abrupt climatic shifts caused by changes in ocean and atmospheric circulation (Kirby et al., 2002). Post-glacial streams occupied some channels previously carved by glacial torrents, filling glacial scours with deposits of alluvium. Glacial rebound continued, and the base level of local streams fell accordingly, while the postglacial sediment load of streams on a vegetated land surface fell, causing Holocene streams to cut down into Pleistocene to early Holocene stream terraces and abandon their former floodplains.

Expanded descriptions of map units

af Artificial fill (Holocene) — Sand and gravel or other unconsolidated materials in areas of artificial cut and fill reworked through human activity. Clay deposits are graded and filled to form road/railway embankments and dams. The unit is not extensively mapped in densely developed areas and many small bodies are not shown on the map. The depths of cuts and the thickness of fill is variable but are generally less than 20 feet (6 meters).

Hw Wetland (Holocene) — Loam and partially decomposed organic material (peat), clay, silt, sand, and organic-rich wetland deposits in poorly drained areas. Some clays are light-gray, olive, dark-brown, or black. Large boulders are found in some wetlands underlain by or surrounded by till. Inorganic matter accumulated by a combination of colluvial, alluvial and eolian processes. In places, the unit grades into alluvium. Extensive wetland deposits occur adjacent to the Ashuelot River near Keene. The deposits are generally 1 to 10 feet (½ meter to 3 meters) thick but may be as much as 30 feet (9.1 meters) thick.

Ha Alluvium (Holocene) — Sand, silt, and gravel deposited within channels and along the floodplains of active streams/rivers, including minor wetland and windblown sand deposits. Pebble gravel is found on floodplains in some areas. Alluvium along the Connecticut and Ashuelot Rivers consists mainly of fine sand and silt. In the Connecticut River valley, the floodplains presently stand as much as 40 feet (12.2 meters) above the current river in areas are scoured by historic floods. The areas mapped as Ha are based in part on evidence that they are flooded every few years and so the extent of alluvium indicates areas flooded in the past which may be subject to future flooding. In the Connecticut and Ashuelot river basins, active stream alluvium grades into and is indistinguishable from lake-bottom deposits. In areas upstream from dams, alluvium may be drowned stream terraces. Many small areas of alluvium are not mapped due to scale limitations. The deposits near rivers are as much as 40 feet (12.2 meters) thick; those furthest from the river may locally form discontinuous patches that overlie adjacent units.

Qst Stream terrace alluvium (late-Pleistocene-Holocene) — Sand, gravel, and silt deposited on the floodplains of late-glacial and post-glacial streams and rivers. May include minor wetlands. In the town of Hinsdale, these terraces were cut by the late-glacial and post-glacial Ashuelot River and its tributaries, as it cut through lake bottom and deltaic deposits of former glacial-Lake Hitchcock after base levels dropped due to failure of glacial drift dams within their watersheds. Most of these terrace deposits disconformably overlie varved clay. Deposits near the tip of a scarp may be as much as 40 feet (12 meters) thick, while those near the base of the next highest scarp commonly form discontinuous patches that overlie varved clay (Campbell and Hartshorn, 1980). As many as five terrace levels were identified on the Ashuelot River upstream of the Connecticut River confluence. These terraces appear to match Connecticut River terraces (Qrt), suggesting both rivers were responding to the same drops in base level. This unit also include erosional terraces that are discontinuously veneered with stream-terrace deposits. In the Hinsdale area, they form an alluvial veneer overlying up to 100 feet of fine-grained lacustrine and deltaic sediments derived from the flood waters of glacial Lake Ashuelot.

Qrt River terrace alluvium of the Connecticut River (late-Pleistocene-early Holocene) — Light Grey, light olive, olive brown, and brown interbedded silt and very fine sand as much as 10 feet (3.0 meters) thick; overlie as much as 30 feet (9.1 meters) of light grey, light olive, and light-yellow fine to coarse sand with minor amounts of interbedded silt to pebbly sand and granule to pebble gravel. Deposited on floodplain of early Holocene to Late Pleistocene Connecticut River, as it cut down through lake bottom and deltaic deposits of former glacial-Lake Hitchcock. Most terrace deposits disconformably overlie varved clay. The beds immediately above the clay contact commonly are stained orange, dark brown, or black. Deposits near top of scarp commonly as much as 40 feet (12.2 meters) thick.; those near base of next highest scarp commonly from discontinuous patches that overlie varved clay. Most terraces graded to Lily Pond bedrock barrier near Turner Falls in the Greenfield quadrangle Massachusetts (Campbell and Hartshorn, 1980; Jahns and Willard, 1942) or to a higher base level. The unit includes terraces cut into the former glacial lake, stream deposits, and till. The erosional terraces are discontinuously veneered with stream-terrace deposits, minor swamp deposits, and some alluvium. Deposits may be as much as 40 feet (12 meters) thick.

Qsto Older stream terrace alluvium (late-Pleistocene-early Holocene) — Sand, silt, gravel, and minor muck graded to 330 feet (100 meters), the highest alluvial terrace deposited on the banks of the late-glacial and post-glacial Ashuelot and Connecticut Rivers as they down-cut through glacial lake sediments. This unit was probably graded to the Lily Pond bedrock barrier near Turner Falls in the Greenfield quadrangle Massachusetts (Campbell and Hartshorn, 1980; Jahns and Willard, 1942). These stream sediments are 1 to 20 feet (up to 6 meters) thick and form an alluvial veneer over up to 100 feet of fine-grained lacustrine and deltaic sediments derived from the flood waters of glacial Lake Ashuelot.

Qf Alluvial fan deposits (late-Pleistocene-early Holocene) — Sand and pebble gravel deposited at the mouth of tributary valleys of the Connecticut River including minor amounts of alluvium and stream terrace deposits along associated streams. The deposits are generally less than 30 feet (9.12 meters) thick, and thin downslope from the apex. Alluvial fans are generally underrepresented in the map area as many were too small to map at the 1:24,000 scale and were lumped into glaciofluvial and alluvial depositional systems. The alluvial fans that were mapped in the Northfield quadrangle were formed by reworking and redepositing deltaic lacustrine sediments of glacial Lake Hitchcock.

Pe Eolian sand (late Pleistocene) — Well sorted very fine to medium sand with minor amounts of interbedded silt and coarse sand. The uniform grain size of the sand and the absence of pebbles and stones identifies the material as windblown. The deposits were formed from glacial Lake Hitchcock sediments and early stream terrace surfaces exposed to prevailing winds from the west and northwest following the drainage of the lake. The thickest deposits occur on high ground east of the Connecticut River. In the Connecticut valley, deposits occur chiefly as sand dunes that overlie deposits of Lake Hitchcock or the oldest river-terrace deposits. The unit includes thick accumulations of windblown sand not having a distinct morphology and windblown sand found as a thin veneer over bedrock, to small dunes on a variety of older glacial deposits. Individual dunes are as much as 2,700 feet (823 meters) long, and dune complexes are as much as one mile (1.6 kilometers) long. These dunes cannot readily be distinguished from low sandy kames by their mound like form. Ventifacts and slightly fluted bedrock outcrops are associated with many of these deposits. The deposits are as much as 30 feet (9.1 meters) thick.

Pf Glaciofluvial deposits, undifferentiated (Pleistocene) — Poorly to well sorted fine to coarse sand, pebble to boulder gravel, and minor silt and clay. The gravels are commonly well rounded. Deposits are commonly stratified and may have interbedding, with minor amounts of flow-till. The sediments may be greyish-brown, light-olive, and light-yellow. The deposits were formed by glacial meltwater discharging from the ice sheet terminus during the last fluctuation of the Laurentide Ice Sheet during the Wisconsinan Glaciation of the Pleistocene. As the glacier front retreated northward, meltwaters under, within, on top of, and between glacial ice and adjacent hillsides led to the deposition of proximal ice-contact deposits such as eskers, ice-channel filling, kames, and course outwash. As meltwater carried sediments away from the ice margin to more distal settings, outwash plains consisting of finer-grained sediments were deposited. The deposits are graded to various local ice, till, or bedrock spillways. Eskers are present as small linear to sinuous ridges and are often composed of coarse- to medium-grained well-rounded gravel. The eskers have variable trends, are widely disbursed, and are associated with kame and kettle topography characterized by highly irregular collapse topography and disrupted internal structure. Minor amounts of clay and flow till may be associated with ice-contact deposits and may grade downstream to more stratified deposits. The deposits are as much as 100 feet (30 meters) thick.

Plfa Glaciolacustrine to glaciofluvial deposits of glacial Lake Ashuelot (Pleistocene) — Poorly to well sorted sand, gravel (pebble to cobble), silt, and clay deposited into former glacial Lake Ashuelot. Previous mapping identified 11 sequential units based on successively lowering spillway elevations and subsequent base level changes at or near the ice margin during stagnation-zone retreat of the ice sheet. The sediments were derived chiefly from debris eroded from the bed of the glacier that was carried into the former glacial Lake Ashuelot by meltwater streams. Some materials were deposited in the lake at the ice margin, and some were deposited further into ponded water bodies between the ice margin and a spillway. These materials formed kame-delta, shore, and nearshore deposits. Some upper glacial Lake Ashuelot deposits were formed in contact with and beyond adjacent ice as kame-terrace deposits. The level of the glacial lake was controlled by a spillway at 470 feet elevation immediately south of the current course of the Ashuelot River in Winchester near the Hinsdale town border. As the glacial lake level dropped due to failure of glacial drift dams within its watershed, deposits continued to be formed on the floodplains of the late-glacial and post-glacial Ashuelot River and their tributaries as they cut down their channels through lake bottom and deltaic deposits of the former glacial lake. Most of these deposits disconformably over lie varved clay. The deposits are as much as 60 feet (18 meters) thick.

Pls Glaciolacustrine deposits of glacial Lake Sip (Pleistocene) — Fine to coarse sand, silt, and clay deposited into former glacial Lake Sip in the town of Fitzwilliam.

Pla Lake-bottom deposits of glacial Lake Ashuelot (Pleistocene) — Clay, silt, fine to coarse sand, pebble gravel; poorly to well sorted. The unit is overlain in places by dominantly deltaic sand, pebble gravel deposits, and subordinate wind-blown sand. Some varved clay deposits in the Keene area were deposited in glacial Lake Ashuelot. The deposits were derived from erosion of sediment beneath the glacier that was eroded by subglacial meltwater and was carried into glacial Lake Ashuelot by meltwater streams, forming kame-deposits, shore deposits, nearshore deposits, and bottom-set beds of glacial Lake Ashuelot. This unit includes lake-bottom and nearshore deposits in glacial Lake Ashuelot in the Ashuelot Valley. The level of glacial Lake Ashuelot was controlled by a spillway at 470 feet elevation immediately south of the current course of the Ashuelot River in Winchester near the Hinsdale town border. The deposits are up to 130 feet (40 meters) thick.

Plda Glaciolacustrine deltas of glacial Lake Ashuelot (Pleistocene) — Sand, pebble gravel, and minor silt and clay. The deposits were formed in contact with and downgradient of glacial ice as glaciolacustrine, deltaic and kame deposits. In the towns of Keene and Swanzey, deltas emanate from constricted meltwater channels currently occupied by Minnewana Brook to the Branch and the South Branch of the Ashuelot River, respectfully. In the town of Winchester, deltas emanate from constricted meltwater channels currently occupied by Roaring Brook and unnamed streams. Deltas grade to local spillways up to 540 feet elevation as well as the main Ashuelot spillway of 470 feet. Up to 150 feet (45 meters) thick.

Plf Glaciolacustrine to glaciofluvial deposits, undifferentiated (Pleistocene) — Sand (fine to coarse), gravel (pebble to boulder), flow-till and minor silt and clay. Sand is stratified, moderately to well sorted, fine-to medium-grained, and is interbedded with thin (usually measured in inches) silt and clay beds, and layers of cobble and pebble gravels. The unit includes ice-contact deposits such as eskers, kames, and outwash as well as glaciolacustrine deposits such as deltaic and lake-bottom sediments. The unit also includes smaller alluvial fans. During the early history of the village of Troy, a pottery industry was based on the clay deposits found in this unit. The deposits are up to 115 feet (35 meters) thick.

Plfao Glaciolacustrine to glaciofluvial deposits of the high stages of glacial Lake Ashuelot (Pleistocene) — Sand (medium to coarse), gravel (pebble to boulder), and minor silt and clay deposited in contact with and beyond adjacent ice as kame-terrace deposits laid down by meltwaters grading to at least three local spillways between 705-525 feet. The highest and earliest of these spillways activated between Franconia Mountain Range and Hewes Hill at an elevation of 705 feet. When this spillway was active, ice still occupied the Keene Valley north of Hewes Hill, blocking lower spillways. After ice receded enough to expose the valley constriction through Rabbit Hollow Road, meltwater began grading sediments to 690 feet. Once ice receded north of the drainage divide between Indian Brook and Perry Brook, meltwater carved a sinuous gorge there and began grading sediments to 525 feet. The unit includes glaciolacustrine sediments, such as deltaic and lake-bottom sediments, deposited in ponded water between hillsides and glacial ice impoundments. The deposits are up to 100 feet (30 meters) thick.

Plfc Glaciolacustrine to glaciofluvial deposits of glacial Lake Contoocook (Pleistocene) — Sand, gravel, silt, and clay deposited in contact with or beyond adjacent ice, representing different stages of a glacial lake within the Contoocook River Valley. The unit includes ice-contact deposits such as kames and outwash as well as glaciolacustrine deposits such as deltaic and lake-bottom sediments. As ice melted, it first exposed the southern parts of Contoocook basin, which allowed meltwater to pond between the southern drainage divide and the ice. At this time, spillways northwest and southwest of Pool Pond at 1050-1020 feet elevation were activated ("stage 3" of Hildreth and Moore, 1996). As the glacial front receded northward, glacial Lake Contoocook was controlled by this outlet until the ice front reached a 940–960-foot elevation divide in the Wapack Range at the east edge of the Peterborough North quadrangle. The deposits are as much as 75 feet (23 meters) thick.

Plfh Glaciolacustrine to glaciofluvial deposits of glacial Lake Hitchcock (Pleistocene) — Mainly outwash and deltaic sand, gravel, silt, and clay deposited by glacial meltwaters in contact with or beyond adjacent ice as kame-delta, shore, nearshore, outwash and minor bottom-set beds of glacial lake Hitchcock, whose level was controlled by a glacial drift dam at Rocky Hill, Connecticut, and a spillway at New Britain, CT. Glacial meltwater sources for these deposits came directly from the terminus of the ice sheet or from the many tributary valleys from both New Hampshire and Vermont. Deltas in this area were formed in Lake Hitchcock after about 15,500 years ago (Ridge and others, 2012). The unit includes kame-delta and outwash deposits laid down by meltwaters draining the Ashuelot River valley, mostly sand and gravel grading west and south to finer grained sand where the meltwaters entered glacial Lake Hitchcock at around 400-450 feet elevation. Due to post-glacial uplift in the areas, the water plane is tilted at 4.54 ft/mi (0.86 m/km) in a N21.5-degree W direction, so that shore deposits and deltas built into the lake north of the area are found at respectively higher elevations (Koteff and Larsen, 1989; Larsen, 1992; Hooke and Ridge, 2016). The deposits are up to 150 feet (50 meters) thick.

Plh Glaciolacustrine lake-bottom deposits of glacial Lake Hitchcock (Pleistocene) — Mainly bottom-set clay, silt, sand, and minor poorly to well sorted gravel, poorly to well sorted. Some sediments may be grey, olive, light olive, and light yellow, and compact. Varved clay is common and is interbedded with sand and silt with minor amounts of massive silt and fine gravel. The unit includes a thin cover of colluvium over bottom deposits along many fluvial scarps. The deposits were formed from sediments in glacial meltwaters flowing in contact with and beyond adjacent ice. Deposits were laid down in Lake Hitchcock whose level was controlled by the New Britain Spillway in Connecticut. The lake level at the west edge of the map was about 400-450 feet (120-138 meters) elevation; this is based on the projection (Koteff and Larsen, 1989; Hooke and Ridge, 2016) from data outside the quadrangle and assumes a postglacial tilt to the lake profile of about 4.54 ft/mi (0.86 m/km) up to the N21 degrees W. Glacial Lake Hitchcock occupied this section of the Connecticut River valley for a few thousand years between ~15,500 and 12,500 years ago (Ridge et al., 2012). The deposits are up to 100 feet (30 meters) thick.

Pt Till (Pleistocene) — Loose to very compact; non-sorted to poorly sorted; unconsolidated mixture of clay, silt, sand, and pebble to boulder gravel (diamicton). Dominant grain size is silt to small pebbles; massive to weakly stratified. The deposit may include small irregular masses of water laid sand and gravel. Where the proportion of clay is high, the till has a slightly greenish tint and is characteristically poorly drained, whereas tills with a higher percentage of sand in the matrix are moderately well drained. The till matrix contains a variety of rock fragments of different sizes and shapes. The deposits were formed from sediments directly deposited from glacial ice or by subglacial sediment sheared and dragged beneath the glacier. Two till types are found which represents the style of deposition. The lower till is more compact, siltier, and locally bearing clay, and may be interpreted as a basal melt-out or subglacial till, having been deposited directly by moving basal ice. The upper till is looser and sandier, representing till that was winnowed by meltwater or originated from loose till on top of the ice sheet, or flowtill, redeposited by slumping under the influence of gravity. The lower till is olive grey to dark gray;

the upper till is generally olive grey to brown. Till generally underlies all other units in the area except where it is removed by fluvial processes or glacial ice. In the Winchendon quad, in partial regard to ground penetrating radar (GPR) data collected on drumlins, Prentice (2020) noted that stratification in surface and underlying sediments is generally distorted and faulted due to post depositional collapse related to melting of buried ice. Stagnant-ice deposits may be confined to irregular hummocky hills, bounded by ice-contact slopes, generally deposited on hillsides and hilltops higher in elevation than stratified sediments. Deposits may be aligned in belts parallel to the retreating ice margin. Drumlins, streamlined hills of till which were shaped by moving ice, are present. The deposit thickness varies but may be locally up to 180 feet (55 meters) thick under the crests of drumlins and on the stoss sides of bedrock hills.

Ptt Thin till (Pleistocene) and bedrock — Till deposits in areas where bedrock outcrops are common and/or surficial sediments are inferred to be generally less than 10-15 feet (3-4.5 meters) thick.

Acknowledgements

The authors are grateful to thoughtful reviews from John C. Ridge, P. Thompson Davis, and Michael L. Prentice, whose commentary greatly improved the map and written geologic history. Thanks also to Rebecca LeCain, Outreach Coordinator of the New Hampshire Geological Survey, for coordinating peer review comments and participation in the collaborative review. Many thanks to Shane Csiki, New Hampshire State Geologist, for his reviews, coordination, and management of the Geologic Mapping Program.

References

Antevs, E., 1922, The recession of the last ice sheet in New England: *American Geographical Society*. Research Series 11, 120 p. (with a preface and contributions by J. W. Goldthwait).

Barker, G.A., 2020, Surficial Geologic Map of the Lowell 30x60’ Sheet, New Hampshire and Massachussets: New Hampshire Geological Survey, Open-File Reports GEO-013-100000-SMOF, scale 1:100,000.

Billings, M.P., 1942, Structural Geology: New York: Prentice-Hall, Inc., 19 plates, 473 pp.

Campbell, K.J., and Hartshorn, J.H., 1980, Surficial geologic map of the Northfield quadrangle, Massachusetts, New Hampshire, and Vermont: U.S. Geological Survey, Geologic Quadrangle Map GQ-1440, scale 1:24,000.

Halsted, C.T., Bierman, P.R., Shakun, J.D., Davis, P.T., Corbett, L.B., Caffee, M.W., Hodgdon, T.S. and Licciardi, J.M., 2022, Rapid southeastern Laurentide Ice Sheet thinning during the last deglaciation revealed by elevation profiles of in situ cosmogenic 10Be. *GSA Bulletin*.

Hildreth, C.T., 1995, Surficial geologic map of the Monadnock Mountain 7.5 minute quadrangle, New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports GEO-192-024000-SMOF, scale 1:24,000.

Hildreth, C.T., 1997, Surficial geologic map of the Troy 7.5 minute quadrangle, New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports GEO-191-024000-SMOF, scale 1:24,000.

Hildreth, C.T. and Moore, R.B., 1996, Late Wisconsinan deglaciation styles of parts of the Contoocook, Souhegan, and Piscataquog drainage basins, New Hampshire. US Department of the Interior, US Geological Survey.

Hildreth, C.T., and Pendleton, R.M., 2000, Surficial geologic map of the Hinsdale 7.5 minute quadrangle, New Hampshire-Vermont: New Hampshire Department of Environmental Services, Open-File Reports GEO-189-024000-SMOF, scale 1:24,000.

Hodgdon, T., 2016, Developing a chronology for thinning of the Laurentide Ice Sheet in New Hampshire during the last deglaciation (Master’s thesis, University of New Hampshire).

Hooke, R.L. and Ridge, J.C., 2016, Glacial lake deltas in New England record continuous, not delayed, postglacial rebound. *Quaternary Research*, 85(3), pp.399-408.

Hughes, P.D. and Gibbard, P.L., 2015, A stratigraphical basis for the Last Glacial Maximum (LGM). *Quaternary International*, *383*, pp.174-185.

Jahns, R.H. and Willard, M.E., 1942, Late Pleistocene and recent deposits in the Connecticut Valley, Massachusetts. *American Journal of Science*, 240(3), pp.161-191.

Koteff, Carl, and Larsen, F.D., 1998, Surficial geologic map of the Putney 7.5 minute quadrangle, Vermont-New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports GEO-172-024000-SMOF, scale 1:24,000.

Larsen, F.D., 1999, Surficial geologic map of the Spofford 7.5 minute quadrangle, New Hampshire-Vermont: New Hampshire Department of Environmental Services, Open-File Reports GEO-173-024000-SMOF, scale 1:24,000.

Larsen, F.D., and Koteff, Carl, 1997, Surficial Geologic Map of the Keene 7.5' x 15' quadrangle, Cheshire County, New Hampshire, and Windham County, Vermont: New Hampshire Department of Environmental Services, Open-File Reports NH-97-02, scale 1:24,000.

Nelson, A.E., and Nelson, Joan, 2001, Surficial geologic map of the Dublin 7.5 minute quadrangle, New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports GEO-176-024000-SMOF, scale 1:24,000.

Pendleton, R.M., 1998, Surficial Geologic Map of the West Swansey 7.5 minute quadrangle, New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports NH-98-XX, scale 1:24,000.

Pendleton, R.M., 2000, Surficial Geologic Map of the Marlborough 7.5 Minute quadrangle, Cheshire County, New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports NH-00-02, scale 1:24,000.

Pendleton, R.M., 2000, Surficial geologic map of the Brattleboro East 7.5 minute quadrangle, Vermont-New Hampshire: New Hampshire Department of Environmental Services, Open-File Reports GEO-188-024000-SMOF, scale 1:24,000.

Prentice, M.L., 2019, Surficial Geologic Map of the Royalston 7.5' Quadrangle, New Hampshire: New Hampshire Geological Survey, Open-File Reports GEO-205-024000-SMOF, scale 1:24,000.

Prentice, M.L., 2019, Surficial Geologic Map of the Mount Grace 7.5' Quadrangle, New Hampshire: New Hampshire Geological Survey, Open-File Reports GEO-204-024000-SMOF, scale 1:24,000.

Prentice, M.L., 2021, Surficial Geologic Map of the Winchendon 7.5' Quadrangle, New Hampshire: New Hampshire Geological Survey, Open-File Reports GEO-206-024000-SMOF, scale 1:24,000.

Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B. and Wei, J.H., 2012, The new North American Varve Chronology: A precise record of southeastern Laurentide Ice Sheet deglaciation and climate, 18.2-12.5 kyr BP, and correlations with Greenland ice core records. *American Journal of Science*, 312(7), pp.685-722.

Sirkin, L. and Stuckenrath, R., 1980, The Portwashingtonian warm interval in the northern Atlantic coastal plain. *Geological Society of America Bulletin*, *91*(6), pp.332-336.

Stanford, S.D., Stone, B.D., Ridge, J.C., Witte, R.W., Pardi, R.R. and Reimer, G.E., 2021, Chronology of Laurentide glaciation in New Jersey and the New York City area, United States. *Quaternary Research*, *99*, pp.142-167.

Thompson, P.J., 2013, Thoreau on Monadnock: A Philosopher Naturalist's Observations on Geology. *Appalachia*, *64*(1), p.8.

Tinkham, D., Newton, R., Thompson, W., Fowler, B., and Brooks, J., 2022, Surficial Geology of New Hampshire's Lakes Region. Field Trip Guide, 83rd Annual Reunion, Northeast Friends of the Pleistocene. 56p. 5 Maps.

Wheelock, G.A., 1873, Striae on Mount Monadnock. *The American Naturalist*, *7*(8), pp.466-470.