Friends of the Pleistocene - Fieldtrip Log
Lebanon-Hanover Area

Erich C. Osterberg, Andrew J. Smith, Meredith A. Kelly (Dartmouth College)

Introduction: During the Last Glacial Maximum (LGM; ~28-23 ka), the Laurentide Ice Sheet reached its maximum late Wisconsinan extent marked by moraines of Long Island, Block Island and Nantucket (e.g., Balco et al., 2002, Fig. 1). The deglaciation of the Laurentide Ice Sheet in New England and New York has been the subject of significant debate, partially fueled by issues with radiocarbon ages of bulk sediment and marine fossils. Recent work by Ridge (2003, 2004, 2008) and Ridge et al. (1999, 2001) building on the research of Antevs (1922, 1928), has established a high-resolution chronology of deglaciation in New England based on varved lacustrine sediments preserved in the Hudson, Connecticut and Merrimack Valleys. Accelerator Mass Spectrometer (AMS) radiocarbon dating of terrestrial macrofossils within varved sediments provides absolute ages used to calibrate the varve chronologies. Deglaciation based on this chronology is interpreted using basal varves (i.e., varves overlying till or very thick (basal) varves)(Fig. 1).

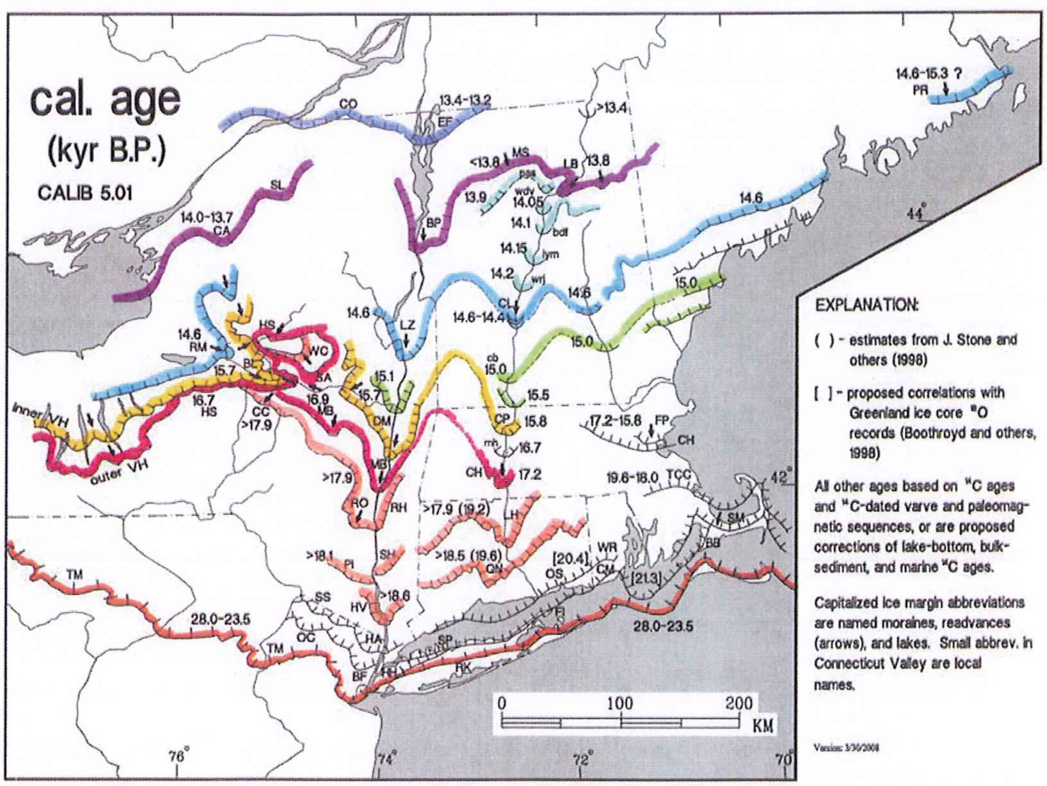


Figure 1. Map of New England and New York showing the maximum extent of the Laurentide Ice Sheet during the LGM and the pattern of ice sheet retreat based on the AMS radiocarbon-calibrated varve chronology (figure from Ridge, 2003).

Drive Log to Stop 1: Take Route 89 to exit 20 in New Hampshire for West Lebanon, Route 12A. Take route 12A south towards Claremont and Plainfield for only 0.1 miles. Turn left at the lights onto Airport Road, and follow for 0.5 miles up the hill to the Lebanon Municipal Airport. Park on the left near the storage lockers.

STOP 1 (30 min). LEBANON MUNICIPAL AIRPORT DELTA AND OVERLOOK. 43°37'46.6"N, 72°18'35.8"W.

The plateau upon which the airport has been constructed is interpreted as the topset beds of a classic Gilbert paleodelta representing the westward drainage of the Mascoma River into glacial Lake Hitchcock (Figs. 2, 3). The airport access road can be approximated as the youngest foreset bed of the delta, with the bottomset Lake Hitchcock varves located within the Connecticut Valley below. This delta was subsequently dissected by the Mascoma River after the drainage of Lake Hitchcock when the Connecticut River became local base level. Sedimentological remnants of the delta are clearly visible to the north of the airport in the form of a large active gravel and sand pit in West Lebanon (Figure 1b). This sand and gravel was likely sourced from the erosion of subaerially exposed till within the Mascoma drainage basin above the Lake Hitchcock shoreline. Within the Mascoma Valley beneath deltaic deposits, Antevs (1922) noted two short (~50 years) sequences of Lake Hitchcock varves, one of which (site 64) represents basal varves overlying ~100 feet of till. The basal varve corresponds to NE varve year 6749, calibrated to *ca.* 14.2 ka (Ridge et al., 1999; Ridge, 2004), and representing deglaciation in the White River Junction region. The 50 year span of these varves (terminating at NE varve year 6801-6802) may represent the time it took for the Mascoma paleodelta to prograde westward over the varve site once the region had been deglaciated.

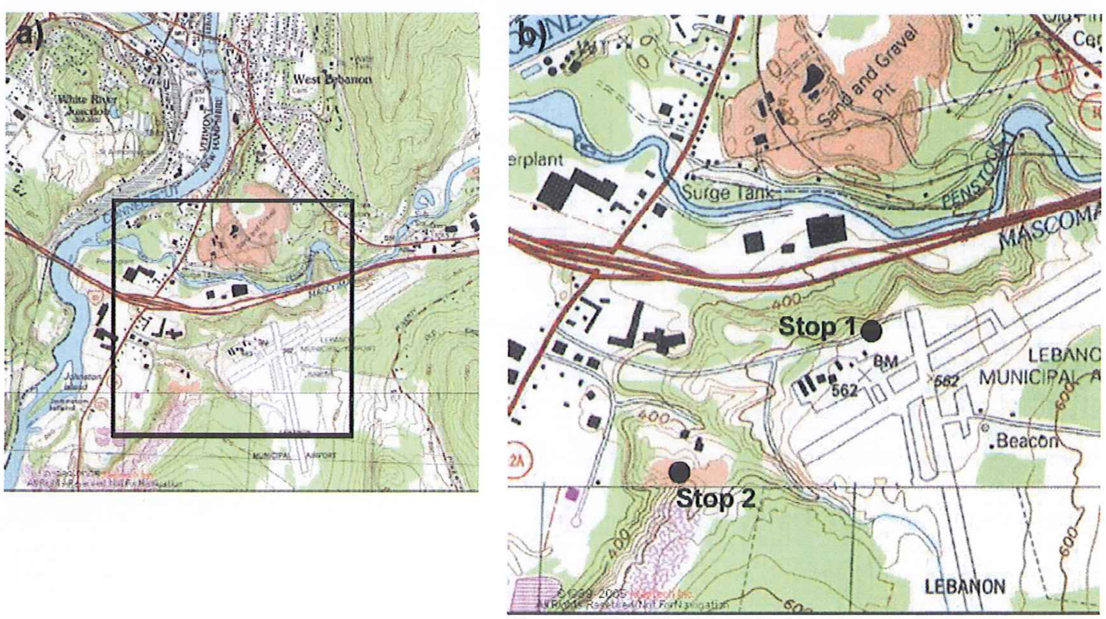


Figure 2*. a) Topographic map and b) detail showing locations of Stops 1 and 2. Note the sand and gravel pit north of Stop 1, and the topographic relationship between topset beds at Stop 1 and bottomset beds at Stop 2. USGS Hanover Quadrangle. Contour interval = 20 feet.*

The 171 m (562 feet) elevation of the airport runway represents a minimum elevation of the Hitchcock lake surface (lake level) during an extended period of relative stability. Estimates of Lake Hitchcock shorelines based on the transition from till (above the lake level) to varves (below the lake level) in the Hanover/Lebanon area indicate a stable level of approximately 171-185 m elevation (Hildreth, 2004). While the timing and character of Lake Hitchcock drainage is still under investigation, recent research by Andrew Smith and Meredith Kelly (Dartmouth College) provides evidence for a drainage event *ca.* 13.1 ka. This would indicate a potential stability period of ~1,100 years between when the White River Junction area was deglaciated *ca.* 14.2 ka (Ridge et al., 1999; Ridge, 2004) and the hypothesized drainage event.

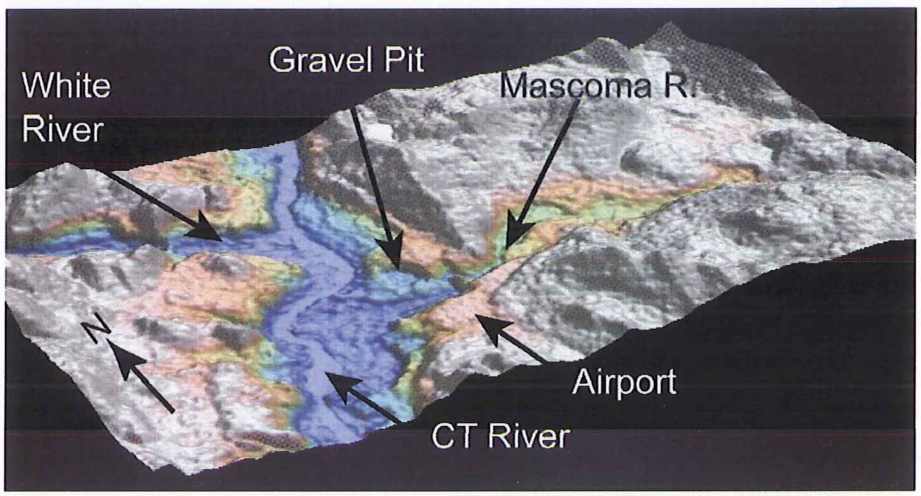


Figure 3*. 3-D digital elevation model (SRTM 30) of the White River Junction region surrounding Stops 1 and 2. Colored contours are below the approximate level of Lake Hitchcock, while white relief is above lake level. The West Lebanon gravel pit is a clear excavation of the north side of the Mascoma paleodelta.*

Drive Log to Stop 2: Return down the airport road hill 0.5 miles to Route 12A. Turn left onto Rt 12A S and take the next left onto Interchange Drive. Continue on Interchange Drive for 0.2 miles, then bear left onto Plaza Heights Road. On the right you will soon see a few warehouses and office buildings part of AH Harris and Sons Construction Supplies. Park your vehicle in the dirt lot to the east of the last warehouse, and follow the badly washed-out dirt road around to the south for ~200 yards, where you will see a section of varves in outcrop.

STOP 2 (45 - 60 min). LAKE HITCHCOCK VARVES BEHIND A.H. HARRIS AND SONS CONSTRUCTION SUPPLY. 43°47'40.1"N, 72°18'21.3"W.
Glacial varves are annual sediment layers deposited in a proglacial lake where laminae are not disturbed by currents or burrowing organisms. Glacial varves consist of a summer and winter layer. In the spring and summer, a glacier's ablation zone undergoes significant melting. This causes larger (generally sand- to silt-sized), more mineral-rich particles to be deposited in the glacial lake. The thickness of the summer layer varies depending on volume of meltwater discharge and the availability of erodable sediment. A common feature of the summer layer is a distinct graded bed of sand and silt that marks the beginning of a spring melt season. The winter layer of a varve consists mostly of organic-rich clay (>90%). The winter layer represents the non-melt season of a glacier, when the only sediment and hydrologic input is from sub-glacial and groundwater sources. During the winter the pro-glacial lake is likely ice covered, so that winds or currents would not affect lake circulation. The lake-ice cover creates a low-energy depositional environment where clays may be deposited continuously. The varves at this site have numerous carbonate (~40-45 wt. %) concretions, which are common throughout the NE varves (Pardi, 1983).

Drive Log to Stop 3. Follow Plaza Heights Road to Interchange Drive and back to route 12A. Turn Right onto route 12A north, and continue 1.3 miles. Turn left at South Main Street in West Lebanon, and continue 0.3 miles. Turn left onto Bridge Street/Rt 4 west and continue 0.5 miles. Turn right onto Rt 5 north and continue 3.8 miles to the Norwich Farmer's Market on your right.

STOP 3. (10 minutes). FLAT TOPOGRAPHY ALONG RT 5 NEAR THE NORWICH FARMER'S MARKET. 43°41'53"N, 72°19'02.2"W.
The relatively flat landscape in this region of Norwich and Wilder, VT represents the surface of the accumulated Lake Hitchcock sediments (varves) when the lake was drained (Fig. 4). To put it another way, this region represents the flat lake floor. The 167 m (550 feet) elevation of these "plains" indicates that this region would have been below approximately 20 m of water. The Connecticut River Valley would have been eroded down to bedrock by the Laurentide Ice Sheet, with a thin layer of ground till deposited as the ice sheet retreated. The Lake Hitchcock shoreline (~600 feet) can be identified in outcrop on the hills to the west as the transition between lake clays and silt (including varves) below and

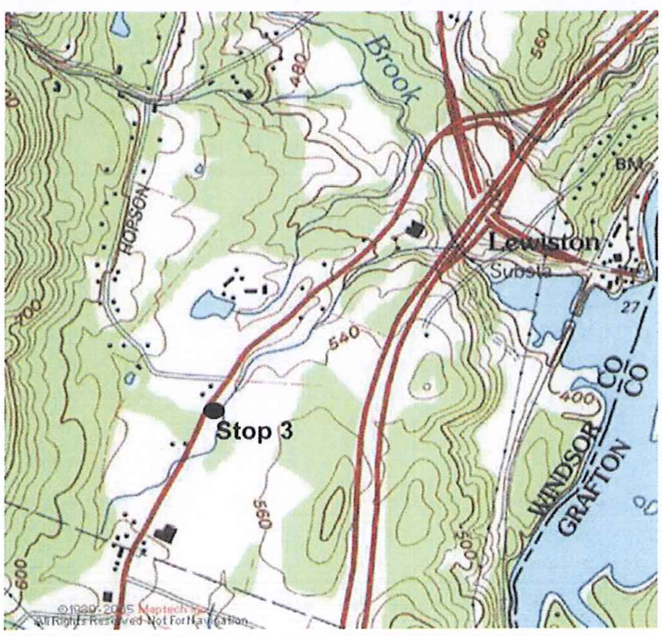


__Figure 4.__ Topographic map of the region surrounding Stop 3. USGS Hanover Quadrangle. Contour interval = 20 feet.

bedrock with a thin layer of till above.

Drive Log to Stop 4. Drive north on Rt 5 for 0.8 miles to a set of lights at South Main Street. Turn right on South Main Street and continue for 0.5 miles passing under the Rt 91 overpass. Turn left onto River Road (just before the bridge to Hanover), and continue 3.4 miles on Rt 5 N to the Gravel Pit.

STOP 4. (30-45 minutes) GRAVEL PIT IN HANOVER ESKER, NORWICH, VERMONT. 43°44'20.5"N, 72°15'23.2"W.

This stop will look at the sand- and gravel-sediment associated with the Hanover Esker, remnants of which can be traced at sporadic locations parallel to the Connecticut River over a distance of ~50 km from North Thetford, VT to Windsor, VT (Goldthwait, 1921). The Esker crosses the modern Connecticut River into New Hampshire just south of Stop 4, where it trends between the River and Occom Pond and continues south towards West Lebanon.

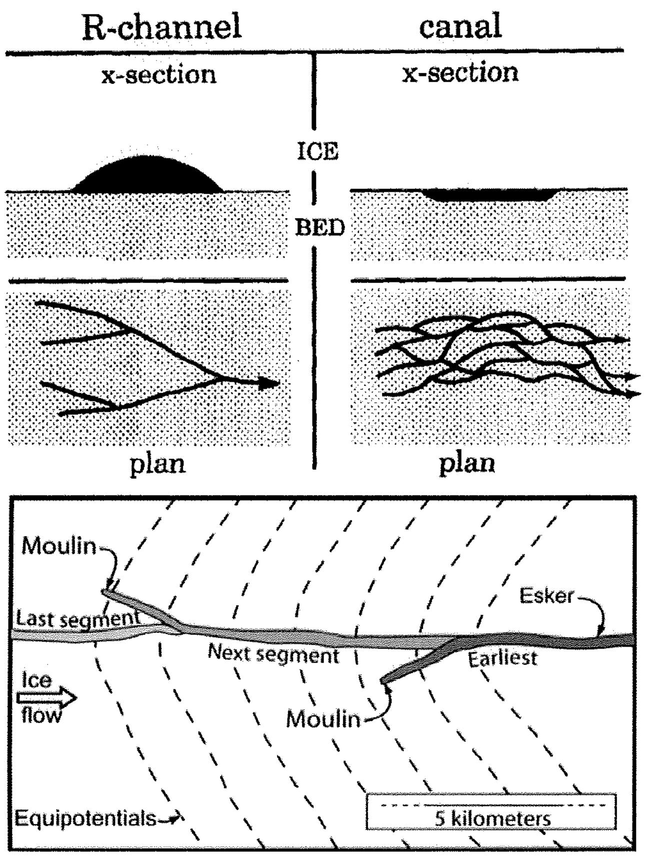


Figure 5. Top: Comparison of R-Channels in which Eskers form, to subglacial canals eroded into the substrate (from Clark and Walder, 1994). Bottom: Plan view model of time-transgressive esker formation via moulins close to the retreating ice sheet margin (from Hooke and Fastook, 2007).

Eskers are long (up to hundreds of km's), often sinuous ridges of ice-contact sediment with a typical height of 20 m and a typical width of 150 m (Flint, 1971; Shreve, 1985). Eskers form within subglacial tunnels, known as Rothlisberger channels (or R-channels), near the largely stagnant terminus of a retreating ice sheet. R-channels are carved into the base of the ice sheet by running water with walls of ice and a typically flat bottom of till or bedrock, as opposed to canals cut into the subglacial substrate with a flat ice surface above (Clark and Walder, 1994). This shape of the subglacial tunnel gives eskers their characteristic morphology, with a single sharp crest and fairly steep sides in cross-section, and a sinuous ridge in plan view (Flint, 1971; Shreve, 1985). Eskers often have branches or spurs, representing the arborescent subglacial drainage network in which they formed (Clark and Walder, 1994). Most researchers interpret a time-transgressive origin of eskers, with formation limited to within several kilometers of the retreating ice margin. While subglacial melting is a significant source for the water melting the R-Channels, penetration of surface meltwater to the ice sheet base via moulins is generally required to form large-sale eskers (Clark and Walder, 1994; Hooke and Fastook, 2007). Thus, one can imagine moulins forming in the summer melt season, feeding sub-glacial R-Channels that subsequently fill with sediment and progressively deposit an esker.

Eskers typically consist of moderately to poorly sorted sand, gravel and boulders (a few of which can be over a meter in diameter) deposited in a high energy environment (Shreve, 1985). Sedimentary structures such as cross-bedding and ripples are generally absent, and bedding is poor and discontinuous. In general, bedding forms an anticlinal structure with beds dipping away from the esker axis. This has been interpreted as a result of slumping of the esker walls after the ice confines were removed, and/or due to the initial deposition of sediment at the esker crest with subsequent migration down its flanks (Shreve, 1985). As eskers are depositional features, the sediment is sourced from melting of the R-Channel walls by the flow friction, rather than erosion of ground moraine. Thus, the esker is composed of sediment that was entrained in the basal ice due to scouring and plucking immediately upstream from the esker (Shreve, 1985). For this reason, esker sediment lithology is closely tied to that of the regional bedrock (Flint, 1971; Shreve, 1985).

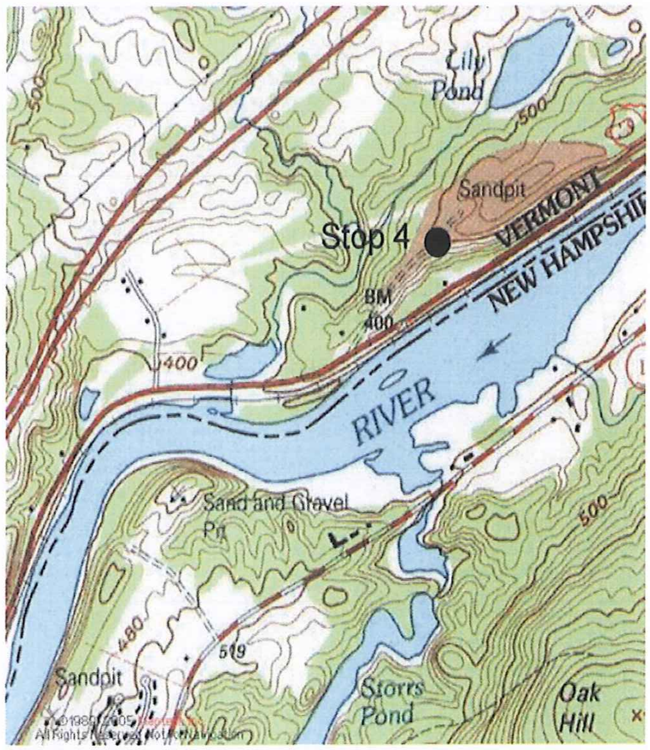
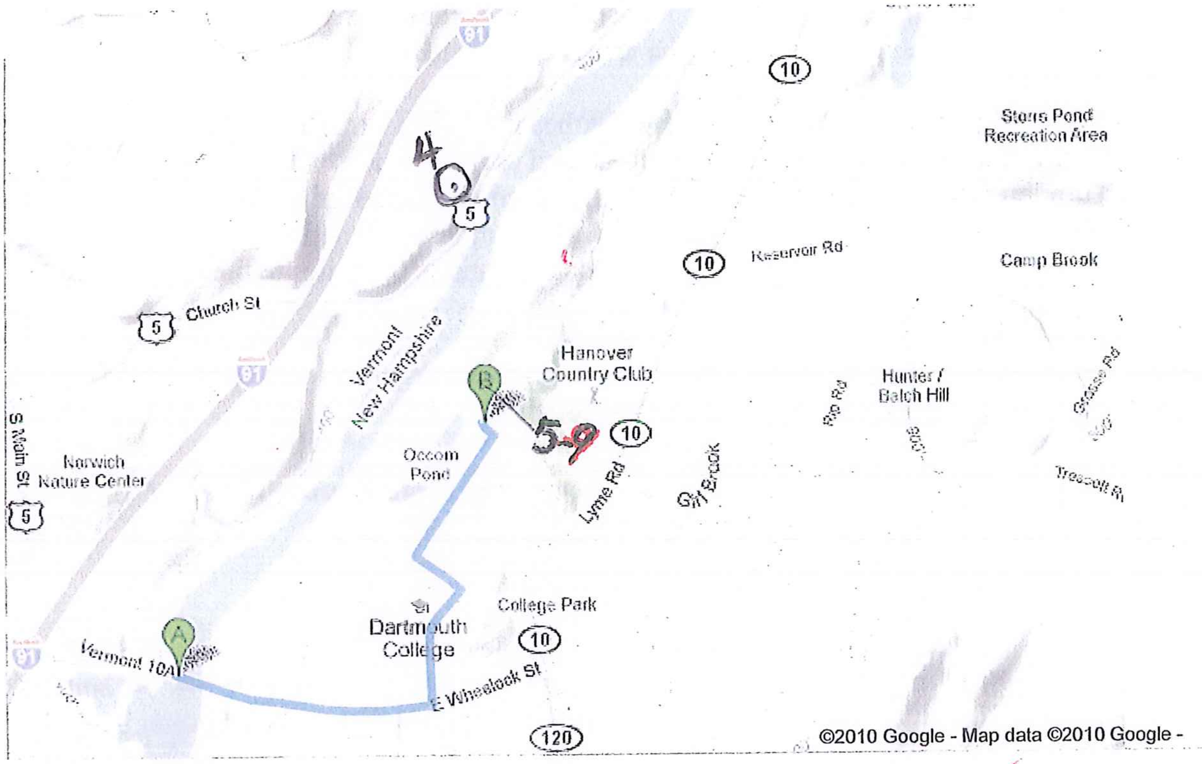


Figure 6. *Location map for Stop 4 showing the Hanover Esker in north Norwich, VT, crossing the CT River as it trends SW towards Hanover, NH (follow the "sand and gravel pits"!). USGS Hanover Quadrangle. Contour interval = 20 ft.*

The Hanover Esker can be difficult to discern on topographic maps because the Lake Hitchcock sediment has draped the feature and the Connecticut River's natural channel can mask the esker's relief. It is of typical size and shape, with an undulating, steeply-sided surface averaging ~20 m above its surroundings, and a sinuous form. It would have been deposited as the Laurentide Ice Sheet retreated *ca.* 14.1 ka, and immediately submerged beneath the surface of Lake Hitchcock, where it was draped and onlapped by varves. Eskers form perpendicular to ice surface gradients (along the



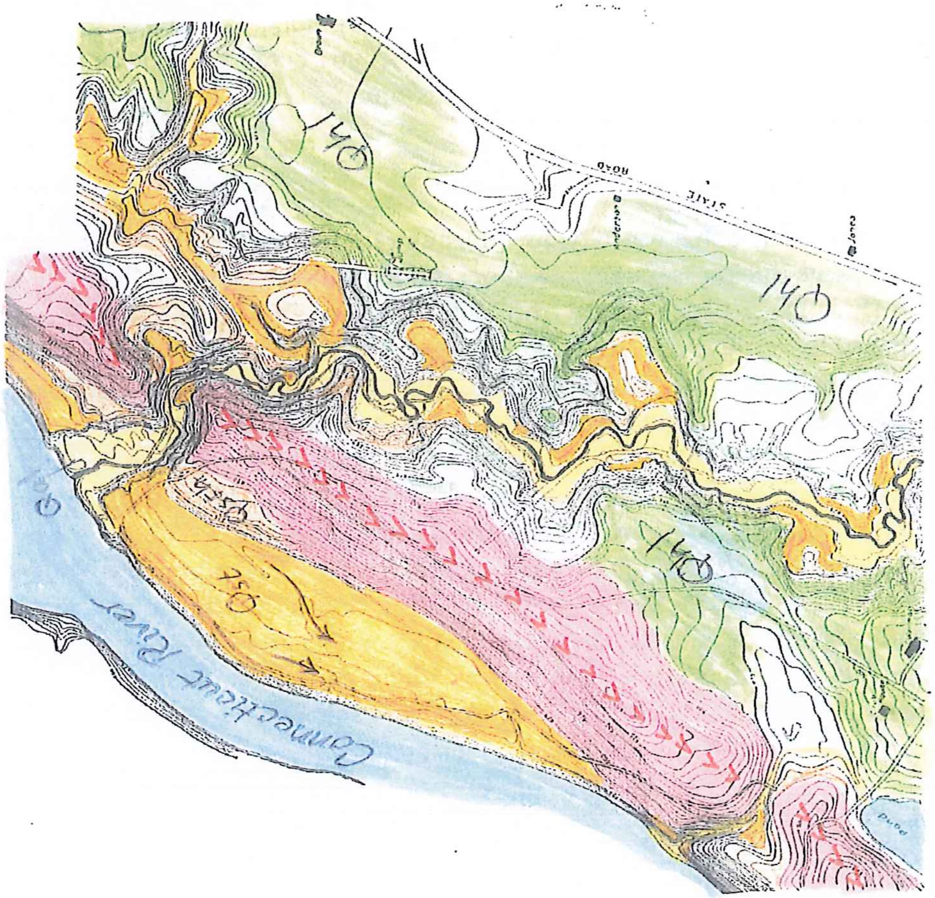


FIGURE 20. Contour map of part of the Hanover Country Club grounds and the Pine Park, showing in detail the sculpture of the Hanover plains by Girl Brook. Terraces of horseshoe form, far above the present valley floor, mark the old meanders of this stream when it was beginning to intrench itself in the clay deposits. The huge size of these old meanders is thought to mean that rainfall at that time was much heavier than now.

(From Goldthwaite, 1925) Contour Interval = 5 feet.

Colored Units interpreted by E.T. Hildreth.

maximum equipotential slope), and thus the N-NE trend of the Hanover Esker provides clues about local ice dynamics as the ice sheet retreated.

Drive Log to Stop 5: From the gravel pit, head south on Rt. 5 (River Road) for 2.3 miles. Bear left at the fork to stay on River Road and continue another 1.1 miles to a stop light. Turn left onto Trescott Rd/Vermont 10A and continue 0.7 over the Wheelock Bridge into Hanover, NH. Turn left at College St and go 0.3 miles. Turn left at Maynard St. and take the next right at N Main St/Rope Ferry Road. Continue 0.3 miles to the DOC House on Occom Pond next to the Dartmouth Golf Course.

STOP 5. (60 minutes). DARTMOUTH OUTING CLUB (DOC) HOUSE ON OCCOM POND. 43°42'44.4"N, 72°17'09.2"W.

Sediment cores from Occom Pond, Hanover, NH: A multi-proxy record of environmental change since ~14 ka

Introduction

Using a Livingstone piston corer, multiple sediment cores were retrieved from Occom Pond in March 2009 (MK0901A, B and C; 43.71084°N, 72.28784°W) and January 2010 (OP1001A and B; 43.71050°N, 72.288819°W). Modern water depth in Occom is ~2.14 m. Cores MK0901A, B and C are adjacent to each other and offset at depth. Together these cores yield a continuous ~9 m-long sediment record. Cores OP1001A and B are from ~100 m south of the MK0901 cores and yield an ~9 m-long sediment record. Senior thesis research by Dartmouth undergraduate Andrew Smith has developed a radiocarbon and varve chronology of the MK0901 cores and a multi-proxy record of environmental conditions registered by the sediments (Figs. 7, 8, 9). Andrew's research is summarized below.

Radiocarbon and varve chronologies

A chronology for the cores was developed using radiocarbon dating of organic material as well as varve thicknesses. Eight radiocarbon ages were obtained from cores MK0901A and B (Fig. 7). All samples are from plant macrofossils, some of which may have been growing at the surface of Occom while it was a peat bog. Radiocarbon ages were calibrated to calendar years before present (ka) using the online program Calib 6.0 based on the IntCal09 dataset (Reimer et al., 2009). The basal radiocarbon age (11,300±60 ^{14}C yr BP; 13.1-13.3 ka; OS-74173) from core MK0901A is of an ~1cm x 1cm piece of wood from a depth of 9.46 m below lake level. The piece of wood was extracted from homogenous clay ~4 cm above varved sediment. All ages above this in cores MK0901A and B are in stratigraphic order except for the radiocarbon age 3,380±30 ^{14}C yr BP (3.5-3.7 ka; OS-77537), from a depth of 8.25 m below lake level. We suggest that this apparently young age is because we sampled a younger plant root that extended into deeper sediments. One radiocarbon sample was obtained from core OP1001A. This radiocarbon age (11,040±60 ^{14}C yr BP; 12.7-13.1 ka; Beta-275320) is of a cluster of leaves from a depth of 11.4 m below lake level. This age is older than we would expect and is not included in the core age model. The core age model (Fig. 7) shows continuous a nearly constant sedimentation rate throughout the Holocene, with somewhat lower sedimentation rates during the glacial-interglacial transition.

The laminated sediments at the base of the Occom cores were interpreted as varves, comprised of winter (clay) and summer (silt/fine sand) couplets. We counted ~400 varves in cores MK0901A and B and measured the thicknesses of these varves. An attempt was made to correlate these varves with the varve section from Newbury, Vermont (Ridge and Toll, 1999), located ~50 km up the Connecticut Valley from Hanover. We based our initial estimate of varve correlation on the radiocarbon age (11,300±60 ^{14}C yr BP; 13.1-13.3 ka; OS-74173) from just above varved sediment in core MK0901A. We estimate that the top of varved sediment in the Occom cores is approximately varve year (vyr) 7900 of the New England Varve Chronology (Ridge, 2004).

Varves of this age in the Upper Connecticut Valley are assumed to be "distal" or "non-glacial" varves, since the Laurentide Ice Sheet margin had receded farther north, and was not in contact with Glacial Lake Hitchcock (Ridge and Toll, 1999; Ridge, 2003, 2004). For some parts of the Occom core, we had difficulty identifying annual varve couplets because laminae are very thin and sometimes contain split winter beds. Therefore, we attempted to correlate five-year running averages of varve thicknesses in the Occom core with the varve record from Newbury, VT (Ridge and Toll, 1999). Sediment accumulation in distal or non-glacial varves was likely controlled by local runoff so there may have been significant variability in varve thicknesses deposited at distant localities.

Fig. 8 shows an approximate correlation between the Occom varves and the Newbury varves (Ridge and Toll, 1999). We estimate that the significant increase in varve thickness observed in the Newbury record approximately correlates with the end of varved sedimentation in the Occom cores. In addition, thick summer beds in the Occom varves were interpreted to represent regional hydrologic events. We suggest that these beds in Occom correlate with thick summer beds in the Newbury varve record (Ridge and Toll, 1999) at vyr 7923, 7794, 7704, 7636, 7605 (Fig. 8).

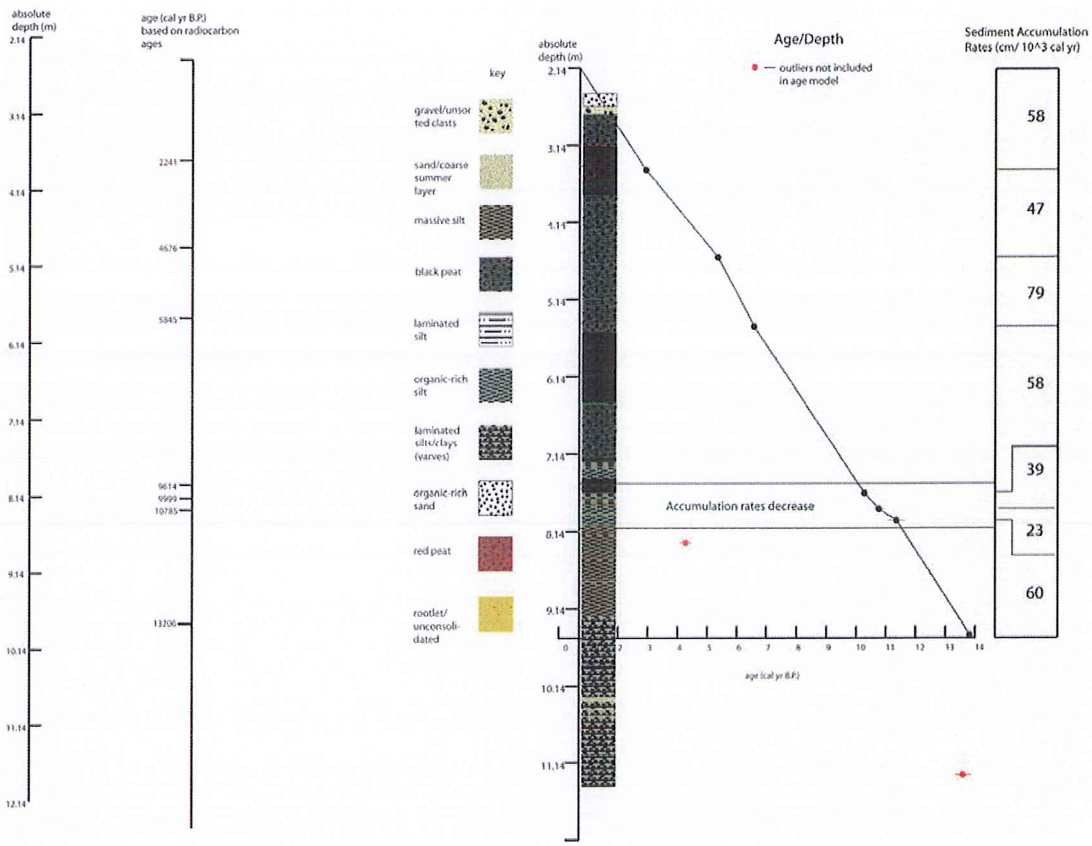


Figure 7. *Age-depth model of the Occom Pond cores MK0901A and B. Black points show calibrated radiocarbon ages with horizontal bars indicating 2σ uncertainties. Red points show two calibrated radiocarbon ages not used in the age model. The visual stratigraphy is a combined section of representing both A and B cores.*

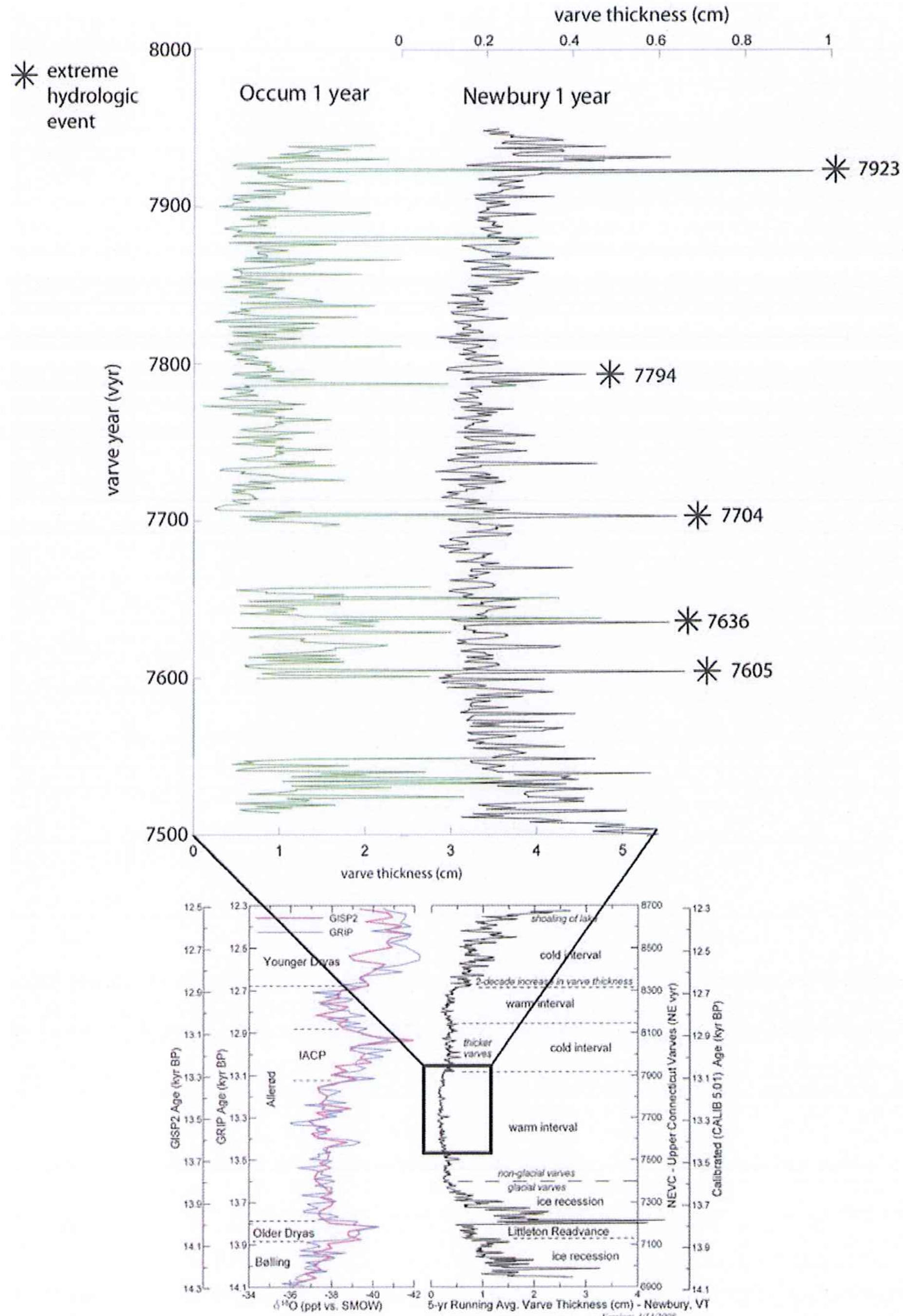


Figure 8. *Approximate correlation between Occom Pond varved sediments and varves from Newbury, Vermont (Ridge and Toll, 1999). Also shown is the New England Varve Chronology record that shows the increase in varve thickness at ~vyr 7920 (Image from Ridge and Toll, 1999). We interpret this varve thickness increase to have resulted from the lowering of the level of Glacial Lake Hitchcock.*

Multi-proxy records

Multi-proxy records for the MK0901 cores include visual stratigraphy, magnetic susceptibility, loss-on-ignition, grain-size, and Carbon and Nitrogen isotopic data (Fig. 9). The visual stratigraphy, magnetic susceptibility and loss-on-ignition data all show a transition at ~11.1-9.5 ka from a glacial clay and silt dominated lacustrine environment to a peat bog. This transition was not smooth, but was interrupted by intermediate, organic-rich lacustrine sediments and finally very organic rich, gyjtta and peat. One interesting segment of the core occurs just above the varved silt and clay. This segment consists of ~1 m of homogenous gray clay with some silt (Fig. 8). Grain-size analyses of sediment in this segment show particle-size distributions very similar to those of the underlying varved sediments. We hypothesize that the homogenous sediment may have been varved, but that laminae were disturbed by bioturbation. We suggest that bioturbation in this segment may have occurred due to a lowering of lake level after vyr 7900. Carbon and Nitrogen isotopes and C/N ratios were measured on organic material in the peat segment of the cores. These data do not show significant variation but would likely indicate the influence of terrestrial or subaqueous vegetation.

Interpretations and discussion

The Occom Pond cores are significant because they provides a sedimentary record of the last deglaciation of the Hanover region, the climatic transition from glacial to interglacial conditions and the environmental conditions and variability during the Holocene Epoch.

We suggest that a comparison of varved sediments in cores from Occom Pond (146 masl), Post Pond (127 masl) in Lyme, New Hampshire, and the Newbury varve section (Ridge and Toll, 1999) yields information about the lowering of the level of Glacial Lake Hitchcock. As discussed above, varved sediments in the Occom cores are overlain by homogenous clay with some silt. The timing of this transition (~vyr 7900) is similar to the timing of an increase in varve thickness in the Newbury section (at ~vyr 7920; Ridge and Toll, 1999). A new core from Post Pond obtained by the authors also yields a varved sediment correlative with the Newbury varve section. The Post Pond varves show a transition from thinner to thicker varves at ~vyr 7920. We suggest that, at vyr 7920, the level of Glacial Lake Hitchcock lowered to between 146 and 127 masl. This lake level lowering removed Occom Pond from the glacial lake basin, and resulted in Occom being a very shallow lake fed by runoff in the local catchment area and influenced by bioturbation. The level of Glacial Lake Hitchcock must have been higher that ~127 masl, since Post Pond was still within the glacial lake basin, receiving varved sedimentation. We suggest that the increase in varve thicknesses in the Post Pond varves and Newbury varves at ~7920 is a result of lake level lowering and enhanced erosion of shoreline sediments.

Although for most of the Holocene, Occom was a bog that contained a thick accumulation of organic material, some notable events may be observed in the sediment record. Fluctuations in visual stratigraphy, magnetic susceptibility, and loss on ignition during the early Holocene suggest local environmental changes associated with the 9.5 and 8.2 cold events registered by Greenland ice cores and North Atlantic Ocean sediments (e.g., Alley et al., 1997; Bond et al., 1997)(Figs. 7, 9). A shift from black oxidized fibrous peat (725-655 cm below lake level) to reddish-brown peat consisting of large soft-bodied organics (655-525 cm below lake level) may represent an increase in the water level at Occom between 9-6 ka. The uppermost sediments of Occom register a shift from peat to sand and gravel with overlying organic rich silt. This transition out of peat bog conditions likely represents the formation of Occom Pond as we know it today, which was dammed in 1920 by a Dartmouth College professor who lived in the area and believed that the bog was "unsightly".

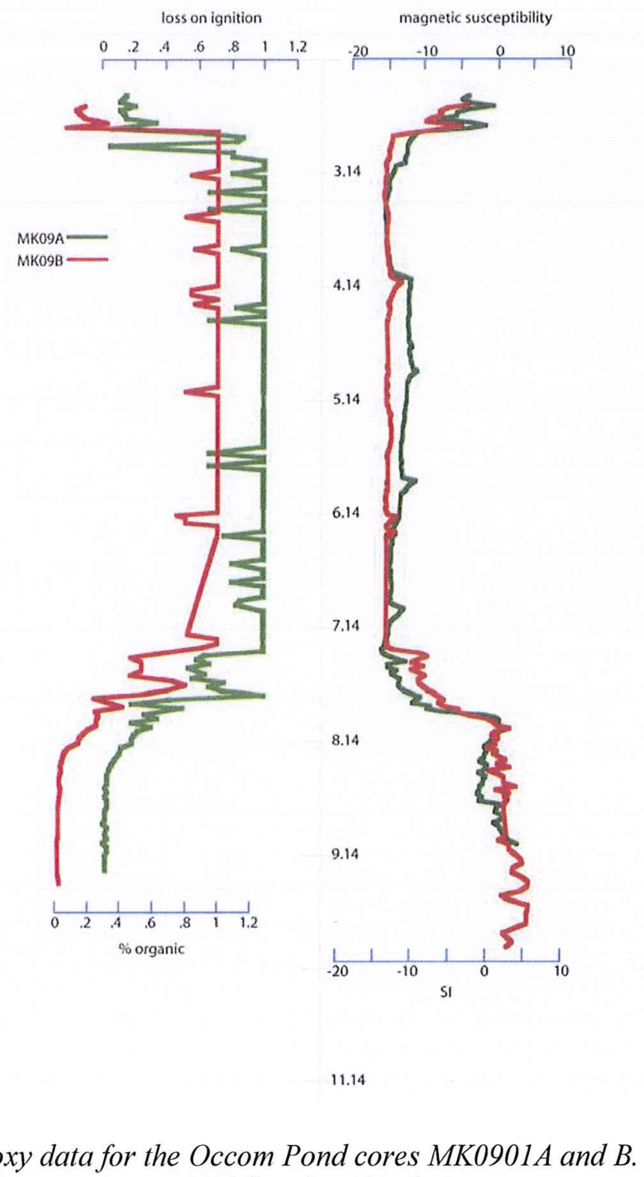


Figure 9. *Multi-proxy data for the Occom Pond cores MK0901A and B. Shown are the loss-on-ignition and magnetic susceptibility data for the cores.*

WALK FROM THE DOC HOUSE TO STOP 6 ALONG THE HANOVER ESKER CREST (~15 minutes).

Leave vehicles parked at the DOC house and walk along the Hanover Esker on the west side of Occom Pond (known as Occom Ridge) and the Hanover golf course. We will walk north on the esker until we reach a trail which goes down to the Girl Brook delta into the modern Connecticut River. While walking along the crest of the esker, note its steep sides, undulating crest, and sinuous form. The sand and gravelly nature of the sediment underfoot can sometimes be seen where the soil is thin on steep slopes. Also note the difference in vegetation growing on the esker (trees that thrive in well-drained soils like paper birch), and the Hitchcock sediments below (trees that thrive in poorly-drained soils like maple).

STOP 6 (30 minutes). TRANSITION FROM ESKER TO GLACIAL LAKE HITCHCOCK SEDIMENT. 43°43'16.2"N, 72°16'45.3"W.

While we cannot see a definitive contact between the esker and Hitchcock varves, we can see a transition in the soil/surface sediment and an associated change in the vegetation. The sand, gravel and cobbles of the esker are replaced by fine sand and silt associated with the Lake Hitchcock sediments. Hitchcock sediment can be seen by digging out the channel edge of Girl Brook, while esker deposits can be seen by digging into the flanks of the esker.

Walk to Stop 7: We will walk roughly S-SE along a path next to Girl Brook (away from the CT River) for about 10 minutes until we reach Stop 7. Note how Girl Brook has dissected the Lebanon Plain representing Hitchcock varves. Steep active slopes flanking the brook show evidence of mass wasting and characteristic bent tree trunks indicative of soil creep.

STOP 7. (30 MINUTES). SLUMPED GLACIAL LAKE HITCHCOCK VARVES. 43°43'05.4"N, 72°16'45.9"W.

Along girl brook there is a location where Lake Hitchcock varves have been slumped due to undercutting of the steep slope by Girl Brook. The back-rotated varve bedding planes confirm that the sequence of thin (distal) varves has been slumped from a location higher within the Hitchcock sediments. These ~3 mm thick varves are from much higher in the Lake Hitchcock sediment column than the ~20 cm thick varves we observed at Stop 2.

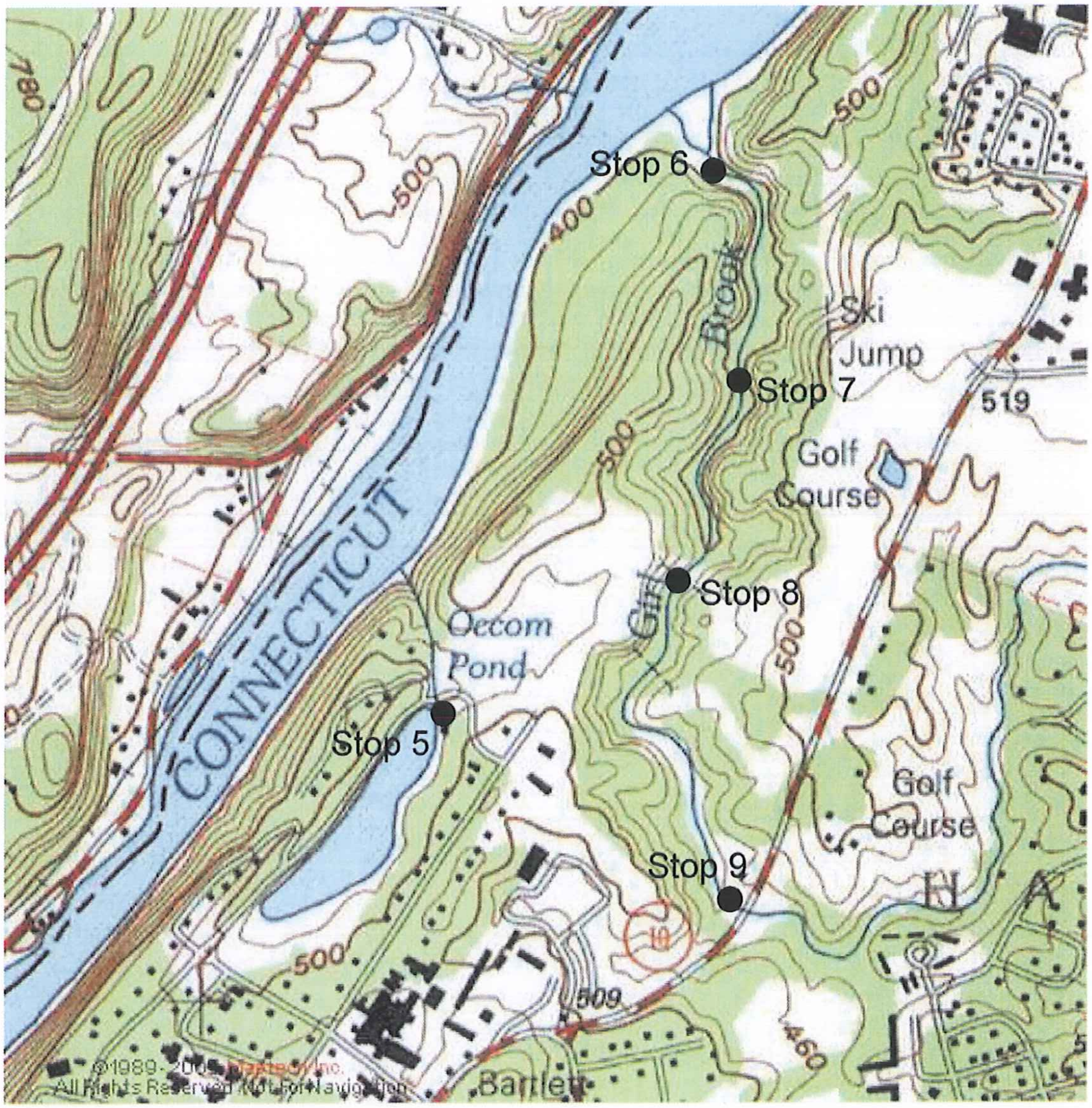


Figure 9. Topographic map and location for Stops 5-9. USGS Hanover Quadrangle. Contour interval = 20 feet.

Walk to Stop 8: Continue walking south along Girl Brook for another ~10 minutes to reach Stop 8, which is marked by the position where a golf-cart bridge passes overhead, 50 feet above Girl Brook.

STOP 8. (45 MINUTES). CROSS-BEDDED SANDY DEPOSIT WITH MASS WASTING. 43°44'20.5"N, 72°15'23.2"W.

This location along Girl Brook is marked by a large, recent mass wasting scar related to undercutting of the slope by Girl Brook. Here, however, rather than varves, we find a thick sequence of cross-bedded sands with climbing ripples and other high-energy sedimentary features. While we are still developing an interpretation of this deposit, it may be related to paleodrainage between Balch Hill and Oak Hill located to the east (Fig. 10). It may also represent reworking of esker sediment during a high-energy lake drainage event.

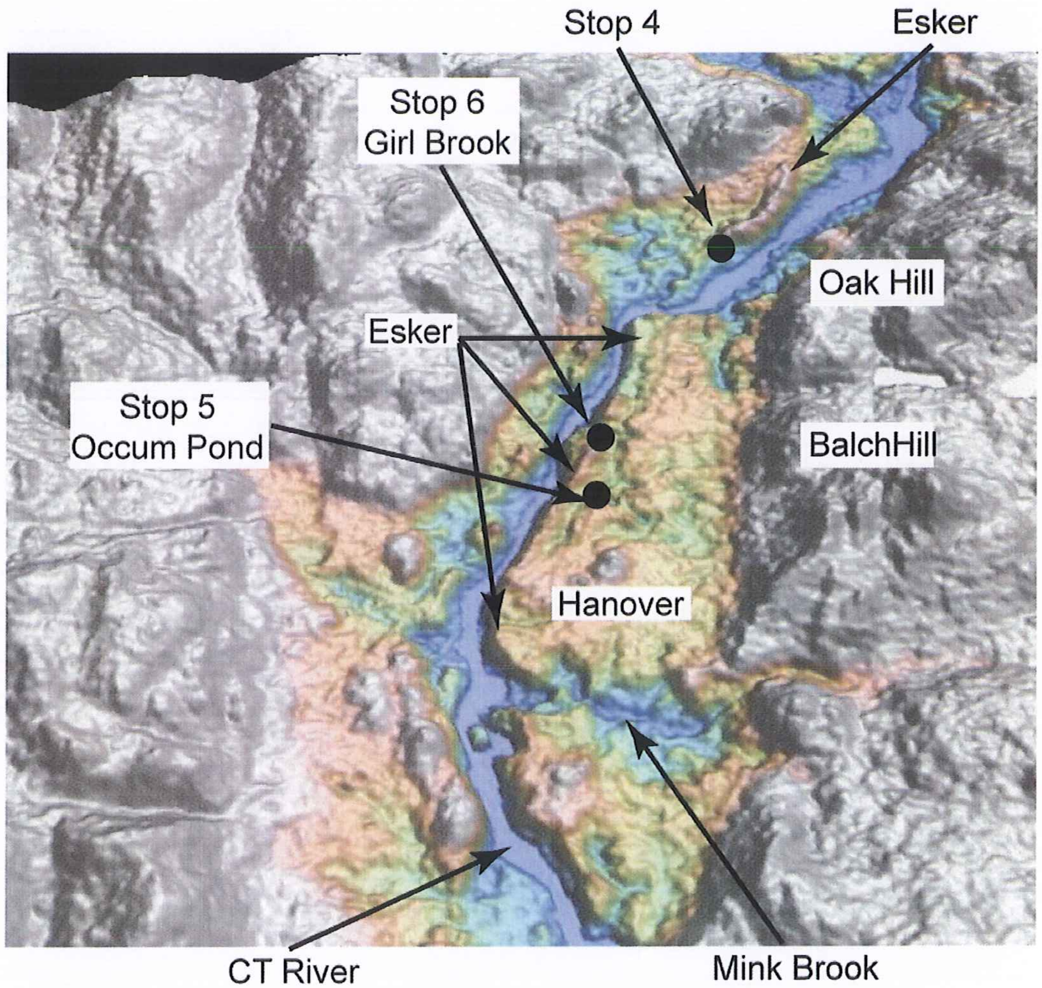


Figure 10. *3-D digital elevation model (SRTM 30) of the Hanover, NH region, showing the Hanover Esker, Hanover Plain, regional topographic features, and the locations of Stops 4, 5 and 6. Colored contours are below the approximate level of Lake Hitchcock, while white relief is above lake level.*

Walk to Stop 9: Continue walking SE along Girl Brook for ~10-15 minutes until you reach Rt. 10. On either side of Rt. 10 along Girl Brook there are two more outcrops of Hitchcock varves.

STOP 9. (15 MINUTES). GLACIAL LAKE HITCHCOCK VARVES. 43°42'33.1"N, 72°16'40.8"W.
These two outcrops of Hitchcock varves along Girl Brook on either side of Rt. 10 are thicker than the slumped varves we saw at Stop 7, and akin to the varves we observed at Stop 2 in West Lebanon. Unlike the varves at Stop 7, these do not show evidence of back rotation indicative of slumping, or any other evidence of mass wasting. Given the higher elevation of this stop compared to Stop 7 (we walked upstream), and given that varves thin up-section as the ice sheet sediment source becomes more distal, an interpretation of the Stop 7 varves as slumped is further corroborated.

References cited

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., and Clark, P.U., 1997. Holocene climatic instability: A prominent, widespread event at 8200 yr ago. *Geology* **6**, 483–486.

Antevs, E., 1922. The recession of the last ice sheet in New England. *American Geographical Society Research Series* **11**, 120.

Antevs, E., 1928. The last glaciations with special reference to the ice sheet in North America. *American Geographical Society Research Series* **17**, 292.

Balco, G., Stone, J.O.H. Porter, S.C., and Caffee, M., 2002. Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA. *Quaternary Science Reviews* **21**, 2127-2135.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G., 1997. A pervasive millenial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**, 1257–1266.

Clark, P.U., and Walder, J.S., 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian Ice Sheets. *Geological Society of America Bulletin,* **106**, 304-314.

Flint, R.F., 1971. *Glacial and Quaternary Geology.* New York: John Wiley and Sons, 892 pp.

Goldthwait, J.W., 1921. Geology of the Hanover District.

Hooke, R.L., and Fastook, J., 2007. Thermal conditions at the bed of the Laurentide ice sheet inMaine during deglaciation: implications for esker formation, *Journal of Glaciology* **53**, 646-658.

Pardi, R.R., 1983. The origin of carbonate concretions within glaciolacustrine and glaciomarine sediments of the Northeast United States. *Unpublished PhD Dissertation,* University of Pennsylvania, 358 pp.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey , C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J. and Weyhenmeyer, C.E., 2009. INTCAL 09 and MARINE09 radiocarbon age calibration curves, 0-50,000 years Cal BP. *Radiocarbon*, **51**, 1111-1150.

Ridge, J.C., 2008. "The North American Glacial Varve Project": (http://ase.tufts.edu/geology/varves), sponsored by The National Science Foundation and The Geology Department of Tufts University, Medford, Massachusetts.

Ridge, J.C., 2004. The Quaternary glaciation western New England with correlations to surrounding areas. *In* (Ehlers, J., and Gibbard, P.L., Eds.) *Quaternary Glaciations – Extent and Chronlogy, Part II.* Elsevier, Amsterdam, the Netherlands, 169-200.

Ridge J.C., 2003. The last deglaciation of the Northeastern United States: a combined varve, paleomagnetic, and calibrated ^{14}C chronology. *In* (Cremeens, D.L., and Hart, J.P., Eds.) *Geoarcheology of Landscapes in the Glaciated Northeast.* New York State Museum Bulletin **497**, The State Education Department, Albany, NY, 15-45.

Ridge, J.C., and Toll, N.J., 1999. Are late glacial climate oscillations recorded in varves of the upper Connecticut Valley, northeastern United States? *Geologiska Foreningens I Stockholm Förhandlingar* **121**, 187-193.

Ridge, J.C., Canwell, B.A., Kelly M.A., and Kelley, S.Z., 2001. Atmospheric ^{14}C chronology for late Wisconsinan deglaciation and sea-level change in eastern New England using varve and paleomagnetic records. *Geological Society of America Special Paper* **351**, 171-189.

Ridge, J.C., Bensonen, M.R., Brochu, M., Brown, S.L., Callahan, J.W., Cook, G.J., Nicholson, R.S., and Toll, N.J., 1999. Varve, paleomagnetic, and 14C Chonologies for late Pleistocene events in New Hampshire and Vermont (U.S.A.). *Geographie Physique et Quaternaire* **53**, 79-107.

Shreve, 1985. Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. *Geological Society of America Bulletin* **96**, 639-646.