Rapid Retreat of a Marine-Terminating Margin of the Laurentide Ice Sheet in the Seacoast Region of New Hampshire, USA

Julia E. Brazo
University of New Hampshire

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RAPID RETREAT OF A MARINE-TERMINATING MARGIN OF THE LAURENTIDE ICE SHEET IN THE SEACOAST REGION OF NEW HAMPSHIRE, USA

By

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B.A. Physics & Mathematics, State University of New York at Geneseo, 2019

THESIS

Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of Master of Science in Earth Science: Geology

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ABSTRACT

A better understanding of the transition of marine-terminating margins of the Laurentide Ice Sheet (LIS) to land-based termini is instructive for monitoring modern glaciers that are currently undergoing a similar transition and influencing sea-level. Expanded knowledge of regional ice retreat rates and the timing of deglaciation of the LIS also provides insight on mechanisms of ice sheet retreat and collapse. Here we reconstruct the style and timing of ice recession and attendant marine regression in coastal New Hampshire during the last deglaciation. Our approach involves geospatial analysis of glaciomarine deposits to assess regional marine limit variability combined with $^{10}$Be surface exposure dating of glacial features to evaluate the potential for contrasting exposure histories above and below the marine limit during deglaciation. Geospatial analyses reveal a variable marine limit from north to south in New England with maximum elevations of glaciomarine deposits ranging from 20 meters near Boston, Massachusetts, 57 to 103 meters within the Seacoast of New Hampshire, and up to 152 meters in central Maine. We report 13 new $^{10}$Be exposure ages from erratics and bedrock distributed throughout the Seacoast region along an elevation transect that extends above and below the marine limit. Our results suggest rapid retreat of the LIS margin through the Seacoast of New Hampshire and indicate that the glacier front transitioned from marine- to land-terminating at \(~17 \text{ ka. Exposure ages of erratics below the marine limit suggest rapid postglacial marine regression from ~ 17–16 ka. Our reconstructions of rapid rates of deglaciation and marine regression are consistent with previously published regional ice recession rates and sea-level histories. However, the timing of deglaciation is ~1-2 ka earlier than suggested by recently compiled isochron maps of former ice margin positions in New England during the last deglaciation.}
CHAPTER I: INTRODUCTION

The Laurentide Ice Sheet (LIS) covered most of northern North America during the Last Glacial Maximum (LGM), a period from 26.5 ka to 19 ka when ice sheets on Earth reached their maximum extent and global eustatic sea-level was at a minimum (Clark et al., 2009). The LIS was one of the largest ice masses on Earth during the LGM and constituted the majority of the North American Ice Sheet (NAIS) complex which also included the Cordilleran, Inuitian, and Greenland Ice Sheets (Figure 1).

![Map of the North American Ice Sheet Complex (NAISC), including the Laurentide, Cordilleran, Inuitian, and Greenland Ice Sheets, during the LGM. The red box highlights the New England region which includes the field area of this study in coastal New Hampshire. Base map of North America is a topographic relief map constructed by the United States Geological Survey, 2022. The maximum extent of the NAISC vector file was download as a supplement of Dalton et al. (2022).]

At its maximum extent, the LIS reached the edge of the continental shelf with marine margins in the northern Arctic and eastern margins of the ice sheet. The LIS, which initiated over the eastern Canadian Arctic, was highly sensitive to changes in climate due to its extension into
lower latitudes and marine margins, as well as the temperate nature of the ice sheet (Clark et al., 1993; Lowell et al., 1999; Dorion et al., 2001; Kaplan, 2007). As a vast dynamic system with an estimated maximum area of $1.3 \times 10^7$ km², the LIS had asynchronous maxima in different regions across northern North America during the LGM (Dyke et al., 2004; Dalton et al., 2020).

Detailed reconstructions of the past extents and dynamics of the LIS are valuable for understanding mechanisms of ice sheet retreat and collapse during glacial terminations and ice sheet-climate interactions. During its growth and decay, the LIS influenced ocean circulation, sea-level changes, and changes to the Earth’s lithosphere (Broccoli and Manabe, 1987; Bond et al., 1993; Clark et al., 2009, Birkel, 2010). The LIS also held approximately 50 meters of sea-level equivalent and consequently, the growth and melting of the LIS was a major contributor to global and local sea-level fluctuations during the late Pleistocene and Holocene (Stokes, 2017). Constraints on the regional glacial and sea-level history are important for assessing ice sheet morphometry, geologic factors, and climatic influences on both regional and local scales that control ice sheet variability (Stokes, 2017).

Marine-terminating and land-terminating glacial systems behave and respond differently to changes in local factors and climate conditions. Due to limited observations of marine-terminating systems, the processes involved in the stability or collapse of marine-terminating glaciers are not completely understood. Still, modern observations reveal that marine-terminating glaciers behave more dynamically and are more vulnerable to rapid ice loss, flow acceleration, and surface thinning due to calving processes and ocean conditions (Vieli, 2021). Understanding this transitional stage is valuable for evaluating modern glaciers such as those in Greenland and Antarctica that are currently undergoing a similar transition and leading contributions to modern-day sea-level rise (Bamber et al., 2018; Catania et al., 2020; Vieli, 2021).
The LIS margin along the New England coast from Boston to northern Maine was temperate, marine-terminating, and highly erosive in low-relief regions. Erosional and depositional processes beneath the LIS dramatically modified the landscapes of northern North America, leaving behind glacial landforms and deposits that document the history of the ice sheet. Yet in many regions, including New England, comprehensive knowledge of the glacial history of the LIS is incomplete, thus hindering efforts to assess ice sheet impacts on regional sea-level and isostasy during the late Pleistocene (Dalton et al., 2020). This study reconstructs the timing, rate, and style of ice retreat and the associated marine regression in the Seacoast region of New Hampshire, hereafter referred to as “NH Seacoast”, where previous investigations have been limited.

Age control for the timing of deglaciation in New Hampshire following the LGM has been developed at only a few sites (Ridge et al., 1999; Thompson et al., 1999; Balco et al., 2002; Bromley et al., 2015; Hodgdon, 2016; Corbett et al., 2019; Bromley et al., 2020). The ice retreat chronology in the NH Seacoast remains sparsely documented due to complexities related to regional inundation of coastal areas caused by local glacio-isostatic effects and eustatic sea-level rise following ice recession. Surface exposure dating chronologies have been established at other localities in New Hampshire, including moraine systems in the White Mountains (Balco et al., 2009; Bromley et al., 2015; Bromley et al., 2020). While there are moraines in the NH Seacoast, they formed subaqueously and therefore are not a typical target for surface exposure dating (Sinclair et al., 2018). There is also a scarcity of organic material available for radiocarbon dating of glacial deposits in this area (Kelley et al., 1992; Ward & Adams, 2001; Dalton et al., 2020). This project provides the first direct age control for ice retreat and the associated rate of marine regression in the NH Seacoast using in situ $^{10}$Be surface exposure dating.
To gather evidence for when the LIS transitioned from a marine- to a land-terminating margin in the NH Seacoast, we obtained $^{10}$Be exposure ages from samples collected above and below the marine limit. This sampling strategy involves a seldom-used approach for $^{10}$Be surface exposure dating, as most exposure dating studies avoid previously submerged locations because of the complications involved in interpreting exposure ages affected by temporary shielding by water. However, this study intentionally targets sites below the marine limit in order to determine the timing of marine regression in the NH Seacoast.

Radiocarbon-based sea-level curves from northern Massachusetts and coastal Maine document overall rapid marine regression, variable marine limits from north to south, and different timings of highstands and lowstands across New England during the late Pleistocene (Oldale et al., 1993; Kelley et al., 2010). The New England coastline experienced a spatially complex pattern of marine regression due to differing magnitudes and rates of localized subsidence and post-glacial isostatic rebound. In this study, we assessed the variability of the marine limit across the field area and the entire New England coast through a geospatial analysis of glaciomarine deposits in New England. This study assembles the first detailed regional synthesis of marine limits in New England and provides improvements over previous studies due to the availability LiDAR data for elevation measurements. Assessment of how sea-level has fluctuated in the past is valuable to evaluating future sea-level change that threatens our coastlines today (Love et al., 2016).
2.1: Geologic Setting

Bedrock in the NH Seacoast is composed of metasedimentary and plutonic igneous rocks (Figure 2) (Novotny, 1969; Lyons et al., 1997). These bedrock lithologies are the primary source material for surficial deposits, including glacially transported sediments, in the NH Seacoast.

Figure 2: Map of the bedrock geology of the NH Seacoast (NH GRANIT). White dots show the locations of surface exposure samples collected for this study and described in the methods section, Chapter 3. Most boulder samples are suspected to be from the Exeter Pluton, Eliot Formation, or Concord Granite. Concord Granite, a member of the New Hampshire Plutonic Suite, is a gray two-mica granite. The Eliot Formation is metasedimentary, a constituent of the Merrimack group, and composed of gray to green phyllite, calcareous quartzite, quartz-mica schist, and well-bedded calc-silicate. The Exeter Pluton is one of the two major intrusive bodies of the NH Seacoast. Exeter diorite is an intrusive igneous unit found throughout the Seacoast region and the largest member of the unit is the Exeter Pluton. Exeter diorite is a coarse-grained, light to dark rock unit that contains biotite-quartz diorite, pyroxene-amphibole diorite, granodiorite, gabbro, and granite (Novotny, 1969; Bothner, 1974; Lyons et al., 1997).
Glacial landforms and deposits in the NH Seacoast were largely created during the last glacial period by the LIS and are used in this study to reconstruct the local ice sheet history (Bradley 1964; Dyke et al., 2002). As the LIS retreated from the landscape, rock debris was released from the melting ice, deposited in ice-contact landforms, and transported by meltwater. Till deposited during the last deglaciation blankets the bedrock surface of southeastern New Hampshire as a gently irregular and discontinuous layer that ranges from 5 to 60 meters thick (Figure 3). Other depositional landforms such as glaciomarine deltas, kames, kettles, eskers, recessional moraines and De Geer moraines, and erosional features such as roches moutounées are found in the Seacoast (Bradley, 1964). The NH Seacoast has individual drumlins that are well-distributed throughout the region, such as Hick’s Hill, and a swarm of drumlins found in the south (Figure 3) (Bradley, 1964; Novotny, 1969).

De Geer moraines are clustered, narrow ridges that form subaqueously at a previous ice front in coastal regions, recording the interactions between the LIS and the sea. In previous work, Sinclair et al. (2018) investigated the origin of De Geer moraines in the NH Seacoast as revealed by LiDAR imagery and stratigraphic characteristics, but did not develop any age control. Our project expands on this earlier work by providing new exposure ages for this locality. Although De Geer moraine formation is still debated, the findings of Sinclair et al. (2018) suggest that they formed in the NH Seacoast due to annual oscillations of a marine-terminating ice front where winter advances pushed sediment at the base of the ice margin and summer calving caused retreat. The average spacing between these annually deposited De Geer moraines implies a retreat rate of approximately 100 m a⁻¹. Curvilinear orientations of tight clusters of De Geer moraines provide evidence for a lobate margin in the Seacoast suggesting that ice flow was still active and dynamic during overall LIS recession.
Figure 3: Surficial geology map of southeastern New Hampshire within the context of this project. Surficial geology layers were downloaded from NH GRANIT. Samples collected in this study are highlighted by white points and described in the method section, Chapter 3. Glacial till and glaciomarine deposits are shaded in yellow and red, respectively. Glaciomarine deposits illustrate the extent of prior marine inundation. The thick black line demonstrates an assumed marine limit of 70 meters above present-day sea-level. There are two missing quadrangles (white boxes) of glaciomarine deposits in the southwest region of the map.
Glaciomarine deposits were deposited at and in front of the ice margin during glacier recession when the LIS was marine-terminating and local sea-level rose due to glacio-isostatic effects and eustatic (global) sea-level changes, inundating coastal New England (Figure 3) (Belknap et al., 1987; Kelley et al., 1992; Barnhardt et al., 1995; Licht, 2009). The distribution of glaciomarine sediments delimits zones of previous marine inundation as they were deposited over other deposits or glacially eroded surfaces when erosion was absent. However, glacial readvance and erosion can erase glaciomarine records; therefore, these deposits mark the minimum extent of marine inundation (Licht, 2009). These glaciomarine deposits include the Presumpscot Formation, raised glaciomarine outwash deltas, raised beaches, and radiocarbon dated fossils, seaweed, and wood (Bloom, 1963, Stuiver & Borns 1975, Dalton et al. 2020). The Presumpscot Formation is characterized as layered submarine silts and clays composed of very fine-grained minerals such as quartz, felspar, and micas that originated from the local bedrock and formed in a proglacial marine environment. The Presumpscot Formation has been extensively studied since the 1800s, but was not named until 1960 by Bloom, who examined exposures along the Presumpscot River Valley in southern Maine, near Portland. In coastal Maine, the Presumpscot Formation is very common and expansive, however it is ambiguous whether the glaciomarine deposits in New Hampshire are also associated with this unit. Radiocarbon ages from fossils of marine organisms embedded in the Presumpscot Formation in Maine provide age control for the timing of marine submergence and constrain relative sea-level changes for coastal Maine between 14,000 and 11,000 years BP (Bloom, 1963; Stuiver & Borns, 1975; Smith, 1985; Retelle & Weddle, 2001; Kelley et al., 2010). However, these radiocarbon ages from localities in Maine, north of the Seacoast of New Hampshire, are not a direct indication of the timing of marine submergence in New Hampshire.
2.2: Sea-Level History in New England

The NAIS complex was a major contributor to global sea-level changes as it was a repository of 80 ± 8 meters of global sea-level equivalent (Simms et al., 2019). At the LGM, eustatic sea-level was approximately 134 meters lower than present-day sea-level and when New England reached its highstand, global sea-level was at least 70 m below present day (Belknap et al., 1987; Lambeck et al., 2014). The position of the New England coastline varied during the Pleistocene due to eustatic changes and the advances and retreat of the LIS which induced isostatic changes. The maximum altitude or highstand reached by sea-level is referred to as the marine limit. Local sea-level was strongly influenced by glacial isostatic adjustment (GIA) as loading of the LIS depressed the Earth’s crust and unloading of the LIS caused the depressed lithosphere to rebound (Thompson et al., 1989; Barnhardt et al., 1995). When the crust is depressed isostatically, the total downward displacement of the crust depends on the thickness and density of the ice sheet and the properties of the mantle below (Peltier, 1999). Isostatic depression or rebound can be determined by subtracting the eustatic sea-level from local relative sea-level observations (Koteff et al., 1993). This happened along the New England coastline as the LIS began to retreat and the sea submerged the present-day coast from Boston to northern Maine in contact with the grounded, tidewater ice margin (Thompson et al., 1989).

When ice sheets melted following the LGM, water that was held up in ice sheets was released back into the oceans and eustatic sea-level began to rise. However, in New England the rebound rate of the Earth’s crust initially outpaced eustatic sea-level rise and local sea-level fell rapidly to the lowstand (Kelley et al., 1996). Eventually, the rate of eustatic sea-level rise surpassed crustal rebound rates. During the Holocene, eustatic sea-level changes were the dominant control on local sea-levels (Kelley et al., 1996).
Glaciomarine deposits in coastal New England record the geographic extent of past marine inundation caused by glacial isostatic depression (Figure 4). Glaciomarine deposits in New Hampshire and southern Maine extend above 70 meters altitude (Belknap et al., 1987; Ward & Adams, 2001). Previously published highstands of glaciomarine deposits in New England also suggest spatially variable marine limits from north to south. Marine inundation in New England reached up to 100 kilometers inland in lowlands and 175 kilometers inland in major river valleys. This study creates a regional synthesis of variable marine limits by geospatially analyzing glaciomarine deposits in New England.

Figure 4: Map of glaciomarine deposits in coastal New England highlighting the variable marine limit with different highstands (HS) and lowstands (LS) at different localities. GIS data for the surficial geology in Northeastern Maine is incomplete. Therefore, glaciomarine deposits represented in Maine are not shown in their entirety.
Well-documented sea-level curves and marine limits in New England are vital for testing and reconstructing total isostatic depression and rebound (Oakley & Boothroyd, 2012; Baril et al., 2023). Relative sea-level curves for northern Massachusetts and coastal Maine were created based on radiocarbon dating of paleo deltas, marine fossils from glaciomarine clays, shells from a submerged barrier beach, and freshwater peat (Figure 5). The Maine sea-level curve is better constrained with more radiocarbon ages than the northern Massachusetts curve. Radiocarbon ages constrain maximum and minimum sea-level elevations above and below the interpolated curves (Figure 5). The timing of highstands and lowstands have been resolved by radiocarbon dating of organic material found in glaciomarine deposits (Figure 4) (Oldale & Colman, 1993; Barnhardt et al., 1995; Kelley et al., 2010). Lowstands are marked by now-submerged deltas that formed during marine regression, and highstands are recorded by inland glacial-marine deltas.
that formed during marine transgression (Kaye & Barghoorn, 1964; Thompson et al., 1989). Investigations of ice-contact deltas, submarine fans, and stratified end moraines deposited across submerged zone of New England is evidence that the LIS margin was marine and grounded to the bed due to shallow water depths.

In Northern Massachusetts, the highstand of +33 meters occurred at approximately 17,000 cal years BP and the lowstand of -43 meters occurred at 13,500 cal years BP (Oldale & Coleman, 1993; Hein et al., 2012). In coastal Maine, the highstand of +70 meters was reached approximately 14,000 cal years BP and the lowstand of -60 meters below PSL occurred 12,500 cal years BP. Radiocarbon ages from fossils of marine organisms embedded in the Presumpscot Formation in Maine range from approximately 14,000 to 11,000 years BP (Bloom, 1963; Stuiver & Borns, 1975; Smith, 1985; Retelle & Weddle, 2001). These ages estimate that the timing of marine inundation following ice recession probably lasted less than 2,000 years (Thompson, 1987; Baril et al., 2023). The sea-level curves for Massachusetts and Maine both exhibit late Pleistocene submergence followed by pre-Holocene emergence and late Holocene re-submergence, but have different rates of regression and transgression due to variable magnitudes of glacial isostatic adjustment (Oldale,1986; Oldale & Coleman, 1993; Barnhardt et al., 1995; Hein et al., 2012; Kelley et al., 2010). Although dated sea-level indicators are sparse in New Hampshire, the trend in sea-level changes for the NH Seacoast is expected to fall somewhere between the curves for northern Massachusetts and coastal Maine.

In coastal Maine, marine regression caused by crustal rebound was more rapid than northern Massachusetts with a rate of approximately 43 mm/yr (Kelly & Belknap, 1996). The Maine sea-level curve exhibits a slowstand between 11,500- and 7,500- cal years BP when sea-level only rose less than 5 meters due to regional isostatic adjustment and change in meltwater
events (Kelley et al., 2010). At 7,500 years BP, sea-level began to rise rapidly again before decreasing to historic rates that reached present-day sea-level (Figure 5) (Gehrels et al., 1996; Kelley et al., 2010).

Radiocarbon dating of paleoshoreline features suggests that levels of marine inundation and altitudinal ranges between highstands and lowstands have varied over time at different coastal localities in New England (Figure 4a). Ice thickness differences caused varying degrees of GIA from south to north along the New England coast. Thicker ice in the north caused greater isostatic depression and greater marine submergence. The timing and rate of ice retreat and eustatic sea-level rise produced variable rates and degrees of post glacio-isostatic effects from south to north along the New England coast (Quilan & Beamount, 1981; Oldale & Colman, 1993; Barnhardt et al., 1995). Throughout New England, lowstands range from -21 to -65 meters below present-day sea-level and highstands range from 18 to 130 meters above present-day sea-level. There is evidence to suggest that the scale of the lowstands in coastal Maine could be partially attributed to the migration of a forebulge through the region. The forebulge had an estimated 20-25 meters amplitude and rate of migration of 7 to 11 kilometers per 1,000 years (Barnhardt et al., 1995).

2.3: Chronology of Deglaciation in New England

During the late Pleistocene, growth of the LIS began approximately 116 to 100 ka, and reached its maximum extent around 26 to 25 ka (Stokes, 2017). Although the landscape of New Hampshire contains abundant glacial landforms created by the LIS during the last glacial period, age control for deglaciation following the LGM has been well-established at only a few sites in New Hampshire. Glacial chronologies in New England are derived from terminal and recessional moraines, and mountain peaks using cosmogenic beryllium-10 exposure dating, and varves and
glaciomarine deltas using radiocarbon dating (Figure 6). In New Hampshire, cosmogenic nuclide exposure dating has been utilized in the central and northern region, but most deglaciation chronologies in the state are derived from radiocarbon ages (Ridge et al., 2012; Bromley et al., 2015). Radiocarbon dating of glacial landforms has not been developed in the Seacoast region due to absence of focused efforts in the region and scarcity of organic material available for radiocarbon dating. The dearth of organic material associated with glacial deposits in the NH Seacoast is likely because vegetation was scarce in New England’s glacial environments during the late Pleistocene (Balco & Schaefer, 2006).

Figure 6: a) Map of overall ice retreat chronology for New England. Surface exposure ages are highlighted by yellow points. Ice retreat isochrons (dashed lines) are shown for context (Dalton et al., 2020). Thirteen localities were dated used the dipstick method.* b) Map of established radiocarbon chronology in New England. Minimum-limiting radiocarbon ages (red triangles) were compiled by Dalton and others (2020). Labeled radiocarbon ages are the median of the average minimum values from each site, presented in cal years BP. Time-averaged ice margin positions (isochrons) are constructed from the radiocarbon ages and shown in orange (19.5 cal ka), yellow (18.0 cal ka), green (16.8 cal ka), blue (15.5 cal ka), purple (14.9 cal ka), and pink (14.2 cal ka) (Dalton et al., 2020). The maximum extent of the LIS is illustrated by the black line and inferred from the terminal moraine of the LIS.
2.3.1: Radiocarbon Chronology

Varve records are annual layers that were deposited by meltwater in proglacial lakes during ice retreat (Ridge et al., 2003). The North American Varve chronology (NAVC) is based on a 5659-year sequence of varved lake sediments in glacial Lakes Hitchcock and Merrimack that were dated based on $^{14}$C ages of fossils and organic matter (Ridge and Larson, 1990; Ridge and Toll, 1999; Ridge, 2012). The NAVC extends from central Connecticut to the northernmost border of New Hampshire and Vermont and ages sequentially range from 18.6 to 13.4 cal ka, respectively. The NAVC provides a detailed timeline for deglaciation in New England at specific locations coinciding with the former locations of proglacial lakes and yields ice retreat rates for New England during the Pleistocene (Dyke et al., 2003; Ridge et al., 2003). Based on the NAVC, from 18 to 16 ka the LIS retreated at a rate of 30-40 m/yr. The initial ice retreat rate of the LIS through southern New Hampshire was 90 m/yr between 15.5 and 14.6 cal ka and increased to 300 m/yr after 14.6 cal ka as the ice retreated further north (Ridge et al., 2003; Ridge et al., 2012). Varve records from Glacial Lake Merrimack, approximately 20 kilometers north and 100 kilometers west of the coast, also suggest that ice retreated from the NH Seacoast prior to 15.1 ka and provide a broad chronological constraint on deglaciation (Ridge, 2008).

In addition to the NAVC, radiocarbon dating of organic units found in glaciolacustrine sediments cored from modern lake environments and glaciomarine deposits found on the landscape or on the seafloor has been developed throughout the region. Sediments that were deposited in past glacial lake or glaciomarine environments and overlay glacial till also provide minimum ages of ice retreat (Thompson et al., 1999; Dyke et al., 2003). There are extensive radiocarbon ages from these deposits in Maine and northern New Hampshire, but published radiocarbon ages are completely lacking in the NH Seacoast (Figure 6b).
Dalton and others (2020) provide the most up-to-date and comprehensive ice margin chronology for the LIS with 36 radiocarbon-based isochrons that track retreat of the LIS. The updated ice retreat isochrons by Dalton and others (2020) include radiocarbon datasets between ~21.7 cal ka and ~0.9 cal ka that were published between 2003 and 2018. The updates in New England are heavily based on the NAVC and site-specific radiocarbon ages from shell and/or plant material found in glaciomarine and glaciolacustrine sediments (Borns Jr. et al., 2004, Ridge et al., 2012). Radiocarbon ages are younger than the timing of ice retreat due to variable biological lag times, specifically the time it took for plants to develop and grow following deglaciation and the stratigraphic relationship between the glaciolacustrine or glaciomarine sediments and the underlying till. In regions where a range of ages are published, Dalton and others (2020) constructed the isochrons based on the oldest published ages from individual sites in a stratigraphic series. When few age constraints are available in a given region, Dalton and others (2020) constructed the new isochrons based on only reliable points or maintained the previously published margins (Figure 6b) (Dyke et al., 2003). Not every data point shown in Figure 6b was used as a control point for ice retreat isochron construction. The isochrons are not intended for high-resolution interpretations on a local scale or resolutions finer than 1:1,000,000. The isochrons that are drawn closest to the field area of this study are ambiguous and based on one average of radiocarbon ages from the inner continental shelf off the coast of New Hampshire. This sediment core only provides a minimum age for deglaciation as the age is derived from the average of ages from eleven macrofossils found in the glaciomarine clay layer that overlays lodgment till (Birch, 1990). The ages from the glaciomarine clays range from 13,670 to 11,920 radiocarbon year BP which is generally consistent with measurements from the Presumpscot formation in coastal Maine. The major shortcoming of radiocarbon dating is that it
indirectly dates paleo-ice margin positions and only provides minimum-limiting ages for
deglaciation by dating deposits that are stratigraphically above glacial deposits. Results from
Birch (1990) are the first and only indirect age control for deglaciation in the Seacoast, which
estimate that deglaciation occurred no later 14,500 radiocarbon years BP.

2.3.2: Cosmogenic $^{10}$Be Exposure Ages

Cosmogenic $^{10}$Be surface exposure dating has been applied to glacial landforms at a
growing number of localities in New England (Figure 8) (e.g., Balco et al, 2002; Balco et al.,
2009; Bromley et al., 2015; Bierman et al., 2015; Davis et al., 2015; Hall et al., 2017; Barth et
al., 2019; Corbett et al., 2019; Koester et al., 2020; Halstead et al., 2022). Some of these studies
have focused on exposure dating of ice-marginal features to define ice retreat patterns whereas
others have exposure-dated elevation transects (“dipsticks”) to constrain ice thinning rates. Our
study marks the first application of surface exposure dating to the NH Seacoast.

The terminal moraine complex in Martha’s Vineyard, Nantucket, and Long Island
delimits the maximum extent of the LIS with a recalculated exposure age of 27.5 ± 2.2 ka. Early
retreat of the ice margin is marked by the Buzzards Bay recessional moraine on Cape Cod, which
is dated to 20.3 ± 1.2 ka (Balco et al. 2002; Halsted et al., 2022). Initial retreat from the terminal
moraine occurred at estimated rates of 10 to 30 m/yr (Ridge et al., 2012; Stanford et al., 2020).

Recessional moraines in Massachusetts and northern New Hampshire mark ice
readvancement or periods of ice stagnation followed by ice retreat. In northern New Hampshire,
three moraine systems mark past ice-margin positions and have been dated by $^{10}$Be, the
Androscoggin (13.2 ± 0.4 ka), the Littleton-Bethlehem (13.8 ± 0.2 ka), and the Berlin (13.7 ± 0.6
ka) moraines (Figure 6a). Together these moraine complexes mark a readvance or stabilization of
the LIS during the Bølling-Allerød and are evidence that the LIS margin was north of the White
Mountains in New Hampshire by 14 ka (Balco et al., 2009; Bromley et al., 2015; Bromley et al., 2020). The Pineo Ridge moraine complex in northern coastal Maine was also produced by readvancement of the LIS approximately 15.0 ± 0.2 ka (Hall et al., 2017). There is a large geographic gap in coastal New England geochronology and a wide time interval between the ages from coastal southern Massachusetts and northern New Hampshire and Maine, and the field area of this study is between these sites.

The dipstick approach of exposure-dating elevation transects has been employed at thirteen localities with high relief throughout New England (Figure 6a). Ages from these peaks provide evidence for ice thinning rates in New England, but also mark the beginning of deglaciation at those localities. Dipstick results suggest that most peaks within 150 kilometers of the LGM margin in New England were uncovered by 18 ka (Bierman et al., 2015; Corbett et al., 2019; Koester et al., 2021; Halsted et al. 2022). Between 17 and 15 ka, the LIS thinned more than 600 meters across the region while the ice margin was retreating at a rate of 90 m/yr (Ridge et al., 2012; Halsted et al., 2022). Cosmogenic nuclide inheritance in bedrock samples on mountain peaks also reveal that high relief regions in northern New England were covered by non-erosive cold-based ice. Therefore, the LIS in New England is interpreted to have been polythermal with a subglacial thermal boundary at approximately 1200 meters above present-day sea-level (Kleman & Glasser, 2007; Bierman et al., 2015; Corbett et al., 2019; Halsted et al., 2022). The highest peak in Maine, Katahdin, was uncovered ~2-3 ka later than most peaks in New England as it was exposed 15.5 ka. Ages from high peaks in Maine indicate that thinning of the LIS in Maine was rapid between 15.5 and 14.5 ka, which was also when ice began to retreat from coastal Maine (~15 ka) (Davis et al., 2015; Hall et al., 2017; Koester et al., 2017).
The closest exposure ages to the field area of this project come from Mount Major (15.3 ± 0.8 ka), Mount Monadnock (15.4 ± 0.5 ka), and Wachusett Mountain, MA (exposure ages range from 17.7 ± 0.7 ka to 16.2 ± 0.8 ka) (Hodgdon, 2016; Halsted et al., 2022). The three exposure ages closest to the NH Seacoast agree well with the radiocarbon-based ice retreat isochrons constructed by Dalton and others (2020). However, within 150 kilometers of the terminal ice margin, $^{10}\text{Be}$ exposure ages and radiocarbon ages significantly diverge. Therefore, neither may be an accurate representation of the true timing of ice retreat in this region (Balco & Schaefer, 2006; Peteet et al., 2012; Halsted et al., 2022). However, exposure ages and radiocarbon ages in northern New Hampshire and Maine are in better agreement with each other (Halsted et al., 2022).

2.4: Ice flow patterns in coastal New Hampshire

It is valuable to assess how ice retreat relates to flow patterns when reconstructing the style and timing of deglaciation. Striations in bedrock found in previously glaciated regions record the flow directions of ice sheets from the most recent glaciation (Wright, 2015). Ice flow patterns in the NH Seacoast have been measured by Hitchcock (1878) and more recently by Kotulak and Licciardi (2022). Ice flowed towards the southeast in the Seacoast region with an average ice flow direction from both studies of 147 degrees. However, local ice flow was highly variable with a range of 110 to 180 degrees azimuth (Figure 7) (Hitchcock, 1878; Wright, 2015; Kotulak and Licciardi, 2022). Ice flow direction varied by elevations, ranging from 45 to 175 meters above sea-level. As the LIS thinned, glacial erosion was still active, and striations record more ice flow variability at lower elevations indicating that ice flow was influenced by topography (Kotulak and Licciardi, 2022).
Figure 7: Ice flow patterns (yellow arrows) indicated by striations measured in the NH Seacoast (left. The region of postglacial marine inundation is shaded in blue. Striation azimuths are shown on the rose diagram (right) (NH GRANIT; Hitchcock, 1978; Kotulak and Licciardi, 2022).
CHAPTER III: METHODS

3.1: Geospatial Analysis of the Marine Limit

It is imperative for this study to define the marine limit in New Hampshire to assess the exposure history of six exposure ages collected below the marine limit. QGIS 3.14 was used to analyze the pattern of the variable marine limit in New England by determining the maximum elevations of glaciomarine deposits. Nine 1/3 arc-second DEMs of coastal Massachusetts, New Hampshire and Maine were downloaded from the U.S. Geological Survey National Map database. The DEMs are a seamless product of the 3D Elevation Project (3DEP) that have a resolution of 10 meters, a vertical accuracy of 1.55 meters, and a root mean square error of 0.82. Geospatial surficial geology data for each state was downloaded from NH GRANIT database, Maine Geolibary, and MassGIS database. All data were compiled from the U.S. Geological Survey and digitized by the state entities.

Analysis of glaciomarine deposits are minimum-limiting indicators of the marine limit as the deposits may have eroded away over time. Here, glaciomarine deposits layers were filtered and extracted from the surficial geology vector data. The glaciomarine deposits layer is composed of polygons with random size within the geographic area that they map. The nine DEMs were merged and reprojected to fit the extent of the glaciomarine deposits vector file. Zonal statistics was performed to extract the maximum, average, and range of elevations from the merged DEM raster file for each individual polygon in the glaciomarine vector file. The polygons were color-coded by maximum elevation values to show how the marine limit varied from north to south in coastal New England.
3.2: Cosmogenic Surface Exposure Dating

3.2.1: Sampling Strategy

In glacial studies, surface exposure dating is commonly used to determine when a glacially transported boulder or glacially scoured bedrock surface was no longer covered by ice. The duration of exposure of a rock surface since deposition and/or ice retreat can be calculated based on the concentration of terrestrial in-situ cosmogenic nuclides and the known production rate (Gosse and Phillips, 2001). For this project, we employ $^{10}$Be because the rock samples have an abundance of quartz (SiO$_2$) which is resistant to physical and chemical weathering, quartz has a simple chemical formula, quartz can be chemically separated and purified from other rock minerals, and the $^{10}$Be production rate in New England is well-constrained by the NENA calibration (Gosse and Phillips, 2001; Balco et al., 2009).

For this study, surface exposure dating was performed on samples collected from boulders found on till deposits, drumlins, and De Geer moraines. A total of 27 samples were collected from glacial erratics and glacially scoured bedrock for cosmogenic $^{10}$Be surface exposure dating analyses. Samples were collected from near present-day sea-level to 125 meters in altitude and are well distributed geographically throughout the NH Seacoast. The samples and field sites fall under 3 different categories: 1) below the marine limit, 2) inland and above the marine limit, and 3) vertically above the marine limit but within the inundated region (Table 1, Figure 8). Originally, the marine limit was set at a uniform 70 meters above present day sea-level for analysis based on the previously defined marine limit for coastal Maine. However, geospatial analysis completed in this project indicates that a new method of defining the marine limit is more appropriate for classifying each sample. The reclassification is discussed in the results and discussion sections (Table 1).
Table 1: Transect of 13 samples selected for ¹⁰Be measurements based on their surface quality (discussed in Section 3.2.2), elevation, and location. Transect extends above (yellow) and below (green) the marine limit with two samples within the inundated region, but vertically above the marine limit (orange). Elevations were extracted from LiDAR data provided by GRANIT (2013). *Sample SCNH21-07 is the only bedrock sample of the collection.

<table>
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<tr>
<th>Sample ID</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Discrete ML value (m)</th>
<th>Elevation from LiDAR (m.a.s.l.)</th>
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<tr>
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<td>22</td>
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Figure 8: Geographic distribution of samples with respect to the region of postglacial marine inundation (blue). Sample locations are color-coded to indicate categories as shown in the table above. Base hillshade relief map created in QGIS using LiDAR data provided by GRANIT (2013).
An atypical surface exposure dating approach was used by directly targeting a field area with a complex surface exposure history to provide the first direct age control for deglaciation in the Seacoast of New Hampshire. In New England, only one other study has produced exposure ages from sites within the region of marine inundation, but only targeted samples vertically above the marine limit to avoid the complications related to past submergence (Hall et al., 2017).

In this study, samples collected above the marine limit are interpreted to indicate the timing of the last deglaciation. Samples collected below the marine limit were partially or completely shielded by water due to postglacial marine inundation. Therefore, exposure ages obtained from these previously submerged surfaces may not closely limit the timing of ice retreat but should still provide viable minimum age estimates for deglaciation (Schildgen 2005, Heyman, 2011). Differences between exposure ages from samples above and below the marine limit in the same region should reflect the duration of marine submergence following ice recession, thus elucidating the timing of marine regression.

Cosmogenic nuclides can still be produced in a rock surface covered by water, snow, vegetation, or soil. The production of cosmogenic nuclides in a covered surface is affected by duration, thickness, and density of the cover. Some of the samples collected in this project were submerged in several tens of meters of water following their deposition by the LIS. Therefore, the duration of total and partial shielding by water must be accounted for when interpreting exposure age results. The water shielding correction factor as a function of water depth is shown in Figure 9. A water depth of 5 meters shields 95 percent of incoming cosmic radiation and at a depth of 10 meters nearly 100 percent is shielded (Table 2).
Table 2 (left): The percentage of shielding for two water densities (1.0 and 1.03 g/cm$^3$) are shown for specific water depths.

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<th>% Shielded (1.03 g/cm$^3$)</th>
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<td>100.0</td>
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</tr>
</tbody>
</table>

Figure 9 (right): Water shielding correction factor as a function of water depth for two water densities. An attenuation coefficient of 170 g/cm$^2$, assuming 0 degrees of surface dip and topographic shielding. Freshwater has a density of ~1.0 g/cm$^3$ and surface seawater density increases to 1.03 g/cm$^3$ at 4 degrees Celsius.

All exposure ages are treated as minimum ages for regional deglaciation. Samples collected below the marine limit are representative of when glacial erratics were no longer shielded by water following their deposition. Samples geographically inland from the marine limit and samples within the inundated region but vertically above the marine limit are indicative of when the boulders were deposited by the retreating ice (Figure 10).

Field expeditions were completed during the summer and fall of 2021 at fourteen sample sites in the Seacoast. Sampled glacial erratics were selected based on their size, shape, surface qualities, stability, and lack of evidence of disturbance. An ideal boulder for surface exposure dating is taller than one meter, exhibits evidence of glacial transport (rounding, smoothing, facets, striations, etc.), shows minimal surface weathering, has a stable base, and does not have signs of rolling or anthropogenic disturbance (Gosse and Phillips, 2001). It is important to collect the sample from the original glacially modified surface of a boulder that is placed in its original position and location of deposition (avoiding any post-deposition movement). Bedrock samples were extracted from 3 locations at Stonehouse Pond Conservation Area in Barrington, NH. These bedrock samples were selected based on their glacially polished and/or striated surface,
Figure 10: A conceptual model of the exposure history of boulders deposited at different localities in the sampled region. Boulders are exaggerated in size and were deposited in order (1 to 4). A) Boulders 1 and 2 were deposited when the glacier was a grounded tidewater margin. Boulder 1 was deposited above the marine limit on a topographic high and Boulder 2 was deposited below the marine limit on a shelf of a lower topographic high, composed of glacial till deposits. B) The glacier has transitioned to a land-terminating margin and as the glacier retreats the lithosphere begins to rebound. Boulder 3 was deposited just below the marine limit and Boulder 4 was deposited, but never covered by marine inundation. As sea-level begins to drop, Boulder 2 is exposed to incoming cosmic radiation. C) The glacier continues to retreat, and isostatic rebound continues causing a rapid drop in local relative sea-level. Here, both Boulders 1 and 4 do not have a complex exposure history. Boulder 4 was the last to be deposited, yet it should have an older exposure age than Boulders 2 and 3. Boulder 3 was deposited after Boulder 2 and could have an older exposure age due to the pattern of marine regression. However, with rapid marine regression, Boulders 2 and 3 may not have discernible age differences with error margins. Boulders 1, 4, 3 and 2 are in order from oldest to youngest exposure ages.
quartz composition (vein), elevation, and low potential for environmental disturbance. There is a chance the bedrock exposures around Stonehouse Pond were previously covered by vegetation.

Rock pieces were extracted from the top 1-3 cm of the rock surface using a chisel, hammer, and diamond blade saw (Figure 11). Three photos were taken for each sample of: 1) the boulder or bedrock location, 2) the sampled surface before collection and, 3) the sampled surface after collection. Site details including GPS coordinates (Garmin handheld GPS), elevation, boulder size (tape measure), surface strike and dip (SUUNTO compass), and topographic shielding (clinometer) were recorded at each sample location (Appendix A). Sample lithologies were investigated using a hand lens. More accurate elevations were later extracted from LiDAR data (NH GRANIT). A total of thirteen (n=13) of the 27 collected samples were selected for accelerator mass spectrometry analysis for $^{10}$Be surface exposure dating. These samples were prioritized based on their abundance of quartz, ideal boulder characteristics, and geographic location and altitude with respect to the marine limit.

Figure 11: Photos of sampled boulders from Hick’s Hill, Madbury (top left); Rock Rimmon Hill, Kingston (top center); Jeff’s Hill, Durham (top right); Stonehouse Pond, Barrington (bottom left); Stratham Hill Park (bottom center); and Goodwill Conservation, Barrington (bottom right).
3.2.2: Sample Preparation

Selected samples were prepared for $^{10}$Be surface exposure dating following established and routinely followed procedures in laboratory facilities at the University of New Hampshire, as adapted and modified from Licciardi (2000) and Corbett and others (2016). Approximately 650 g of each rock sample was first crushed and sieved to a grain size fraction of 600-250 μm. Magnetic and mafic minerals were then separated from each crushed sample using hand magnets. Felsic minerals such as feldspars and micas were removed from the sample fraction using froth flotation, which separates minerals based on diverging surface wettability (Whelan and Brown, 1956). A solution of carbonated dilute glacial acetic acid and laurylamine with a trace of tea tree oil was used to remove non-quartz minerals from the samples. Each sample fraction was then prepared chemically to purify the quartz using two different acid treatments. The first acid treatment removed carbonates, iron oxides, organic material, and some mafic minerals using a 6N hydrochloric acid solution. Lastly, samples received multiple hydrofluoric and nitric acid etches to remove any remaining non-quartz minerals (feldspars and mafics) and external, meteoric $^{10}$Be. Quartz sample fractions were prepared and sent to Syracuse University for purity testing using ICP-AES analysis before proceeding to beryllium extraction procedures.

Following purity testing, each sample of pure quartz was spiked with a $^9$Be carrier and digested in hydrofluoric acid. The hydrofluoric acid was then evaporated, and the samples went through a series of perchloric and hydrochloric dry downs before proceeding to column chromatography. Next, samples went through a series of anion and cation column chromatography separations using calibrated columns and specific acid recipes that elute and separate the Fe, Ti, Al, and Be in each sample. The Be fractions were dried down into beryllium hydroxide gels then precipitated and rinsed to remove potential boron containments. The
beryllium hydroxide gels were oxidized to beryllium oxide powder in a rapid incinerator. The beryllium oxide target material for each sample was packed into a cathode and sent for accelerator mass spectrometry (AMS) analysis. The thirteen samples were sent to the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory in Livermore, California in three separate sample batches. AMS results provide the $^{10}\text{Be}/^{9}\text{Be}$ ratios and uncertainties needed to calculate the exposure ages. Batch-specific blanks were prepared with each of the three batches of samples to account for potential background $^{10}\text{Be}$ which could be introduced to a sample during the chemical processing or AMS analysis of the individual batch. When two blanks were included in the batch, an average of the two blanks was used for background $^{10}\text{Be}$.

3.2.4: $^{10}\text{Be}$ Exposure Age Calculations

Exposure ages were calculated using version 3 of the CRONUS-Earth online cosmogenic nuclide calculator. Ages were calibrated using the Northeastern North America (NENA) production rate of $^{10}\text{Be}$ and reported using the Lifton-Sato-Dunai (LSDn) nuclide + time dependent scaling scheme. Elevations were extracted in QGIS from LiDAR data downloaded from the NH GRANIT database. An average rock density of 2.7 g cm$^{-3}$ was used for exposure age calculations as most samples are granite, granodiorite, and diorite. Topographic shielding corrections were calculated using version 2 of the CRONUS-Earth topographic shielding calculator. Corrections were not made for snow shielding and surface erosion. $^{10}\text{Be}$ concentrations and uncertainties were calculated from the ratios of $^{10}\text{Be}/^{9}\text{Be}$ and uncertainties results provided by the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. Blanks and background $^{10}\text{Be}$ were accounted for when converting the ratios
of $^{10}\text{Be}/^{9}\text{Be}$ to $^{10}\text{Be}$ concentrations. The uncertainty in the $^{10}\text{Be}$ concentrations accounts for the uncertainty in the isotope ratio measurement and the processed blank uncertainties.
CHAPTER IV: RESULTS

4.1: Variability of Marine Limit Levels in New England

Glaciomarine deposits in coastal New England extend from the Boston area to the northern coast of Maine (Figure 12). The vertical marine limit in New England ranges from 20 meters above sea-level in the Boston area to 152 meters above sea-level in central Maine, with values generally increasing northward (Figure 12). There are no glaciomarine deposits mapped south of Boston, where the LIS was always land-terminating. Preserved and/or mapped glaciomarine deposits are most geographically extensive in New Hampshire and southwestern Maine. These deposits extend inland up to 5 kilometers in Massachusetts, 45 kilometers in New Hampshire, and 150 kilometers in Maine.

Figure 12: Map of glaciomarine deposits in coastal New England shaded by maximum altitude. The minimum marine limit of 20 meters is presented in the Boston area and the maximum marine limit of 152 meters is recorded in central Maine.
These results are largely consistent with previously published sea-level highstands in New England, with exceptions noted below. Our analysis shows that maximum marine limits by region are 20 meters in Boston and 39 meters in northern Massachusetts, which agree with previously published highstands of 18 and 33 meters, respectively (Kaye & Barghoorn, 1964; Oldale & Colman, 1993). Results from this study deviate from previously published marine limits in Maine. In southern Maine, highstand values range from 73 meters to 102 meters along the geographic marine limit of preserved glaciomarine deposits. This is greater than the 70-meter marine limit published for southern Maine and included in the Maine relative sea-level curve (Belknap et al., 1987; Kelley et al., 2010). Most notably, new values for central Maine present a new marine limit maximum for New England at 152 meters above sea-level, previously published as 130 meters (Thompson et al., 1989). These maximum elevations are from deposits that were identified as marine regressive deposits and ice-contact marine deltas and mapped in the New Portland and Farmington quadrangles (Weddle, 2003; Hildreth, 2009). In the northeastern coast of Maine, Kelley and others (2010) published a highstand of 75 meters yet results from this study reveal a highest value of 111 meters (Figure 12). The results from Maine do not document all the glaciomarine deposits that have been previously mapped in Maine. Only glaciomarine deposits that were cataloged as GIS data were used for this analysis, therefore geospatial analysis is restricted for Maine.

Previous studies have assumed a marine limit of 70 meters based on the Maine relative sea-level curve (Kelley et al., 2010). Most glaciomarine deposits that are preserved and mapped in New Hampshire are below 55 meters altitude. Along the geographic marine limit, the highest elevations of glaciomarine deposits in New Hampshire range from 57 to 103 meters above present-day sea-level, with an overall increase in elevation from south to north in both coastal
New Hampshire and New England. (Figure 13). The highest elevations in New Hampshire along the geographic marine limit are found in the Cocheco River Valley.

These results were used to reclassify the localized marine limit or maximum water depth at the thirteen surface exposure sample sites. Deposits in the northern portion of the NH Seacoast are no more than 2-3 kilometers from the fixed assumed marine limit of 70 meters altitude above the present-day. Glaciomarine deposits in the southwestern portion of the region are up to 10 kilometers away from an assumed marine limit of 70 meters and approximately 5 to 15 meters altitude below 70 meters (Figure 3) (Ibey, 2021). Originally, the strategy was to assume one uniform value of 70 meters for the marine limit of the NH Seacoast. However, the wide range of maxima along the westward geographic extent of glaciomarine deposits (Figure 13) is evidence
that a uniform value would poorly represent the marine limit at each $^{10}$Be sample. Three discrete marine limit levels were used for exposure age analysis. These values are based on the maximum altitude of glaciomarine deposits localized in the northern (77 m), southern (65 m), and central (70 m) regions of the Seacoast. A few localities highlighted were disqualified from the classification of the local marine limit near samples due to human interference. For example, in Rochester, NH, glaciomarine deposits were mapped prior to the creation of a landfill over the deposits and the LiDAR data from which elevations are extracted were collected in 2013 after landfill use had begun. Therefore, elevations of 83 and 103 meters are not reliable. (Figure 13).

A marine limit of 77 meters altitude is used for the most northerly samples (SCNH21-01, -03, -07, -08, -09, and -11A) which are generally adjacent to and less than 5 kilometers from the inland marine limit. Samples adjacent to the coastline or Great Bay (SCNH21-02, -19, -21, -22, -23) are interpreted with a localized marine limit of 70 meters altitude, as indicated by glaciomarine deposits that are mapped at Stratham Hill Park (Figure 13). Lastly, two samples (SCNH21-16 and -17) from southern New Hampshire that are outside of the geographic extent of glaciomarine deposits use a local marine limit of 65 meters altitude.

4.2: Cosmogenic $^{10}$Be Exposure Ages

Thirteen exposure ages from twelve boulders and one bedrock exposure in the NH Seacoast range from 14.6 ka to 19.6 ka and are clustered between 17 to 16 ka (Tables 3 & 4, Figure 14). Exposure ages from above the marine limit range from 16.2 to 19.6 ka, and those from below the marine limit range from 14.6 to 17.4 ka. The oldest age in our data set (19.6 ± 0.4 ka) (uncertainty is reported as 1 S.D. internal uncertainty) is from the Hick’s Hill drumlin, located above the marine limit and within the inundated region. Sample SCNH21-21 (17.4 ± 0.3 ka) is the from the sample location closest to the present-day coastline and yields the oldest age
below the marine limit. The bedrock sample (SCNH21-07), 15.5 ± 0.3 ka, and boulder sample (SCNH21-03), 16.2 ± 0.3 ka, from Stonehouse Pond Conservation Area do not agree within 1 S.D. uncertainty. The boulder and bedrock samples are from the same field site, but the boulder is not perched directly on the dated bedrock outcrop. Two samples, SCNH21-08 and -09, are geographically adjacent to and above the marine limit in the northern region of the field area and yielded ages of 18.7 ± 0.4 ka and 17.3 ± 0.3, respectively. Two samples collected below the marine limit from Stratham, SCNH21-22 (17.2 ± 0.3 ka) and -23 (16.3 ± 0.3 ka), yielded an average exposure age of 16.8 ± 0.6 ka. The two oldest ages, SCNH21-01 (19.6 ± 0.4) and SCNH21-08 (18.7 ± 0.4), that are older than expected and greater than 1 ka older than the rest of the samples, were not removed from analysis as outliers because they almost agree with each other within uncertainty and are approximately 7 km apart relative to ice flow direction. Also, the exposure ages above the marine limit and within the inundated region and those adjacent to the marine limit geographically are expected to be the oldest ages in this set. Sample SCNH21-19 from Jeff’s Hill (14.6 ± 0.3 ka) is an outlier as it is 1 or more ka younger than the entire sample collection, does not agree within internal uncertainty with any other boulder ages in the dataset, and approximately 2-3 S.D. from the mean of the sample set.

Six samples collected above the reconstructed marine limit in the Seacoast region yield an arithmetic mean exposure age of 17.6 ± 1.3 ka (1 S.D. uncertainty), excluding the bedrock sample (Table 4). The six samples collected from below the marine limit yield an average exposure age of 16.3 ± 1.0 ka. Excluding the young outlier (SCNH21-19), the average exposure age below the marine limit is 16.6 ± 0.6 ka. At face value, our exposure age results indicate that samples above and adjacent to the assumed marine limit yield older ages than samples below the marine limit. A statistical ANOVA test was performed to determine if these two averages, 17.6 ±
1.3 ka (above) and 16.6 ± 0.4 ka (below, excluding outlier) are statistically distinct or within the noise of uncertainty. The resulting P-value of the ANOVA test is 0.19, indicating a 19 percent probability the results occurred by chance.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
<th>Elevation (m)</th>
<th>Thickness (cm)</th>
<th>Shielding Factor</th>
<th>Quartz (g)</th>
<th>$^{10}$Be carrier (mg)</th>
<th>$^{10}$Be/Be concentration (AMS ratio)</th>
<th>$^{10}$Be/Be uncertainty</th>
<th>$^{10}$Be concentration (10$^6$ atoms g$^{-1}$)</th>
<th>$^{10}$Be uncertainty (10$^6$ atoms g$^{-1}$)</th>
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<td>43.16951</td>
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<td>86.5</td>
<td>1.75</td>
<td>0.999782</td>
<td>20.0393</td>
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<td>2.11E-15</td>
<td>8.08</td>
<td>0.15</td>
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<td>1.8</td>
<td>0.999471</td>
<td>12.0773</td>
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<td>1.12E-15</td>
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<td>0.14</td>
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<td>1.65E-16</td>
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<td>43.17038</td>
<td>-70.94038</td>
<td>66</td>
<td>2.75</td>
<td>0.998913</td>
<td>25.2759</td>
<td>0.198</td>
<td>1.23E-13</td>
<td>2.34E-15</td>
<td>6.39</td>
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<td>10.7823</td>
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<td>-70.89601</td>
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<td>6.66</td>
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<td>-70.89034</td>
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<td>30.0812</td>
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<td>0.999205</td>
<td>30.0552</td>
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<td>43.21238</td>
<td>-71.02226</td>
<td>86</td>
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<td>0.999778</td>
<td>29.9973</td>
<td>0.185</td>
<td>1.855E-13</td>
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<td>-71.09408</td>
<td>93</td>
<td>2</td>
<td>0.997856</td>
<td>30.0663</td>
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<td>1.666E-13</td>
<td>3.14E-15</td>
<td>6.83</td>
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<td>SCN121-17</td>
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<td>1.75</td>
<td>0.998486</td>
<td>30.0666</td>
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<td>1.618E-13</td>
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<td>-70.81721</td>
<td>22</td>
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<td>26.426</td>
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<td>-</td>
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<td>8.741E-16</td>
<td>1.42E-16</td>
<td>-</td>
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</table>

Table 3: $^{10}$Be/Be ratios were determined at the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory. Samples were processed in three separate batches with 5 different blanks (-89 & -90, -91 & -92, and -93). A rock density of 2.7 g cm$^{-3}$ was used for all samples. All cosmogenic $^{10}$Be concentrations and associated ages for individual samples are reported with 1σ analytical uncertainty and all other parameters necessary for exposure age calculations and interpretations.
All Exposure Ages

$n = 12$
Average $= 17.1 \pm 1.1$ ka

Above ML

$n = 6$
Average $= 17.6 \pm 1.3$ ka
Figure 14: Camel plots for all samples (left), samples above the marine limit (center), and samples below the marine limit (right). All $^{10}$Be ages are plotted with one sigma internal uncertainty.

Table 4: $^{10}$Be exposure ages including the associated internal and external (in parentheses) uncertainties for each sample. Exposure ages are reported for the global and New England North America (NENA) production rates using the Lifton-Sato-Dunai (LSDn) nuclide + time dependent scaling scheme. Mean ages for above and below the marine limit are reported with 1 standard deviation of uncertainty. Sample SCNH21-07 is not included in the average NENA age above the marine limit as it is the only bedrock sample.*. Sample SCNH21-19 is also not included in the average age below the marine limit as it is an outlier.** Sample elevations, discrete marine limit values (discussed in section 4.1), and elevations relative to the marine limit are reported for each sample. Samples are shaded based on their position relative to the marine limit: above (yellow), below (green), and within the inundated region, but vertically above the marine limit (orange).

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Discrete ML value (m)</th>
<th>Elevation relative to the ML (m)</th>
<th>Global (LSDn) (ka)</th>
<th>NENA (LSDn) (ka)</th>
<th>Average NENA Age (ka)</th>
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<tr>
<td>SCNH21-03</td>
<td>Stonehouse</td>
<td>125</td>
<td>77</td>
<td>48</td>
<td>16.3 ± 0.3 (1.4)</td>
<td>16.2 ± 0.3 (1.4)</td>
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<tr>
<td>SCNH21-07</td>
<td>Stonehouse</td>
<td>117</td>
<td>77</td>
<td>40</td>
<td>15.6 ± 0.3 (1.3)</td>
<td>15.5 ± 0.3 (1.3)</td>
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<tr>
<td>SCNH21-01</td>
<td>Rock Rimmon</td>
<td>93</td>
<td>65</td>
<td>28</td>
<td>16.9 ± 0.3 (1.4)</td>
<td>16.8 ± 0.3 (1.4)</td>
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<tr>
<td>SCNH21-08</td>
<td>Hick’s Hill</td>
<td>86.5</td>
<td>77</td>
<td>9.5</td>
<td>19.8 ± 0.4 (1.7)</td>
<td>19.6 ± 0.4 (1.7)</td>
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<tr>
<td>SCNH21-09</td>
<td>Goodwill</td>
<td>86</td>
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<td>9</td>
<td>18.8 ± 0.4 (1.6)</td>
<td>18.7 ± 0.4 (1.6)</td>
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<td>SCNH21-17</td>
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<td>77</td>
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<td>SCNH21-23</td>
<td>Kingman Farm</td>
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<td>-11</td>
<td>16.2 ± 0.3 (1.4)</td>
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<tr>
<td>SCNH21-22</td>
<td>Stratham</td>
<td>55</td>
<td>70</td>
<td>-15</td>
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<td>SCNH21-22</td>
<td>Barker</td>
<td>42</td>
<td>70</td>
<td>-28</td>
<td>17.3 ± 0.3 (1.5)</td>
<td>17.2 ± 0.3 (1.5)</td>
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<tr>
<td>**SCNH21-19</td>
<td>Jeff’s Hill</td>
<td>36</td>
<td>70</td>
<td>-34</td>
<td>14.7 ± 0.3 (1.3)</td>
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<td>SCNH21-02</td>
<td>East Foss</td>
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<td>17.6 ± 0.3 (1.5)</td>
<td>17.4 ± 0.3 (1.5)</td>
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</table>
The style of deglaciation is examined by analyzing how exposure age relates to elevation relative to the marine limit as well as to ice flow direction. The geographic distribution of exposure ages is shown with reference to a grid system orthogonal to the average ice flow direction (147 degrees) and with respect to the region of marine inundation (Figure 15). This grid system was created to analyze relationships between exposure age and distance along ice flowlines because typically older exposure ages are expected closest to the ice front when it is straight. Exposure ages from Brown Brook (16.7 ± 0.3 ka) and Rock Rimmon Hill (16.8 ± 0.3 ka) are younger than other ages that are adjacent to the marine limit in Barrington, NH and are further up ice. The oldest exposure ages below the marine limit are found closest to the present-day coastline.
Figure 15: a) Map of the NH Seacoast with deglaciation chronology. Sample locations are color coded into three categories: vertically above the marine limit but within the inundated region (orange star), above the marine limit (yellow circle), and below the marine limit (green circle). Marine inundation is projected across the Seacoast region of NH in blue. b) Visual representation of where exposure ages fall with respect to the grid system orthogonal to ice flow direction and elevation.
CHAPTER V: DISCUSSION

5.1: Variable Marine Limit in New England

In New England, glaciomarine sediments were deposited adjacent to a grounded tidewater ice margin in shallow marine environments. Glaciomarine deltas are less likely to form when the retreat of a tidewater margin is rapid. Deltas are scarce in coastal Maine but more evenly distributed on the coasts of New Hampshire and Massachusetts (Thompson et al., 1989; Thompson, 2001). Glaciomarine deposits are found at generally higher maximum elevations in Maine than in New Hampshire and Massachusetts. This is most likely due to thicker ice in the north when the LIS was near its maximum extent, causing greater isostatic depression and deeper marine inundation after the ice sheet retreated. Lower elevations of glaciomarine deposits in New Hampshire imply that there was less isostatic depression in the NH Seacoast immediately after deglaciation. Therefore, higher marine limits in coastal Maine than New Hampshire and Massachusetts are evidence that ice thicknesses covering coastal New Hampshire may not have been as thick as the ice that once covered coastal Maine and the LIS may have been even thinner in coastal Massachusetts (Figure 16).

Figure 16: Ice thickness distributions of the LIS based on three different models, the ANU, ICE-6G, and 9927 at three different time intervals (Baril et al., 2023). The NH Seacoast is indicated by a black box in the top left.
Other possible reasons for variable marine limits include spatially heterogeneous lithospheric conditions, the timing of the migration of a 20-25 m amplitude forebulge across the region, and different timings and rates of deglaciation and the unloading on the crust relative to global sea-level rise (Belknap et al, 1987; Thompson, 1987; Barnhardt et al., 1995). Rapid rates of ice retreat may have caused delayed crustal rebound, while ice thinning and slower ice retreat rates would cause gradual uplift of the crust. Relative sea-level is also dependent on eustatic sea-level changes and therefore dependent on how the timing of ice retreat and crustal rebound relates to eustatic sea-level at the time. Marine submergence was more extensive in Maine than in New Hampshire and Massachusetts (Figure 17). LIS retreat through the coast of Maine may have been more rapid than through New Hampshire and northern Massachusetts because glaciomarine deltas are scarcer in coastal Maine, but this could also be a result of poorer preservation of glaciomarine deltas in Maine (Thompson, 2001). There are no glaciomarine deposits found south of Boston because the LIS was not thick enough to depress the land surface below local sea-level at the time of ice retreat (Oakley & Boothroyd, 2012).

Ice retreat through Maine was also later than coastal New Hampshire and Massachusetts and coincided with a time when eustatic sea-level was rising to higher altitudes. Relative sea-level along the coast of New England is dependent on the thickness of the ice that contributed to isostatic depression and on fluctuating eustatic sea-level (Thompson, 1987). The thickness of the LIS and magnitude of isostatic rebound in New England cannot be resolved from this study because both these factors are time-dependent and our results only provide context for the time of isostatic adjustment and land emergence from the sea (Love et al., 2016).
Figure 17: Map of the projected region of prior marine inundation in New England shaded by elevation. Note that islands existed below 150 meters in the inundated region and are not shown in the figure (Maine Geological Survey).
5.2: Timing and Style of Ice Retreat in the NH Seacoast

The thirteen new exposure ages reported in this study provide details for the timing and style of deglaciation in the NH Seacoast. Sample SCNH21-19 (14.6 ± 0.3 ka) was eliminated from analysis as an outlier because it was approximately 1.5 ka younger than the other 5 samples collected below the marine limit or 2-3 S.D. from the mean of the sample set. Shielding after initial exposure or surface erosion could make ages too young. Shielding from snow, topography and vegetation is possible at all sample sites. Topographic shielding was corrected for, but snow and vegetation shielding was not accounted for. Snow shielding varies from year to year and a correction is complicated as it is dependent on the total months covered, snow depth, boulder height, boulder shape, and snow density. Samples SCNH21-01 (19.6 ± 0.4 ka) and SCNH21-08 (18.7 ± 0.4 ka) were older than expected and more than 1 ka older than the other samples collected above the marine limit, but not removed from the analysis. Isotope inheritance, when a surface inherits cosmogenic nuclides from previous exposure, is a possible explanation for older ages. This is possible if the boulder did not experience subglacial erosion. Boulder provenance can give context clues about the transport distance of a boulder. It was observed in this study that most sample lithologies are from local bedrock lithologies. Most glacial erratics in this study are locally sourced and far-traveled erratics are comparatively rare. Sample SCNH21-01 is a granite with unknown provenance origin and SCNH21-08 is a Concord granite which is locally sourced. Isotope inheritance is possible for SCNH21-01.

Most exposure ages are clustered around 16 to 17 ka. It was expected that ages would be tightly clustered with 1 ka of each other due to the expectation that ice retreat was rapid. The results of this study support previously published rapid ice recession rates across the NH Seacoast based on the NAVC record (Ridge et al., 2012) and the distribution and morphology of
De Geer moraines in the NH Seacoast (Sinclair et al., 2018). However, a retreat rate cannot be resolved from our exposure age data because the internal uncertainty of the exposure ages is of the same magnitude as the expected retreat duration through the area (45 km × 100 m/yr = 450 years) (Figure 15a). Ages from above the marine limit are the best indicators from this set of exposure ages for the timing of deglaciation in the NH Seacoast because they do not have complex exposure history and represent when the boulder was deposited by the LIS. The overlap between exposure ages that are adjacent to the geographic extent of glaciomarine deposits and ages below the marine limit suggest that the Laurentide Ice Sheet transitioned from marine- to land-terminating in the Seacoast approximately 17 ka.

Analysis of the mechanisms of ice retreat in the Seacoast is based on the relationship of exposure age with distance up-ice and elevation relative to the marine limit. Exposure ages do not follow a simple ice retreat pattern such that samples in the southeastern portion of the study area are expected to be the oldest and trend toward progressively younger ages in the up-ice direction toward the northwest. However, this is expectation based on the assumption that the ice front was straight. However, curvilinear ridges of De Geer moraines (Sinclair et al., 2018) in the NH Seacoast provide evidence for a lobate ice front during deglaciation. For samples above the marine limit, there is no correlation between exposure age and distance up-ice orthogonal to average ice flow direction (147 degrees) and from the coastal border of Massachusetts and New Hampshire (Figure 18). The best-fit trendline trends in the opposite direction of expected with younger ages closer to the origin. There is a substantial correlation ($R^2=0.74$) for exposure ages only below the marine limit to distance up-ice orthogonal to average ice flow direction. Exposure ages below the marine limit that are furthest to the southeast are older than the ages further up-ice (Figure 18). However, distance does not imply water depth or time of emergence because the
boulders are at different depths below the water level for these samples. For samples below the marine limit it is difficult to evaluate any trends that might be seen between distance and age because of water shielding. All of these samples were at different water depths and it is more appropriate to assess age versus elevation with respect to the marine limit to determine if exposure age has a relationship with water depth.

**All Ages**

![Graph showing relationship between exposure age and distance for all ages.](image)

**Above ML**

![Graph showing relationship between exposure age and distance for samples above the marine limit.](image)
Figure 18: Exposure age versus distance up ice from the coastal border of Massachusetts and New Hampshire. The grid system is orthogonal to average ice flow direction as shown in Figure 15a. The relationship is shown for all samples, only samples above the marine limit, and only samples below the marine limit. Samples use the same previously established color scheme for representing sample type. Dashed lines represent weak or absent trends.
There is no strong relation between exposure age and elevation relative to the assumed marine limit (Figure 19). Samples furthest below the water should have been uncovered last and...
therefore have the youngest ages. Yet, there is no strong relationship between water depth and exposure age. There is a 1 ka difference between the average ages of samples above and below the marine limit. Exposure ages from above the marine limit have more scatter than those below the marine limit. According to the ANOVA test, there is a 19 percent chance (p-value = 0.19) these differences occurred by random chance. A p-value of 0.05 or 5 percent is the accepted value in statistical significance. Overall, exposure ages have a scattered spatial trend that does not follow a simple pattern of ice retreat or expected pattern of marine transgression. A lobate ice margin and variable local isostasy could help explain the variability of ages across field area.

5.3: Comparison to Regional Chronology

$^{10}$Be ages from this study have been plotted alongside the published regional radiocarbon-based ice retreat isochrons and previously published, site-specific $^{10}$Be ages to determine if they are consistent with the regional chronology (Figure 20). The ages from this study are older than site-specific $^{10}$Be ages to the north and west, which is consistent with ice retreat patterns. The average ages above and below the marine limit deviate from the regional radiocarbon-based ice retreat isochrons (Dalton et al., 2020). Results from this study suggest a revision to the 16.8 and 18.0 cal ka isochrons in the NH Seacoast as exposure ages reveal that the timing of deglaciation was earlier than indicated by the ice margin positions of Dalton and others (2020). The NH Seacoast lies between the 16.8 cal ka and the 15.5 cal ka isochrons, but six exposure ages from this study fall outside of this range. $^{10}$Be ages from this study are evidence that ice retreat through the Seacoast occurred earlier than minimum radiocarbon dating in the region indicates. The ice retreat isochrons published by Dalton and others (2020) are based on only a few radiocarbon ages off the coast of New Hampshire (Birch, 1990) and were not intended for use at a fine resolution such as the size of the Seacoast region. Dalton and others (2020) used one
average radiocarbon age that is stratigraphically overlying glacial till from a core collected on the inner continental shelf off the coast of New Hampshire to interpolate the isochrons near the NH Seacoast (Birch, 1990). One age from one site off the coast of New Hampshire is not a strong basis for the 16.8 cal ka and 18.0 cal ka ice retreat isochrons in the NH Seacoast. The \(^{10}\text{Be}\) ages from this study provide more direct evidence for the timing of ice retreat in the NH Seacoast. However, a new isochron guided by our \(^{10}\text{Be}\) data was not drawn due to the different dating methods that were used to resolve these ages.

As expected, the \(^{10}\text{Be}\) ages from below the marine limit fall between the timing of the highstands in northern Massachusetts and coastal Maine which occurred at 17 cal ka and 14 cal ka, respectively. Results from samples below the marine limit are consistent with the relative sea-level curves for coastal Maine and northern Massachusetts because ages fall between the timing of marine regression for localities north and south of the field area (Kelley et al., 2010; Hein et al., 2012). Exposure ages from below the marine limit are evidence that marine regression took place between 16 and 17 ka, following ice retreat. Published sea-level curves to the north and south of the field area suggest rapid rates of marine regression (Kelley et al., 2010; Hein et al., 2012). Samples from the region of inundation in this study were covered by water within the window of shallow submergence (5-10 meters) thus experiencing partial nuclide production for part of their history. Therefore, samples collected below the marine limit only demonstrate the minimum ages of ice retreat and better represent the timing of marine regression. This is consistent with previously published sea-level curves that illustrate rapid postglacial marine regression (Kelley et al., 2010; Hein et al. 2012). Exposure ages cluster within 1.5 ka of each other which is also consistent with previously published chronologies for marine submergence that concluded that inundation lasted less than 2 ka after deglaciation.
Figure 20: Map highlights the regional ice retreat chronology in New England. Yellow points plot the location of $^{10}$Be exposure ages. Mountain peaks that were used as dipsticks are notated with an (*). Ages from this study are highlighted in yellow. Ice retreat isochrons updated by Dalton and others (2020) are shown as dashed lines with the maximum extent of the LIS shown as a thick solid line. The extent of post glacial marine inundation in New England is shaded by elevation (Maine Geological Survey, this study).
5.4: Paleoclimatic Implications

Ice retreat in the NH Seacoast occurred during Heinrich Stadial 1 (~19 to 14.6 ka), which was marked by a subtle increase in air temperatures in the Northern Hemisphere caused by increasing insolation (Clark et al., 2009; Osman et al., 2021). Large ice sheets, such as the LIS, are not typically impacted immediately by climatic changes; however, the marine margin in New England made the LIS more dynamic and vulnerable to changes in this region. Therefore, it is possible that the LIS began to retreat rapidly due to ice flow characteristics and increased calving events at the marine margin (Hodgdon, 2016; Vieli, 2021). Regional oceanic warming or the weakening of the Atlantic Meridional Overturning Circulation at the time may have been drivers of increased calving events (Koester et al., 2017). Results from this study are generally consistent with the idea that marine-terminating margins are more vulnerable to rapid and irreversible retreat.
CHAPTER VI: CONCLUSION

The thirteen $^{10}$Be exposure ages from this study provide the first direct age control for deglaciation and associated marine regression in the NH Seacoast. These new ages indicate that LIS margin retreated through the Seacoast region at approximately 18-17 ka and marine regression succeeded ice retreat from approximately 17-16 ka. The average of $^{10}$Be ages from sites above the marine limit is older than previously published radiocarbon-based ice retreat isochrons in the vicinity of coastal New Hampshire (Dalton et al., 2020). However, the average $^{10}$Be age of samples below the marine limit is between the published timings of marine regression in Massachusetts and coastal Maine.

Exposure ages from this study are consistent with rapid ice retreat and marine regression in the NH Seacoast. Yet, precise rates of ice retreat and marine regression cannot be resolved from this study as the exposure age uncertainties are comparable in magnitude to the estimated ~400 year duration of ice retreat across the field area (Ridge et al., 2012; Sinclair et al., 2018). The $^{10}$Be ages from this study and the new geospatial analysis of glaciomarine deposits are indicators for the timing and behavior of the transition of LIS from marine- to land-terminating. This transition most likely occurred ~17 ka, at the onset of marine regression. Ages from below the marine limit are generally consistent with previously published chronologies that suggest an interval of <2 kyr of marine submergence following deglaciation. Geospatial analysis of glaciomarine deposits reveal that the late Pleistocene marine limit in New England was highly variable. Possible reasons for this variability include geographically contrasting ice thickness histories resulting in different degrees of isostatic depression, heterogeneous lithospheric conditions, and different timings and rates of deglaciation relative to global sea-level rise.
Spatial analysis of exposure ages reveal that the LIS margin did not follow a simple retreat pattern in this region. Moreover, the spatial variability and scatter of exposure ages may be explained by a dynamic and lobate ice margin. Additional exposure ages from glacial deposits in coastal New Hampshire above, below, and adjacent to the marine limit would enable further evaluation of the timing and style of ice retreat in the NH Seacoast and coastal New England.
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Sample SCNH21-01

Date Collected: 06-08-2021
Site: Hick’s Hill, Madbury, NH
Location: 43.16948 °N, 70.94170 °W
Elevation: 86.5 m a.s.l.
Type: Boulder
Boulder Size: 292/231/112/188 (Length/Width/Uphill Height/Downhill Height in cm)
Surface Strike/Dip: 175°/7°
Sample Thickness: 1.75 cm
Horizontal Shielding: 091°/0°, 110°/6°, 153°/5°, 175°/0°
Description: Boulder is embedded into the Hick’s Hill drumlin and located off-center of the long axis. Hick’s Hill is an island within the assumed inundated region (above the marine limit, but within the inundated region). The sample was collected from the high point of the boulder.
Bedrock Lithology: Eliot formation
Sample Description: felsic, intermediate to coarse-grained granite; mineral composition: muscovite mica, sodium feldspars, amphibole, garnets (rich), quartz; different from concord granite
Sample SCNH21-01 (cont.)

Sample: SCNH21-01
Location: Hicks Hill, Madbury NH
Elevation: 86.5m
Above ML, but within inundated region
Sample SCNH21-02

Date Collected: 07-08-2021
Site: East Foss Farm, Durham, NH
Location: 43.11898 °N, 70.9807 °W
Elevation: 26 m a.s.l.
Type: Boulder
Boulder Size: 185/270/170/185 (L/W/UH/DH in cm)
Surface Strike/Dip: 204°/4°
Sample Thickness: 1.8 cm
Horizontal Shielding: <1-2° in all directions

Description: Boulder deposited between De Geer moraines. Top of boulder is fractured by it remains in its original position with no missing pieces.

Bedrock Lithology: Exeter Diorite (Early Devonian)
Sample Lithology: Exeter Diorite
Sample Description: Pyroxene gabbro identified as Exeter diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; boulder deposited between De Geer moraines
Sample SCNH21-02 (cont.)

Sample: SCNH21-02
Location: East Foss Farm, Durham, NH
Elevation: 26 m
Below ML
Sample SCNH21-03

Date Collected: 08-17-2021

Site: Stonehouse Pond Conservation Area, Barrington, NH

Location: 43.20086 °N, 71.09830 °W

Elevation: 125 m a.s.l.

Type: Boulder

Boulder Size: 320/400/155/220 (L/W/UH/DH in cm)

Surface Strike/Dip: 82°/2°

Sample Thickness: 2.0 cm

Horizontal Shielding: 010°/5°, 055°/2°, 095°/4°, 117°/3°, 169°/4°, 215°/10°, 250°/5°, 302°/7°

Description: Sample collected from smoothed surface between weathering pits and along a ridge that had a small amount of erosion.

Bedrock Lithology: Concord Granite (Late Devonian)

Sample Lithology: Concord Granite

Sample Description: felsic, medium to fine-grained with some large grains granite; mineral composition: felspars, mica, amphibole, garnets, very similar to sample SCNH21-10
Sample SCNH21-03 (cont.)
Sample SCNH21-04

Date Collected: 08-17-2021

Site: Stonehouse Pond Conservation Area, Barrington, NH

Location: 43.19849 °N, 71.09737 °W

Elevation: 162 m a.s.l.

Type: Bedrock

Surface Strike/Dip: 320°/4°

Sample Thickness: 1.5 cm, not prepared for AMS measurements

Horizontal Shielding: 016°/0°, 052°/0°, 125°/0°, 200°/1°, 285°/2°, 335°/0°

Notes: First bedrock sample collected from the pond overlook on Ledge Loop Trail. Sample collected from a glacial polished and striated quartz vein. Striations were measured with an average azimuth of 154°.

Sample Lithology: Concord Granite (Late Devonian)

Sample Description: Felsic, medium to coarse-grained granite; sample collected from a quartz vein
Sample SCNH21-05

Date Collected: 08-17-2021

Site: Stonehouse Pond Conservation Area, Barrington, NH

Location: 43.198622 °N, 71.097092 °W

Elevation: 160 m a.s.l.

Type: Bedrock

Surface Strike/Dip: Sub horizontal

Sample Thickness: 1.75 cm, not prepared for AMS measurements

Horizontal Shielding: 016°/0°, 052°/0°, 125°/0°, 200°/1°, 285°/2°, 335°/0°

Notes: Sample collected from a glacially polished and striated quartz vein near the cliff of the overlook bedrock exposure. SCNH21-05 is approximately 20 meters apart from SCNH21-04 and 1.3 meters from the cliff drop off.

Sample Lithology: Concord Granite (Late Devonian)

Sample Description: Felsic, medium to coarse-grained granite; sample collected from a quartz vein
**Sample SCNH21-06**

Date Collected: 08-17-2021

Site: Stonehouse Pond Conservation Area, Barrington, NH

Location: 43.198622 °N, 71.097092 °W

Elevation: 126 m a.s.l.

Type: Boulder

Boulder Size: 300/400/150/185 (L/W/UH/DH in cm)

Surface Strike/Dip: 314°/20°

Sample Thickness: not crushed, not prepared for AMS measurements

Horizontal Shielding: 025°/1°, 083°/0°, 133°/3°, 160°/9°, 180°/6°, 279°/7°, 333°/5°

Notes: Sample collected from exposed pegmatic vein that lies horizontally along top of the glacially polished boulder surface.

Bedrock Lithology: Concord Granite (Late Devonian)

Sample Lithology: Felsic to intermediate, intrusive, coarse-grained granite; surface sample is weathered and oxidized; mineral composition: biotite, amphibole, feldspars (abundant, orange color), muscovite mica, quartz
Sample SCNH21-06 (cont.)

Sample: SCNH21-06
Location: Stonehouse Pond, Barrington NH
Elevation: 126 m
Above MSL
Sample SCNH21-07

Date Collected: 09-21-2021
Site: Stonehouse Pond Conservation Area, Barrington, NH
Location: 43.201118 °N, 71.09592 °W
Elevation: 117 m a.s.l.
Type: Bedrock
Surface Strike/Dip: 16°/9°
Sample Thickness: 1.5 cm
Horizontal Shielding: 028°/0°, 127°/9°, 159°/2°, 194°/4°, 215°/7°, 245°/4°, 266°/3°, 295°/11°, 320°/8°, 351°/0°
Notes: Sample collected from a bedrock outcrop adjacent to Stonehouse Pond. The surface sample was collected from a glacially smoothed, quartz and feldspar rich surface.
Sample Lithology: Concord Granite (Late Devonian)
Sample Description: Felsic, medium-grained granite; sample collected from a quartz vein
Sample SCNH21-08

Date Collected: 09-26-2021

Site: Goodwill Conservation Trail, Barrington, NH

Location: 43.21238 °N, 71.02226 °W

Elevation: 86 m a.s.l.

Type: Boulder

Boulder Size: 380/198/120/132 (L/W/UH/DH in cm)

Surface Strike/Dip: 271°/2°

Sample Thickness: 2.5 cm

Horizontal Shielding: 026°/1°, 109°/0°, 170°/3°, 204°/2°, 230°/8°, 260°/7°, 325°/3°, 354°/4°

Notes: Boulder is located near a hillslope. Sample was collected from a high point at the central part of the boulder.

Bedrock Lithology: Concord Granite (Late Devonian)

Sample Lithology: Concord Granite

Sample Lithology: intermediate, coarse-grained (intrusive) diorite, mineral composition: two micas (biotite - large grains), two feldspars (pyroxene dominant), smoky quartz, amphibole, absent of garnets; similar to SCNH21-03 and SCNH21-10
Sample SCNH21-08 (cont.)
Sample SCNH21-09

Date Collected: 09-26-2021

Site: Barrington Watershed Area, Barrington, NH

Location: 43.16598 °N, 71.01614 °W

Elevation: 77 m a.s.l.

Type: Boulder

Boulder Size: 396/320/117/142 (L/W/UH/DH in cm)

Surface Strike/Dip: 172°/4°

Sample Thickness: 1.75 cm

Horizontal Shielding: <1-2° in all directions

Notes: Sample collect from the high point which was approximately 20 centimeters from the top, rounded corner.

Bedrock Lithology: Berwick Formation

Sample Lithology: Concord Granite

Sample Description: felsic to intermediate, coarse-grained (intrusive) granite; mineral composition: feldspars (dominant), two micas (more biotite than muscovite), smoky quartz, amphibole, absent of garnets
Sample SCNH21-09 (cont.)

Sample: SCNH21-09
Location: Barrington Watershed Area
Elevation: 727m
Above ML (adjacent)
Sample SCNH21-10

Date Collected: 09-28-2021

Site: Barrington Watershed Area, Barrington, NH

Location: 43.172285 °N, 71.017827 °W

Elevation: 83 m a.s.l.

Type: Boulder

Boulder Size: 310/230/85/130 (L/W/UH/DH in cm)

Surface Strike/Dip: 223°/4°

Sample Thickness: 2.25 cm

Horizontal Shielding: <1-2° in all directions

Notes: Boulder was very round with a stable base and covered completely with moss.

Bedrock Lithology: Berwick Formation

Sample Lithology: Concord Granite

Sample Description: felsic, coarse-grained (intrusive) granite; mineral composition: two micas, quartz, feldspars, amphibole, smoky quartz, garnet (sparse); similar to samples SCNH21-03 and SCNH21-08
Sample SCNH21-10 (cont.)

Sample: SCNH21-10
Location: Barrington Watershed Area
Elevation: 83 m
Above ML (adjacent)
Sample SCNH21-11A

Date Collected: 10-20-2021

Site: Kingman Farm, Madbury, NH

Location: 43.17038 °N, 70.94038 °W

Elevation: 66 m a.s.l.

Type: Boulder

Boulder Size: 400/420/195/200 (L/W/UH/DH in cm)

Surface Strike/Dip: 197°/11°

Sample Thickness: 2.75 cm

Horizontal Shielding: 010°/0°, 065°/2°, 090°/4°, 140°/0°, 170°/4°, 185°/6°, 201°/10°, 225°/6°, 250°/4°, 275°/2°

Notes: Boulder is located at the base of Hick’s Hill drumlin. Rolling is not a concern because it is far enough away and on flat terrain.

Bedrock Lithology: Eliot formation

Sample Lithology: Exeter Diorite

Sample Description: Pyroxene-hornblende gabbro (mafic) identified as Exeter diorite; surface sample has crystals of quartz, amphibole, pyroxene, mica, feldspars; boulder deposited near Hick’s Hill drumlin
Sample SCNH21-11A (cont.)

Sample: SCNH21-11A
Location: Kingman Farm, Madbury NH
Elevation: 66 m
Below ML
**Sample SCNH21-12**

Date Collected: 10-21-2021

Site: Hick’s Hill, Madbury, NH

Location: 43.17036 °N, 70.94267 °W

Elevation: 62 m a.s.l.

Type: Boulder

Boulder Size: 235/165/140/162 (L/W/UH/DH in cm)

Surface Strike/Dip: 284°/4°

Sample Thickness: 3.0 cm

Horizontal Shielding: 14°/1°, 45°/4°, 88°/6°, 111°/10°, 135°/12°, 167°/9°, 186°/5°, 205°/1°, 290°/2°, 339°/3°

Notes: Sample was collected from the high point of the boulder. The boulder is located near the stoss side of the Hick’s Hill drumlin with a small chance that it could have rolled. This boulder was not selected for AMS analysis.

Bedrock Lithology: Eliot formation

Sample Lithology: Exeter Diorite

Sample Description: intermediate, coarse-grained (intrusive) diorite, mineral composition: mica, quartz, pyroxene
Sample SCNH21-12 (cont.)

Sample: SCNH21-12
Location: Hicks Hill, Madbury NH
Elevation: 62m
Below ML
Sample SCNH21-13

Date Collected: 10-22-2021

Site: West Foss Farm, Durham, NH

Location: 43.12335 °N, 70.94397 °W

Elevation: 21 m a.s.l.

Type: Boulder

Boulder Size: 280/210/137/185 (L/W/UH/DH in cm)

Surface Strike/Dip: 206°/12°

Sample Thickness: 2.0 cm

Horizontal Shielding: 9°/3°, 38°/2°, 80°/4°, 124°/5°, 179°/4°, 210°/0°, 269°/1°, 323°/0°, 357°/0°

Notes: Boulder

Bedrock Lithology: Exeter Diorite

Sample Lithology: Exeter Diorite

Sample Description: Pyroxene-hornblende diorite identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; boulder deposited between De Geer moraines
SCNH21-13 (cont.)
Sample SCNH21-14

Date Collected: 10-24-2021

Site: UNH College Woods, Durham, NH

Location: 43.13135 °N, 70.94863 °W

Elevation: 24 m a.s.l.

Type: Boulder

Boulder Size: 340/205/105/115 (L/W/UH/DH in cm)

Surface Strike/Dip: 292°/20°

Sample Thickness:

Horizontal Shielding: 5°/0°, 109°/0°, 159°/2°, 179°/3°, 210°/0°, 240°/1°, 275°/3°, 322°/4°

Notes: This boulder was not selected for AMS analysis. The boulder is located near a small rock wall. The surface had large weathering pits that were avoided.

Bedrock Lithology: Exeter Diorite

Sample Lithology: Exeter Diorite

Sample Description: Pyroxene-hornblende gabbro (mafic rich) identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; crystals are not as defined as other Exeter diorite samples
Sample SCNH21-14 (cont.)

Sample: SCNH21-14
Location: College Woods, Durham NH
Elevation: 24 m
Below ML
Sample SCNH21-15

Date Collected: 10-29-2021

Site: Tucker & French Family Forest

Location: 42.94870 °N, 71.08370 °W

Elevation: 50 m a.s.l.

Type: Boulder

Boulder Size: 270/230/100/130 (L/W/UH/DH in cm)

Surface Strike/Dip: sub horizontal

Sample Thickness: 2.25 cm

Horizontal Shielding: <1-2° in all directions

Notes: Boulder is perched on small hill, adjacent to a small swampy area. This sample was also not selected for AMS analysis.

Bedrock Lithology: Eliot formation

Sample Description: felsic and oxidized; surface sample was weathered and crumbling; mineral composition: biotite, feldspars, and smoky quartz
Sample SCNH21-15 (cont.)

Sample: SCNH21-15
Location: Tucker and French Family Forest, Kingston NH
Elevation: 50m
Below ML
Sample SCNH21-16

Date Collected: 10-29-2021

Site: Rock Rimmon Hill, Kingston, NH

Location: 42.92772 °N, 71.09408 °W

Elevation: 93 m a.s.l.

Type: Boulder

Boulder Size: 210/192/100/142 (L/W/UH/DH in cm)

Surface Strike/Dip: 31°/12°

Sample Thickness: 2.0 cm

Horizontal Shielding: 24°/3°, 96°/1°, 135°/0°, 210°/0°, 270°/4°, 292°/8, 330°/16°, 350°/14°

Notes: Boulder is located near, but not at the top of Rock Rimmon Hill.

Bedrock Lithology: Two-mica granite of northern and southeastern New Hampshire (similar to Concord granite)

Sample Description: intermediate to mafic, coarse-grained (intrusive) granite; mineral composition: micas, hornblende, amphiboles, potassium feldspar (abundant), quartzs
Sample SCNH21-16 (cont.)

Sample: SCNH21-16
Location: Rock Rimmon Hill, Kingston NH
Elevation: 93m
Above ML, but within the inundated region
Sample SCNH21-17

Date Collected: 11-09-2021

Site: Brown Brooks Forest, Fremont, NH

Location: 43.00508 °N, 71.12601 °W

Elevation: 66 m a.s.l.

Type: Boulder

Boulder Size: 290/190/125/145 (L/W/UH/DH in cm)

Surface Strike/Dip: 298°/13°

Sample Thickness: 1.75 cm

Horizontal Shielding: 25°/1°, 78°/1°, 126°/2°, 154°/4°, 195°/3°, 267°/1°, 296°/3°, 345°/2°

Notes: Boulder rests on top of a steep hill. Sample was collected from the high point of the boulder where glacial polish was evident, and weathering was minimal.

Bedrock Lithology: Berwick Formation

Sample Lithology: felsic, medium to coarse-grained granite; mineral composition: feldspars, micas (muscovite dominant), garnets, smoky quartz
Sample SCNH21-17 (cont.)

Sample: SCNH21-17
Location: Brown Brook Forest, Fremont NH
Elevation: 64 m
Below ML
**Sample SCNH21-18**

Date Collected: 11-09-2021

Site: Rock Rimmon Hill, Kingston, NH

Location: 42.92974 °N, 71.09453 °W

Elevation: 76 m a.s.l.

Type: Boulder

Boulder Size: 230/250/90/95 (L/W/UH/DH in cm)

Surface Strike/Dip: 236°/8°

Sample Thickness: 1.75 cm

Horizontal Shielding: 20°/1°, 85°/4°, 150°/6°, 182°/14°, 213°/15°, 250°/7°, 270°/1°, 330°/0°

Notes: Sample was not selected for AMS analysis because it is less than 1 meter tall and lies at the base of a steep slope. There is potential that it was plucked from the top of Rock Rimmon Hill.

Bedrock Lithology: Two-mica granite of northern and southeastern New Hampshire (similar to Concord granite)

Sample Description: intermediate, medium to coarse-grained; mineral composition: feldspars (pink), biotite, quartz
Sample SCNH21-18 (cont.)

Sample: SCNH21-18
Location: Rock Rimmon Hill, Kingston NH
Elevation: 76 m
Above ML (inundated region)
**Sample SCNH21-19**

<table>
<thead>
<tr>
<th>Date Collected:</th>
<th>11-17-2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site:</td>
<td>Jeff’s Hill, Durham, NH</td>
</tr>
<tr>
<td>Location:</td>
<td>43.08009 °N, 70.90894 °W</td>
</tr>
<tr>
<td>Elevation:</td>
<td>36 m a.s.l.</td>
</tr>
<tr>
<td>Type:</td>
<td>Boulder</td>
</tr>
<tr>
<td>Boulder Size:</td>
<td>580/400/265/280 (L/W/UH/DH in cm)</td>
</tr>
<tr>
<td>Surface Strike/Dip:</td>
<td>248°/8°</td>
</tr>
<tr>
<td>Sample Thickness:</td>
<td>1.75 cm</td>
</tr>
<tr>
<td>Horizontal Shielding:</td>
<td>3°/0°, 176°/1°, 210°/2°, 239°/1°, 298°/0°</td>
</tr>
<tr>
<td>Notes:</td>
<td>Boulder is perched at the top of Jeff’s Hill on flat terrain. The sample was collected near the top surface of the boulder where there was minimal weather and a glacially smoothed surface.</td>
</tr>
<tr>
<td>Bedrock Lithology:</td>
<td>Exeter Diorite</td>
</tr>
<tr>
<td>Sample Lithology:</td>
<td>Exeter Diorite</td>
</tr>
<tr>
<td>Sample Description:</td>
<td>intermediate to mafic, coarse-grained (intrusive) diorite; mineral composition: amphibole, feldspars, micas, quartz</td>
</tr>
</tbody>
</table>
Sample SCNH21-19

Location: Sweet Trail / Jeff’s Hill, Durham NH
Elevation: 36 m
Below ML
Sample SCNH21-20

Date Collected: 11-18-2021

Site: Jeff’s Hill, Durham, NH

Location: 43.08246 °N, 70.91093 °W

Elevation: 21 m a.s.l.

Type: Boulder

Boulder Size: 450/220/160/250 (L/W/UH/DH in cm)

Surface Strike/Dip: 42°/11°

Sample Thickness: 2.5 cm

Horizontal Shielding: 15°/1°, 55°/2°, 85°/3°, 110°/6°, 123°/8°, 155°/7°, 180°/9°, 200°/5°,

208°/2°, 220°/0°, 340°/0°

Notes: The large boulder is deposited on a bedrock exposure.

Bedrock Lithology: Exeter Diorite

Sample Lithology: Exeter Diorite

Sample Lithology: Pyroxene-hornblende diorite identified as Exeter Diorite, surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars, boulder is perched on a bedrock exposure
Sample SCNH21-20 (cont.)
**Sample SCNH21-21**

Date Collected: 11-18-2021

Site: Whites Lane, Hampton, NH

Location: 42.95333 °N, 70.81721 °W

Elevation: 22 m a.s.l.

Type: Boulder

Boulder Size: 320/200/135/180 (L/W/UH/DH in cm)

Surface Strike/Dip: 202°/1°

Sample Thickness: 2.0 cm

Horizontal Shielding: <1-2° in all directions

Notes: The sample was collected from a glacially polished and striated surface on the highest point of the boulder.

Bedrock Lithology: Rye Complex

Sample Description: felsic, medium to coarse-grained granite; mineral composition: feldspars (light colored or orange alteration), muscovite (abundant), amphibole (sparse), absent of biotite
Sample SCNH21-21 (cont.)

Sample: SCNH21-21
Location: Hampton Whites Lane
Elevation: 22m Below ML
Sample SCNH21-22

Date Collected: 11-19-2021

Site: Barker Farm, Stratham, NH

Location: 43.03360 °N, 70.89610 °W

Elevation: 42 m a.s.l.

Type: Boulder

Boulder Size: 470/370/110/120 (L/W/UH/DH in cm)

Surface Strike/Dip: 63°/4°

Sample Thickness: 2.75 cm

Horizontal Shielding: 145°/2°, 162°/5°, 175°/11°, 190°/8°, 200°/6°, 218°/0°

Notes: The boulder is not far from Jewel Hill, a drumlin, but far enough from it that there are no concerns of rolling.

Bedrock Lithology: Eliot formation

Sample Lithology: Exeter Diorite

Sample description: Pyroxene-hornblende diorite identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; boulder deposited near two drumlins (Stratham Hill and Jewel Hill); boulder surface was glacially smoothed and rounded
Sample SCNH21-22 (cont.)
Sample SCNH21-23

Date Collected: 11-20-2021

Site: Stratham Hill Park, Stratham, NH

Location: 43.04088 °N, 70.89034 °W

Elevation: 59 m a.s.l.

Type: Boulder

Boulder Size: 540/330/166/190 (L/W/UH/DH in cm)

Surface Strike/Dip: 125°/4°

Sample Thickness: 2.0 cm

Horizontal Shielding: 30°/0°, 120°/1°, 145°/4°, 160°/9°, 180°/14°, 190°/15°, 240°/12°, 260°/8°,
280°/5°, 300°/0°

Notes: The boulder is embedded into the side of a drumlin (near the stoss side) about halfway down the slope. The slope of the drumlin is approximately 15 degrees.

Bedrock Lithology: Eliot formation

Sample Lithology: Exeter Diorite

Sample description: Pyroxene-hornblende gabbro (mafic rich) identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars
Sample SCNH21-24

Date Collected: 11-20-2021

Site: Stratham Hill Park, Stratham, NH

Location: 43.04088 °N, 70.89034 °W

Elevation: 59 m a.s.l.

Type: Boulder

Boulder Size: 245/210/115/125 (L/W/UH/DH in cm)

Surface Strike/Dip: 290°/3°

Sample Thickness: 1.75 cm

Horizontal Shielding: 135°/0°, 160°/4°, 185°/6°, 195°/9°, 225°/9°, 255°/7°, 265°/5°, 271°/5,
283°/4°, 285°/1

Notes: The boulder is located on the lee side of the drumlin with a slope of approximately 12 degrees.

Bedrock Lithology: Eliot formation

Sample Lithology: Exeter Diorite

Sample Description: Pyroxene-hornblende gabbro (mafic rich) identified as Exeter Diorite;
surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars
Sample SCNH21-24 (cont.)
Sample SCNH21-25

Date Collected: 11-23-2021

Site: Henderson-Swasey Town Forest, Exeter, NH

Location: 42.99792 °N, 70.95388 °W

Elevation: 26 m a.s.l.

Type: Boulder

Boulder Size: 310/260/105/110 (L/W/UH/DH in cm)

Surface Strike/Dip: 66°/9°

Sample Thickness: 1.6 cm

Horizontal Shielding: 10°/2°, 50°/1°, 97°/1°, 142°/3°, 202°/3°, 252°/1°, 286°/2°, 300°/3°

Notes: This boulder is located southeast of a small swarm of boulders. The sample was collected from the highest point of the boulder to avoid small weathering pits.

Bedrock Lithology: Exeter Diorite

Sample Lithology: Exeter Diorite

Sample description: Pyroxene-hornblende diorite identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; quartz-rich surface with glacial polish
Sample SCNH21-25 (cont.)
Sample SCNH21-26

Date Collected: 11-23-2021

Site: Henderson-Swasey Town Forest, Exeter, NH

Location: 42.99601 °N, 70.95188 °W

Elevation: 21 m a.s.l.

Type: Boulder

Boulder Size: 225/180/100/120 (L/W/UH/DH in cm)

Surface Strike/Dip: 5°/12°

Sample Thickness: 2.0 cm

Horizontal Shielding: 90°/0°, 122°/2°, 140°/5°, 155°/7°, 180°/8°, 220°/7°, 249°/4°, 274°/2°,
                   308°/1°, 321°/3°, 350°/0°

Notes: The sample was collected from a smooth, polished surface at one high point and along the top ridge of the boulder.

Bedrock Lithology: Exeter Diorite

Sample Lithology: Exeter Diorite

Sample description: Granodiorite identified as Exeter Diorite; surface sample has large crystals of quartz, amphibole, pyroxene, mica, feldspars; quartz and plagioclase rich sample
Sample SCNH21-26 (cont.)

SCU Sample: SCNH21-26
Location: Henderson-Swasey Town Forest, Exeter NH
Elevation: 21m
Below ML
**Sample SCNH21-27**

Date Collected: 11-23-2021  
Site: Windham Town Forest, Windham, NH  
Location: 42.84541°N, 71.25788°W  
Elevation: 96 m a.s.l.  
Type: Boulder  
Boulder Size: 260/190/90/125 (L/W/UH/DH in cm)  
Surface Strike/Dip: 202°/22°  
Sample Thickness: N/A (this sample was not selected for crushing)  
Horizontal Shielding: 11°/5°, 22°/6°, 65°/7°, 95°/7°, 115°/5°, 145°/1°, 180°/1°, 207°/2°, 240°/1, 265°/1°, 282°/2°, 350°/0°  
Notes: The surface was highly weathered, and the sample was collected below the highest point of the boulder.  
Bedrock Lithology: Berwick Formation  
Sample Lithology: Felsic, medium to coarse-grained granodiorite; mineral composition: feldspar (dominant), hornblende, two mica, quartz (sparse)
Sample SCNH21-27 (cont.)

Sample: SCNH21-27
Location: Windham Town Forest
Elevation: 96 m
Above ML
APPENDIX B

FIELD SITES

1. Hick’s Hill/Kingman Farm
   Contacts: UNH Stephen Eisenhaure - stephen.eisenhaure@unh.edu, Madbury Board of Selectmen - Town Admin – Eric Fiegenbaum (adminmadbury@comcast.net)

2. East and West Foss Farm
   Contact: UNH Stephen Eisenhaure - stephen.eisenhaure@unh.edu

3. Stonehouse Pond Conservation Area (SELT)
   Contacts: T. Parker Schuerman (t.parker@seltnh.org), Debbie Goard (deborah@seltnh.org)

4. Goodwill Conservation Trail (SELT)
   Contacts: T. Parker Schuerman (t.parker@seltnh.org), Debbie Goard (deborah@seltnh.org)

5. Barrington Watershed Area
   Contact: Ken Grossman – Barrington Conservation Commission (ken.grossman.100@gmail.com)

6. College Woods
   Contact: UNH Stephen Eisenhaure - stephen.eisenhaure@unh.edu

7. Tucker French Family Forest (SELT)
   Contacts: T. Parker Schuerman (t.parker@seltnh.org), Debbie Goard (deborah@seltnh.org)

8. Rock Rimmon Hill (State Forest)
   Contact: Robert Spoerl (Robert.f.spoerl@dncr.nh.gov)

9. Brown Brooks Forest (SELT)
   Contact: T. Parker Schuerman (t.parker@seltnh.org), Debbie Goard (deborah@seltnh.org)

10. Sweet Trail/Jeff’s Hill
    Contact: Durham Town Administrator – Tod Selig (tselig@ci.durham.nh.us)

11. Whites Lane, Hampton, NH
    Contacts: Hampton Conservation Commission, Debra Wrobel - Chair (dwrobel@hamptonnh.net), Brianna O’Brien – Conservation Coordinator (bobrien@hamptonnh.gov)

12. Barker Farm – Privately-owned, but open to the public under an easement
    Contact: Edie Barker (barkersfarm@myfairpoint.net)
13. Stratham Hill Park
   Contact: Stratham Select Board, Town Park Manager – Seth Hickey
   (shickey@strathamnh.gov)

14. Henderson- Swasey Town Forest
   Contact: Exeter Conservation Commission, Natural Resource Planner – Kristen
   Murphy (kmurphy@exeternh.gov), Chair of Exeter Conservation Commission – Andrew Koff (drewkoff@gmail.com)