University of Rhode Island

DigitalCommons@URI

Open Access Dissertations

2012

LATE QUATERNARY DEPOSITIONAL ENVIRONMENTS, TIMING AND RECENT DEPOSITION: NARRAGANSETT BAY, RHODE ISLAND AND MASSACHUSETTS

Bryan Andrew Oakley

University of Rhode Island, BOakley@my.uri.edu

Follow this and additional works at: https://digitalcommons.uri.edu/oa_diss

Recommended Citation

Oakley, Bryan Andrew, "LATE QUATERNARY DEPOSITIONAL ENVIRONMENTS, TIMING AND RECENT DEPOSITION: NARRAGANSETT BAY, RHODE ISLAND AND MASSACHUSETTS" (2012). *Open Access Dissertations*. Paper 88.

https://digitalcommons.uri.edu/oa_diss/88

This Dissertation is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Dissertations by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons-group@uri.edu.

**LATE QUATERNARY DEPOSITIONAL ENVIRONMENTS, TIMING AND
RECENT DEPOSITION: NARRAGANSETT BAY, RHODE ISLAND AND
MASSACHUSETTS**

BY

BRYAN ANDREW OAKLEY

**A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN
GEOSCIENCES**

UNIVERSITY OF RHODE ISLAND

2012

Library Rights Statement

In presenting this dissertation in partial fulfillment of the requirements for an advanced degree at the University of Rhode Island, I agree that the Library shall make it freely available for inspection. I further agree that permission for copying, as provided for by the Copyright Law of the United States (Title 17, U.S. Code), of the dissertation for scholarly purposes may be granted by the Librarian. It is understood that any copying or publication of this dissertation for financial gains shall not be allowed without my written permission.

I hereby grant permission to the University of Rhode Island Library to use my dissertation for scholarly purposes.

Signature

Date

DOCTOR OF PHILOSOPHY
OF
BRYAN ANDREW OAKLEY

APPROVED:

Thesis Committee:

Major Professor _____

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2012

ABSTRACT

Glacial Lake Narragansett, which occupied much of the southern portion of Narragansett Basin during Late Wisconsinan deglaciation, and was contiguous with glacial lakes in Rhode Island Sound and Block Island Sound, is the focus of this study. This dissertation examines the deposits of glacial lakes to develop a history of deglacial chronology, isostatic rebound, and climate change across the glaciated northeast. All of these issues are addressed in this dissertation. This work synthesizes the Late Wisconsinan deglacial evolution of Glacial Lake Narragansett using digital elevation models, sub-bottom seismic reflection, ground penetrating radar profiles, sediment cores and borehole stratigraphy. The impetus for the research was to fill a perceived gap in the understanding of the Quaternary geology of southern New England. While the spatial extent of the Late Wisconsinan Laurentide Ice Sheet and general timing of deglaciation is known, more detailed analyses of the nature and timing of deglaciation are needed, particularly near the terminal margin of the Laurentide Ice Sheet. Improving the understanding of the timing and nature of deglaciation allows links to be made between the Laurentide Ice Sheet and northern hemisphere climate.

ACKNOWLEDGMENTS

This dissertation is largely a reflection of the patience and guidance offered by my advisor, Jon C. Boothroyd, for countless hours of discussion, edits, and time in the field. His foresight to see the potential in a young geologist set me on my current career path and for that, I will always be grateful. Jon has allowed me to meld my personal and professional interests, and gave me great academic freedom to pursue projects and opportunities in a wide range of depositional environments. As our working relationship has evolved from advisor to colleague, I continue to learn from his example. To my committee: John King, Cheryl Hapke, Dan Murray, and Pete August. Your generosity and flexibility with your time ultimately made this possible. You all offered insight that challenged me and made me a better writer and scientist and vastly improved this dissertation. Similarly, I am grateful for the support of the other faculty members of the department, who have all made me a better scientist and educator in some way.

More graduate students than I can possibly list have contributed time and support throughout the graduate process, either in the field or by providing reviews and discussion. I have attempted to acknowledge specific contributions at the end of each chapter. My relationship with three alumni in particular, Mark Borrelli, Jon Alvarez and Rachel Henderson, has evolved from office mates to colleagues to close friends. Cheryl Grasso, who keeps the Department of Geosciences sane and organized has been invaluable in navigating the fine print and red tape that is involved when attempting to get a paycheck, travel to a conference or purchasing field supplies.

The support of my colleagues at Bryant University has allowed me to expand my teaching skills immensely while accommodating my schedule as a graduate student, giving me invaluable professional experience. I have had the privilege to work with folks from a variety of agencies and department beyond the geosciences department. In particular, Jim Turenne, (USDA-NRCS), Dan Goulet (RI CRMC), Chris Damon and Mike Bradley (URI-EDC) have all contributed time and effort in the field or lab that contributed to this work. I am happy to count you all as colleagues, and more importantly consider you all good friends.

On a personal level, I am forever indebted to my wife Julie for her support through the long process of graduate school. We transitioned from dating to marriage to parenthood during this ordeal and her support, and at times, subtle pushes have contributed greatly to this dissertation. My parents George and Laura have always supported what I was doing, even if they did not always understand the process. Their support, emotionally, financially, providing childcare and reminders that they were always proud helped immensely during this process. Similarly, I need to thank my in-laws, Jeri and Roland, and Brian and Annick, whose generosity with their time since the birth of Aidan has been immeasurable and allowed us to keep a day-to-day working schedule, knowing Aidan was in good hands. Last, and of course not least, I need to thank my son Aidan, who was born during the ABD phase of my dissertation. Thank you for always being there with a hug or a smile as well as with welcome (and needed!) distraction during this process. Without knowing it, you continually serve both as I reminder as to why I do what I do, and provide much needed doses of perspective.

PREFACE

During late Wisconsinan deglaciation in New England, a series of glacial lakes formed along the margin of the retreating ice sheet were impounded in topographic lows behind bedrock outcrops, sediment dams or blocks of stagnant ice. The deposits of glacial lakes provide a record of deglacial chronology, isostatic rebound, and climate change across the glaciated northeast. All of these issues are addressed in this dissertation. Glacial Lake Narragansett, which occupied much of the southern portion of Narragansett Basin during deglaciation, and was contiguous with glacial lakes in Rhode Island Sound and Block Island Sound, is the focus of this study. This work synthesizes the late Wisconsinan deglacial evolution of Glacial Lake Narragansett using digital elevation models, sub-bottom seismic reflection profiles, ground penetrating radar profiles, sediment cores and borehole stratigraphy. This dissertation is presented in manuscript format, and comprises a series of papers that address different aspects of the late Quaternary evolution of Narragansett Bay. There is some overlap and differences in formatting between chapters, as two are only slightly modified from manuscripts submitted for publication.

The impetus for the research was to fill a perceived gap in the understanding of the Quaternary geology of southern New England. The spatial extent of the Late Wisconsinan Laurentide Ice Sheet and general timing of deglaciation is well documented, however, more detailed analyses of the nature and timing of deglaciation are needed, particularly near the terminal margin of the Laurentide Ice Sheet. Improving the understanding of the timing and nature of deglaciation allows links to be made between the Laurentide Ice Sheet and northern hemisphere climate. Debate

still exists over the timing of the last glacial maximum and beginning of Laurentide Ice Sheet recession (Denton et al., 2010; Peltier and Fairbanks, 2006; Toucanne et al., 2009). Understanding the timing of Late Wisconsinan deglaciation is critical to understanding the climate dynamics and links to ice sheet behavior during that time (Clark et al., 1999; Denton et al., 2010).

Recent work on the deglaciation of southern New England has focused on glacial lakes in other areas, including Long Island Sound (Lewis and Stone, 1991; Stone et al., 2005), Connecticut, and Massachusetts (Ridge and Larsen, 1990; Ridge et al., 1999; Ridge et al., 2001; Ridge et al., 2003; Ridge et al., 2004; Rittenour et al., 2000). Previous work on the subsurface sediment of Block Island and Rhode Island Sounds (Goss, 1995; Needell and Lewis, 1984; Needell et al., 1983) provide insight into the Quaternary evolution of these areas, however, those studies did not extend into Narragansett Bay, and offered a limited view of Quaternary glacial depositional environments.

Glacial lakefloor sediment, interpreted to be varves, was previously identified in several areas within or around Narragansett Bay, including the Providence River (Antevs, 1922; Antevs, 1928; Pickart, 1987), Bristol (Smith, 1955) and the West Passage (Peck, 1989; Peck and McMaster, 1991). Two of these studies (Peck and McMaster, 1991; Pickart, 1987) also proposed estimates of water levels of Glacial Lake Narragansett. Previous studies on the Holocene stratigraphy of Narragansett Bay, (McMaster, 1960; McMaster, 1984), did not take a detailed approach to deciphering the late Quaternary evolution of Narragansett Bay. This work is the first to focus on the extent, timing, volume, and water level of Glacial Lake Narragansett,

and the distribution of Quaternary depositional environments throughout present-day Narragansett Bay.

The first paper (Chapter 1; Accepted for publication in *Quaternary Research*, 23 January 2012), recreates the topography of southern New England prior to isostatic rebound and evaluates Late Wisconsinan isostatic depression in the region based on the limit of marine inundation in New England. Determining the pre-rebound topography is also an important component to interpreting glacial lake water levels, drainage patterns, spillways and other geomorphic features (Leverington et al., 2002). Narragansett Bay and adjacent areas, situated close to the terminal margin of the ice sheet and adjacent to the Atlantic Ocean, is an ideal location to examine the total isostatic depression, using relative sea level curves based on different values of total isostatic depression from previous studies and local indicators of ice thickness. The well-mapped limit of Late Pleistocene marine inundation north of the study area provides a constraint for maximum depression. Relative sea level curves created using published values of isostatic depression in southern New England, suggest inundation of the study area well south of the mapped limit of marine inundation.

Different models of isostatic rebound are tested, and the maximum isostatic depression in southern New England is constrained. The response of the lithosphere, specifically the amount of isostatic depression under the ice sheet in North America has been studied extensively; primarily using continental scale models based on inferred ice thicknesses and assumed properties of the lithosphere. Reconstructions of isostatic rebound at the terminal margin have previously been a compromise between local indicators of ice thickness near the margin and estimates of ice thickness in the

central portion of the ice sheet (Braun et al., 2008; Peltier, 2004). Isostatic depression near the margin was poorly constrained.

The second paper (Chapter 2) provides measurements of the elevation of delta plain-delta slope contacts within deltas deposited into Glacial Lakes Block Island, Rhode Island and Narragansett, and examines the water levels of these lakes. The now isostatically uplifted water level of Glacial Lake Narragansett extends above and below present sea level. Previously mapped and formerly unmapped glacial deltas below present sea level were imaged using high-resolution seismic reflection profiles. Deltas above present sea level were imaged using ground-penetrating radar (GPR). Determining the elevation of these deltas served two purposes. The first was to determine the former water level(s) of Glacial Lake Narragansett; the second was to compare the isostatic uplift profile recorded by Glacial Lake Narragansett with measured uplift in central New England. Projected water levels reflecting regional isostatic rebound were fit to the present elevation of the deltas, supporting the hypothesis that one large lake occupied much of the southern portion of the Narragansett Basin during deglaciation. The lake levels were projected onto the pre-rebound topographic model reported in chapter 1 to determine the extent and geometry of Glacial Lake Narragansett as the Laurentide Ice Sheet retreated north through present-day Narragansett Bay.

The third paper (Chapter 3) investigates the timing of Glacial Lake Narragansett based on a new 265-year varve series collected in the Providence River. The hypothesis of this paper was that varves from Glacial Lake Narragansett could be correlated with the calibrated North American Varve Chronology (NAVC) of Antevs

(1922; 1928), and Ridge (2010, and references contained therein). The varve series from Glacial Lake Narragansett was not correlated with the NAVC, and it is interpreted that Glacial Lake Narragansett is older than both the varve sequences of the NAVC, and the other uncorrelated records in southern New England and eastern New York. The regional context of the Glacial Lake Narragansett varves was examined using these varve records and cosmogenic exposure dates on recessional end moraines, and the age of Glacial Lake Narragansett was constrained between 20,400 and 19,500 yBP.

The fourth paper (Chapter 4) synthesizes the Quaternary evolution of Narragansett Bay based on the interpretation of 800 km of seismic reflection profiles. Interpreted side-scan sonar records from portions of Narragansett Bay (Chapter 6; Oakley et al., 2012) provided additional information on the extent of some of the glacial depositional environments. Previous studies on the stratigraphy and depositional environments of Narragansett Bay focused on the Holocene stratigraphy (McMaster, 1984). Other studies using seismic reflection profiles and sediment cores focused on select areas of Narragansett Bay (Peck, 1989; Peck and McMaster, 1991; Pickart, 1987). This work represents the first comprehensive, detailed mapping of the Quaternary glacial depositional environments throughout Narragansett Bay. Mapping the deglacial depositional environments provides an understanding of the style of deposition and subglacial dynamics of the Laurentide Ice Sheet. This chapter also includes a 1:50,000 scale Quaternary Geologic map of Narragansett Bay.

The extent, continuity, and elevation of lakefloor deposits support the hypothesis of a single-lake occupying the southern portion of the Narragansett Basin

during deglaciation. A key deglacial depositional environment is the lacustrine fans deposited at the margin of the ice sheet beneath the surface of the glacial lake. These mark the position of the ice margin and the location of subglacial tunnels during deglaciation. The presence of lacustrine fans indicates that a considerable amount of meltwater reached the base of the Laurentide Ice Sheet, and the spacing of subglacial tunnels indicated by the distribution of lacustrine fans provides insight into the nature of subglacial drainage of the Laurentide Ice Sheet. The total volume of sediment deposited in the present-day watershed of Narragansett Bay indicates that this drainage was very efficient, and began > 5 km from the southern margin of the ice sheet. Subglacial drainage has become a controversial topic in recent years, and it has been hypothesized that subglacial meltwater of the Greenland Ice Sheet may be accelerating flow of outlet glaciers (Luthcke et al., 2006; Zwally et al., 2002). These similarities point to the importance of understanding the Late Pleistocene dynamics of the Laurentide Ice Sheet, especially in a world of changing climate.

The fifth paper (Chapter 5, Accepted for publication in the Journal of Coastal Research 11 December 2011) examines the distribution of modern depositional environments in two shallow embayments within Narragansett Bay using side-scan sonar, surface sediment grab samples, underwater video imagery and digital aerial photography. The concept of benthic geologic habitats is introduced and defined, and the areas were classified using a flexible naming convention that combines information about natural geologic and anthropogenic processes, morphologic form, sediment characteristics and biota. The result of this work contributes to the overall understanding of the distribution of depositional environments in glaciated estuaries,

where the distribution of facies is controlled by the extent of the glacial depositional environments and the present geologic processes.

The papers presented here provide a scientific foundation that addresses questions regarding the Late Quaternary evolution of Narragansett Bay and southern New England. The effects of climate change on ice sheets, especially the Greenland Ice Sheet, remains highly debated within the scientific literature. A more thorough understanding of the behavior of the Laurentide Ice Sheet, especially during the early stages of deglaciation, can help guide models and predictions regarding the fate of the modern ice sheets. The conclusions of chapters 1 through 4 contribute to the growing evidence for a thinner, older ice sheet in southern New England (Clark, 1992; Clark et al., 1999; Dyke and Prest, 1987; Peltier and Fairbanks, 2006).

The interpretations of this work extend into research areas beyond the deglacial evolution of southern New England. The conclusions of chapter 1 and 2 contribute to models of isostatic rebound or thickness of the Laurentide Ice Sheet in southern New England. Chapter 3 places the uncorrelated varve sequences in southeastern New England in a regional context, and constrains the age of Glacial Lake Narragansett. The age ($> 19,500$ yBP) of varves in the northern terminus of the lake (75 km from the terminal margin of the Laurentide Ice Sheet) indicates deglaciation was fully underway by this time, and rebuts the hypothesis that deglaciation began 18,000 to 20,000 yBP (Denton et al., 2010).

Chapter 4 contributes information on processes and behavior of the Laurentide Ice Sheet during Late Wisconsinan deglaciation, which can inform models of present ice sheets in a world of changing climate. The Quaternary depositional environments

mapped can be applied in other regions of the glaciated northeast, and provides managers with an understanding of the subsurface resources of Narragansett Bay, particularly for future dredging projects, disposal of dredged material, marina construction, and siting of offshore wind farms. Chapter 5 introduces the concept and definition of benthic geologic habitats, and builds the understanding between Quaternary (glacial) depositional environments and the present distribution of benthic geologic habitats within two areas of Narragansett Bay. This paper provides a concise method of mapping these areas in a manner that is useful to managers and scientists within other disciplines, and has been applied successfully in lagoon, shoreface, and inner shelf depositional environments.

References:

- Andersen, K.K., Svensson, A., Johnsen, S.J., Rasmussen, S.O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Peder Steffensen, J., Dahl-Jensen, D., Vinther, B.M., and Clausen, H.B., 2006, The Greenland Ice Core Chronology 2005, 15-42 ka. Part 1: constructing the time scale: *Quaternary Science Reviews*, v. 25, p. 3246-3257.
- Andrews, J.T., 1974, Cainozoic glaciations and crustal movements of the Arctic, *in* Ives, J.D., and Barry, R.G., eds., *Arctic and alpine research*, p. 999.
- Antevs, E., 1922, The recession of the last ice sheet in New England: *American Geological Society Research series*, v. 11, p. 120.
- , 1928, The last glaciation with special reference to the ice sheet in North America: *American Geographical Society Research Series*, v. 17, p. 292.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., and Schaefer, J.M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: *Quaternary Geochronology*, v. 4, p. 93-107.
- Balco, G., and Schaefer, J.M., 2006, Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England: *Quaternary Geochronology*, v. 1, p. 15-28.
- Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: *Quaternary Science Reviews*, v. 21, p. 2127-2135.
- Boothroyd, J.C., Freedman, J.H., Brenner, H.B., and Stone, J.R., 1998, Glacial geology of south and central Rhode Island, *in* Murray, D.P., ed., *Guidebook to Field Trips in Rhode Island and Adjacent Regions of Connecticut and Massachusetts*. New England Intercollegiate Geological Conference, 90th Annual Meeting: Kingston, Rhode Island., University of Rhode Island, p. C5-1 - C5-22.
- Braun, A., Kuo, C.Y., Shum, C.K., Wu, P., van der Wal, W., and Fotopoulos, G., 2008, Glacial isostatic adjustment at the Laurentide ice sheet margin: Models and observations in the Great Lakes region: *Journal of Geodynamics*, v. 46, p. 165-173.
- Clark, P.U., 1992, Surface form of the southern Laurentide Ice Sheet and it's implications to ice-sheet dynamics: *Geological Society of America Bulletin*, v. 104, p. 595-605.

- Clark, P.U., Alley, R.B., and Pollard, D., 1999, Northern Hemisphere Ice-sheet influences on global climate change: *Science*, v. 286, p. 1104-1111.
- Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., and Putnam, A.E., 2010, The Last Glacial Termination: *Science*, v. 328, p. 1652-1656.
- Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: *Geographie physique et Quaternaire*, v. 41, p. 237-263.
- Goldsmith, R., 1982, Recessional moraines and ice retreat in southeastern Connecticut: *Dubquene, Kendall - Hunt*, 61-76 p.
- Goss, M.C., 1995, High-resolution seismics and ice-marginal sedimentation in Block Island Sound and adjacent southern Rhode Island [Masters thesis], Rutgers University, New Brunswick, NJ.
- Leverington, D.W., Teller, J.T., and Mann, J.D., 2002, A GIS method for reconstruction of late Quaternary landscapes from isobase data and modern topography: *Computers & Geosciences*, v. 28, p. 631-639.
- Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S., 2006, Recent Greenland ice mass loss by drainage system from satellite gravity observations: *Science*, v. 314, p. 1286-1290.
- McMaster, R.L., 1960, Sediments of Narragansett Bay system and Rhode Island Sound, Rhode Island: *Journal of Sedimentary Research*, v. 30, p. 249-274.
- , 1984, Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, USA: *Sedimentology*, v. 31, p. 777-792.
- Needell, S.W., and Lewis, R.S., 1984, Geology and structure of Block Island Sound, Rhode Island and New York, U. S. Geological Survey Miscellaneous Field Studies Map MF-1621 (4 Sheets).
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983, Quaternary geology of the Rhode Island inner shelf: *Marine Geology*, v. 53, p. 41-53.
- Oakley, B.A., Alvarez, J.D., and Boothroyd, J.C., 2012, Benthic geologic habitats of shallow estuarine environments: Greenwich Bay and Wickford Harbor, Narragansett Bay, Rhode Island, USA: *Journal of Coastal Research*, v. In press.

- Peck, J.A., 1989, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay [Masters thesis]: Kingston RI, University of Rhode Island.
- Peck, J.A., and McMaster, R.L., 1991, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay, Rhode Island, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, ed., Quaternary Geology of Long Island Sound and Adjacent Coastal Areas, Journal of Coastal Research, Special Issue 11, p. 25-37.
- Peltier, W.R., 2004, Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE: Annual reviews of Earth and Planetary Sciences, v. 32, p. 111-149.
- Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3322-3337.
- Pickart, D.S., 1987, Physical stratigraphy and geological evolution of the Providence River, Narragansett Bay, Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island.
- Rasmussen, S.O., Seierstad, I.K., Andersen, K.K., Bigler, M., Dahl-Jensen, D., and Johnsen, S.J., 2008, Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimate implications: Quaternary Science Reviews, v. 27, p. 18-28.
- Ridge, J.C., 2003, The last deglaciation of the Northeastern United States: A combined varve, paleomagnetic and calibrated ^{14}C Chronology, *in* Hart, J.P., and Cremeens, D.L., eds., Geoaarcheology of landscapes in the glaciated Northeast: New York State Education Department, Albany, New York.
- , 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J., and Gibbard, P.L., eds., Quaternary glaciations - extent and chronology: Part II: North America. Developments in Quaternary Science, Volume 2B: Amsterdam, Elsevier, p. 163-193.
- , 2010, The North American glacial varve project:
<http://geology.tufts.edu/varves/default.asp>.
- Ruddiman, W.F., 2001, Earth's climate past and future: new York, W.H. Freeman.

- Schafer, J.P., and Hartshorn, J., 1965, The Quaternary of New England, *in* Wright, J., and Frey, D., eds., The quaternary of the United States: Princeton, N.J., Princeton University Press, p. 113-127.
- Sirkin, L.A., 1982, Wisconsinan glaciation of Long Island, New York to Block Island, Rhode Island, *in* Larson, G.J., and Stone, B.D., eds., Late Wisconsinan glaciation of New England: Dubuque, IA, Kendall/Hunt, p. 35-60.
- Smith, J.H., 1955, Bristol and Vicinity, Rhode Island-Massachusetts Surficial geology: Washington, DC., U.S. Geological Survey Quadrangle Map GQ-70 U.S. Geological Survey.
- Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., 2005, Quaternary Geologic Map of Connecticut and Long Island Sound Basin, U.S. Geological Survey Geologic Investigations Series Map I-2784, scale 1:125,000, 2 sheets and pamphlet. p. 1-72.
- Toucanne, S., Zaragosi, S., Bourillet, J.F., Cremer, M., Eynaud, F., Van Vliet-LanoÃ, B., Penaud, A., Fontanier, C., Turon, J.L., Cortijo, E., and Gibbard, P.L., 2009, Timing of massive Fleuve Manche discharges over the last 350kyr: insights into the European ice-sheet oscillations and the European drainage network from MIS 10 to 2: Quaternary Science Reviews, v. 28, p. 1238-1256.
- Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002, Surface melt-induced acceleration of Greenland Ice-sheet flow: Science, v. 297, p. 218-222.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iii
PREFACE	v
TABLE OF CONTENTS	xvii
LIST OF TABLES	xxv
LIST OF FIGURES	xxvi
CHAPTER 1: Reconstructed topography of southern New England prior to isostatic rebound with implications of total isostatic depression and relative sea level.....	1
Abstract	2
Introduction	3
<i>Glacial isostatic adjustment</i>	4
<i>Modeled and Observed Isostatic Rebound in the Great Lakes</i>	6
Methods	7
<i>Present terrain model</i>	7
<i>Isobase surfaces</i>	9
Results	10
<i>Relative sea level</i>	10
<i>Constraints on maximum isostatic depression</i>	12
<i>75 m of depression at terminal moraine</i>	12
<i>50 m of depression at terminal moraine</i>	13

<i>30 m of depression at terminal moraine</i>	13
Discussion	14
<i>Assumptions</i>	14
<i>Relative sea level vs. glacial marine limit.....</i>	15
<i>Evidence of the marine limit</i>	16
<i>Peripheral forebulge blocks transgression</i>	16
<i>Isostatic rebound is not linear.....</i>	18
<i>Isostatic rebound was not delayed</i>	19
<i>Less isostatic depression.....</i>	19
<i>Implications.....</i>	20
Conclusions	23
Acknowledgments.....	24
References cited	25

CHAPTER 2: The geometry and extent of Glacial Lakes Narragansett, Block

Island and Rhode Island.....	38
Abstract	39
Introduction	40
<i>Water level indicators</i>	41
<i>Previous work</i>	42
Methods.....	43
<i>Sub-bottom profiling</i>	43
<i>Ground Penetrating Radar</i>	44
<i>Vertical error</i>	46

<i>Interpreted water levels</i>	47
<i>Pre-isostatic rebound topographic models</i>	47
Results	49
<i>Block Island Sound</i>	49
<i>Pettaquamscutt River</i>	49
<i>Dutch Island</i>	50
<i>Annaquatucket River</i>	50
<i>Mill Creek and Hunt-Quonset</i>	51
<i>Potowomut</i>	51
<i>Island Park</i>	51
<i>Warwick Plains</i>	52
<i>Conimicut Point</i>	52
<i>Barrington</i>	52
<i>Riverside</i>	53
<i>New Meadow Neck</i>	54
<i>Providence Plains</i>	54
<i>Smith Hill</i>	54
<i>Blackstone River</i>	55
<i>Water levels</i>	57
Discussion	57
<i>Assumptions</i>	57
<i>Isostatic rebound profile</i>	58
<i>Spillways</i>	59

Water levels.....	60
Projected extent of glacial lakes on pre-isostatic rebound models	60
<i>Glacial Lake Block Island</i>	60
<i>Relationship to Glacial lake Connecticut</i>	62
<i>Glacial Lakes Block Island and Rhode Island</i>	63
<i>Glacial Lake Narragansett</i>	64
<i>Glacial Lake Barrington</i>	65
<i>Lake Drainage</i>	66
Conclusions.....	67
Acknowledgments.....	69
References cited	70

CHAPTER 3: Constraining the age of Glacial Lake Narragansett and the deglacial chronology of the Laurentide Ice Sheet in southeastern New

England	91
Abstract	92
Introduction	93
Study area.....	95
<i>Previous work</i>	95
Methods.....	97
<i>Varve matching</i>	99
Results	100
<i>Core deformation</i>	101
<i>Varve correlation</i>	101

Discussion	102
<i>Nature of deposition</i>	102
<i>Correlation with the NAVC</i>	104
<i>Regional context of uncorrelated varve sequences</i>	105
<i>Correlation with Northern Hemisphere climate</i>	105
<i>Constraining the age of Glacial Lake Narragansett</i>	107
Future work	109
Conclusions	110
Acknowledgements	111
References	112

CHAPTER 4: Late Quaternary deglaciation of Narragansett Bay: Rhode Island

and Massachusetts, USA	126
Introduction	127
Study area	128
Methods	129
Sub-bottom seismic reflection profiling	129
Interpretation	130
Thickness and volume of stratified deposits	131
Water depths and volume of Glacial Lake Narragansett	132
Results	132
Seismic facies and interpreted depositional environments	132
Interpolated raster surfaces	140
Thickness of stratified deposits	140

Volume of stratified sediment deposited.....	140
Discussion	142
Morphosequence concept.....	142
Ice margin positions and ages	142
Deglaciation of Narragansett.....	143
Late Pliestocene non-glacial deposits	148
Extent of lakefloor deposits	148
Elevation of glacial lakefloor sediment, minimum water-depths and volumes of Glacial Lake Narragansett.....	150
Lacustrine fans and subglacial drainage	150
Volume of sediment	152
Climate	155
Patterns in the seismic record.....	157
Conclusions	159
Acknowledgements	161
References	162

CHAPTER 5: Benthic geologic habitats of shallow estuarine environments:

Greenwich Bay and Wickford Harbor, Narragansett Bay, Rhode Island, USA	185
Abstract	186
Introduction	187
Benthic geologic habitats	187
Study sites	189

Methods.....	192
<i>Side-scan sonar</i>	192
<i>Side-scan data interpretation</i>	192
<i>Surface sediment samples</i>	193
<i>Underwater imagery</i>	194
<i>Aerial photography</i>	194
<i>Naming convention of benthic geologic habitats</i>	195
Results.....	196
<i>Benthic geologic habitats</i>	196
<i>Estuarine Bayfloor</i>	196
<i>Estuarine Cove</i>	199
<i>Estuarine marginal habitats</i>	200
<i>Geologic features</i>	203
<i>Anthropogenic features</i>	205
Discussion	207
Conclusions	213
Acknowledgements	215
References cited	216
APPENDICES	234
APPENDIX 1: Supplemental figures, chapter 1	234
APPENDIX 2: Sedimentological descriptions of cores used in chapter 4.....	249
APPENDIX 3: Varve counts from cores collected in the Providence River, Rhode Island	262

APPENDIX 4: Paleomagnetic results from cores PVD-3 and PVD-5 collected in the Providence River, Rhode Island.....	287
APPENDIX 5: Process for collection and processing high-resolution seismic reflection profiles	294

LIST OF TABLES

TABLE	PAGE
Chapter 2	
Table 1. Elevations of delta plain-delta slope contacts measured in Glacial Lakes Block Island, Rhode Island, Narragansett, and Taunton.....	56
Chapter 3	
Table 1. Summary of basic sedimentology of the cores used in this study	100
Chapter 4	
Table 1. Seismic facies identified in Narragansett Bay	139
Table 2. Sediment volume for deltas and lakefloor deposits in Glacial Lake Narragansett, in and around present-day Narragansett Bay	141
Chapter 5	
Table 1. Depositional environments	224
Table 2. Sediment textures and descriptors	225
Table 3. Benthic geologic habitats	226

LIST OF FIGURES

FIGURE	PAGE
Chapter 1	
<p>Figure 1. Digital elevation model generated for the study area, showing the location of pertinent geographic locations discussed in the text and the maximum extent of the Laurentide Ice Sheet modified from Dyke and Prest (1987). Details of digital elevation model discussed in the text. Hatched region on inset map of New England shows extent of glacial marine inundation based on Stone and Peper, (1982) and Thompson and Borns, (1985).....</p>	32
<p>Figure 2. Schematic diagram showing A- Depression of the lithosphere and formation of a peripheral forebulge beyond the margin B - Uplift of the lithosphere under the former ice sheet and the potential migrating forebulge. Modified from (Andrews, 1974; Ruddiman, 2001) C – Earth models used to model isostatic rebound in the Great Lakes (modified from Clark et al., 1994) D – ‘Thick’ ice and ‘Thin’ ice profiles used by Clark et al., (1994).....</p>	33
<p>Figure 3. A - Isobase surface reflecting 30 m of depression at the terminal moraine south of Block Island, with a profile of rebound of 0.85 m km^{-1}. B - Schematic cross-section of modern topography, an isobase surface and the pre-isostatic rebound topography (Modified from Leverington et al., 2002).....</p>	34

FIGURE	PAGE
Figure 4. Relative sea level and isostatic rebound curve for the Late Wisconsinan terminal margin south of Block Island, RI. Ages in calendar years before present (1987).	35
Figure 5. Figure 5: A - Elevation relative to sea level at 21 ka assuming 75 m of isostatic depression at the terminal margin. Note the inundation of most of Martha's Vineyard and eastern Long Island, as well as the marine grounded ice margin. Extent of the Laurentide Ice Sheet modified from Schafer and Hartshorn (1965), Goldsmith (1982), Sirkin (1982) and Dyke and Prest (1987). B - Elevation relative to sea level at 16.5 ka assuming 75 m of isostatic depression at the terminal margin. The southern margin of the Laurentide Ice Sheet had retreated north of Rhode Island by this time. C - Elevation relative to sea level at 21 ka, assuming 30 m of depression at the terminal margin. D - Elevation relative to sea level at 16.5 ka assuming 30 m of depression at the terminal margin. Marine water may have begun to inundate the channel south of Block Island by 16.5 ka. The southern margin of the Laurentide Ice Sheet had retreated north of Rhode Island by this time.	36
Figure 6. Ice thickness (solid lines) and isostatic adjustment (dashed lines) for three published ice sheet reconstructions (Clark et al., 1994; Dyke et al., 2002; Peltier, 2004) and the calculated ice sheet profile based on observed isostatic rebound in New England. Geographic locations are noted, including SNH (Southern New Hampshire, USA) and BI (Block Island, Rhode Island, USA).	37

FIGURE	PAGE
Chapter 2	
Figure 1. Digital elevation model of Narragansett Bay and adjacent waters, showing the location of geographic locations discussed in the text and the maximum extent of the Laurentide Ice Sheet	77
Figure 2. Schematic view of an ice-marginal deltaic morphosequence, A. Prior to isostatic rebound, B. After isostatic rebound.	78
Figure 3. Location of delta plain-delta slope contacts measured in this study and the mapped extent of glacial deltas around upper Narragansett Bay.....	79
Figure 4. Schematic figure of A. Sub-bottom seismic reflection profiler and B. Ground Penetrating Radar	80
Figure 5. A. Seismic reflection profile of the higher elevation Glacial Lake Block Island from Block Island Sound. B. Interpreted seismic reflection profile showing the minimum lake level at -17 m below MSL. See figure 3 for location.....	81
Figure 6. A. Seismic reflection profile from Block Island Sound showing the dipping delta beds of the lower Glacial Lake Block Island delta. B. Interpreted seismic reflection profile showing the minimum lake level at - 26 m below MSL. See figure 3 for location....	82
Figure 7. A. Sub-bottom seismic reflection profile of the Dutch Island delta, lower West Passage, Narragansett Bay. B. Interpreted seismic reflection profile showing the minimum lake level at - 9.8 m below MSL. See figure 3 for location.....	83
Figure 8. A. 200 MHz Ground penetrating radar profile of the Warwick Plains Delta. B. Interpreted ground penetrating radar profile showing the delta plain – delta slope	

FIGURE	PAGE
contact at 3 m above MSL. See figure 3 for location.....	84
Figure 9. A. 120 MHz Ground penetrating radar profile from the northern Barrington delta. B. Interpreted ground penetrating radar profile showing the delta plain – delta slope contact at 10 m above MSL. See figure 3 for location... ..	85
Figure 10. A. 120 MHz Ground penetrating radar profile from Smith Hill. B. Interpreted ground penetrating radar profile. The delta plain – delta slope contact is 18 m above present MSL. See figure 3 for location... ..	86
Figure 11. Projected water levels and spillways of Glacial Lakes Block Island, Rhode Island, Narragansett, and Taunton. Water levels show an uplift profile of 0.85 m km^{-1} . Delta abbreviations are the same as figure 3.....	87
Figure 12. Comparison of uplifted water levels of Glacial lake Narragansett, Glacial Lake Hitchcock, Glacial Lake Merrimack.....	88
Figure 13. Pre-isostatic rebound topographic model showing the extents of A. Glacial Lake Block Island at the Corn Neck moraine position approximately 23,000 yBP. B. Glacial Lakes Block Island and Rhode Island. Approximately 22,000 yBP. Red box indicates extent of figure 12 A. C. Charlestown – Point Judith – Buzzards Bay moraine position approximately 21,300 yBP	89
Figure 14. Pre-isostatic rebound topographic model showing the extent of Glacial Lake Narragansett. A. Approximately 20,200 yBP, B.19,500 yBP.....	90

Chapter 3

Figure 1. Location of sediment cores and varve records used in this study. Inset map of Southern New England shows extent of the study area, the maximum extent of the Laurentide Ice Sheet..... 117

Figure 2. Ice-margin positions, cosmogenic exposure dates (calendar years before present) and the location of varve records in southern New England and eastern New York and New Jersey not correlated to the NAVC. Length of varve series indicated for each location. Modified from Boothroyd et al., (1998), Ridge, (2003, 2004) and Stone et al., (2005). All dates reported as calendar years before present 118

Figure 3. Correlation of varve records based on close annual matches in total couplet thickness. A. Correlation of varve records collected in the Providence River for Narragansett Bay varve years 5000 to 5150. A constant offset was added to some of the records to display them on one graph without overlap. EW-1 was originally collected by Pickart (1987). B. Correlation of varve records collected in the Providence River for Narragansett Bay varve years 5150 to 5260. A constant offset was added to some of the records to display them on one graph without overlap. C. Correlation of varve records from the Providence River and Seekonk River (Antevs, 1928). Arrows point to two discrepancies, where it appears one varve may be missing from each sequence. The Providence composite curve was offset by 3 cm to display the records on one graph without overlap. D. Correlation of varve records from Pawtuxet Cove (Pickart, 1987) and Gaspee Point Varve thickness of PC-6 was offset by 3 cm to display the records on one graph without overlap 119

FIGURE	PAGE
Figure 4. Varves from Glacial Lake Narragansett years 5069 to 5075 from core PVD-1. Note the stacks of graded beds in the melt season layer	122
Figure 5. Varves with thick (~ 1 cm) winter layers from core PVD-1. Red numbers indicate the Glacial Lake Narragansett varve year. Black arrows point to examples of some of the sedimentary features commonly seen in the Providence Cores. A: Sand parting at the top of the winter layer representing a late winter-early spring melting, overturning or a storm runoff event. B: Fault in the core, not induced during coring. C: Scour at the top of the winter layer. D: Prominent sandy layer capped by thin (1 mm) silt/clay layer at the base of the summer layer representing early season melting or storm runoff followed by a period of little/no sediment input into the lake.....	123
Figure 6. NGRIP ice core chronology and $\delta^{18}\text{O}$ profile of the NGRIP ice core (Andersen et al., 2006; Rasmussen et al., 2008). Red arrows indicate cosmogenic exposure ages of the Ledyard-Congdon Hill (L-CH) and Old Saybrook-Wolf Rocks (OS-WR) recessional end moraines in southern New England (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Dashed black lines refer to potential correlation with Greenland Ice Cores LIS fluctuations.....	124

Figure 7. Proposed minimum ages of Glacial Lake Narragansett and other uncorrelated varve series in southern New England and eastern New York shown in comparison with the base of the North American Varve Chronology. Red arrows indicate cosmogenic exposure dates from (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Green arrows indicate proposed correlated ages of the Congdon Hill and Wolf Rock end moraines. Blue arrow marks the minimum age of Glacial Lake Narragansett.....	125
---	-----

Chapter 4

Figure 1. Shaded relief map of Narragansett Bay showing the geographic subdivisions discussed in the text and the locations of figures 3-5. Inset map shows the location of sub-bottom seismic reflection profiles collected for this study	172
Figure 2. A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile from the West Bay of Narragansett Bay showing facies T, LF and M. See Figure 1 for location	173
Figure 3. A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile showing facies T, PF, DF, LF and M. See Figure 1 for location	174
Figure 4. A. Sub-bottom seismic reflection profile of the Dutch Island delta, lower West Passage, Narragansett Bay. B. Interpreted seismic reflection profile showing facies. See Figure 1 for location.....	175

FIGURE	PAGE
Figure 5. A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile showing facies T, LF, E, M and NG. See Figure 1 for location	176
Figure 6. Thickness of stratified deposits in Narragansett Bay.....	177
Figure 7. Correlation diagram of Quaternary deposits in present-day Narragansett Bay. Deposits are grouped by geographic sections of Narragansett Bay. Correlation with moraine deposits west of Narragansett Bay are shown on the left; uncorrelated deposits are shown on the right side	178
Figure 8. Recessional ice-margins of Narragansett Bay and adjacent areas. Positions correlated with margins outside of Narragansett Bay are modified from Smith (2010). Red lines indicate the margin of the ice sheet marked by a lacustrine fan	179
Figure 9. Extent of glacial lakefloor deposits throughout mapped throughout Narragansett Bay.....	180
Figure 10. The elevation of the upper surface of lakefloor sediment digitized from seismic reflection profiles throughout Narragansett Bay and elevation of the delta plain-delta slope contact used as a proxy for water level of Glacial Lake Narragansett.	181
Figure 11. Minimum water depths within Glacial Lake Narragansett.....	182

Figure 12. Schematic model of lacustrine fan deposition in Glacial Lake Narragansett. A: Fan deposition at the margin of the Laurentide Ice Sheet. Note meltwater from Moulin reaching the base of the ice sheet and the dominance of subglacial meltwater and density underflows (Modified from Gustavson and Boothroyd, 1987). B: Same area after the ice margin had retreated north. The ‘stacked’ fans suggest that the ice tunnels are staying in approximately the same location an extended period (years). Glacial lakefloor deposits have buried the entire sequence as the ice sheet retreated north.	183
---	-----

Figure 13. Location of proximal lacustrine fans in Narragansett Bay. Dashed black lines represent the thalweg of the bedrock valleys identified by Upson and Spencer (1964). Fans likely exist in the upper East Passage and Sakonnet River, but seismic penetration was limited in these areas.....	184
---	-----

Chapter 5

Figure 1. A. Location map of Narragansett Bay, Rhode Island, USA. B. Location of Greenwich Bay and Wickford Harbor along the western shoreline of Narragansett Bay C. Close-up maps of Greenwich Bay and D. Wickford harbor showing the locations of figures 5-7.	227
---	-----

Figure 2. Modified Shepard (1954) sediment classification scheme showing the percentage of sand silt and clay for samples collected in Greenwich Bay and Wickford Harbor, and includes samples collected by McMaster (1960). Representative samples are labeled, and their location is shown on figure 3.....	228
--	-----

FIGURE	PAGE
Figure 3. Benthic geologic habitats of Greenwich Bay overlain on 2003/2004 digital orthophotographs, showing the location of figures 5 and 7.	229
Figure 4. Benthic geologic habitats of Wickford Harbor overlain on 2003/2004 digital orthophotographs, showing the location of figure 6	230
Figure 5. Selected side-scan images of geologic features. See figures 1 and 3 for location. A. Facies boundary between bayfloor sand sheet Sssa and low-energy basin organic silt (Lebsio) in southwest Greenwich Bay. B. Dark patches within the bay channel organic silt (Bcsiop). Patches are interpreted to be shell aggradations. C. Wave-formed bars in southeast Greenwich Bay on the depositional platform (Dpsa). D. Tidal bedforms on the bayfloor sand sheet (Sssa). Crest to crest spacing averages 8 m. The distinct furrow in the upper right of the image was produced by a hydraulic dredge used for collecting shellfish. E. Isolated boulders cropping out on the depositional platform sand sheet (Dpsa), Greenwich Bay	231

Figure 6. Examples of macroalgae and submerged imaged using side-scan sonar. See Figure 1 for geographic locations. A. Side-scan image in central Wickford Harbor. The distinct speckled pattern on the right side of the image is Eelgrass (*Zostera Marina*). The line delineates the boundary between the eelgrass (Lebsie) and the adjacent, low-energy basin coarse silt (Lebsic). B. Photograph of the Wickford Harbor eelgrass bed collected by a diver using a still camera in the summer of 2007) (M. Cole-Ekberg, Personal Communication). The red arrow points to a representative clump of eelgrass in the side-scan image. C. Side-scan image in southwest Wickford Harbor. The blotchy pattern throughout the image is macroalgae. The feature in the upper left of the image is the shoreline. D. 2008 Digital aerial photograph of a portion of southwest Wickford Harbor (PIC, 2008). The elongated alternating pattern of attached macroalgae is shaped by tidal currents 232

Figure 7. Anthropogenic impacts mapped in Greenwich Bay. See figure 1 for geographic locations. A. Trails formed by rakes dragged across the bottom during the harvesting of shellfish (*Mercenaria mercenaria*, locally called Quahogs). Scale across each rake trail is ~0.6 m. Geologic habitat is low-energy basin silt (Lebsi). Box shows the extent of figure 7B. B. Inset of figure A showing no portion of the bayfloor in this area untouched by a rake. C. Mooring drag in southeast Greenwich Bay. The circular feature in the lower right of the image is caused by the ground chain dragging along the bayfloor as the boat pivots around mooring anchor. Geologic habitat is low-

FIGURE	PAGE
energy basin silt (Lebsi). The vertical mooring chain and keel of the boat are also visible in the image. D. Shipwreck on the depositional platform (Dpsa) south of Oakland Beach in Greenwich Bay	233

Plate 1. Quaternary geologic map of Narragansett Bay

CHAPTER 1

Reconstructed topography of southern New England prior to isostatic rebound with implications of total isostatic depression and relative sea level

Accepted for publication in Quaternary Research, 7 March, 2012

Bryan A. Oakley

Department of Geosciences, College of the Environment and Life Sciences, University
of Rhode Island

Jon C. Boothroyd

Department of Geosciences, College of the Environment and Life Sciences, University
of Rhode Island

State Geologist, Rhode Island Geological Survey

Corresponding author:

Bryan A. Oakley

Department of Geosciences

College of the Environment and Life Sciences

University of Rhode Island

317 Woodward Hall

9 East Alumni Ave

Kingston, RI, 02881

BOakley@my.uri.edu

ABSTRACT

Topographic models of the late Quaternary landscape prior to isostatic rebound are easily created in a Geographic Information System using surfaces reflecting measured profiles of isostatic rebound. These models aid interpretations of glacial lake water levels and other geomorphic features as well as ice thickness, mantle viscosity and lithospheric strength. The well-established limit of glacial marine inundation in central and northern New England provides a test of total isostatic depression. Relative sea levels reflecting differing magnitudes of isostatic rebound show that published values of isostatic depression in southern New England would inundate the landscape in southern New England with marine water south of the mapped limit of Late Pleistocene marine inundation. This suggests that isostatic depression at the terminal margin of the Laurentide Ice Sheet (LIS) could not have exceeded 35 m, and that previous workers overestimate isostatic depression in southern New England by > 50 m. A first order estimate of ice thickness based on total isostatic depression and the observed uplift profile in southern New England supports the 'thin ice' models in New England with ice thickness ranging from 100 m near the southeastern margin of the LIS, to > 1000 m 300 km north of the terminal margin of the LIS in New England. This regional model places constraints on continental ice sheet and geophysical models that should be considered in the future.

Introduction:

The Late Wisconsinan Laurentide Ice Sheet (LIS) depressed the lithosphere beneath the ice sheet and in areas adjacent to the margin. The previously depressed terrain rebounded upward after the ice sheet retreated north of central New England, producing a landscape that has been preferentially uplifted to the north to northwest. Pre-rebound Quaternary topographic models are an important component of interpreting glacial lake levels, drainage patterns, spillways and other geomorphic features, as well as ice thickness, mantle viscosity, lithospheric strength. This has been done for large regions ($1 \times 10^6 - 1 \times 10^7 \text{ km}^2$) using digital elevation models (DEM's) with a resolution of 80 – 150 m (Leverington et al., 2002; Rayburn and Teller, 2007), and small areas with DEM's created using LiDAR (Light Detection and Ranging) with resolution $< 1\text{m}$ (Salcher et al., 2010). Digital elevation models with $< 30 \text{ m}$ resolution allow for a shift in focus from coarse regional reconstructions to finer scale local reconstructions. Total isostatic rebound and ice sheet thickness remain poorly defined near the terminal margin. This represents a critical region for the deglacial history of the ice sheet, particularly in comparing models and observations of modern ice sheets to the LIS. By projecting relative sea level on to pre-rebound topographic models and comparing the modeled limit of marine inundation to the mapped glacial marine limit (Figure 1), the amount of total isostatic depression in southern New England can be constrained, and the method outlined here can be utilized in other previously glaciated areas.

Glacial isostatic adjustment

Glacial isostatic adjustment refers to the change in elevation of the lithosphere due to the loading and unloading of an ice sheet. Isostatic depression refers to the downward correction of the Earth's lithosphere under the weight of the ice sheet, while isostatic rebound will refer to the upward motion of the Earth's surface after unloading of the ice sheet (Figure 2A, B). The response of the lithosphere under the LIS in North America has been studied extensively; primarily using models based on inferred ice thicknesses, and remains largely unresolved at a local level due to the coarse nature of ice sheet models (Braun et al., 2008; Peltier, 2004). The amount of surface load, and the resultant downward adjustment imparted, is directly dependent on the thickness and density of the overlying ice and properties of the underlying mantle (Peltier, 1999). Reconstructions of ice sheet thickness and resultant isostatic adjustment are typically a compromise between local indicators of ice thickness near the margin and coarse estimates of ice thickness in the central portion of the ice sheet (Braun et al., 2008; Peltier, 2004).

The uplift profile of isostatic rebound in New England is recorded by the formerly horizontal water levels of proglacial lakes. The present elevation of deltas deposited into Glacial Lake Hitchcock in the Connecticut River Valley project on a linear plane, with an uplift profile of 0.89 m km^{-1} , towards the presumed center of the LIS in Hudson Bay, Canada (339°). The uplift profile in coastal central New England is slightly less, at 0.85 m km^{-1} , also towards the northwest (331°) (Koteff and Larsen, 1989; Koteff et al., 1993). Based on the linear trend of rebound Koteff and Larsen (1989) inferred that isostatic rebound did not begin until onset of Glacial Lake

Hitchcock drainage sometime after 16 ka, thus a significant portion of southern New England was ice-free for 5,000 – 8,000 yr. Further to the west, in the Champlain (Rayburn, 2004) and Hudson River (Stanford and Harper, 1991) valleys, isostatic rebound was found to be similar to the observations from central New England, with linear uplift profiles measured between (0.7 - 1.0 m). Delayed, linear isostatic rebound implies that in New England, the lithosphere responded as a rigid block, and rebound did not begin until the southern margin of the Laurentide Ice Sheet was in northern New England (Koteff and Larsen, 1989; Koteff et al., 1993). This differs from geophysical models that suggest uplift is contemporaneous with ice retreat (Clark et al., 1994; Peltier, 1982, 2004).

While the uplift profile of isostatic rebound is well understood in New England, the total isostatic adjustment in New England remains poorly constrained by a few scattered data points or coarse regional models. Based on the elevation and extent of the marine incursion in North America, 150 m of maximum total isostatic rebound was reported at the northern boundary of this study. This work was done at a very coarse scale (1:30,000,000) and was not designed to provide detailed information along the southern extent of the ice sheet (Andrews, 1973). An interpreted glacial marine delta 40 m below present sea level in central Long Island Sound is thought to represent a marine incursion prior to the onset of rebound (Lewis and Stone, 1991; Stone et al., 2005b). Comparing the present elevation of this delta with the eustatic sea level curve of Bard et al. (1990), Lewis and Stone (1991) and Stone et al., (2005b) concluded that the minimum amount of isostatic depression in Central Long Island Sound was 80 m.

Modeled and Observed Isostatic Rebound in the Great Lakes

The margin of the LIS south of the Great Lakes has been extensively studied and the timing of margins is better constrained than any other segment of the ice sheet (Dyke et al., 2002). Clark et al. (1994) compared the results from five different solid Earth models (Models E1 – E5, Figure 2) with existing shoreline and outlet elevations in the Great Lakes to determine which geophysical and ice thickness model that best describes observed isostatic rebound. The models varied lithosphere thickness and upper mantle viscosity, ranging from a 112 to 212 km thick lithosphere overlying different heterogeneity models of upper mantle viscosity (Figure 2C). The thick (212 km E2) elastic lithosphere model did not produce a good fit with the Great Lakes, and can be discounted for New England where the lithosphere thickness ranges from 90-110 km (Griffin et al., 2004; Rychert et al., 2005). The other models (E1, E3-E5) used a 112 km elastic lithosphere, with varying upper mantle properties. Clark et al (1994) tested a thick ice sheet model (Boulton et al., 1985; Hughes et al., 1981) and thin ice sheet model (Dyke and Prest, 1987) (Figure 2D) for each of the solid earth models, at different ice sheet durations, including 10,000 yr, which is similar to the duration of the LIS in southern New England (Clark et al., 1994; Dyke et al., 2002).

While none of the models completely matched the observed isostatic rebound in the Great Lakes region, an important conclusion was that the thick ice models overestimated the amount of isostatic adjustment, and the thin ice models underestimated it. Thin ice models came closer to producing a better fit, and by increasing the ice thickness by 30%, the thin ice model more closely matched the predicted rebound (Clark et al., 1994). The underestimation in total rebound in the

thin ice models may have different results if a model was used that closely matches the lithosphere characteristics in New England. The Clark et al. (1994) E3 Model did not agree with the outlet chronology of the Great Lakes that required a rapid initial isostatic adjustment and rebound, and underestimated the present rate of tilting in the Great Lakes region. Uncertainties in ice sheet thickness and loading history prevented discrimination between lithosphere models; i.e. the same results obtained using a thicker or stiffer lithosphere can be offset by a thinner ice sheet. The lithosphere properties, especially the presence of a stiff, relatively thick lithosphere is the dominant factor controlling the amount and relaxation rate of isostatic rebound (Dyke and Peltier, 2000).

Methods

Present terrain model

A seamless grid of the present topography and bathymetry of southern New England provides the base map for recreating the pre-isostatic rebound topography. While terrestrial digital elevation models are readily available, Quaternary features in the study area extend below present sea level, necessitating the addition of hydrographic data into the model. The raster National Elevation Database (NED) 30 m DEM was combined with hydrographic soundings from the National Ocean Service (NOS). The 30 m DEM was downloaded from the National Elevation dataset as a raster grid, and converted to a vector dataset, using the ESRI, ArcMapTM 9.3 Spatial Analyst extension, producing one point per pixel, (13,000,000 points) (USGS, 2010). Hydrographic soundings were downloaded from the National Ocean Service,

(2,100,000 points) with variable spacing (mean = 27 m) depending on the resolution of the survey (NGDC, 2010). The projection of both data sets is Universal Transverse Mercator (UTM), zone 19N, North American Datum (NAD) 1983. The 1997 shoreline from the Rhode Island Geographic Information System was input into the terrain as a hard break line, with an elevation of 0 m as a boundary between the terrestrial and hydrographic data. This vector coastline was digitized at a scale of 1:5000, and verified during the creation of the 1997 orthophotography of Rhode Island (RIGIS, 2001).

Point data were imported into an ESRI ArcMapTM geodatabase and a terrain was created, clipped to an area extending from 50 km south of Block Island north beyond the northern border of Rhode Island (Figure 1). The terrain was exported as a raster grid, with a cell size of 15 m (50 ft). The two datasets are based on different vertical datums; terrestrial elevations are relative to the North American Vertical Datum of 1988 (NAVD88), and the hydrographic soundings are relative to mean low water (MLW) or mean lower low water (MLLW) (NOS, 2009). The elevation difference between MLLW and NAVD88 within the study area (0.6 m) (NOS, 2010a) is well within the vertical error of the NED (Root mean square error of 2.5 m (Gesch, 2007)). Spatial accuracy of hydrographic soundings depends on the age of the data, (1943 to 1991). Surveys after 1965 conform to international hydrographic standards, with vertical accuracy +/- 0.3 m in < 20 m water depth, +/- 1 m in 20 -100 m water depth and 1% of the water depth > 100 m. Horizontal accuracy also varies depending on age, but is < 30 m, with higher accuracy in more recent surveys (NOS, 2009).

Isobase surfaces

Isostatic adjustment was accounted for by creating isobase surfaces reflecting the total isostatic depression. Using the linear plane of rebound measured in coastal New England of $0.85 \text{ m} \cdot \text{km}^{-1}$ uplifted northwest (336°) towards the presumed center of the LIS in Hudson Bay Canada (Koteff and Larsen, 1989; Koteff et al., 1993), raster surfaces were created in a geographic information system (ESRI ArcMapTM 9.3). A 1 km grid of points matching the extent of the study area ($\sim 24,000$ points) was created using 'Hawth's Tools' extension for ESRI ArcMapTM 9.3, and the 'Near' command calculated the distance from each of the generated points to the baseline 50 km south of the terminal margin. This assumes that the uplift profile of rebound ($0.85 \text{ m} \cdot \text{km}^{-1}$) was consistent beyond the terminal margin of the Laurentide Ice Sheet. Assuming 30 m of isostatic depression at the terminal margin of the Laurentide Ice Sheet, this produces an isobase surface with no isostatic depression at the baseline. If the profile of isostatic depression decreases with increasing distance from the terminal margin (Figure 2), then these isobase surfaces may overestimate depression in the area between the baseline and terminal margin. This does not change the inundation across southern New England, and does not affect the conclusions of this work.

This distance was multiplied by the assumed uplift profile of rebound to create a point dataset reflecting the isostatic adjustment across southern New England. Surfaces with additional isostatic depression were created by increasing total isostatic depression at the terminal margin, assuming the same linear rebound profile. The points were interpolated into a Triangular-irregular network (TIN), and converted into a raster grid surface (pixel size 15 m) (Figure 3A). The isobase surfaces were

subtracted from the modern DEM in ESRI ArcMap ‘Raster Calculator’ to produce the pre-rebound isostatic elevation models (Figure 3B).

Results:

Three pre-isostatic rebound digital elevation models were generated using differing values of total isostatic depression. The total isostatic depression at the terminal ice margin of the LIS in the first model is 30 m, equivalent to the isostatic adjustment for a local minimum ice thickness of 100 m at Block Island. The other models created had isostatic depressions of 50 m and 75 m at the terminal margin of the LIS. The 75 m model fits the published isostatic depression in Long Island Sound (80 m) and northern Rhode Island (150 m), and was similar to the modeled adjustment for the Great Lakes (Andrews, 1973; Clark et al., 1994; Stone et al., 2005b). The final model used 50 m of depression at the terminal margin of the LIS and was chosen as an intermediate value.

Relative Sea Level

Relative sea level curves were generated using the algebraic difference between isostatic adjustment and eustatic sea level. The eustatic sea level curve presented here (Figure 4) is based on previously published sea level data (Donnelly and Bertness, 2001; Oldale and O'Hara, 1980; Peltier and Fairbanks, 2006; van de Plassche et al., 1998). The age, projected sea level, and source material of all of the samples used to generate the selected sea level curves were entered into a database and were converted from radiocarbon years before present to calendar years before present

using the calibration of Fairbanks et al., (2005). The resulting points were plotted for comparison with previously published curves, and a best-fit line was drawn through the data. Late Pleistocene and Early Holocene time portion of the curve closely mirrors the curve of Peltier and Fairbanks (2006), and includes two portions of the curve with extremely rapid ($> 2 \text{ m} \cdot \text{yr}^{-1}$) rates of sea level rise, interpreted to be meltwater pulses 1A and 1B (Fairbanks et al., 1992; Peltier, 2005; Peltier and Fairbanks, 2006). The Late Holocene portion of the curve skews sea level in southern New England slightly older than the original Peltier and Fairbanks (2006) model. This local trend is governed by a reasonable best fit between the Peltier and Fairbanks (2006) curve and samples with good stratigraphic control recovered by Oldale and O'Hara (1980). The latest Holocene portion of the curve is a best fit line describing the sea level rise history of a salt marsh in Clinton, CT and other sites in New England (Donnelly and Bertness, 2001; van de Plassche et al., 1998) (Figure 4).

The isostatic rebound curves have a half-life of 1000 yr, and are flat prior to 16 ka with the assumption that isostatic rebound did not begin prior to this time. Based on the projected water level of Glacial Lake Hitchcock, it was originally proposed that rebound was delayed until 14.0 cal ka (Koteff and Larsen, 1989). More recent work suggests the drainage of history of lakes in the Connecticut River Valley was more complicated, and rebound may have begun earlier than 14.0 ka (Ridge, 2004). Regardless of these differing interpretations, the assumed onset of rebound at 16.0 ka used in this paper appears to be consistent with regional observations at this time.

Differing half-lives of isostatic rebound have been proposed, including a rate of 1750 yr in Long Island Sound (Stone et al., 2005). A half-life of 1750 yr would

imply isostatic rebound was still occurring < 5 ka, which is not consistent with sea level rise curves in southern New England. A half-life of 1000 yr is favored near the terminal margin if the LIS and is consistent with other studies in New England (Belknap et al., 1987; Dyke and Peltier, 2000).

Constraints on maximum isostatic depression

The relationship between relative sea level and the total downward adjustment of the lithosphere was evaluated by creating three reconstructed terrain models reflecting relative sea level at 26 ka, 21 ka and 16.5 ka for each of the models discussed above. These three time slices represent the last glacial maximum (26 ka) (Peltier and Fairbanks, 2006), the formation of the Charlestown-Point Judith-Buzzards Bay end moraine based on cosmogenic exposure dates (21 ka) (Balco et al., 2009; Balco et al., 2002), and conditions prior to the onset of isostatic rebound (16.5 ka).

75 m of depression at Terminal Moraine

Using the 75 m isostatic model, relative sea level at 26 ka, 21 ka, and 16.5 ka was 45 m, 41 m and 29 m below sea level. When the terrain model is adjusted to project these sea levels, it becomes apparent that at 26 ka, marine water would have extended to the margin of the ice sheet (Figure 5A). Most of Block Island, as well as the southwest shoreline of Rhode Island, Martha's Vineyard, Massachusetts, and eastern Long Island, NY would have been inundated with marine water by 21 ka (Figure 5B). Marine inundation extends across most of the ice-free Narragansett Basin and southeastern Massachusetts at 16.5 ka (Figure 6A).

50 m of depression at Terminal Moraine

Using the 50 m isostatic model, relative sea level at 26 ka, 21 ka, and 16.5 ka was 70 m, 66 m and 53 m below present sea level. Similar results to the 75 m model are obtained when relative sea level is projected onto the terrain model. The southern margin of the LIS would be grounded in marine water at both 26 ka and 21 ka. Marine waters would have inundated most of Narragansett Basin and much of southeastern Massachusetts south of the glacial marine limit by 16.5 ka (Figure 6B).

30 m of depression at Terminal Moraine

When the terrain model reflects 30 m of isostatic adjustment at the terminal margin of the ice sheet, relative sea level at 26 ka, 21 ka and 16.5 ka was 90 m, 86 m, and 73 m below present (Figure 4). The margin of the ice sheet was not grounded in marine water at either 26 ka or 21 ka in this scenario, and marine water does not inundate any of the study area. By 16.5 ka marine waters may be just south of the study area, extending into Block Channel, but did not extend into Rhode Island or Block Island Sounds (Figure 7).

Discussion

Assumptions

A major assumption in this work is that there has not been significant erosion or deposition on the landscape after the LIS retreated from southern New England. The ubiquitous presence of the eolian mantle over the landscape suggests that other than in the present river valleys, where channel incision and floodplain deposition has occurred, most of the landscape has been largely unchanged. Grading and filling in urban areas has altered the landscape, however most alterations probably fall within the range of uncertainty of the terrain model and this does not change the results of this work. The topography below present sea level was not corrected to reflect post-glacial deposition. The thickness of postglacial sediment is less than 6 m across most of the study area, except in deep channels in the East Passage of Narragansett Bay, Rhode Island Sound and Block Island Sound (Boothroyd. and Oakley, 2005; McMaster, 1984; Neddell et al., 1983; Needell and Lewis, 1984; O'Hara and Oldale, 1980). Due primarily to large uncertainties in the amount of sediment eroded during the transgression, there was no attempt to account for sediment lost to erosion since deglaciation, and it is assumed that the post-glacial deposition is in the same order of magnitude of post-glacial erosion.

Isostatic depression resulting from water loading as sea level rose from the Late Wisconsinan low-stand was not considered here. While some isostatic adjustment probably occurred due to water loading since the last glacial maximum, this would have begun after isostatic rebound was complete when relative sea level inundated the inner continental shelf (Figure 4). Total isostatic displacement at the

present shoreline in southern New England from water-loading was likely < 5 m (Bloom, 1967).

Relative Sea Level vs. Glacial Marine Limit

Projecting relative sea levels on the reconstructed terrain models provide some constraints on the downward adjustment of the lithosphere in southern New England. The limit of glacial marine deposition in New England has been well established to intersect present sea level just south of Boston, Massachusetts and extends north into coastal New Hampshire and Maine (Figure 1) (Bloom, 1963; Dyke et al., 2005; Koteff et al., 1993; Stone and Peper, 1982; Thompson and Borns, 1985). If a projected relative sea level shows inundation across parts of the study area south of the mapped limit of marine inundation, then another explanation must be examined. Possible explanations include:

1. The marine limit as mapped is incorrect
2. A peripheral forebulge on the continental shelf blocked sea level rise
3. The uplift profile of isostatic rebound was not linear, resulting in a more complicated isobase surface near the ice margin
4. There was less total isostatic adjustment, resulting in a lower relative sea level.

Each of these will be examined and discussed below.

Evidence of the marine limit

The projected inundations in the 75 and 50 m models do not fit with the current extent of glacial marine sediment. Areas that were inundated, i.e. northern Massachusetts and coastal Maine, have a distinct stratigraphy, dominated by the presence of a fossiliferous marine deposit (Bloom, 1963; Hitchcock, 1861; Stone and Peper, 1982). Wave-formed features (Spits, swash bars etc.) are also common (Koteff et al., 1993). The fact that no glacial marine deposits are found above present sea level within the study area supports the idea that the area was not inundated by marine water during deglaciation. Numerous glacial varve sequences from Rhode Island and southeastern Massachusetts (Antevs, 1928) indicate these areas contained glacial lakes and were not inundated with marine water during deglaciation. If the marine limit is correct as mapped, and glacial marine inundation of the landscape did not happen south of Boston, Massachusetts, then any reconstruction that shows marine inundation of the landscape can be considered incorrect and an alternative explanation is warranted.

Peripheral forebulge blocks transgression

The presence of a marginal forebulge, beyond the terminal margin of the LIS resulting from the lateral displacement of the mantle from beneath the ice sheet has been debated for decades. The distance beyond the ice margin and height is very poorly constrained, with distances ranging from 30 - 250 km, and total relief of 10 - 70 m (Barnhardt et al., 1995; Dillon and Oldale, 1978; Knebel et al., 1979; Pardi and Newman, 1987; Peltier, 1982; Stanford, 2010; Uchupi et al., 2001). A prominent

bulge on the continental shelf would have impeded glacial lake drainage across the shelf in both Hudson and Block Channels, depending on the timing of drainage and forebulge migration/collapse. Drainage of glacial lakes down the Hudson River Valley at 13.3 cal ka reached the edge of the continental shelf (Thieler et al., 2007), suggesting that at that time a forebulge did not exist on the continental shelf. Stanford (2010) suggests that a 40 m high forebulge existed near the edge of the continental shelf in the Hudson shelf valley that collapsed and did not migrate north up the Hudson River Valley. Migration of a forebulge, centered 100 kilometers south of the ice sheet, beginning immediately after the last glacial maximum, would have migrated through southern New England between 12– 17 ka, based on migration rates proposed by Barnhardt et al., (1995). No forebulge migration has yet been recognized in lacustrine water levels in the Connecticut River Valley (Koteff and Larsen, 1989) from 18.2 to 12.5 cal ka (Ridge, 2004, 2011).

The lack of a migrating forebulge recorded in southern New England, compared to Maine and Atlantic Canada, may be due to differences in the rigidity of the lithosphere offshore of Atlantic Canada, or lateral changes in mantle temperature, both of which cause significant changes in mantle viscosity (Barnhoorn et al., 2011; Zheng and Arkani-Hamed, 2002). Alternatively, the higher rates of Holocene subsidence in Atlantic Canada and Coastal Maine compared to the rest of New England may suggest that active forebulge collapse is occurring, where in southern New England, the forebulge has already migrated inland (Dyke and Peltier, 2000).

This study assumes that if there was a peripheral forebulge, it was either; a collapsing, non-migrating forebulge (amplitude 20 - 40 m (Barnhardt et al., 1995;

Dyke and Peltier, 2000; Stanford, 2010)) at a distance > 150 km beyond the terminal margin), or the forebulge migrated through southern New England after the onset of isostatic rebound. A forebulge > 150 km south of the terminal margin of the LIS would have been located beyond the edge of the continental shelf, where it may have impacted southern Atlantic and Caribbean sea levels (Potter and Lambeck, 2004), and would not have had a major impact on relative sea level in southern New England.

Isostatic rebound is not linear

The topographic reconstructions presented here assume that isostatic rebound was linear, based on isostatically uplifted water levels of glacial lakes in New England and eastern New York (Koteff and Larsen, 1989; Rayburn, 2004; Stanford and Harper, 1991). Early models of the Great Lakes proposed a more ‘hinged’ profile of uplift, with a relatively stable area south of the hinge, and increasing uplift to the north (Goldthwait, 1908). An uplift profile of this shape would increase depression to the north, further inundating the landscape with marine water. Models suggest that over thousands of kilometers, the uplift profile may be slightly exponential (Clark et al., 1994), but for distances of < 300 km (recorded by the uplifted water-levels of glacial lakes in New England and the Hudson River Valley), the plane of rebound is linear (Koteff and Larsen, 1989; Koteff et al., 1993; Rayburn, 2004).

Isostatic rebound was not delayed

The assumption that isostatic rebound was delayed until after ~16 ka, and perhaps as late as 14.2 cal ka (Koteff and Larsen, 1989), is based on the initiation of drainage of Glacial Lake Hitchcock. If isostatic rebound began immediately after ice retreat, the landscape would have had to be even more depressed to meet the required elevation for a marine delta in Long Island Sound. As stated above, increasing the amount of depression further inundates the ice-free portions of the landscape, and produces a grounded marine ice margin in southern New England.

Less isostatic depression

The simplest explanation to align the amount of isostatic rebound to the observed geology in New England is that the total amount of isostatic depression was less than previously assumed. The results presented here suggest that total isostatic adjustment at the terminal margin of southern New England was approximately 30 m and best fits the observed marine inundation history of the area. Total isostatic adjustment of ≥ 35 m at the terminal margin would have inundated the isostatically depressed landscape well south of the known glacial marine limit. Similar values for total isostatic depression have been proposed in the Hudson River Valley. Stanford (2010) interpreted total isostatic depression of approximately 40 m at the terminal moraine, based on the assumed 40 m forebulge and projected plane of rebound. An important note is that the forebulge height is based on radiocarbon ages of non-in situ marine shells (Ewing et al., 1963; Richards and Werner, 1964), and a slightly lower

forebulge (30 m) would bring the isostatic depression in the Hudson Valley in line with the interpretations presented here for southeastern New England.

Implications

This work has several implications. First, previously published values of isostatic rebound in southern New England overestimate total isostatic adjustment by 50 m or more. The glacial marine limit has been well constrained by over 100 years of mapping throughout New England (Bloom, 1963; Stone and Peper, 1982). The glacial marine delta in Long Island Sound remains enigmatic, as it requires 70 to 80 m isostatic depression to intersect eustatic sea level at the onset of isostatic rebound (Lewis and Stone, 1991; Stone et al., 2005b). Reexamination of radiocarbon dates that aided the original interpretation of a Late Pleistocene marine incursion into Long Island Sound, suggests the incursion is closer to 10 cal ka (Varekamp et al., 2004; Varekamp et al., 2006).

The volume of the delta ($11.5 \times 10^9 \text{ m}^3$) requires a significant source of sediment, and is interpreted to record drainage of glacial lakes down the present-day Connecticut River valley (Lewis and DiGiacomo-Cohen, 2000; Lewis and Stone, 1991). The sea level curve presented here (Figure 4) suggests that deposition of this delta (and drainage of a lake(s) in the Connecticut River Valley) culminated around 11 cal ka, after isostatic rebound had uplifted the landscape, creating enough gradient to incise the present-day Connecticut River through Late Wisconsinan glacial deposits (R. Lewis, personal communication). This is just after meltwater pulse 1B (MWP-1B) (Fairbanks 1989; Fairbanks et al., 1992). While the timing and magnitude of MWP-

1B is still debated (Bard et al., 2010), rapid marine incursion into Long Island Sound during MPW-1B could account for the apparently complicated transgression history (Stone et al., 2005b; Varekamp et al., 2004; Varekamp et al., 2006).

The linear profile of rebound in New England, coupled with the maximum depression presented here and the relatively thick lithosphere beneath southern New England supports the ideal of Koteff and Larsen's (1989) 'crustal block' model for delayed rebound across southern New England. The lower value of isostatic adjustment also supports a thinner Laurentide Ice Sheet, (Clark, 1992; Clark et al., 1999), which would produce less isostatic rebound. Rayburn (2004) suggested the profile of the Laurentide Ice Sheet was thin and relatively flat south of the Canadian Shield, with a thicker, steeper ice profile in the central portion of the ice sheet. This conclusion is in line with a proposed ice sheet profile with a profile of $> 4 \text{ m} \cdot \text{km}^{-1}$ in Maine and the mid-western United States (Clark, 1992; Shreve, 1984). Maximum marine inundation in Maine approximately 400 km from the terminal margin of the LIS at 15.1 ka requires isostatic depression to be 170 m approximately 1000 yr after the onset of isostatic rebound in New England (Barnhardt et al., 1995). Based on a 1000 yr half-life of isostatic rebound near the terminal margin of the LIS (Belknap et al., 1987; Dyke and Peltier, 2000), total isostatic depression at the Maine coast was 340 m, and would be in line with 30 m of isostatic depression at the terminal margin presented here.

A simple estimation of isostatic depression at equilibrium can be calculated for a given ice thickness using the density ratio of glacial ice ($900 \text{ kg} \cdot \text{m}^{-3}$) to the underlying crust and upper mantle ($3300 \text{ kg} \cdot \text{m}^{-3}$). Using this ratio, the amount of

isostatic depression for a given ice sheet model can be approximated by dividing ice sheet thickness by 3.6. Three reconstructions of the LIS (solid lines) and the calculated isostatic depression in southern New England (dashed lines) are shown in Figure 8. The resultant isostatic depressions show that the ice thickness of Dyke et al., (2002) overestimates both the total and relative uplift profile observed in southern New England. Ice thickness can be estimated by using the same isostatic relationship and the ice sheet model that best describes the observed isostatic rebound in southern New England is a simple, linear ice sheet, with a profile of $3.3 \text{ m} \cdot \text{km}^{-1}$ (Figure 8). The best fits to this ice sheet profile are the ICE-5G model of Peltier (2004) and the ‘thin ice’ model of Clark et al., (1994). The ICE-5G ice sheet reconstruction shows a step pattern due to the coarse resolution, however the end points of ICE-5G are almost identical to the proposed ice sheet profile presented here. The resultant isostatic depression under the ICE-5G and ‘thin ice’ models also closely match the rebound profile observed in southern and central New England.

The isostatic rebound model presented here supports a transgression history in southern New England with inundation of Block Island Sound and Narragansett Bay during latest Pleistocene and Holocene time (McMaster, 1984; Oldale and O'Hara, 1980). This differs from the interpretation of a marine incursion into Rhode Island, Block Island, and Long Island Sounds prior to isostatic rebound (Lewis and Stone, 1991; Stone et al., 2005b). It is possible that marine water inundated parts of Long Island Sound via the western end (Gayes, 1987), although the moraine acting as a dam at the southern end of the Hudson River Valley was probably not breached until at

least 15.5 cal ka (Stanford, 2010), and maybe as late as 13.4 cal ka (Donnelly et al., 2005).

Conclusions

High-resolution topographic models of the landscape prior to isostatic rebound can be created in a GIS environment by subtracting interpreted isobase surfaces from modern topographic and bathymetric data. By creating multiple reconstructions with differing values of total isostatic depression, the maximum downward adjustment can be constrained based on the mapped glacial marine limit in New England. The result of this work suggests that previous interpretations of isostatic depression in southern New England would inundate the landscape with marine water south of the mapped limit of glacial marine deposition, suggesting that these published values overestimate isostatic depression in southern New England by 40-50 m or more. A first order estimate of ice-thickness based on total isostatic depression and the observed uplift profile in southern New England is in line with the published ICE-5G model and ‘thin ice’ models of Clark et al (1994). This produces an ice thickness ranging from 100 m near the southeastern margin of the LIS, to > 1000 m 300 km north of the terminal margin of the LIS in New England. This regional model constrains both continental ice sheet reconstructions and geophysical models that should be considered in future work in both disciplines.

Acknowledgements

Thanks to C. Damon (University of Rhode Island Environment Data Center) for assistance creating the topobathy model and providing comments on the methods section of this manuscript. C. Troskosky (University of Rhode Island Department of Geosciences) assisted with compiling the sea level data. B. Savage (University of Rhode Island Department of Geosciences) provided helpful comments on prior drafts of this manuscript. J.C. Ridge, (Tufts University) provided insight into the evolution and drainage of lakes in the Connecticut River valley, and many helpful comments that improved the clarity of the manuscript. R. Lewis (Long Island Sound Resource Center here at the University of Connecticut-Avery Point) provided helpful discussion on the marine transgression of Long Island Sound and helpful comments on a prior draft of this manuscript.

The authors were supported by the Department of Geosciences, College of Environment and Life Sciences, University of Rhode Island, and funded by the Rhode Island Coastal Resources Management Council Cooperative agreement 50A00311741; The Rhode Island SeaGrant Program BayMap Project and NOAA CSC grant NA06NOS4730220.

REFERENCES

- Andrews, J.T., 1973, Maps of the maximum post glacial marine limit and rebound for the former Laurentide Ice Sheet: Arctic and alpine research, v. 5, p. 41-48.
- , 1974, Cainozoic glaciations and crustal movements of the Arctic, *in* Ives, J.D., and Barry, R.G., (Eds.), Arctic and alpine research, p. 999.
- Antevs, E., 1928, The last glaciation with special reference to the ice sheet in North America: American Geographical Society Research Series, v. 17, p. 292.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., and Schaefer, J.M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: Quaternary Geochronology, v. 4, p. 93-107.
- Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: Quaternary Science Reviews, v. 21, p. 2127-2135.
- Bard, E., Hamelin, B., and Delanghe-Sabatier, D., 2010, Deglacial meltwater pulse 1B and Younger Dryas sea levels revisited with boreholes at Tahiti Science, v. 327, p. 1235-1237.
- Bard, E., Hamelin, B., and Fairbanks, R.G., 1990, U-TH ages obtained by mass-spectrometry in corals from Barbados - Sea-level during the past 130,000 years: Nature, v. 346, p. 456-458.
- Barnhardt, W.A., Gehrels, R., and Kelley, J.T., 1995, Late Quaternary relative sea-level change in the western Gulf of Maine: Evidence for a migrating glacial forebulge: Geology, v. 23, p. 317-320.
- Barnhoorn, A., Van der Wal, W., Vermeersen, B.L.A., and Drury, M.R., 2011, Lateral, radial and temporal variations in upper mantle viscosity and rheology under Scandinavia: Geochemistry Geophysics Geosystems, v. 12, p. 1-19.
- Belknap, D.F., Anderson, B.A., Anderson, R.S., Anderson, W.A., Borns Jr., H.W., Jacobson, G.L., Kelley, J.T., Shipp, R.C., Smith, D.C., Stuckenrath Jr., R., Thompson, W.B., and Tyler, D.A., 1987, Late Quaternary sea-level changes in Maine, *in* Nummedal, D., (Ed.), Sea-level fluctuation and coastal evolution: Society of economic paleontologists and mineralogists Special Publication Volume 41, p. 71-85.
- Bloom, A.L., 1963, Late-Pleistocene fluctuations of sealevel and postglacial crustal rebound in coastal Maine: American Journal of Science, v. 261, p. 862-879.
- , 1967, Pleistocene shorelines: a new test of isostasy: Geological Society of America Bulletin, v. 78, p. 1477-1494.

- Boothroyd., J.C., and Oakley, B.A., 2005, Benthic Geologic Habitats of Greenwich Bay, RI, in *Special area management plan for Greenwich Bay and watershed*: Wakefield, RI, Rhode Island Coastal Resources Management Council, 1:10,000 scale maps and side-scan sonar images.
- Boulton, G.S., Smith, G.D., and Jones, A.S., 1985, Glacial geology and glaciology of the last mid-latitude ice sheets: Geological Society of London Journal, v. 142, p. 447-474.
- Braun, A., Kuo, C.Y., Shum, C.K., Wu, P., van der Wal, W., and Fotopoulos, G., 2008, Glacial isostatic adjustment at the Laurentide ice sheet margin: Models and observations in the Great Lakes region: Journal of Geodynamics, v. 46, p. 165-173.
- Clark, J.A., Hendriks, M., Timmermans, T.J., Struck, C., and Hilverda, K.J., 1994, Glacial Isostatic deformation of the Great Lakes region: Geological Society of America Bulletin, v. 106, p. 19-31.
- Clark, P.U., 1992, Surface form of the southern Laurentide Ice Sheet and it's implications to ice-sheet dynamics: Geological Society of America Bulletin, v. 104, p. 595-605.
- Clark, P.U., Alley, R.B., and Pollard, D., 1999, Northern Hemisphere Ice-sheet influences on global climate change: Science, v. 286, p. 1104-1111.
- Dillon, W.P., and Oldale, R.N., 1978, Late Quaternary sea-level curve: Reinterpretation based on glaciotectionic influenc: Geology, v. 6, p. 56-60.
- Donnelly, J.P., and Bertness, M.D., 2001, Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise: Proc. Natl. Acad. Sci. U.S.A, v. 98, p. 14214-14223.
- Donnelly, J.P., Driscoll, N.W., Uchupi, E., Keigwin, L.D., Schwab, W.C., Thielert, E.R., and Swift, S.A., 2005, Catastrophic meltwater discharge down the Hudson Valley: A potential trigger for the intra-Allerod cold period: Geology, v. 33, p. 89-92.
- Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J., 2002, The Laurentide and Innuitian ice sheets during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, p. 9-31.
- Dyke, A.S., Dredge, L.A., and Hodgson, D.A., 2005, North American deglacial marine and lake-limit surfaces: Geographie physique et Quaternaire, v. 59, p. 155-185.
- Dyke, A.S., and Peltier, W.R., 2000, Forms, response times and variability of relative sea-level curves, glaciated North America: Geomorphology, v. 32, p. 315-333.

- Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: *Geographie physique et Quaternaire*, v. 41, p. 237-263.
- Ewing, J., LePichon, X., and Ewing, M., 1963, Upper stratification of Hudson aprin region: *Journal of Geophysical Research*, v. 68, p. 6303-6316.
- Fairbanks, R.G., 1989, A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation: *Nature*, v. 342.
- Fairbanks, R.G., Charles, C.D., and Wright, J.D., 1992, Origin of global meltwater pulses, *in* Long, A., and Kra, R.S., (Eds.), *Four decades of radiocarbon studies*, Springer, p. 473-500.
- Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., Grootes, P.M., and Nadeau, M.-J., 2005, Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}\text{Th}/^{234}\text{U}/^{238}\text{U}$ and ^{14}C dates on pristine corals: *Quaternary Science Reviews*, v. 24, p. 1781-1796.
- Gayes, P.T., 1987, Buried paleoshorelines in Long Island Sound: Evidence for irregularities in the post-glacial marine transgression in Long Island Sound [PhD. thesis], State University of New York at Stony Brook.
- Gesch, D.B., 2007, The National Elevation dataset, *in* Maunne, D., (Ed.), *Digital Elevation Model Technologies and Applications: The DEM Users manual*: Bethesda, MD, American Society for photogrammetry and remote senseing, p. 99-118.
- Goldthwait, J.W., 1908, A reconstruction of water planes of the extinct glacial lakes in the Lake Michigan basin: *Journal of Geology*, v. 16, p. 459-476.
- Griffin, W.L., O'Reilly, S.Y., Doyle, B.J., Pearson, N.J., Coopersmith, H., Kivi, K., Malkovets, V., and Pokhilenko, N., 2004, Lithosphere mapping beneath the North American plate: *Lithos*, v. 77, p. 873-922.
- Hitchcock, C.H., 1861, General report on the geology of Maine: Maine Board of Agriculture, v. 6th annual report, p. 146-328.
- Hughes, T., Denton, G.H., Anderson, B.G., Schilling, D.H., Fastook, J.L., and Lingle, C.S., 1981, The last great ice sheet: A global view, *in* Denton, G.H., and Hughes, T.J., (Eds.), *The last great ice sheets*: New York, John Wiley and Sons, p. 263-317.
- Knebel, H.J., Wood, S.A., and Spiker, E.C., 1979, Hudson River: evidence for extensive migration on the exposed continental; shelf during Pleistocene time: *Geology*, v. 7, p. 254-258.

- Koteff, C., and Larsen, F.D., 1989, Postglacial uplift in western New England: geologic evidence for delayed rebound, *in* Gregersen, S., S. Basham, (Ed.), Earthquakes at North-Atlantic passive margins: Neotectonics and postglacial rebound 105-123.
- Koteff, C., Robinson, G.R., Goldsmith, R., and Thompson, W.B., 1993, Delayed postglacial uplift and synglacial sea levels in coastal central New England: *Quaternary Research*, v. 40, p. 46-54.
- Leverington, D.W., Teller, J.T., and Mann, J.D., 2002, A GIS method for reconstruction of late Quaternary landscapes from isobase data and modern topography: *Computers & Geosciences*, v. 28, p. 631-639.
- Lewis, R.S., and DiGiacomo-Cohen, M., 2000, A review of the geologic framework of the Long Island Sound basin with some observations relating to postglacial sedimentation: *Journal of Coastal Research*, v. 16, p. 522-532.
- Lewis, R.S., and Stone, J.R., 1991, Late Quaternary stratigraphy and depositional history of the Long Island Sound Basin: Connecticut and New York, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, eds., *Quaternary Geology of Long Island Sound and Adjacent Coastal Areas: Journal of Coastal Research, Special Issue 11*, p. 1-23.
- McMaster, R.L., 1984, Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, USA: *Sedimentology*, v. 31, p. 777-792.
- Neddell, S.W., O'Hara, C.J., and Knebel, H.J., 1983, Maps showing geology and shallow structure of western Rhode Island Sound, Rhode Island, U.S. Geological Survey Miscellaneous Field Studies Map MF-1537.
- Needell, S.W., and Lewis, R.S., 1984, Geology and structure of Block Island Sound, Rhode Island and New York, U. S. Geological Survey Miscellaneous Field Studies Map MF-1621 (4 Sheets).
- NGDC, 2010, NOS Hydrographic Survey Data, National Geophysical Data Center.
- NOS, 2009, NOS Hydrographic surveys specifications and deliverables, U.S. Department of Commerce National Oceanic and Atmospheric Administration, p. 161.
- , 2010, Elevations on station datum: Newport, Narragansett Bay, RI, Volume 2010, National Ocean Service/National Oceanic and Atmospheric Administration.
- O'Hara, C.J., and Oldale, R.N., 1980, Maps showing geology and shallow structure of eastern Rhode Island Sound and Vineyard Sound, Massachusetts, U.S. Geological Survey Miscellaneous Field Studies Map MF-1186.

- Oldale, R.N., and O'Hara, C.J., 1980, New radiocarbon dates from the inner continental shelf off southern Massachusetts and a local sea-level rise curve for the past 12,000 years: *Geology*, v. 8, p. 102-106.
- Pardi, R.R., and Newman, W.S., 1987, Late Quaternary sea levels along the Atlantic coast of North America: *Journal of Coastal Research*, v. 3, p. 325-330.
- Peltier, W.R., 1982, Dynamics of the ice age Earth: *Advances in Geophysics*, v. 24, p. 1-146.
- , 1999, Global sea level rise and glacial isostatic adjustment: *Global and Planetary Change*, v. 20, p. 93-123.
- , 2004, Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE: *Annual reviews of Earth and Planetary Sciences*, v. 32, p. 111-149.
- , 2005, On the hemispheric origins of meltwater pulse 1A: *Quaternary Science Reviews*, v. 24, p. 1571-1655.
- Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: *Quaternary Science Reviews*, v. 25, p. 3322-3337.
- Potter, E.-K., and Lambeck, K., 2004, Reconciliation of sea-level observations in the Western North Atlantic during the last glacial cycle: *Earth and Planetary Science Letters*, v. 217, p. 171-181.
- Rayburn, J.A., 2004, Deglaciation of the Champlain Valley, New York and Vermont and its possible effects on North Atlantic Climate Change [Ph.D. thesis]: Binghamton, NY, State University of New York.
- Rayburn, J.A., and Teller, J.T., 2007, Isostatic rebound in the northwestern part of the Lake Agassiz basin: Isobase changes and overflow: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 246, p. 23-30.
- Richards, H.G., and Werner, E., 1964, Invertebrate fossils from cores from the continental shelf off New Jersey: *Notulae Naturae of the Academy of Natural Sciences of Philadelphia*, v. 372, p. 1-7.
- Ridge, J.C., 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J., and Gibbard, P.L., (Eds.), *Quaternary glaciations - extent and chronology: Part II: North America. Developments in Quaternary Science, Volume 2B*: Amsterdam, Elsevier, p. 163-193.
- , 2011, The North American glacial varve project: <http://geology.tufts.edu/varves/default.asp>.

- RIGIS, 2001, Rhode Island State, Coastline and Town Boundaries, Volume 2010, Rhode Island Geographic Information System.
- Ruddiman, W.F., 2001, *Earth's climate past and future*: new York, W.H. Freeman.
- Rychert, C.A., Fischer, K.M., and Rondenay, S., 2005, A sharp lithosphere-asthenosphere boundary imaged beneath eastern North America: *Nature*, v. 436, p. 542-545.
- Salcher, B.C., Hinsch, R., and Wagreich, M., 2010, High-resolution mapping of glacial landforms in the North Alpine Foreland, Austria: *Geomorphology*, v. 122, p. 283-293.
- Shreve, R.L., 1984, Glacier sliding at subfreezing temperatures: *Journal of Glaciology*, v. 30, p. 341-347.
- Stanford, S.D., 2010, Onshore record of Hudson River drainage to the continental shelf from the late Miocene through the late Wisconsinan deglaciation, USA: synthesis and revision *Boreas*, v. 39, p. 1-17.
- Stanford, S.D., and Harper, D.P., 1991, Glacial lakes of the lower Passaic, Hackensack and lower Hudson valleys *Northeastern Geology*, v. 13, p. 271-286.
- Stone, B.D., and Peper, J.D., 1982, Topographic control of the deglaciation of eastern Massachusetts: ice lobation and the marine incursion, *in* Larson, G.J., and Stone, B.D., (Eds.), *Late Wisconsinan glaciation of New England*: Dubuque, Kendall-Hunt.
- Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., 2005, Quaternary Geologic Map of Connecticut and Long Island Sound Basin, U.S. Geological Survey Geologic Investigations Series Map I-2784, scale 1:125,000, 2 sheets and pamphlet. p. 1-72.
- Thieler, E.R., Butman, B., Schwab, W.C., Allison, M.A., Driscoll, N.W., Donnelly, J.P., and Uchupi, E., 2007, A catastrophic meltwater flood event and the formation of the Hudson Shelf Valley: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 246, p. 120-136.
- Thompson, W.B., and Borns, H., 1985, *Surficial Geologic Map of maine*: Augusta, ME, Maine Geological Survey.
- Uchupi, E., Driscoll, N., Ballard, R.D., and Bolmer, S.T., 2001, Drainage of late Wisconsin glacial lakes and the morphology and late quaternary stratigraphy of the New Jersey-southern New England continental shelf and slope: *Marine Geology*, v. 172, p. 117-145.
- USGS, 2010, National Elevation Data.

- van de Plassche, O., van der Borg, K., and de Jong, A.F.M., 1998, Sea level-climate correlation during the past 1400yr: *Geology*, v. 26, p. 319-322.
- Varekamp, J.C., Thomas, E., and Groner, M., 2004, The late Pleistocene-Holocene History of Long Island Sound, Seventh Biennial LIS Research Conference Proceedings: Stony Brook, NY, State University of New York, p. 27-32.
- Varekamp, J.C., Thomas, E., and Lewis, R.S., 2006, Early history of Long Island sound, Eighth biennial Long Island Sound research conference: Proceedings, U.S. Coast Guard Academy, New London, CR.
- Zheng, Y., and Arkani-Hamed, J., 2002, Rigidity of the Atlantic oceanic lithosphere beneath New England seamounts: *Tectonophysics*, v. 359, p. 359-369.

Figure 1: Digital elevation model generated for the study area, showing the location of pertinent geographic locations discussed in the text and the maximum extent of the Laurentide Ice Sheet modified from Dyke and Prest (1987). Details of digital elevation model discussed in the text. Hatched region on inset map of New England shows extent of glacial marine inundation based on Stone and Peper, (1982) and Thompson and Borns, (1985).

Figure 2. Schematic diagram showing A- Isostatic depression and formation of a peripheral forebulge beyond the margin B - Uplift of the lithosphere under the former ice sheet and the potential migrating forebulge. Modified from (Andrews, 1974; Ruddiman, 2001) C – Earth models used to model isostatic rebound in the Great Lakes (modified from Clark et al., 1994) D – ‘Thick’ ice and ‘Thin’ ice profiles used by Clark et al., (1994).

Figure 3: A - Isobase surface reflecting 30 m of depression at the terminal moraine south of Block Island, with a profile of rebound of 0.85 m km^{-1} . B - Schematic cross-section of modern topography, an isobase surface and the pre-isostatic rebound topography (Modified from Leverington et al., 2002)

Figure 4: Relative sea level and isostatic rebound curve for the Late Wisconsinan terminal margin south of Block Island, RI. Total isostatic depression is assumed to be 30 m. Ages in calendar years before present.

Figure 5: A - Elevation relative to sea level at 21 ka assuming 75 m of isostatic depression at the terminal margin. Note the inundation of most of Martha's Vineyard and eastern Long Island, as well as the marine grounded ice margin. Extent of the Laurentide Ice Sheet modified from Schafer and Hartshorn (1965), Goldsmith (1982), Sirkin (1982) and Dyke and Prest (1987). B - Elevation relative to sea level at 16.5 ka assuming 75 m of isostatic depression at the terminal margin. The southern margin of the Laurentide Ice Sheet had retreated north of Rhode Island by this time. C - Elevation relative to sea level at 21 ka, assuming 30 m of depression at the terminal margin. D - Elevation relative to sea level at 16.5 ka assuming 30 m of depression at the terminal margin. Marine water may have begun to inundate the channel south of Block Island by 16.5 ka. The southern margin of the Laurentide Ice Sheet had retreated north of Rhode Island by this time.

Figure 6: Ice thickness (solid lines) and isostatic adjustment (dashed lines) for three published ice sheet reconstructions (Clark et al., 1994; Dyke et al., 2002; Peltier, 2004) and the calculated ice sheet profile based on observed isostatic rebound in New England with 30 m of depression at the terminal margin of the ice sheet. Geographic locations are noted, including SNH (Southern New Hampshire, USA) and BI (Block Island, Rhode Island, USA).

CHAPTER 2

THE GEOMETRY AND EXTENT OF GLACIAL LAKES NARRAGANSETT, BLOCK ISLAND, AND RHODE ISLAND, RHODE ISLAND, USA

Bryan A. Oakley
Department of Geosciences, University of Rhode Island, Kingston, RI, USA, 02881

Corresponding author:
Bryan A. Oakley
Department of Geosciences
College of the Environment and Life Sciences
University of Rhode Island
317 Woodward Hall
9 East Alumni Ave
Kingston, RI, 02881
BOakley@my.uri.edu

Ph: 401-874-4560
Fax: 401-874-2190

Abstract

The elevation of Late Wisconsinan delta plain-delta slope contacts in and around Narragansett Bay, as well as Block Island and Rhode Island Sounds, were determined using ground-penetrating radar and sub-bottom seismic reflection profiles. Water levels reflecting regional isostatic rebound were fit to the deltas and are interpreted to record three, lowering water levels. Water levels were projected onto a pre-isostatic rebound terrain model of southern New England to examine the extent of Glacial Lakes Block Island, Rhode Island and Narragansett. The reconstructions of the lakes suggested that drops in water level coincide with lower elevation spillways becoming ice-free as the southern margin of the Laurentide Ice Sheet retreated north. The projected extent of the glacial lakes shows that Glacial Lake Narragansett was contiguous with Glacial Lakes Block Island and Rhode Island, and one large lake occupied much of the southern portion of Narragansett Basin. The linear trend of the measured deltas further validate the idea of delayed isostatic rebound, and the behavior of New England as a lithospheric block during rebound, as first suggested by Koteff and Larsen (1989).

Introduction

This paper examines the water levels of Glacial Lakes Block Island, Rhode Island and Narragansett by measuring the elevation of the delta plain-delta slope contact within deltas deposited into these lakes in and around Narragansett Bay and adjacent waters (Figure 1). The overall goal was to determine the extent of glacial lakes within Narragansett Bay. A critical component of this is determining the water level of the glacial lake(s). The water levels were projected onto a pre-isostatic rebound topographic model of southern New England to examine the extent of Glacial Lake Narragansett.

The hypothesis is that during Late Wisconsinan deglaciation, one large lake (Glacial Lake Narragansett), occupied most of Narragansett Bay, and extended into adjacent waters. Because the deltas of Glacial Lake Narragansett fall on linear planes reflecting the regional trend of rebound, it is surmised that a single lake occupied the study area during deglaciation. The similar north to south trend (roughly parallel to isostatic rebound) of Glacial Lake Narragansett, and of Glacial Lake Hitchcock, where earlier measurements of rebound were made, is important to consider when making comparisons between these areas. Determining the rebound profile, (the amount of uplift over a given distance), is an important component of reconstructing the deglacial topography of previously glaciated areas.

Water level indicators

The primary indicator of water levels in glacial lakes is the elevation of the delta plain-delta slope contact (often referred to as the topset-foreset contact). The deltas measured in this study are ice marginal or ice contact, Gilbert style deltas (Gilbert, 1890), with a fluvial (braided river) delta plain overlying a delta slope, deposited into, and graded to a standing (lacustrine) body of water (Figure 2). This style of deposition is common in both modern and Late Wisconsinan deglacial depositional environments (Gustavson and Boothroyd, 1987; Stone and Stone, 2005). Within each delta system there may be one or more morphosequences.

Morphosequences are time-equivalent groups of landforms that extend from the collapsed former ice margin at the proximal end of the deposit. There is generally a decrease in grain-size from gravel near the ice margin to sand and silt in more distal portions of the sequence (Koteff and Pessl, 1981; Stone and Stone, 2005). Where more than one morphosequence was mapped as part of a delta system, attempts were made to obtain elevations of both sequences.

The contact between the relatively flat-lying delta plain beds and underlying dipping (10-30°) delta slope beds is readily identifiable in outcrop exposures and geophysical imagery (Smith and Jol, 1997). The erosional surface is used as a proxy for determining glacial lake level, but actually represents the elevation of the bottom of a fluvial channel on the delta plain, and is lower in elevation than the actual water level of the lake (Gustavson et al., 1975). Observations on glacial deltas in Alaska that are similar to those deposited in Glacial Lake Narragansett report channel depths

< 1.0 m (Boothroyd and Ashley, 1975), and the delta plain-delta slope contact is assumed to be less than 1 m below the true water level of the lake.

Previous work

The elevation of two deltas was reported in earlier studies of Narragansett Bay (Peck, 1989; Peck and McMaster, 1991; Pickart, 1987). The elevations of the delta plain-delta slope contact of several deltas in southeastern Mass and northeastern Rhode Island were estimated from 1:24,000 and 1:25,000 scale topographic maps (Stone, 2010) or published geologic maps (Hartshorn, 1967; Schafer, 1961a, b; Smith, 1955, 1956). The extent of the deltas around Narragansett Bay has been mapped at scales of 1:24,000 and 1:100,000 (Figure 3) (Boothroyd and McCandless, 2002, 2003; Boothroyd et al., 2003; RIGIS, 1989) or were interpreted from published maps of stratified deposits (Allen and Ryan, 1960; Schiner and Gonthier, 1965). The presence of a glacial lake in Block Island Sound (Glacial Lake Block Island) has been known for decades (Bertoni et al., 1977; Frankel and Thomas, 1966). The water level of Glacial Lake Block Island was previously estimated to be 15 – 20 m below present mean sea level (MSL) (Boothroyd et al., 1998; Lewis and Stone, 1991). Sediment deposited in a glacial lake was also mapped in Rhode Island Sound, however the extent of any deltas were not mapped separately from lakefloor deposits in the original work (Needell et al., 1983b).

Isostatic rebound has uplifted the landscape preferentially to the northwest, indicated by the present elevation of deltas graded to the formerly horizontal water level of glacial lakes (Koteff and Larsen, 1989; Koteff et al., 1993). Anthropogenic development on deltas in northern Narragansett Bay and submergence of deltas

beneath present sea level in southern Narragansett Bay, Block Island Sound, and Rhode Island Sound necessitated the use of geophysical methods to determine the elevation of the delta plain-delta slope contact. Determining the elevation of glacial lacustrine and marine deltas with geophysical tools has been done in other areas (Barnhardt et al., 1997; Kostic et al., 2005; Smith and Jol, 1997; Tary et al., 2007). This present work represents the first attempt to combine these techniques in the context of evaluating the former water level and uplift profile of a glacial lake.

Methods

The delta plain-delta slope contact of 15 deltas (Figure 3) was imaged using ground-penetrating radar (GPR) or sub-bottom seismic reflection profiles (Figure 4). The elevation of the delta plain-delta slope contact estimated from topographic maps or published Quaternary geologic maps was examined in comparison with the geophysical data. The highest elevation delta plain-delta slope contact at any given delta is used to estimate the lake level. Wave action during Holocene transgression and anthropogenic activities on the landscape can modify or remove the upper portions of the delta plain and delta slope, but these processes cannot increase the elevation of the delta plain-delta slope contact (Koteff and Larsen, 1989; Koteff et al., 1993).

Sub-bottom profiling

Glacial deltas were interpreted from sub-bottom seismic reflection profiles collected in Lower Narragansett Bay, Rhode Island and Block Island Sounds, using an

EdgeTech (Wareham, Massachusetts, USA) 2-16S Chirp Seismic Reflection profiler, producing a linear pulse of energy with a frequency of 2-10 kHz (Figure 4).

Penetration depth in sandy or gravelly delta plain-delta slope depositional environments was limited to < 20 m, which was sufficient to image the dipping reflectors of the delta slope with occasional penetration into the underlying glacial lakefloor deposits. The elevation of the delta plain-delta slope contact was digitized from the seismic reflection profiles using Chesapeake Technologies SonarWebTM (Mountain View, California, USA) software, assuming a sound velocity of $1500 \text{ m} \cdot \text{s}^{-1}$ in both water and sediment (Hamilton, 1974). The elevation of the towfish was maintained at 1 m beneath the surface of the water, and the elevation of the delta plain-delta slope contact was corrected to present mean sea level (MSL) based on recorded water levels at the Newport, RI tide gauge.

Ground Penetrating Radar (GPR)

GPR was utilized to determine the elevation of the delta plain-delta slope contact of delta surfaces now above present mean sea level (MSL) (Figure 4). The non-intrusive nature of GPR is ideal for working in urban or developed areas where no exposures are available. GPR works best in unsaturated sand and gravel, making it ideal for imaging glacial deltas (Smith and Jol, 1995, 1997) and has been used successfully on glacial-marine deltas in northern New England (Tary et al., 2007). GPR signals will not penetrate sediment saturated with soluble salts, limiting its use in saline and tidally influenced areas near the coast (Buynevich and FitzGerald, 2003). The system used in this study was a SIR3000 system (manufactured by Geophysical

Survey Systems, Inc (GSSI), (Salem, New Hampshire, USA), utilizing either a 120 MHz or a 200 MHz antenna. Vertical resolution of a 120 MHz antenna is 0.35 to 0.65 m; the resolution of 200 MHz antenna is 0.2 to 0.5 m, depending on the saturation of the sediment (Smith and Jol, 1997; Widess, 1973).

The depth to reflectors in GPR profiles was calculated using equation (1) (Ulriksen, 1982).

$$d = c \cdot t/2 \cdot Er^{1/2} \quad (1)$$

Where: d = depth in feet.
c = velocity of light (1 foot/nanosecond).
t = pulse travel time in nanoseconds.
Er = relative dielectric permittivity of sediment

The ground surface above identified delta plain-delta slope contacts was surveyed with Real-time Kinematic Global Positioning System (RTK - GPS) relative to the North American Vertical Datum, 1988 (NAVD88), accurate to < 0.05 m (Trimble, 2008) and the elevation relative to NAVD88 was converted to MSL based on the datums at the Newport, RI tide gauge (NOS, 2010a). The elevation of the New Meadow Neck, Blackstone River and East Providence Plains deltas was determined from a continuous interpolated grid (cell size 1 m) generated from LiDAR data of the area surrounding the Providence River. The accuracy of this raster surface was validated by comparing the RTK-GPS elevations determined on the other deltas around the Providence River (n = 46); the average difference between the raster surface and RTK-GPS points was < 0.2 m.

Vertical Error

The largest source of error in GPR surveys is the result of uncertainty in the dielectric permittivity of the sediment profile. The elevation of the water table is also important and in most cases, the water table was visible as a distinct, horizontal reflector on the GPR profiles. The vertical scale was calculated using dielectric permittivity above and below the water table corresponding to dry and saturated sediment. The elevation of the ground surface above delta plain-delta slope contacts determined using either RTK - GPS or LiDAR is not a significant source of error, with vertical accuracy of $\pm .05$ m and 0.2 m respectively.

Sub-bottom seismic reflection profiles were corrected to MSL based on the water level at the Newport, RI tide gauge at the time of data collection. The delta plain-delta slope contact was less than 5 m below the present seafloor on all the seismic reflection profiles, so differences in sound velocity are not a significant source of error. The vertical elevation of the delta plain-delta slope contact is reported here to be ± 2 m, which includes the < 1 m difference between the delta plain-delta slope contact and the actual lake level.

Interpreted water levels

The measured delta plain-delta slope contacts were plotted based on the present elevation and northing (Universal Transverse Mercator, zone 19N). No regression line intersected all of the measured delta plain-delta slope contacts. Multiple water levels are interpreted based on subsets of the data, selected based on geographic location (i.e. Block Island Sound, lower Narragansett Bay, and upper Narragansett Bay).

Pre-isostatic rebound topographic models

The interpreted water levels were projected onto a pre-isostatic rebound digital terrain model to reconstruct the extent of Glacial Lakes Block Island, Rhode Island and Narragansett. This model used a seamless grid of the present topography and bathymetry of southern New England using the raster National Elevation Database 30 m DEM combined with hydrographic soundings from the National Ocean Service . Isostatic depression that occurred due to the mass of the ice sheet was accounted for by creating isobase surfaces reflecting the total isostatic adjustment using the linear plane of rebound measured in central New England of $0.85 \text{ m} \cdot \text{km}^{-1}$ uplifted towards the northwest (336°). The isobase surfaces were subtracted from the modern DEM in ESRI ArcMapTM 'Raster Calculator' to produce the pre-rebound isostatic elevation models.

The position of the retreating Laurentide Ice Sheet is critical to determining the extent of Glacial Lake Narragansett as the ice retreated north. Ice margins used are a combination of previously published moraine locations (Boothroyd et al., 1998; Dyke

and Prest, 1987; Ridge, 2003; Schafer and Hartshorn, 1965; Smith, 2010; Stone and Borns, 1986; Stone and Peper, 1982) and proximal lacustrine fan or recessional end moraines interpreted from high resolution sub-bottom seismic reflection profiles. Ages of four ice margins are tied to regional cosmogenic beryllium (Be^{10}) exposure dates of boulders on moraines (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Ages of other ice margins are based on assumed ice margin retreat rate of $75 \text{ m} \cdot \text{yr}^{-1}$. These average retreat rates are estimated from the existing exposure dates, and are consistent with regional retreat rates (Ridge, 2004).

Thickness of post-glacial deposits, primarily Holocene estuarine and shelf sediment, was determined using seismic reflection profiles throughout the study area. Holocene sediment thickness estimates in Narragansett Bay were generated from the sub-bottom seismic reflection profiles calculated by using Chesapeake Technologies SonarWebTM (Version 3.3) software. Thickness of post-glacial sediment in Rhode Island Sound and Block Island Sound was digitized from published U.S. Geological Survey maps (Needell and Lewis, 1984; Needell et al., 1983a; O'Hara and Oldale, 1980). Interpolated Holocene thickness layers were subtracted from the topobathy grid using Raster Calculator prior to adjusting the grid to account for isostatic rebound. Seismic penetration in the Sakonnet River was limited, and the true estimate of post-glacial sediment thickness is not well constrained.

Results

The elevation of delta plain-delta slope contact of fifteen glacial deltas was determined using either seismic reflection profiles (6) or ground-penetrating radar (9). The results are discussed for each delta below. See table 1 for a summary of the measured delta plain-delta slope contacts.

Block Island Sound

Several large deltas that extend south from the Charlestown Moraine into Block Island Sound are interpreted to have been deposited into Glacial Lake Block Island (Boothroyd et al., 1998). Sub-bottom seismic reflection profiles were collected from the present upper shoreface south into the interpreted glacial lake basin. South dipping (5 - 15°) reflectors imaged in seismic reflection profiles offshore of the Rhode Island south shore are interpreted to have been deposited in a delta slope depositional environment. The delta plain-delta slope contacts are 17 m and 26 m (Figures 5, 6; Table 1) below present MSL, in two discrete sets 5 km apart. The higher elevation delta is north of the lower elevation set (Figure 3).

Pettaquamscutt River Delta

The only delta measured in Rhode Island Sound was deposited offshore of Narragansett Beach by meltwater routed down the valley presently occupied by the Pettaquamscutt River (Figure 3). No estimation of the elevation of the delta plain-delta slope contact had previously been made, although it had been realized that the sequence extended below present sea level (Boothroyd and August, 2008; Schafer,

1961a, b; Smith, 2010). Seismic reflection profiles show an interpreted delta plain-delta slope contact at 14 m below present MSL (Table 1). Flat lying seismic reflectors overlying the delta slope reflectors are interpreted to be sandy delta plain deposits, and the elevation of the delta plain-delta slope contact here appears unaltered.

Dutch Island

The southernmost deltas directly deposited into present day Narragansett Bay were in the lower West Passage, west of Dutch Island and south of the Jamestown-Verrazano Bridge (Figure 3). This previously unmapped delta is interpreted to be a small ice-contact delta deposited when the margin of the Laurentide Ice Sheet extended across the lower West Passage of Narragansett Bay. The elevation of the delta plain-delta slope measured in seismic reflection profiles is 9.8 m below MSL (Figure 7; Table 1).

Annaquatucket delta

The Annaquatucket delta (Figure 3) was first discussed by Peck (1987), and Peck and McMaster (1991) who estimated the elevation at 5 m below MSL based on borehole data and a seismic reflection profile collected prior to construction of the Jamestown Verrazano Bridge (Figure 3). The delta likely formed when the ice margin was near Wickford, RI, 9 km further north (Schafer, 1961b; Smith, 2010). Sub-bottom lines collected for this study refined the Peck and McMaster (1991) estimate, placing the delta plain-delta slope contact at an elevation of 5.8 m below present MSL (Table 1).

Mill Creek and Hunt-Quonset deltas

The Mill Creek and Hunt-Quonset deltas were deposited in Glacial Lake Narragansett in the present West Passage of Narragansett Bay (Figure 3) (Schafer, 1961b; Smith, 2010). The delta plain here has been heavily modified by construction during and after World War II. No previous estimates of lake level were made for deltas, although the thickness of the interpreted delta plain deposits near Wickford Harbor was measured at 1 – 2 m, and it was noted that the mapped morphosequence extended below sea level (Schafer, 1961b). The estimated elevation of the delta plain-delta slope contact is just above present MSL, but cannot be accurately determined due to the heavily altered nature of the area.

Potowomut

The Potowomut delta south of Greenwich Bay was deposited as two morphosequences extending southeast into the West Passage of Narragansett Bay (Figure 3). GPR profiles (3 km total line length) collected near the present shoreline of Narragansett Bay at the southern end of the delta, showed an extremely high (presumably salt) water table. This limited penetration of the radar signal; however, several reflectors interpreted to be dipping delta slope beds were imaged, placing the elevation of the delta plain-delta slope contact at 3.5 m above present MSL (Table 1).

Island Park

The previously unnamed Island Park delta makes up the northeastern end of Aquidneck Island at the head of the Sakonnet River (Figure 3). Ground penetrating

radar profiles were collected 500 m from the northern shoreline of the Sakonnet River, and the highest delta plain-delta slope contact was measured at 1.5 m above MSL (Table 1). Borehole data (USACE, 1957) supports this interpretation based on the transition from sand and gravel (delta plain) to sand (delta slope) at approximately 1 m above present MSL.

Warwick Plains Delta

The Warwick Plains delta extends from the Pawtuxet River into present Greenwich Bay (Figure 3) (Boothroyd and McCandless, 2003). 1.5 km of ground-penetrating radar profiles were collected at two sites < 1 km apart. The elevation of the highest interpreted delta plain-delta slope contact was determined to be 3.3 m above present MSL 0.1 km north of the present Greenwich Bay shoreline and 4.1 m above present MSL 0.7 km north of Greenwich Bay (Figure 8; Table 1).

Conimicut Point Delta

Southwest of Conimicut point (Figure 3), dipping seismic reflectors interpreted to be delta slope beds, were mapped at an elevation of 4 m below present MSL (Table 1). This delta extends along the western side of upper Narragansett Bay, as a broad, sandy platform.

Barrington

The Barrington delta system consists of three morphosequences deposited into Glacial Lake Narragansett (Smith, 1955; Smith, 2010). The southern Barrington delta

(BTS) is a narrow (0.6 km north to south) ice marginal delta that extends east to west along a portion of the present upper Narragansett Bay shoreline (Figure 3). The delta has a maximum ground surface elevation of 15 m above MSL. GPR surveys here were inconclusive due to extensive collapse of the glacial beds, and the elevation of the delta plain-delta slope contact can only be estimated at < 12 m above present MSL (Stone, 2010).

The northern delta (BTN) is approximately 1 km north of BTS, and was deposited into Glacial Lake (Smith, 2010). The elevation of the delta plain-delta slope contact of the northern delta was determined to be 10 m above MSL (Figure 9, Table 1). This elevation is < 2 m lower than unpublished and published estimates of the delta plain-delta slope contact (Smith, 1955; Stone, 2010). Smith (2010) mapped a third delta within the Barrington delta system that was not measured here due to lack of suitable field locations.

Riverside

The Riverside delta extends from the eastern shoreline of the present Providence River to the Barrington River (Figure 3) (Boothroyd and McCandless, 2002, 2003; Smith, 1955, 1956; Smith, 2010). The delta plain-delta slope contact was imaged with GPR along the western end of the delta at an elevation of 11.5 m above (Table 1) MSL (Table 1). Unpublished estimates of the delta plain-delta slope contact in the northern end of the delta (Figure 3) place the elevation at 15 – 18 m above MSL (Stone, 2010).

New Meadow Neck

Located between the Barrington and Palmer Rivers, the New Meadow Neck delta is lower than the adjacent Riverside, Barrington and Warren River deltas (Figure 3) (Smith, 1955). The delta plain-delta slope contact was imaged in two different areas of the delta at 6.3 and 4.8 m above MSL respectively (Table 1).

Providence Plains Delta

The Providence Plains Delta extends along the northwest side of the Providence River (Boothroyd and McCandless, 2002) (Figure 3). The elevation of the delta plain-delta slope contact was estimated at 10 m above MSL based on the topography of the area (Pickart, 1987). The surface of the delta plain is heavily developed, and GPR profiles (1.8 km total line length) were limited to side streets, sidewalks and lawns. Beds interpreted to have been deposited in a delta slope depositional environment, with an apparent dip of 15° towards the southeast (towards the Providence River, Narragansett Bay) were imaged in GPR lines close to the present shoreline of Narragansett Bay. RTK elevations agree with the original interpretation, placing the interpreted delta plain-delta slope contact at 10.1 m above MSL (Table 1).

Smith Hill

One of the few areas available to survey on the heavily developed Smith Hill delta surface, was the front lawn of the Rhode Island State House located in the center of Providence, RI. Ground Penetrating Radar profiles (300 m total line length) were

collected to determine the elevation of the delta plain-delta slope contact. The ground surface here represents the altered delta plain, and the elevation of the delta plain-delta slope contact is interpreted to be 18 m above MSL (Figure 10; Table 1).

Blackstone River

The Blackstone River Delta is along the eastern shoreline of the Seekonk River in northeastern Narragansett Bay, deposited into and graded to Glacial Lake Narragansett in the area now occupied by the Seekonk River (Boothroyd and McCandless, 2002) (Figure 3). The delta surface is highly developed; however, a cemetery along the western shoreline of the delta where the GPR profiles were collected has been in existence since 1871 suggests the topography has remained mostly unchanged (Ancestry, 2010). Ground surface elevation here is 20 m MSL, and the delta plain-delta slope contact is 18.5 m above MSL (Table 1).

Table 1: Elevations of delta plain-delta slope contacts measured in Glacial Lakes Block Island, Rhode Island, Narragansett, and Taunton

Location	Source	Elevation of dp-ds contact - m MSL	Northing - UTM 19N	Easting - UTM 19N
Block Island Low	SB	-26.0	4,574,980	280,031
Block Island High	SB	-17.0	4,577,780	277,414
Block Island High	SB	-17.0	4,579,060	280,017
Pettaquamscutt River	SB	-14.2	4,589,530	295,627
Pettaquamscutt River	SB	-14.2	4,589,740	295,965
Dutch Island	SB	-9.5	4,597,190	298,885
Dutch Island	SB	-9.5	4,597,310	298,813
Dutch Island	SB	-9.5	4,597,410	298,824
Annaquatucket	SB	-5.8	4,599,770	299,410
Annaquatucket	SB	-5.8	4,599,840	299,618
Annaquatucket	SB	-5.9	4,600,060	299,777
Wickford	TM	2.0	4,609,570	282,729
Island Park	GPR	1.5	4,610,630	313,964
Potowomut	GPR	3.3	4,612,140	299,236
Potowomut	GPR	3.5	4,612,280	299,242
Warwick Plains	GPR	3.2	4,618,100	299,645
Warwick Plains	GPR	3.1	4,618,110	299,629
Warwick Plains	GPR	3.1	4,618,110	299,622
Warwick Plains	GPR	3.0	4,618,130	299,687
Warwick Plains	GPR	4.5	4,618,280	299,081
Warwick Plains	GPR	4.5	4,618,290	299,034
Warwick Plains	GPR	4.2	4,618,300	299,005
Conimicut Point	SB	-4.0	4,619,920	304,763
Barrington	TM	12.0	4,622,180	307,401
Barrington	TM	12.2	4,622,390	305,534
Riverside	GPR	9.7	4,623,590	307,310
Riverside	GPR	10.1	4,623,620	307,315
Riverside	GPR	9.5	4,623,630	307,351
Riverside	TM	12.2	4,623,760	307,056
Riverside	TM	13.0	4,623,760	307,298
New Meadow Neck	GPR	4.8	4,625,030	307,721
Riverside	GPR	11.4	4,625,340	303,769
New Meadow Neck	GPR	6.3	4,626,680	308,016
New Meadow Neck	GPR	5.9	4,626,770	307,717
Providence Plain	GPR	10.0	4,627,500	301,314
Riverside	TM	15.2	4,627,790	305,926
Riverside	TM	15.2	4,628,980	306,947
S. Rehoboth MA	TM	15.2	4,629,840	312,127
S. Rehoboth MA	TM	15.2	4,630,630	310,125
East Providence Plains	GPR	19.9	4,631,380	301,689
East Providence Plains	GPR	19.9	4,631,580	301,683
Riverside	TM	18.2	4,631,540	306,428
East Providence Plains	GPR	19.6	4,631,770	301,624
Rehoboth Ma	TM	17.5	4,632,060	310,861
Smith Hill	GPR	17.8	4,633,810	299,380
Blackstone River	GPR	18.6	4,636,530	303,633

Note: Northing and Easting Universal Transverse Mercator (meters), Zone 19 North, relative to the North American Datum of 1983. Elevation (meters) relative to MSL at the Newport, RI tide gauge. Deltas are arranged south (top) to north. Source abbreviations: SB = Sub-bottom seismic reflection profile, GPR = Ground penetrating radar, TM = Topographic map

Water levels

A best-fit linear regression using all of the delta plain-delta slope contacts measured had an uplift profile of $0.7 \text{ m} \cdot \text{km}^{-1}$ and was a good fit ($r^2 = 0.92$), but did not intersect all of the deltas measured. A linear regression line intersects all the delta plain-delta slope contacts from the Block Island Sound low delta, north to the Potowomut delta ($n = 11$) with a very good fit ($r^2 = 0.994$), but does not intersect the deltas further to the north. The uplift profile of this line is similar to the regional trend of rebound ($0.84 \text{ m} \cdot \text{km}^{-1}$) (Figure 11). A separate linear regression line from Warwick Plains to the Blackstone River deltas ($n = 14$), showed a good fit ($r^2 = 0.961$) with an uplift profile of ($0.9 \text{ m} \cdot \text{km}^{-1}$). The Block Island Sound High, the East Providence Plains and New Meadow Neck deltas are outliers to these water levels, and are discussed separately.

Discussion

Assumptions

A major assumption in this work is that the elevations of the delta plain-delta slope contacts have not been significantly altered since deposition. The ubiquitous presence of eolian mantle and active development of soils suggests that other than in the present river valleys, where channel incision and floodplain deposition has occurred, most of the landscape has been largely unchanged. Grading and filling in urban areas has altered the landscape, but historic topographic maps (topography mapped 1890 – 1940) were examined, and the surveyed areas appear to have undergone little topographic change.

Deltas below MSL represent a minimum elevation, and some sediment may have been eroded and/or redeposited during Holocene transgression. This remains difficult to quantify because a relatively flat erosional unconformity could be mistaken for a delta plain-delta slope contact in geophysical images. Working on glacial deltas in central New England, Koteff et al. (1993) assumed < 2 m of the delta slope beds had been removed based on a detailed examination of borrow pit exposures. Similar alteration of the delta plain-delta slope contact in Glacial Lakes Narragansett, Block Island and Rhode Island would not change the interpretations presented here.

Isostatic Rebound profile

Throughout this work, the uplift profile is assumed to match the regional trend of isostatic uplift. The uplift profile in central New England was determined by surveying the delta plain-delta slope contacts in Glacial Lake Hitchcock in the Merrimack and Connecticut River Valleys. It was consistent over > 300 km, producing a linear plane of rebound of $0.85 - 0.89 \text{ m} \cdot \text{km}^{-1}$ (Koteff and Larsen, 1989; Koteff et al., 1993). The plane of rebound tilts towards the assumed center of a single-domed ice sheet over Hudson Bay, Canada, although the geometry and thickness of the Laurentide Ice Sheet is still highly debated (Clark et al., 1996; Dyke and Peltier, 2000; Peltier, 2004). Similar uplift profiles have been measured in the Hudson River Valley in eastern New York (Rayburn, 2004). Figure 12 compares the relative uplift profile of Glacial Lake Narragansett, Glacial Lake Hitchcock and Glacial Lake Merrimack (Koteff and Larsen, 1989; Koteff et al., 1993). The similarity between the regional rebound trend ($0.85 \text{ m} \cdot \text{km}^{-1}$) and the trend of the deltas measured in this

study suggest that the relative, linear uplift profile of isostatic rebound is consistent across southern New England.

Spillways:

The spillway for Glacial Lakes Block Island and Connecticut has been assumed to be at Block Channel, located between Block Island, RI and Montauk Point, Long Island NY (Figure 1) (Goss, 1995; Lewis and Stone, 1991; Stone et al., 2005b; Uchupi et al., 2001). The present configuration of the Block Channel runs generally north to south, with a bend to the southwest behind the subtidal portion of the Beacon Hill Moraine known on charts as Southwest Ledge (NOAA-NOS, 1998). The shallowest and narrowest portion of the channel extends for 5 km and has an average depth of 35 m below MSL.

Spillways for Glacial Lakes Narragansett and Rhode Island have remained largely unidentified, although suppositions were that these glacial lakes, along with Glacial Lake Taunton, in southeastern Massachusetts, drained through Narragansett Bay and Rhode Island Sound (Uchupi et al., 2001). A deep (water depth > 60 m) closed depression in Rhode Island Sound east of Block Island known as the ‘Mud Hole’ (Figure 1) is a possible spillway for these lakes. Previous workers have not discussed the Mud Hole as a potential spillway. The southern end of the basin is at a present elevation of 45 m below MSL.

Water levels

The hypothesis is that one lake occupied Narragansett Bay. To test the hypothesis, a single water level, reflecting the regional trend of isostatic rebound ($0.85 \text{ m} \cdot \text{km}^{-1}$ towards the northwest) should intersect all of the delta plain-delta slope contacts. No single water level intersects all of the deltas measured, leading to the interpretation that the delta plain-delta slope contacts record a lake with three distinct water levels (Figure 11). These water levels were projected onto a pre-isostatic rebound topographic model of southern New England and are discussed as lake stages based on the geographic extent of the lake. The elevation of the deltas and continuity of projected water levels suggest the lakes in Rhode Island and Block Island Sounds were contiguous with the lake in Narragansett Bay. The present elevation of spillways at Block Channel and the Mud Hole are shown for comparison with projected water levels (Figure 11).

Projected extent of glacial lakes on pre-isostatic rebound models

Glacial Lake Block Island

The highest projected water level is recorded by the higher Block Island delta at an elevation of 17 m below present MSL. Glacial Lake Block Island began to form as soon as the Laurentide Ice Sheet retreated from the Beacon Hill moraine, as meltwater was trapped between the ice margin and the moraine (Figure 13A). Directly behind the end moraine on the southwest side of Block Island, a delta completely filled a portion of the lake when the ice was still within 10 km of the terminal position (Oakley et al., 2010). Sub-bottom profiles did not penetrate any

dipping delta slope reflectors, and elevation of the delta plain surface can only be estimated at > 25 m below present MSL, projecting to a similar water level as the higher Block Island Sound delta.

Glacial Lake Block Island continued to expand in size as the margin of the ice retreated north, eventually occupying much of the central portion of Block Island Sound. The spillway at Block Channel initially controlled the water level of Glacial Lake Block Island. Previous interpretations suggest the lowering of the spillway at the eastern entrance to Long Island Sound (Figure 1) was controlled by an eroding spillway at Block Channel, down to a final elevation of 60 m below MSL (Goss, 1995; Lewis and Stone, 1991; Stone et al., 2005b; Uchupi et al., 2001). This interpretation was supported by the inferred deposition of > 20 m post-glacial sediment in an incised channel at Block Channel (Needell and Lewis, 1984). Reexamination of existing U.S. Geological Survey seismic reflection profiles (Needell and Lewis, 1984) and new geophysical data has led to an alternative interpretation. Seismic reflection profiles east of the spillway (Needell and Lewis, 1984) extending to the subtidal portion of the Beacon Hill Moraine (Sirkin, 1982), show that the underlying semi-consolidated coastal plain strata are at an elevation of 40 m below MSL. This is > 5m below the present elevation of the Block Channel spillway. Boulders and cobble gravel pavement mapped on the surface of the Beacon Hill moraine in recent geophysical surveys and published nautical charts immediately adjacent (< 1 km) to the spillway suggest that post-glacial sediment deposition has been < 1 m (LaFrance et al., 2010; NOAA-NOS, 1998; Oakley et al., 2010). The glacially derived boulders represent a minimum elevation of the landform, and are essentially in place, left behind as erosion

selectively removed finer-grained sediment. A scenario of erosion and redeposition of > 20 m of post-glacial sediment in Block Channel is unlikely.

Relationship to Glacial Lake Connecticut

Based on the southwest to northeast orientation of the moraines in and around present day Long Island and Block Island Sounds (Schafer and Hartshorn, 1965), Glacial Lake Block Island had to predate Glacial Lake Connecticut. Long Island Sound was not ice-free until the Laurentide Ice Sheet retreated from the Harbor Hill – Charlestown Moraine position, which occurred around 21,000 yBP based on cosmogenic exposure dates (Balco et al., 2009; Balco et al., 2002). The highest water level for Glacial Lake Connecticut projects to 10 m below MSL at the eastern end of Long Island Sound (Lewis and Stone, 1991; Stone et al., 2005b). The highest delta plain-delta slope contact mapped in Block Island Sound (17 m below MSL) is at least 5 m lower than the highest Glacial Lake Connecticut water level.

Lewis and Stone (1991) report a slowly lowering spillway at ‘The Race’ draining Glacial Lake Connecticut into Glacial Lake Block Island. The two lakes would have been separate until the spillway at The Race lowered to the projected elevation of the Block Channel spillway (25 m below present MSL) perhaps around 19,000 yBP (Stone et al., 2005a). Only then could one large lake have been continuous throughout Long Island, Block Island, and Rhode Island Sounds and Narragansett Bay.

Glacial Lakes Block Island and Rhode Island

Glacial Lake Block Island merged with Glacial Lake Rhode Island that was forming in present-day Rhode Island Sound. The combined lake would have continued to expand in size as the ice retreated to the north, eventually extending through most of Block Island and Rhode Island Sounds. A spillway at the Mud Hole controlled the water level of the eastern portion of Glacial Lake Rhode Island (Figure 13B). The projected water level for the lower Block Island Sound and Pettaquamscutt River deltas is > 5 m lower than the initial water level of Glacial Lake Block Island.

Two scenarios can explain the drop in water level. The first scenario is that there was > 5 m of erosion through the moraine deposits and Coastal Plain deposits in Block Channel. As discussed previously, the boulders and cobble gravel pavement in Block Channel suggest that significant redeposition has not occurred. The second, favored interpretation is that spillway control for the lake switched to an outlet lower than Block Channel. The geomorphology of moraines in Rhode Island Sound show that while the moraine positions are correlative, the southern margin of the Narragansett Bay lobe of the Laurentide Ice Sheet extended further south than the adjacent Connecticut-Rhode Island lobe (Schafer and Hartshorn, 1965; Stone and Borns, 1986) and the lobes were diachronous during their retreat (Larson, 1982; Smith, 2010). This behavior of the ice sheet kept the Mud Hole spillway separated from Glacial Lake Block Island until the margin of the ice retreated to the Charlestown-Buzzards Bay position. When the lower outlet became ice-free, the water level of the lake dropped > 5 m (Figure 11), and control switched to the lower Mud Hole spillway (Figure 13C).

Glacial Lake Narragansett

Glacial Lake Narragansett began to form in present day Narragansett Bay when the Laurentide Ice Sheet retreated north of the Whale Rock End Moraine, at the entrance of the present-day West Passage of Narragansett Bay. Glacial Lake Narragansett was contiguous with Glacial Lake Rhode Island to the south (Figure 14A). The water level recorded by three deltas in the present West Passage of Narragansett Bay (Dutch Island, Annaquatucket and Potowomut) are at the same projected water level as the Pettaquamscutt River and Block Island Low deltas, suggesting no drop in lake level (Figure 11). Glacial Lake Narragansett extended throughout the deeper sections of the present East and West Passages of Narragansett Bay.

Glacial Lake Narragansett remained at this water level until the southern margin of the ice retreated north of the Potowomut delta (Figure 3), when the water level dropped approximately 3 meters. This lower water level is recorded by five deltas (Warwick Plains, Barrington, Riverside, Smith Hill, and Blackstone River) (Figure 11). Lowering could be the result of erosion at the Mud Hole spillway or switching spillway control to an unknown, lower spillway. Glacial Lake Narragansett extended throughout much of present Narragansett Bay, except in portions of the Providence River still occupied by ice (Figure 14B). The extent of Glacial Lakes Block Island and Rhode Island remain approximately the same during this time, extending throughout the deeper portions of Block Island and Rhode Island Sounds. By 19,300 yBP, most of Narragansett Bay was ice-free, and Glacial Lake Narragansett extended through most of present day Narragansett Bay.

Three deltas (East Providence Plains, New Meadow Neck, and Conimicut Point) are outliers to the projected water level of Glacial Lake Narragansett. The East Providence Plains Delta is 3 m higher than the adjacent Blackstone River and Smith Hill deltas. This topographic relationship prompted earlier studies to suggest that the East Providence delta is older than adjacent deposits (Boothroyd and McCandless, 2002; Smith, 1956). This delta may have been deposited in a smaller lake impounded behind the active margin of the ice sheet or a large block of stagnant ice in the Providence River valley. The former interpretation requires a complicated ice margin (Figure 14B) (i.e. Boothroyd and McCandless, 2002), that may be related to bedrock valleys in the present-day Seekonk and Barrington/Palmer River valleys (Upson and Spencer, 1964).

The Conimicut Point delta (Figure 3) is the lowest projected delta in the study area, 10 m lower than the projected water level for Glacial Lake Narragansett (Figure 11). This delta is interpreted to have been deposited in a later meteoric lake in upper Narragansett Bay that was significantly lower than Glacial Lake Narragansett. Lakes are considered meteoric when the ice sheet retreats out of the watershed. This lower water level occurred after the onset of isostatic rebound, and the delta probably formed as drainage from the Blackstone River flowed down the present Seekonk and Providence Rivers.

Glacial Lake Barrington

The New Meadow Neck delta (Figures 3) is significantly lower than the surrounding Barrington, Riverside and Warren River deltas (Figure 11) (Smith, 1955).

Two possible scenarios could explain the topographic relationship of the New Meadow neck delta 1. The delta was deposited into, and graded to a lower water level of Glacial Lake Narragansett, or 2. The delta was deposited into a smaller glacial lake between the present Barrington and Palmer River valleys. The latter is the favored interpretation, and the lake is here called Glacial Lake Barrington. Glacial Lake Barrington would have been separate from both Glacial Lake Narragansett and Glacial Lake Taunton. No spillway for Glacial Lake Narragansett has been identified that could account for a drop in water level of Glacial Lake Narragansett prior to the deposition of the New Meadow Neck Delta.

Lake Drainage

The lack of a spillway at an elevation significantly lower than the water level of the lake (Figure 11), suggests that Glacial Lake Narragansett did not begin draining until the onset of isostatic rebound, which tilted the formerly horizontal water plane of the glacial lakes. Based on the geomorphology of Block Island Sound, Rhode Island Sound and Narragansett Bay, and the elevation of the spillways, later non-glacial lakes would have persisted in many of the deeper closed depressions throughout these areas. Ultimately, the lack of data, specifically high-resolution seismic reflection profiles across potential spillways, limit interpretations of lake drainage scenarios.

CONCLUSIONS

- Sub-bottom seismic reflection profiles and ground penetrating radar images are useful for determining elevation of the delta plain - delta slope contacts within glacial deltas submerged below present sea level and on highly developed delta surfaces above present sea level.
- The highest measured delta plain-delta slope contact was deposited in Glacial Lake Block island in present day Block Island Sound. Glacial Lake Block Island predated, and was at a lower elevation than the highest water level of Glacial Lake Connecticut in Long Island Sound. The water level of Glacial Lake Block Island dropped more than 5 m when the ice retreated north of Block Island, and spillway control shifted from Block Channel to the Mud Hole Spillway.
- Glacial Lake Narragansett began to form as the ice margin retreated north of the present-day entrance of Narragansett Bay; the Mud Hole spillway controlled the water level of the lake at this time. The 3 m drop in the water level of Glacial Lake Narragansett is interpreted to be the result of erosion of the Mud Hole Spillway.

- The water levels of Glacial Lake Narragansett, when projected onto pre-isostatic rebound topographic models, show that the lake extended throughout much of the basin currently occupied by Narragansett Bay, supporting the hypothesis that one large lake occupied the Bay during Late Wisconsinan deglaciation.
- The New Meadow Neck Delta, between the present Barrington and Palmer River Valleys is significantly lower than the surrounding deltas, and is interpreted to represent deposition in a separate glacial lake, named here Glacial Lake Barrington.
- Smaller, non-glacial lakes existed after the drainage of Glacial Lake Narragansett in present-day Upper Narragansett Bay and the Seekonk River valley, and probably existed in most of the closed depressions within present-day Narragansett Bay, Rhode Island and Block Island Sounds.
- The present elevation of these deltas plot on a linear trend, supporting the idea of delayed isostatic rebound in southern New England. This is in agreement with the regional uplift profiles measured in central New England and eastern New York, suggesting that New England did behave as a lithospheric block during isostatic rebound, as first suggested by Koteff and Larsen (1989).

Acknowledgments

Thanks to J.R. Stone (U.S. Geological Survey) for sharing delta elevations from southeastern Massachusetts. Thanks to C. Troskosky (University of Rhode Island, Department of Geosciences) for field assistance and M. Payne (Natural Resource Conservation Service) for assistance with RTK-GPS in the field and lab. C. Damon (University of Rhode Island Environment Data Center) provided the LiDAR data for the Providence River. D. Goulet (Rhode Island Coastal Resources Management Council) provided boat time and assistance on surveys in Rhode Island and Block Island Sounds. N. Vinhateiro (University of Rhode Island Graduate School of Oceanography), T. Smith (U.S. Geological Survey), M. Sutherland (University of New Hampshire), and J. Doolittle (Natural Resource Conservation Service) provided helpful comments on prior drafts of this manuscript. The authors are especially indebted to J. Turenne (Natural Resource Conservation Service) for countless hours of field assistance with the GPR.

The authors were supported by the Department of Geosciences, College of Environment and Life Sciences, University of Rhode Island, and funded by the Rhode Island Coastal Resources Management Council cooperative agreement 50A00311741, Rhode Island SeaGrant Program and NOAA CSC grant NA06NOS4730220

References:

- Allen, W.B., and Ryan, D.J., 1960, Fall River quadrangle, Massachusetts-Rhode Island. RI Water Resources Division of USGS. Ground-water Maps. Map 7.
- Ancestry, 2010, Southern New England Irish, Volume 2011, Rootsweb.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., and Schaefer, J.M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: *Quaternary Geochronology*, v. 4, p. 93-107.
- Balco, G., and Schaefer, J.M., 2006, Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England: *Quaternary Geochronology*, v. 1, p. 15-28.
- Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: *Quaternary Science Reviews*, v. 21, p. 2127-2135.
- Barnhardt, W.A., Belknap, D.F., and Kelley, J.T., 1997, Stratigraphic evolution of the inner continental shelf in response to late Quaternary relative sea-level change, northwestern Gulf of Maine: *Geological Society of America Bulletin*, v. 109, p. 612-630.
- Bertoni, R., Dowling, D.J., and Frankel, L., 1977, Freshwater-lake sediments beneath Block Island Sound: *Geology*, v. 5, p. 631-635.
- Boothroyd, J.C., and Ashley, G.M., 1975, Processes, bar morphology and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, *in* Jopling, A.V., and McDonald, B.C., ed., *Glaciofluvial and glaciolacustrine sedimentation*: Tulsa, OK, Society of Economic Paleontologists and Mineralogists Special Publication 23.
- Boothroyd, J.C., and August, P.V., 2008, Geologic and contemporary landscapes of the Narragansett Bay ecosystem, *in* Desbonnet, A., and Costa-Pierce, B.A., eds., *Science for ecosystem based management*, Springer, 507 p.
- Boothroyd, J.C., Freedman, J.H., Brenner, H.B., and Stone, J.R., 1998, Glacial geology of south and central Rhode Island, *in* Murray, D.P., ed., *Guidebook to Field Trips in Rhode Island and Adjacent Regions of Connecticut and Massachusetts*. New England Intercollegiate Geological Conference, 90th Annual Meeting: Kingston, Rhode Island., University of Rhode Island, p. C5-1 - C5-22.

- Boothroyd, J.C., and McCandless, S.J., 2002, Quaternary geologic map of Providence and East Providence Quadrangles: Kingston, RI, Rhode Island Geological Survey.
- , 2003, Quaternary Geologic map of the East Greenwich quadrangle, including parts of the Bristol and Crompton quadrangles: Kingston, RI, Rhode Geological Survey Open File Map 2003-01.
- Boothroyd, J.C., McCandless, S.J., and Dowling, M.J., 2003, Quaternary Geologic Map of Rhode Island: Kingston, RI, Rhode Island Geological Survey STATEMAP Program.
- Buynevich, I.V., and FitzGerald, D.M., 2003, High-resolution subsurface (gpr) profiling and sedimentology of coastal ponds, Maine, usa.: Implications for Holocene back-barrier evolution: *Journal of Sedimentary Research*, v. 73, p. 559-571.
- Clark, P.U., Licciardi, J.M., MacAyeal, D.R., and Jenson, J.W., 1996, Numerical reconstruction of a soft-bedded Laurentide Ice Sheet during the last glacial maximum: *Geology*, v. 24, p. 679-682.
- Dyke, A.S., and Peltier, W.R., 2000, Forms, response times and variability of relative sea-level curves, glaciated North America: *Geomorphology*, v. 32, p. 315-333.
- Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: *Geographie physique et Quaternaire*, v. 41, p. 237-263.
- Frankel, L., and Thomas, H.F., 1966, Evidence of Freshwater Lake Deposits in Block Island Sound: *The Journal of Geology*, v. 74, p. 240-242.
- Gilbert, G.K., 1890, Lake Bonneville: Washington, D.C., United States Geological Survey.
- Goss, M.C., 1995, High-resolution seismics and ice-marginal sedimentation in Block Island Sound and adjacent southern Rhode Island [Masters thesis], Rutgers University, New Brunswick, NJ.
- Gustavson, T.C., Ashley, G.M., and Boothroyd, J.C., 1975, Depositional sequences in glaciolacustrine deltas, *in* Jopling, A.V., and McDonald, B.C., eds., *Glaciofluvial and glaciolacustrine sedimentation*, Society of Economic Paleontologists and Mineralogists Special Paper 23, p. 264-280: Tulsa, OK.

- Gustavson, T.C., and Boothroyd, J.C., 1987, A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: A modern analog of the southeastern margin of the Laurentide Ice Sheet: Geological Society of America Bulletin, v. 99, p. 187-200.
- Hamilton, E.L., 1974, Geoacoustic models of the seafloor, *in* Hampton, L., ed., Physics of sound in marine sediments: New York.
- Hartshorn, J.H., 1967, Geology of the Taunton Quadrangle, Bristol and Plymouth Counties, Massachusetts, Geological Survey Bulletin 1163-D: Washington DC, United States Department of the Interior Geological Survey, p. 78.
- Kostic, B., Becht, A., and Aigner, T., 2005, 3-D sedimentary architecture of a Quaternary gravel delta (SW-Germany): Implications for hydrostratigraphy: Sedimentary Geology, v. 181, p. 147-171.
- Koteff, C., and Larsen, F.D., 1989, Postglacial uplift in western New England: geologic evidence for delayed rebound, *in* Gregersen, S., S. Basham, ed., Earthquakes at North-Atlantic passive margins: Neotectonics and postglacial rebound 105-123.
- Koteff, C., and Pessl, F., 1981, Systematic ice retreat in New England: Geological Survey Professional Paper 1179: Washington, D.C., United States Government Printing Office, p. 1-20.
- Koteff, C., Robinson, G.R., Goldsmith, R., and Thompson, W.B., 1993, Delayed postglacial uplift and synglacial sea levels in coastal central New England: Quaternary Research, v. 40, p. 46-54.
- LaFrance, M., Shumchenia, E.J., King, J.W., Pockalny, R., Oakley, B.A., Pratt, S., and Boothroyd, J.C., 2010, Benthic habitat distribution and subsurface geology of selected sites from the Rhode Island Ocean Special Management Study Area, Ocean Special Area Management Plan: Wakefield, RI, Rhode Island Coastal Resources Management Council.
- Larson, G.J., 1982, Nonsynchronous retreat of ice lobes from southeastern Massachusetts, *in* Larson, G.J., and Stone, B.D., eds., Late Wisconsinian glaciation of New England: Dubuque, Kendall-Hunt, p. 101-114.
- Lewis, R.S., and Stone, J.R., 1991, Late Quaternary stratigraphy and depositional history of the Long Island Sound Basin: Connecticut and New York, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, eds., Quaternary Geology of Long Island Sound and Adjacent Coastal Areas: Journal of Coastal Research, Special Issue 11, p. 1-23.

- Needell, S.W., and Lewis, R.S., 1984, Geology and structure of Block Island Sound, Rhode Island and New York, U. S. Geological Survey Miscellaneous Field Studies Map MF-1621 (4 Sheets).
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983a, Maps showing geology and shallow structure of western Rhode Island Sound, Rhode Island, U.S. Geological Survey Miscellaneous Field Studies Map MF-1537.
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983b, Quaternary geology of the Rhode Island inner shelf: *Marine Geology*, v. 53, p. 41-53.
- NOAA-NOS, 1998, Block Island Sound and approaches Nautical Chart 13205, United States - East Coast - Rhode Island - Connecticut - New York: Washington, D.C., National Oceanic and Atmospheric Administration.
- NOS, 2010, Elevations on station datum: Newport, Narragansett Bay, RI, Volume 2010, National Ocean Service/National Oceanic and Atmospheric Administration.
- O'Hara, C.J., and Oldale, R.N., 1980, Maps showing geology and shallow structure of eastern Rhode Island Sound and Vineyard Sound, Massachusetts, U.S. Geological Survey Miscellaneous Field Studies Map MF-1186.
- Oakley, B.A., Boothroyd, J.C., and King, J.W., 2010, Benthic geologic habitats and Quaternary depositional environments of the Block Island Ocean SAMP study area, *in* LaFrance, M., Shumchenia, E.J., King, J.W., Pockalny, R., Oakley, B.A., Pratt, S., and Boothroyd, J.C., eds., Benthic habitat distribution and subsurface geology of selected sites from the Rhode Island Ocean Special Area Management study area: Technical Report 4: Kingston, RI, University of Rhode Island.
- Peck, J.A., 1989, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay [Masters thesis]: Kingston RI, University of Rhode Island.
- Peck, J.A., and McMaster, R.L., 1991, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay, Rhode Island, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, ed., Quaternary Geology of Long Island Sound and Adjacent Coastal Areas, *Journal of Coastal Research*, Special Issue 11, p. 25-37.
- Peltier, W.R., 2004, Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE: *Annual reviews of Earth and Planetary Sciences*, v. 32, p. 111-149.

- Pickart, D.S., 1987, Physical stratigraphy and geological evolution of the Providence River, Narragansett Bay, Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island.
- Rayburn, J.A., 2004, Deglaciation of the Champlain Valley, New York and Vermont and its possible effects on North Atlantic Climate Change [Ph.D. thesis]: Binghamton, NY, State University of New York.
- Ridge, J.C., 2003, The last deglaciation of the Northeastern United States: A combined varve, paleomagnetic and calibrated ^{14}C Chronology, *in* Hart, J.P., and Cremeeens, D.L., eds., *Geoarcheology of landscapes in the glaciated Northeast*: New York State Education Department, Albany, New York.
- , 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J., and Gibbard, P.L., eds., *Quaternary glaciations - extent and chronology: Part II: North America. Developments in Quaternary Science, Volume 2B*: Amsterdam, Elsevier, p. 163-193.
- RIGIS, 1989, Rhode Island Glacial Deposits, Rhode Island Geographic Information System.
- Schafer, J.P., 1961a, Surficial geology of the Narragansett Pier Quadrangle, Rhode Island: Washington, DC., US Geological Survey, Quadrangle Map GQ-140.
- , 1961b, Surficial geology of the Wickford Quadrangle, Rhode Island: Washington, DC., US Geological Survey, Quadrangle Map GQ-136.
- Schafer, J.P., and Hartshorn, J., 1965, The Quaternary of New England, *in* Wright, J., and Frey, D., eds., *The quaternary of the United States*: Princeton, N.J., Princeton University Press, p. 113-127.
- Schiner, G.R., and Gonthier, J.B., 1965, Ground-water map of the Tiverton and Sakonnet Point quadrangles, Rhode Island, and the Rhode Island portion of the Westport quadrangle Massachusetts. R.I. Water Resources Coordinating Board. Groundwater. Map GWM 21. .
- Sirkin, L.A., 1976, Block Island, Rhode Island-evidence of fluctuation of the Late Pleistocene ice margin: *Geological Society of America Bulletin*, v. 87, p. 574-580.
- , 1982, Wisconsinan glaciation of Long Island, New York to Block Island, Rhode Island, *in* Larson, G.J., and Stone, B.D., eds., *Late Wisconsinan glaciation of New England*: Dubuque, IA, Kendall/Hunt, p. 35-60.

- Smith, D.G., and Jol, H.M., 1995, Ground penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments: *Journal of Applied Geophysics*, v. 33, p. 93-100.
- , 1997, Radar structure of a Gilbert-type delta, Peyto Lake, Banff national park, Canada: *Sedimentary Geology*, v. 113, p. 195-209.
- Smith, J.H., 1955, Bristol and Vicinity, Rhode Island-Massachusetts Surficial geology: Washington, DC., U.S. Geological Survey Quadrangle Map GQ-70 U.S. Geological Survey.
- , 1956, Providence, Rhode Island Surficial geology: Washington, D.C., US Geological Survey Quadrangle Map GCQ84.
- Smith, T.L., 2010, A conceptual model of the deglaciation of southern Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island
- Stone, B.D., and Borns, H., 1986, Pleistocene glacial and interglacial stratigraphy of New England, Long Island and adjacent Georges Bank and Gulf of Maine, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., *Quaternary glaciations in the Northern Hemisphere*: New York, Pergamon, p. 39-52.
- Stone, B.D., and Peper, J.D., 1982, Topographic control of the deglaciation of eastern Massachusetts: ice lobation and the marine incursion, *in* Larson, G.J., and Stone, B.D., eds., *Late Wisconsinan glaciation of New England*: Dubuque, Kendall-Hunt.
- Stone, B.D., and Stone, J.R., 2005, Sedimentary facies and morphosequences of glacial meltwater deposits, *in* Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., ed., *Quaternary geologic map of Connecticut and Long Island Sound basin*, US Geological Survey Scientific investigations map 2784, scale 1:125,000, p. 72.
- Stone, J.R., 2010, Personal Communication.
- Stone, J.R., Lewis, R.S., and DiGiacomo-Cohen, M., 2005a, The new Quaternary map of Connecticut and Long Island Sound Basin: Part 1, *in* McHone, N.W., and Peterson, M.J., eds., *Guidebook for field trips in Connecticut*: New England Intercollegiate Geological Conference, 97th annual meeting.
- Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., 2005b, *Quaternary Geologic Map of Connecticut and Long*

Island Sound Basin, U.S. Geological Survey Geologic Investigations Series Map I-2784, scale 1:125,000, 2 sheets and pamphlet. p. 1-72.

Tary, A.K., FitzGerald, D.M., and Weddle, T.K., 2007, A ground penetrating radar investigation of a glacial-marine ice-contact delta, Pineo Ridge, eastern coastal Maine: Geological Society of America Special Papers, v. 432, p. 77-91.

Uchupi, E., Driscoll, N., Ballard, R.D., and Bolmer, S.T., 2001, Drainage of late Wisconsin glacial lakes and the morphology and late quaternary stratigraphy of the New Jersey-southern New England continental shelf and slope: Marine Geology, v. 172, p. 117-145.

Ulriksen, C.P.F., 1982, Application of impulse radar to civil engineering: Sweeden, Lund University of Technology.

Upton, J.E., and Spencer, C.W., 1964, Bedrock Valleys of the New England Coast as Related to Fluctuations of Sea Level: U.S. Geological Survey Professional Paper 454-M, p. 1-31.

USACE, 1957, Hurricane survey interim report: Narragansett Bay Area, Rhode Island and Massachusetts: Boston, MA, Corps of Engineers, U.S Army Office of the Division Engineer.

Widess, M.B., 1973, How thin is this bed?: Geophysics, v. 38, p. 1176-1180.

Figure 1: Digital elevation model of Narragansett Bay and adjacent waters, showing the location of geographic locations discussed in the text and the maximum extent of the Laurentide Ice Sheet (modified from Dyke and Prest 1987). Details of digital elevation model discussed in the text.

Figure 2: Schematic view of an ice-marginal deltaic morphosequence, A. Prior to isostatic rebound, B. After isostatic rebound. A postglacial lake may persist in some areas (modified from Gustavson and Boothroyd, 1987; Stone and Stone, 2005).

Figure 3: Location of delta plain-delta slope contacts measured in this study and the mapped extent of glacial deltas around upper Narragansett Bay (Modified from Boothroyd and McCandless, 2002, RIGIS 1989). Deltas are named based on the present watershed or geographic location they lie in. Abbreviations for deltas: BIH-Block Island Sound (High), BIL – Block Island Sound (Low), PR – Pettaquamscutt River, DI – Dutch Island, AN - Annaquatucket, MC – Mill Creek, HQ – Hunt-Quonset, IP -Island Park, PO – Potowomut, BTS – Barrington South, BTN, Barrington North, WP – Warwick Plains, NMN – New Meadow Neck, RV – Riverside, PP - Providence Plains, SH – Smith Hill, CP – Conimicut Point

Figure 4: Schematic figure of (A) Sub-bottom seismic reflection profiler and (B) Ground Penetrating Radar (Modified from Baker et al., 2007).

Figure 5: A. Seismic reflection profile of the higher elevation Glacial Lake Block Island from Block Island Sound. B. Interpreted seismic reflection profile showing the minimum lake level at -17 m below MSL. See figure 3 for location.

Figure 6: A. Seismic reflection profile from Block Island Sound showing the dipping delta beds of the lower Glacial Lake Block Island delta. B. Interpreted seismic reflection profile showing the minimum lake level at - 26 m below MSL. See figure 3 for location.

Figure 7: A. Sub-bottom seismic reflection profile of the Dutch Island delta, lower West Passage, Narragansett Bay. B. Interpreted seismic reflection profile showing the minimum lake level at - 9.8 m below MSL. See figure 3 for location.

Figure 8: A. 200 MHz Ground penetrating radar profile of the Warwick Plains Delta. B. Interpreted ground penetrating radar profile showing the delta plain – delta slope contact at 3 m above MSL. See figure 3 for location.

Figure 9: A. 120 MHz Ground penetrating radar profile from the northern Barrington delta. B. Interpreted ground penetrating radar profile showing the delta plain – delta slope contact at 10 m above MSL. See figure 3 for location.

Figure 10: A. 120 MHz Ground penetrating radar profile from Smith Hill. B. Interpreted ground penetrating radar profile. The delta plain – delta slope contact is 18 m above present MSL. See figure 3 for location.

Figure 11: Projected water levels and spillways of Glacial Lakes Block Island, Rhode Island, Narragansett, and Taunton. Water levels show an uplift profile of 0.85 m km^{-1} . Delta abbreviations are the same as figure 3.

Figure 12: Comparison of uplifted water levels of Glacial lake Narragansett, Glacial Lake Hitchcock, Glacial Lake Merrimack (Koteff and Larsen, 1989; Koteff et al., 1993).

Figure 13: Pre-isostatic rebound topographic model showing the extents of A. Glacial Lake Block Island at the Corn Neck moraine position (Sirkin, 1976, 1982) approximately 23,000 yBP. B. Glacial Lakes Block Island and Rhode Island. Approximately 22,000 yBP. Red box indicates extent of figure 12 A. C. Charlestown – Point Judith – Buzzards Bay moraine position approximately 21,300 yBP.

Figure 14: Pre-isostatic rebound topographic model showing the extent of Glacial Lake Narragansett. A. Approximately 20,000 yBP, B. 19,700 yBP. Ice margin in the present-day Providence River modified from Boothroyd and McCandless (2002).

CHAPTER 3

Constraining the age of Glacial Lake Narragansett and the deglacial chronology of the Laurentide Ice Sheet in southeastern New England

Bryan A. Oakley¹ and Jon C. Boothroyd^{1,2}

¹Department of Geosciences, College of the Environment and Life Sciences, University of Rhode Island, Kingston, RI, USA, 02881

²State Geologist, Rhode Island Geological Survey Kingston, RI, USA, 02881

Corresponding author:
Bryan A. Oakley
Department of Geosciences
College of the Environment and Life Sciences
University of Rhode Island
317 Woodward Hall
9 East Alumni Ave
Kingston, RI, 02881
BOakley@my.uri.edu

Formatted for submission to the Geological Society of America Bulletin

ABSTRACT

The lack of radiocarbon ages and correlated varve sequences in southeastern New England has left the deglacial chronology of the region poorly constrained. A 265-year varve series from Glacial Lake Narragansett was constructed from eight continuous sediment cores collected from the Providence River, Narragansett Bay, Rhode Island. This varve series was not correlated with either the North American Varve Chronology or other varve sequences from southern New England or southeastern New York. The uncorrelated varve sequences presented here represent minimum time of deposition within Glacial Lake Narragansett. These sequences, used in conjunction with the calibrated North American Varve Chronology and cosmogenic exposure ages from recessional end moraines, provide minimum ($> 19,500$ yBP) and maximum ($< 20,400$ yBP) ages for Glacial Lake Narragansett. Correlation with the updated Greenland (NGRIP and GRIP) ice core records suggest that cold periods associated with moraine formation are 200 - 250 years older than the cosmogenic exposure ages. While many studies refer to the last glacial maximum occurring at 18,000 to 20,000 yBP, the constrained age of Glacial Lake Narragansett suggests that at least for the southeastern portion of the Laurentide Ice Sheet, deglaciation was well underway by this time.

INTRODUCTION

The absence of constraining radiocarbon ages and other accurate and precise dating techniques has left the chronology of initial deglaciation from the maximum position of the southeastern Laurentide Ice Sheet in New England only crudely estimated. This is in marked contrast to areas further from the terminal margin that are tied to abundant radiocarbon ages and a well-dated glacial varve chronology. Previous estimates of the timing of deglaciation of southeastern New England used regional correlation and limited radiocarbon ages that have high uncertainties (Boothroyd and August, 2008; Boothroyd and Sirkin, 2002; Schafer and Hartshorn, 1965; Stone and Borns, 1986; Uchupi et al., 2001). This paper presents a varve series from Glacial Lake Narragansett, and discusses its relationship with the North American Varve Chronology (NAVC) and other varve series (Antevs, 1922; Antevs, 1928; Ridge, 2011) and constrains the age of the lake in the context of the deglaciation of southeastern New England.

Glacial Lake Narragansett occupied much of the southern portion of the Narragansett Basin during Late Wisconsinan deglaciation (Oakley and Boothroyd, 2012). Our hypothesis is that varve records from Glacial Lake Narragansett could be correlated with the calibrated NAVC, providing age control on the northern terminus of the lake. The records from Glacial Lake Narragansett were not correlated with the NAVC, nullifying the hypothesis. However, using these uncorrelated varve sequences, and cosmogenic exposure ages from moraines in southern New England, minimum and maximum ages are placed on Glacial Lake Narragansett.

An important concept in glacial varve chronologies is that while distance from the ice margin is an important component to varve thickness (i.e., the closer to the margin of the ice sheet, the coarser and thicker the sedimentary couplets), regional weather patterns are more important. This is because a warmer, wetter melt season will supply more meltwater and sediment to a glacial lake than a colder, drier melt season. Varve records within separate proglacial lakes affected by the same weather conditions contain similar thickness patterns, and correlation between sequences is based on the pattern of couplet thickness through time. Throughout this work, the NAVC refers to varves deposited in Glacial Lake Hitchcock, which occupied a large portion of the Connecticut River Valley, and Glacial Lake Albany in the Hudson River Valley. The NAVC also includes correlated varve sequences from Glacial Lakes Merrimack, Ashuelot, and Winooski; however, these sequences are from northern New England and younger than Glacial Lake Narragansett.

Glacial varves sequences are described using terminology that reflects the level of correlation. The term ‘varve sequence’ is a generic term for any succession of varves. Varve record refers to a sequence of varves from a single outcrop exposure or drill core. Varve series represents a number of varve records correlated within a geographically constrained area (i.e. a single lake). Varve chronologies refer to a correlation of varve series that have a broader regional connection, usually between different lakes (Ridge, 2011).

STUDY AREA

The north to south trending, microtidal (spring range 1.47 m) (NOS, 2010b) Providence River is the uppermost portion of Narragansett Bay (Figure 1). The general geomorphology consists of subtidal flats (< 3 m below mean lower low water (MLLW)) that border a deeper (> 10 m MLLW) dredged navigation channel. The sites discussed in this paper are located 75 km from the Late Wisconsinan terminal margin of the Laurentide Ice Sheet (Schafer and Hartshorn, 1965). The Quaternary geology of the Providence River is dominated by glacial deltas along both the eastern and western shorelines (Boothroyd and McCandless, 2002; Smith, 1956). Coring studies (Pickart, 1987) and seismic reflection profiles (Oakley and Boothroyd, 2012) indicate that glacial lake floor deposits underlie most of the subtidal flats. GIS based reconstructions suggest Glacial Lake Narragansett occupied much of the southern portion of the Narragansett Basin, and was contiguous with Glacial Lakes Block Island and Rhode Island to the south (Figure 1) (Oakley and Boothroyd, 2012).

Previous work

Ernst Antevs (1922; 1928) created the New England Varve Chronology by measuring the thickness of individual couplets at over 100 sites in New England and eastern New York. The thickness of each couplet was averaged using multiple, overlapping sections, and a composite curve spanning 4,152 years of deposition was created (Antevs, 1922; Antevs, 1928)). The terms summer and winter layers date to Antevs' original work, but actually refer to 'melt season' and 'non-melt season'

layers. The melt season in the Late Wisconsinan was probably similar to the present melt season of the Greenland Ice Sheet (3 months, mid-June through mid-August) (Zwally et al., 2002), and unpublished counts of diurnal cycles in thick, ice-proximal varves in the Connecticut River Valley and Maine indicate a minimum of 90 to 140 melt-season days (J.C. Ridge, pers. commun.).

Antevs (1928) correlated a 700-year sequence in the Hudson River Valley, New York, with a 343-year sequence in the Quinnipiac Valley, Connecticut (Figure 2). This chronology is older than the NAVC from Lake Hitchcock (Ridge, 2003). Other uncorrelated varve series older than the NAVC, include four sequences from southeastern Massachusetts; Taunton (41 years), Middleboro (89 years), Bridgewater (165 years, 16 years), five sequences from central Connecticut; Berlin (37 years), Newfield (39 years, 32 years), New Britain (33 years) and Middletown (12 years) (Antevs, 1928). Antevs (1928) also reported three sequences from Rhode Island; Gaspee Point (102 years), Barrington (157 years) and along the Seekonk River (54 years) (Figure 2). The Newfield section of Antevs has been extended to 171 years with recent drilling (Stone, 2012). Correlation of some of the shorter records, particularly the records from Glacial Lake Middletown in Connecticut may be problematic, and may overlap the NAVC (J.C. Ridge, pers commun.).

Recent work has refined and extended Antevs original varve series using additional sites, radiocarbon ages on terrestrial plant macrofossils, and paleomagnetic declination records. Fine-tuning the calibrated age chronology continues today (Ridge and Larsen, 1990; Ridge et al., 1999; Ridge et al., 2001; Rittenour, et al., 2000). The varve chronology is now referred to as the North American Varve Chronology,

covering 5,659 years (American Varve Year (AM) 2,700 to 8,358) extending from 18,200 yBP to 12,500 yBP (15,000 ^{14}C yBP to 10,400 ^{14}C yBP)) (Ridge et al., 2012).

Antevs (1928) was unable to correlate the three varve records near the shoreline of upper Narragansett Bay (Barrington, Gaspee Point and Seekonk) (Figure 2), with the New England Varve Chronology. Pickart (1987) reported rhythmic sediment couplets interpreted to be varves beneath Late Holocene estuarine sediment in the Providence River, but a detailed analysis of the varves was not completed.

Glacial lakefloor sediment has also been identified in surface sediment samples, cores, and interpreted seismic reflection profiles from Block Island and Rhode Island Sounds (Frankel and Thomas, 1966; Goss, 1995; Needell and Lewis, 1984; Needell et al., 1983b).

METHODS

Eight continuous sediment cores were recovered from the Providence River between 2006 and 2009. The coring equipment used here is based on the system of Lanesky et al. (1979), consisting of an 8 horsepower gasoline-powered concrete vibrator, connected to a section of aluminum irrigation tubing (7-cm inside diameter, wall thickness 1.8-mm). The vibration creates a low-amplitude standing wave, which temporarily liquefies the sediment in contact with the core barrel, leaving the remainder of the core undisturbed (Lanesky et al., 1979). Coring was accomplished using a specially outfitted 7 m pontoon boat with a 'moon pool' and a deck mounted

tripod. Cores collected in 2009 utilized a quadrapod assembly placed directly on the bay floor.

The cores were prepared following the protocol of Ridge (2011). Holes (0.635 cm diameter, spacing 0.3 m) were drilled down the length of the core barrel to allow water to evaporate from the core for approximately two weeks prior to splitting. The cores were then cut into 1.5 m sections and split longitudinally. One half of the core was allowed to partially dry to maximize contrast between layers. The original sediment cores collected by Pickart (1987) were not archived; however, photographic slides of the original cores were available. Slides were scanned at 4,000 dots per inch (DPI) using a Nikon slide scanner, and resized to reflect actual core dimensions at 600 DPI.

The Providence River cores were imaged using a GEOTEK core logging system, which generates continuous digital bitmap images in red/green/blue color schemes, and creates a scaled image at 300 DPI. The continuous images were split into overlapping sections (Approximately 600 x 800 pixels), in stratigraphic order from bottom to the top of the core. Varve thickness was determined following the protocol of Ridge (Ridge, 2011). The top of each summer and winter layer was digitized, using script written at Tufts University for Image Tool 3.0. Image Tool is free software designed by the University of Texas Health Science Center in San Antonio for processing and analyzing medical images. The varve analysis script keeps a running total of the thickness and count of each couplet, and exports the data as an ASCII text file for later analysis.

Varve matching

Couplet thickness for each core was plotted in Grapher™ v. 8.0 (Golden software, Golden CO, USA), for visual analysis and matching. Matching was accomplished using a desktop computer with two monitors; one displayed images of the cores, and the other displayed the graphical plots. This allowed for simultaneous visual matching between cores using distinct couplets (specifically, couplets with thick non-melt season layers (>1 cm)), and graphical ‘wobble’ matching, based on the pattern of couplet thickness through time. Once correlated, the thickness of each varve was averaged and a composite series was created.

Following the convention of the NAVC and Swedish varve series (i.e. Antevs, 1922; DeGeer, 1975; Ridge and Larsen, 1990; Wohlfarth et al., 1995), glacial varves are numbered in order of deposition, and older varves have a lower (number) varve year than younger varves. The varves in this study were deposited near the northern terminus of Glacial Lake Narragansett. Contiguous glacial lakes existed in the southern end of Narragansett Basin (Glacial Lake Narragansett), Rhode Island Sound (Glacial Lake Rhode Island), and Block Island Sound (Glacial Lake Block Island) (Figure 1). The base of the sequence in this study was assigned a varve year of 5,000. This should provide enough time to span the existence of glacial lakes in Block Island Sound, Rhode Island Sound, and Narragansett Bay if future work can expand the varve series into these lakes.

The composite curve from Glacial Lake Narragansett was compared to varve sequences from Antevs (1928), downloaded from the database maintained by Ridge (Ridge, 2011). Graphical matching was carried in the same manner discussed above.

Photographs of Antevs original outcrops were not available, so visual matching of his records was not possible.

RESULTS

Five of the recovered cores collected in this study contain sediment couplets interpreted to be varves, as do the two cores of Pickart (1987). Individual varve records span 27 to 200 years. The basic stratigraphy of the cores is summarized in Table 1. Detailed descriptions of the cores can be found in Appendix 2.

TABLE 1. SUMMARY OF THE BASIC SEDIMENTOLOGY OF THE CORES
USED IN THIS STUDY

Core	Total thickness of varves - m	Varve years	Average couplet thickness - cm
PVD-1	6.33	200	2.2
PVD-2	5.93	212	2.7
PVD-3	2.13	68	2.5
PVD-5	3.31	147	2.2
PVD-6	0.65	27	2.44
EW-1	2.66	166	1.66
PC-6	3.65	160	2.28

Core deformation

Some sections of the varve sequences are deformed. It is interpreted that this deformation was induced during coring although some could be the result of mass movement (i.e. delta slumping (Stone, 1976)). Distortion of couplets often coincides with thicker (>1 cm) non-melt season layers, suggesting some deformation induced during coring could be due to the rigidity of the winter layers. ‘Arching’ of couplets, where the edges of the sediment are pulled down by the core barrel is common, but the internal stratigraphy and thickness remains intact and does not impede accurate measurement of couplet thickness

Varve correlations

Individual varve records were correlated into a series spanning 265 years (Glacial Lake Narragansett (GLN) years 5,000 – 5,265) (Figure 3A,B) (See appendices 2 - 4 for data from individual cores). The series includes four continuous sequences of 26, 166, 8, and 31 years separated by deformed couplets. The gap between the 26 and 166-year sequences is estimated to be less than 20 years (GLN years 5,026 -5,046), recorded by a series of thick (> 10 cm), deformed, sandy varves. The gap between the 166 year and 8-year sequence is estimated to only be two years (GLN years 5,209-5,210), and the gap between the 8 and 31-year sequence is estimated to be no more than 9 or 10 years (GLN years 5,223 to 5,233) (Figure 3B).

A correlation exists between the Seekonk sequence of Antevs (1928), and the composite curve created in the Providence River (Figure 3C). Slight discrepancies suggest a varve may be missing in each of the sequences. Core PC-6 (Pickart, 1987)

was not correlated with the cores from further north in the Providence River, but a 79-year correlation exists between core PC-6 and Antevs' record from Gaspee Point (Figure 3D).

DISCUSSION

Nature of deposition

Deposition in glacial lakes is dominated by underflows driven by the density contrast between sediment laden river water, and the lake. Measurements at Malaspina Glacier in Alaska indicate that suspended sediment increases the density of streams draining the glacier 1.7 - 4.7 times the maximum density of freshwater (Gustavson, 1975). Density underflows are interpreted to have deposited varves in Glacial Lake Hitchcock, and this process is responsible for the laminated, usually graded, melt-season layer of the couplet (Ashley, 1975). More (and coarser) sediment is deposited closer to the source of sediment discharge into the lake, with a decrease in grainsize and couplet thickness in more distal areas. There is a very slight decrease in varve thickness from 2.2 to 1.9 cm ($r^2 = .015$) over the 265-year record. The decrease in thickness through time is probably more significant, but is skewed because many of the thick, sandy, ice-proximal varves at the base of the cores are too deformed to accurately measure. This decrease is expected, coinciding with increasing distance from the source of sediment discharge.

Basal varves in core PC-6 (Pickart, 1987), and in the Seekonk sequence of Antevs (1928) record the first years of deposition after the ice margin had retreated

from these locations. Basal varves were not identified in cores PVD-1 – PVD-8, and seismic reflection profiles indicate that 6 m of lakefloor sediment lies below the bottom of the deepest core recovered in the Providence River. Distal varves (16 years, average thickness 1.5 cm) underlie sandy, ice-proximal varves (average thickness 12 cm) at the base of cores PVD-1 and PVD-6. This may record a switch in drainage from a distal to more proximal position, and the thinner varves may represent drainage from the Riverside delta; the thicker varves from the more proximal Providence Plains delta (Figure 1).

Most of the varves are composed of stacks of normally graded beds within the melt-season layer (Figure 4). Erosional features are common at the top of non-melt season layers, and are frequently overlain by a sandy bed at the base of subsequent melt season layer (Figure 5). Similar features in varves from Glacial Lake Hitchcock are interpreted to represent ice-proximal or transitional varves, deposited when the ice margin was within 25 km of the lake (Ridge, 2011). Prominent sand layers in the middle or top of the melt season layers may represent periods of enhanced melting or a significant precipitation event (i.e. a storm) (Figure 5).

The transition between the melt season and non-melt season layers in most varves is gradational, suggesting a gradual change in bottom current velocity at the end of the melt season. Thick (> 1 cm) non-melt season layers occur in two distinct sections of the varve series, including a > 20 year interval (GLN years 5,180 – 5,204). This represents an increase in the volume of sediment introduced into the lake during the melt season that increased the suspended sediment available for deposition during the non-melt season. Thickness of non-melt season is generally positively correlated

with melt season thickness, and has no direct relation to winter temperature (Ridge et al., 2012).

Correlation with the NAVC

The major assumption in glacial varve chronology studies is that varve thickness is controlled by regional weather conditions, and varves can be correlated between lakes. The correlation between varve records from within Narragansett basin (i.e. the correlations of the Providence River composite curve and the Seekonk sequence of Antevs, (1928) (Figure 3C) and between core PC-6 (Pickart, 1987) and the varve record from Gaspee Point (Antevs, 1928) (Figure 3D)), suggest that at least within Glacial Lake Narragansett, these sequences can be correlated to each other. Varves from Glacial Lakes Ashuelot and Merrimack, which are similar in size to Glacial Lake Narragansett, have been correlated to the NAVC, as have ice proximal varves (> 40 cm thick) from Glacial Lake Albany (Antevs, 1928; Ridge, 2003). The intra-basin correlation within Glacial Lake Narragansett, suggest that the varve records presented here should correlate with records from other lake basins if they overlap temporally.

The varve series generated from the Providence River was not correlated with the NAVC or other varve series from New England and eastern New York. Our interpretation is that the varves measured from Glacial Lake Narragansett are older than both the varve sequences from the NAVC and the uncorrelated sequences in New York, Connecticut and southeastern Massachusetts.

Regional context of uncorrelated varve sequences

The lack of correlation between the varve sequences prevents using the calibrated NAVC timescale to provide age control for Glacial Lake Narragansett. Uncorrelated varve series represent minimum time of deposition within a lake (i.e. within the same lake, two 100 year, uncorrelated series represent at least 200 years of deposition). 604 uncorrelated varves have been identified from the Providence River, representing a minimum time of glacial lakefloor deposition in the present-day Providence River prior to the retreat of the Laurentide Ice Sheet out of the watershed.

Timing of deglaciation in southern New England historically has been based on a limited number of radiocarbon ages, the calibrated NAVC, and regional correlation. More recently, cosmogenic exposure ages of boulders on recessional moraines have provided additional ages (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Initially, exposure ages were consistently younger than terrestrial and marine radiocarbon ages and the calibrated NAVC (Balco et al., 2002). The regional production rate for Beryllium¹⁰ has since been adjusted, bringing the NAVC and exposure ages sets into closer alignment (Balco et al., 2009). The offset between the cosmogenic exposure age and the actual deposition of the landform, however, remains difficult to quantify (Applegate et al., 2011; Balco, 2011).

Correlation with Northern Hemisphere climate

The retreat of Laurentide Ice Sheet was linked to hemispheric-scale climate changes, (Schaefer et al., 2006), and some correlation appears to exist between varve thickness in the NAVC and oxygen isotope records from Greenland ice core data after

15,000 yBP (Ridge et al., 2012; Ridge and Toll, 1999). Boothroyd et al. (1998), proposed that recessional moraine formation at the southern margin of the Laurentide can be correlated to colder (more negative $\delta^{18}\text{O}$) intervals in Greenland ice cores. Assuming this hypothesis is correct, the exposure ages should intersect cold periods in Northern Hemisphere climate, if the age is synchronous with the deposition of the landform.

Comparing the cosmogenic exposure ages with the $\delta^{18}\text{O}$ record from the synchronized NGRIP, GRIP and GISP2 ice cores (Rasmussen et al., 2008), the exposure ages do not intersect significant cold periods. We interpret the formation of these moraines as correlative with colder periods at 20,550 and 20,400 yBP (Figure 6). These ages are 200 - 250 years older than the reported cosmogenic exposure ages of Ledyard-Congdon Hill and Old Saybrook – Wolf Rocks moraines (Figure 6) (Balco et al., 2009; Balco and Schaefer, 2006)), and differ slightly from the original correlation of Boothroyd et al. (1998), based on the improved resolution of the NGRIP chronology. The proposed ages for the moraines are within 1 standard deviation of the reported exposure ages ($\pm > 500$ years) (Balco and Schaefer, 2006), and may be closer to the actual exposure ages based on updated cosmogenic production rates for southern New England (G. Balco, pers. commun). Older ages suggested for the Wolf Rocks and Old Saybrook moraines (20,700 (Stone, 2012)) correlate with a relatively warm period record in Greenland, suggesting that deposition at that time would have had to be the result of local ice dynamics. While direct correlation between varve thickness and Greenland temperature prior to 15,000 yBP is weaker than after, some

relationship between moraine formation and varve thickness is still evident (Ridge et al., 2012).

Constraining the age of Glacial Lake Narragansett

Summing the uncorrelated varve sequences older than the base of the NAVC (1,200 years), the minimum age of Glacial Lake Narragansett is 19,400 yBP (Figure 7). Even if the 150 years of deposition recorded by the short varve records in Connecticut are excluded, a minimum 1,050 years elapsed between the deposition of the oldest varves in the NAVC and the youngest varves in Glacial Lake Narragansett. Given the uncertainty in the length of time between deposition of individual varve sequences, the estimate of 1,200 years seems conservative. The former ice margin in the Providence River areas is complicated (Boothroyd and McCandless, 2002), and it is unclear if the Barrington or Gaspee-Pawtuxet Cove sequence is the oldest measured in Glacial Lake Narragansett. Either way, the oldest varve sequences in the present-day Providence River extend to at least 20,000 yBP.

Glacial Lake Narragansett could not have begun to form until the southern margin of the Laurentide Ice Sheet retreated north from the Whale Rock moraine at the entrance to the present-day West Passage of Narragansett Bay. This moraine is interpreted to be correlative with the Wolf Rocks moraine (Figure 2) (Oakley and Boothroyd, 2012; Smith, 2010). Cosmogenic exposure ages for a moraine in southeast Connecticut correlative with the Wolf Rocks moraine place the age at 20,300 yBP (Balco et al., 2009).

The ice retreat rate in central New England based on basal varve sequences in the NAVC (Ridge, 2003, 2004) is estimated to be $30 - 90 \text{ m} \cdot \text{yr}^{-1}$ prior to 14,700 yBP. Assuming the cosmogenic age is the actual age of the landform, this requires the ice to retreat $> 35 \text{ km}$ in approximately 300 years, at a rate of $> 120 \text{ m} \cdot \text{yr}^{-1}$ to reach the oldest measured varve sites in the Providence River by 20,000 yBP. Ages based on the correlation with northern hemisphere climate assign an age of 20,550 yBP on the Wolf Rocks and 20,400 yBP on the Congdon Hill moraine. This allows 500 years between the ice retreating from the moraine and the southern margin of the ice sheet reaching the present-day Providence River, with a retreat rate of $70 \text{ m} \cdot \text{yr}^{-1}$, which falls in the middle of the range for regional ice retreat. The relatively low and uniform $\delta^{18}\text{O}$ prior to 15,000 yBP (Andersen et al., 2006; Rasmussen et al., 2008), supports a systematic retreat rate for the Laurentide Ice Sheet during the proposed age of the lake.

The proposed age range for Glacial Lake Narragansett (20,500 – 19,400 yBP) is considerably older than previous estimates of Uchupi et al. (2001) (18,700 – 18,100 yBP), and Boothroyd and August (2008) (19,000 – 17,600 yBP). This proposed age of Glacial lake Narragansett does not imply that the lake drained at 19,400 yBP, and a non-glacial, meteoric lake likely persisted until the onset of isostatic rebound. While the last glacial maximum for the Laurentide Ice Sheet is often presented as 18,000 to 20,000 yBP (i.e. Denton et al., 2010; Denton and Hughes, 1981), the constrained age of Glacial Lake Narragansett presented here, shows that at least in southeastern New England, deglaciation was well underway by this time.

FUTURE WORK

The potential remains for a correlating the Hudson-Quinnipiac and Glacial Lake Narragansett varve sequences with the NAVC. The oldest sequences at the base of the NAVC and Hudson-Quinnipiac are interpreted to contain more varves in the deeper subsurface. It is interpreted that the base of Glacial Lake Hitchcock varve sequence is less than 800 years older than the present base of the NAVC (Ridge, 2003). Based on regional models of deglaciation, 800 years may long enough to span the current gap between the NAVC and Hudson-Quinnipiac sites. Similarly, the oldest varves measured by Antevs (1928) at both the Hudson and Quinnipiac sites are not the base of these sequences. Extending the base of this sequence would be necessary to correlate with the youngest varves measured in Glacial Lake Narragansett. Additional varve records can be examined from the northern end of Glacial Lake Narragansett, however, Antevs outcrops were at or near the top of the varve section, and it seems unlikely that there are hundreds of varves younger than the sequences measured here.

CONCLUSIONS

- A 265-year varve series from Glacial Lake Narragansett was constructed from eight continuous sediment cores collected from the Providence River, Narragansett Bay, Rhode Island
- The Glacial Lake Narragansett varve series was not correlated with either the North American Varve Chronology, or any other varve sequences from southern New England or southeastern New York. Correlations between cores from different sites within Narragansett Basin suggests that at least within Glacial Lake Narragansett these varves can be correlated
- Uncorrelated varve sequences used in conjunction with the calibrated North American Varve Chronology and cosmogenic exposure ages from recessional end moraines, constrain the minimum ($> 19,400$ yBP) and maximum ($< 20,500$ yBP) ages of Glacial Lake Narragansett
- The relationship between moraine formation and Greenland temperature reconstructions, suggests that at the broadest scale, the behavior of the Laurentide Ice Sheet was controlled by northern hemisphere climate conditions. The variability in ice sheet retreat during periods with relatively low and uniform $\delta^{18}\text{O}$ values may have been controlled by internal ice dynamics or regional climate conditions
- While the last glacial maximum for the Laurentide Ice Sheet is often portrayed as occurring 18,000 to 20,000 yBP, based on the chronology presented here, in southeastern New England, deglaciation was well underway by this time.

ACKNOWLEDGEMENTS

The authors were supported by the Department of Geosciences, College of Environment and Life Sciences, University of Rhode Island and funded by the Rhode Island Coastal Resources Management Council Cooperative agreement 50A00311741; The Rhode Island SeaGrant Program BayMap Project and NOAA CSC grant NA06NOS4730220. Thanks to C. Troskosky, T. Bottenus, M. Tarasevich (University of Rhode Island, Department of Geosciences) and M. Sutherland (University of New Hampshire) for assistance in the field and lab. J. King and D. Cares, University of Rhode Island Graduate School of Oceanography provided assistance with core imaging and paleomagnetic data collection. The North American Glacial Varve website maintained by J.C. Ridge (Tufts University) was invaluable in providing access to Antevs (1922, 1928) and other varve records from New England. M. Sutherland and T. Smith (U.S. Geological Survey) provided helpful comments on prior drafts of this manuscript. J.C. Ridge provided helpful reviews on a previous version of this manuscript and offered valuable discussion of varve deposition and potential links with northern hemisphere climate. The authors are especially indebted to J. Turenne (United States Department of Agriculture-Natural Resource Conservation Service) for providing access to the pontoon boat used for coring and valuable assistance in the field.

REFERENCES CITED

- Andersen, K.K., Svensson, A., Johnsen, S.J., Rasmussen, S.O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Peder Steffensen, J., Dahl-Jensen, D., Vinther, B.M., and Clausen, H.B., 2006, The Greenland Ice Core Chronology 2005, 15-42 ka. Part 1: constructing the time scale: *Quaternary Science Reviews*, v. 25, p. 3246-3257.
- Antevs, E., 1922, The recession of the last ice sheet in New England: *American Geological Society Research series*, v. 11, p. 120.
- , 1928, The last glaciation with special reference to the ice sheet in North America: *American Geographical Society Research Series*, v. 17, p. 292.
- Applegate, P.J., Urban, N.M., Laabs, B.J.C., Keller, K., and Alley, R.B., 2011, Modeling the statistical distributions of cosmogenic exposure dates from moraines: *Geosci. Model Dev.*, v. 3, p. 293-307.
- Ashley, G.M., 1975, Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts-Connecticut, *in* Jopling, A.V., and McDonald, B.C., ed., *Glaciofluvial and glaciolacustrine sedimentation*, Society of Economic Paleontologists and Mineralogists Special Paper 23, p. 304-320.
- Balco, G., 2011, Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990-2010: *Quaternary Science Reviews*, v. 30, p. 3-27.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., and Schaefer, J.M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: *Quaternary Geochronology*, v. 4, p. 93-107.
- Balco, G., and Schaefer, J.M., 2006, Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England: *Quaternary Geochronology*, v. 1, p. 15-28.
- Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: *Quaternary Science Reviews*, v. 21, p. 2127-2135.
- Boothroyd, J.C., and August, P.V., 2008, Geologic and contemporary landscapes of the Narragansett Bay ecosystem, *in* Desbonnet, A., and Costa-Pierce, B.A., eds., *Science for ecosystem based management*, Springer, 507 p.

- Boothroyd, J.C., Freedman, J.H., Brenner, H.B., and Stone, J.R., 1998, Glacial geology of south and central Rhode Island, *in* Murray, D.P., ed., Guidebook to Field Trips in Rhode Island and Adjacent Regions of Connecticut and Massachusetts. New England Intercollegiate Geological Conference, 90th Annual Meeting: Kingston, Rhode Island., University of Rhode Island, p. C5-1 - C5-22.
- Boothroyd, J.C., and McCandless, S.J., 2002, Quaternary geologic map of Providence and East Providence Quadrangles: Kingston, RI, Rhode Island Geological Survey.
- , 2003, Quaternary Geologic map of the East Greenwich quadrangle, including parts of the Bristol and Crompton quadrangles: Kingston, RI, Rhode Geological Survey Open File Map 2003-01.
- Boothroyd, J.C., and Sirkin, L., 2002, The Quaternary geology of Block Island and adjacent regions, *in* Paton, P., Gould, L.I., August, P.V., and Frost, A.O., eds., The Ecology of Block Island: Kingston, Rhode Island, Rhode Island Natural History Survey, p. 13-27.
- DeGeer, 1975, A geochronology of the last 12000 years, *in* Goldthwait, R.P., ed., Glacial Deposits, v. 21, Benchmark Papers in Geology: Stroudsburg, Pennsylvania, Dowden Hutchinson and Ross, p. 432-440.
- Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., and Putnam, A.E., 2010, The Last Glacial Termination: Science, v. 328, p. 1652-1656.
- Denton, G.H., and Hughes, T., 1981, The last great ice sheets: New York, John Wiley and Sons.
- Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: *Geographie physique et Quaternaire*, v. 41, p. 237-263.
- Frankel, L., and Thomas, H.F., 1966, Evidence of Freshwater Lake Deposits in Block Island Sound: *The Journal of Geology*, v. 74, p. 240-242.
- Goldsmith, R., 1982, Recessional moraines and ice retreat in southeastern Connecticut: *Dubquene, Kendall - Hunt*, 61-76 p.
- Goss, M.C., 1995, High-resolution seismics and ice-marginal sedimentation in Block Island Sound and adjacent southern Rhode Island [Masters thesis], Rutgers University, New Brunswick, NJ.

- Gustavson, T.C., 1975, Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska, *in* Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and glaciolacustrine sedimentation, Society of Economic Paleontologists and Mineralogists Special Paper 23, p. 249-263: Tulsa, OK.
- Lanesky, D.E., Logan, B.W., Brown, R.G., and Hine, A.C., 1979, A new approach to portable vibracoring underwater and on land: *Journal of Sedimentary Petrology*, v. 49, p. 654-657.
- Needell, S.W., and Lewis, R.S., 1984, Geology and structure of Block Island Sound, Rhode Island and New York, U. S. Geological Survey Miscellaneous Field Studies Map MF-1621 (4 Sheets).
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983a, Maps showing geology and shallow structure of western Rhode Island Sound, Rhode Island, U.S. Geological Survey Miscellaneous Field Studies Map MF-1537.
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983b, Quaternary geology of the Rhode Island inner shelf: *Marine Geology*, v. 53, p. 41-53.
- , 2010a, Elevations on station datum: Providence, Narragansett Bay, RI, Volume 2010, National Ocean Service/National Oceanic and Atmospheric Administration.
- Oakley, B.A., and Boothroyd, J.C., 2012, The geometry and extent of Glacial Lakes Narragansett, Block Island and Rhode Island, Rhode Island USA: In prep.
- Pickart, D.S., 1987, Physical stratigraphy and geological evolution of the Providence River, Narragansett Bay, Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island.
- Rasmussen, S.O., Seierstad, I.K., Andersen, K.K., Bigler, M., Dahl-Jensen, D., and Johnsen, S.J., 2008, Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimate implications: *Quaternary Science Reviews*, v. 27, p. 18-28.
- Rayburn, J.A., 2004, Deglaciation of the Champlain Valley, New York and Vermont and its possible effects on North Atlantic Climate Change [Ph.D. thesis]: Binghamton, NY, State University of New York.
- Ridge, J.C., 2003, The last deglaciation of the Northeastern United States: A combined varve, paleomagnetic and calibrated ¹⁴C Chronology, *in* Hart, J.P., and

Creameens, D.L., eds., *Geoarcheology of landscapes in the glaciated Northeast*: New York State Education Department, Albany, New York.

—, 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J., and Gibbard, P.L., eds., *Quaternary glaciations - extent and chronology: Part II: North America*. *Developments in Quaternary Science*, Volume 2B: Amsterdam, Elsevier, p. 163-193.

—, 2011, The North American glacial varve project:
<http://geology.tufts.edu/varves/default.asp>.

Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B., and Wei, J.H., 2012, The new North American Varve Chronology: A precise record of southeastern Laurentide Ice Sheet deglaciation and climate: 18.2-12.5 kyr BP: *American Journal of Science*, v. In press.

Ridge, J.C., and Larsen, F.D., 1990, Re-evaluation of Antev's New England varve chronology and new radiocarbon dates of sediment from glacial Lake Hitchcock: *Geological Society of America Bulletin*, v. 102, p. 889-899.

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

RIGIS, 1989, Rhode Island Glacial Deposits, Rhode Island Geographic Information System.

Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Ivy-Ochs, S., Kubik, P.W., Andersen, B.G., Phillips, F.M., Lowell, T.V., and Schluchter, C., 2006, Near-synchronous interhemispheric termination of the Last Glacial Maximum in mid-latitudes: *Science*, v. 312, p. 1510-1513.

Schafer, J.P., and Hartshorn, J., 1965, The Quaternary of New England, *in* Wright, J., and Frey, D., eds., *The quaternary of the United States*: Princeton, N.J., Princeton University Press, p. 113-127.

Sirkin, L.A., 1982, Wisconsinan glaciation of Long Island, New York to Block Island, Rhode Island, *in* Larson, G.J., and Stone, B.D., eds., *Late Wisconsinan glaciation of New England*: Dubugue, IA, Kendall/Hunt, p. 35-60.

- Smith, J.H., 1955, Bristol and Vicinity, Rhode Island-Massachusetts Surficial geology: Washington, DC., U.S. Geological Survey Quadrangle Map GQ-70 U.S. Geological Survey.
- Smith, T.L., 2010, A conceptual model of the deglaciation of southern Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island
- Stone, B.D., 1976, Analysis of slump slip lines and deformation fabric in slumped Pleistocene lake beds: *Journal of Sedimentary Research*, v. 46, p. 313-325.
- Stone, B.D., and Borns, H., 1986, Pleistocene glacial and interglacial stratigraphy of New England, Long Island and adjacent Georges Bank and Gulf of Maine, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., *Quaternary glaciations in the Northern Hemisphere*: New York, Pergamon, p. 39-52.
- Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., 2005b, Quaternary Geologic Map of Connecticut and Long Island Sound Basin, U.S. Geological Survey Geologic Investigations Series Map I-2784, scale 1:125,000, 2 sheets and pamphlet. p. 1-72.
- Uchupi, E., Driscoll, N., Ballard, R.D., and Bolmer, S.T., 2001, Drainage of late Wisconsin glacial lakes and the morphology and late quaternary stratigraphy of the New Jersey-southern New England continental shelf and slope: *Marine Geology*, v. 172, p. 117-145.
- Wohlfarth, B., Björck, S., and Possnert, G., 1995, The Swedish time scale: A potential calibration tool for the radiocarbon time scale during the late Weichselian: *Radiocarbon*, v. 37, p. 347-359.
- Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002, Surface melt-induced acceleration of Greenland Ice-sheet flow: *Science*, v. 297, p. 218-222.

Figure 1: Location of sediment cores and varve records used in this study. Orange areas are the mapped extent of glacial deltas around the Providence River discussed in the text (Boothroyd and McCandless, 2002, 2003; Smith, 1955, 1956). Abbreviations: RIV - Riverside, PP - Providence Plains, EPP - East Providence Plains. Inset map of Southern New England shows extent of the study area, the maximum extent of the Laurentide Ice Sheet modified from Dyke and Prest (1987) and the projected extent of Glacial Lakes Narragansett, Rhode Island and Block Island (Oakley and Boothroyd, 2012).

Figure 2: Ice-margin positions, cosmogenic exposure ages (calendar years before present) and the location of varve records in southern New England and eastern New York and New Jersey not correlated to the NAVC. Length of varve series indicated for each location. Ice margins modified from Schafer and Hartshorn (1965), Goldsmith (1982), Sirkin (1982), Dyke and Prest (1987), Boothroyd et al., (1998), Ridge, (2003, 2004) and Stone et al., (2005b). All ages reported as calendar years before present.

Figure 3: Correlation of varve records based on close annual matches in total couplet thickness. A. Correlation of varve records collected in the Providence River for Narragansett Bay varve years 5000 to 5150. A constant offset was added to some of the records to display them on one graph without overlap. EW-1 was originally collected by Pickart (1987). B. Correlation of varve records collected in the Providence River for Narragansett Bay varve years 5150 to 5260. A constant offset was added to some of the records to display them on one graph without overlap. C. Correlation of varve records from the Providence River and Seekonk River (Antevs, 1928). Arrows point to two discrepancies, where it appears one varve may be missing from each sequence. The Providence composite curve was offset by 3 cm to display the records on one graph without overlap. D. Correlation of varve records from Pawtuxet Cove (Pickart, 1987) and Gaspee Point Varve thickness of PC-6 was offset by 3 cm to display the records on one graph without overlap.

Figure 4: Varves from Glacial Lake Narragansett years 5069 to 5075 from core PVD-1. Note the stacks of graded beds in the melt season layer.

Figure 5: Varves with thick (~ 1 cm) winter layers from core PVD-1. Numbers indicate the Glacial Lake Narragansett varve year. Black arrows point to examples of some of the sedimentary features commonly seen in the Providence Cores. A: Sand parting at the top of the winter layer representing a late winter-early spring melting, overturning or a storm runoff event. B: Fault in the core, likely not induced during coring. C: Scour at the top of the winter layer. D: Thin (1 mm) sandy layer at top of summer layer that represents a late-season storm E: Prominent sandy layer capped by thin (1 mm) silt/clay layer at the base of the summer layer representing early season melting or storm runoff followed by a period of little/no sediment input into the lake.

Figure 6: NGRIP ice core chronology and $\delta^{18}\text{O}$ profile of the NGRIP ice core (Andersen et al., 2006; Rasmussen et al., 2008). Red arrows indicate cosmogenic exposure ages of the Charlestown-Buzzards Bay (CM-BB), Ledyard-Congdon Hill (L-CH) and Old Saybrook-Wolf Rocks (OS-WR) recessional end moraines in southern New England (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Dashed black lines refer to potential correlation with Greenland Ice Cores LIS readvance/still stands.

Figure 7: Proposed minimum ages of Glacial Lake Narragansett and other uncorrelated varve series in southern New England and eastern New York shown in comparison with the base of the North American Varve Chronology. Red arrows indicate cosmogenic exposure ages from (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002). Green arrows indicate proposed correlated ages of the Congdon Hill and Wolf Rock end moraines. Blue arrow marks the maximum range of Glacial Lake Narragansett.

CHAPTER 4

LATE QUATERNARY DEGLACIATION OF NARRAGANSETT BAY, RHODE ISLAND, AND MASSACHUSETTS, USA

Bryan A. Oakley
Department of Geosciences, University of Rhode Island, Kingston, RI, USA, 02881

Corresponding author
Bryan A. Oakley
BOakley@my.uri.edu
Department of Geosciences
University of Rhode Island
317 Woodward Hall
9 East Alumni Ave
Kingston, RI, USA
02881

Ph: 401-874-4560
Fax: 401-874-2190

Introduction

This paper synthesizes the Quaternary depositional environments and deglacial evolution of Narragansett Bay based on ~ 800 km of high-resolution seismic reflection profiles, geotechnical boreholes, and published and unpublished Quaternary maps. The hypothesis carried throughout this work is that a single lake, Glacial Lake Narragansett, occupied much of southern Narragansett Basin and was contiguous with lakes in adjacent areas during Late Wisconsinan deglaciation. This paper focuses specifically on the elevation and continuity of the lakefloor deposits, the distribution of ice-marginal lacustrine fans and the volume of sediment deposited in Glacial Lake Narragansett. Several previous studies focused on the stratigraphy of Narragansett Bay (McMaster, 1960; McMaster, 1984; Pickart, 1987; Peck, 1989; Peck and McMaster, 1991), but this work represents the first detailed mapping of the Quaternary glacial depositional environments. This mapping provides an understanding of the behavior of the southeastern portion of the Laurentide Ice Sheet during the early stages of deglaciation, and provides a better understanding for managers of subsurface resources of Narragansett Bay, particularly for future dredging, disposal of dredged material, marina construction and siting of offshore wind farms.

Study area

Present-day Narragansett Bay lies within Narragansett Basin, a complex of non-marine metamorphosed sedimentary rocks deposited in an intermontaine rift basin and later deformed by the Alleghanian Orogeny in Late Carboniferous-Permian time (Mosher, 1983; Murray et al., 2004). The underlying bedrock is mostly the Rhode Island Formation, a coarse to fine-grained metamorphosed sedimentary rock, with some Cambrian and Precambrian igneous and metamorphic rocks (Hermes et al., 1994). The geologic history of Narragansett Bay between emplacement of the youngest bedrock during the Alleghanian Orogeny (ca. 250 million yBP) and the latest Pleistocene glaciations remains largely unknown. Coastal Plain sediment of Cretaceous to Tertiary age likely covered southern New England, and major river systems in New England may have drained to the southeast, as the result the general tectonic tilt of the region (Denny, 1982). Glacially transported Cretaceous sediment has been sampled in discrete blocks in terminal moraines at Block Island, Rhode Island (Sirkin, 1976; Stone and Sirkin, 1996), and Coastal Plain sediment has been interpreted in seismic reflection profiles from Rhode Island Sound, south of Narragansett Bay (McMaster and Ashraf, 1973; Needell et al., 1983).

Numerous northern hemisphere glaciations likely covered Narragansett Bay with glacial ice during the Quaternary Period (Schafer and Hartshorn, 1965). In-place evidence of all but the most recent (Wisconsinan) glaciation was removed by subsequent glaciations, although deformed, pre-Late Wisconsinan age (Illinoian) beds have been reported at Block Island (Sirkin, 1976) . The Late Wisconsinan Laurentide Ice Sheet reached its terminal position south of New England at the last glacial

maximum around 26,000 yBP, before beginning to retreat northward (Dyke et al., 2002; Peltier and Fairbanks, 2006; Stone and Borns, 1986). Meltwater issuing from the ice deposited sediment in a variety of depositional environments as the Laurentide ice sheet retreated (Koteff and Pessl, 1981; Stone and Stone, 2005).

Marine water first inundated Narragansett Bay after 10,200 yBP (sea level 30 m below present), and continued to transgress up Narragansett Bay. By 2,500 yBP, (sea level 2.5 m below present), Narragansett Bay looked similar to the present configuration (Boothroyd and August, 2008; McMaster, 1984). Present-day Narragansett Bay is microtidal (spring tidal range 1.2 m at Newport, 1.5 m at Providence), mixed-energy estuary according to the classifications of Dalrymple et al., (1992) and Hayes (1979).

METHODS

Sub-bottom seismic reflection profiling

Subsurface interpretations are based on 785 km (490 mi) of sub-bottom seismic reflection profiles collected in Narragansett Bay and adjacent Rhode Island Sound (Figure 1, inset), using an EdgeTech, SB-216S Full-Spectrum sub-bottom profiler (Figure 2), operated at a frequency sweep of 2-10 kHz (vertical resolution < 15 cm (Edgetech, 1998)). Towfish height was maintained at 1 m below the surface of the water, towed at a speed of $< 1.5 \text{ m} \cdot \text{s}^{-1}$. Spatial location was embedded into the sub-bottom files using the serial NEMA output of a Trimble DSM-132 GPS with a reported accuracy of $\pm 1 \text{ m}$ (Trimble, 2004). Depth to reflectors was calculated

using an acoustic velocity of $1,500 \text{ m} \cdot \text{s}^{-1}$. Profiles were post-processed using Chesapeake Technologies (Mountain View, California) Sonar Web v. 3.16. See Appendix 4 for a detailed discussion on seismic reflection profile collection and processing.

Interpretation

Interpreting seismic reflection profiles is done by identifying seismic facies. Seismic facies are sedimentary packages, distinguishable from adjacent units based on internal characteristics, (i.e. the intensity, spacing, continuity, and internal geometry of seismic reflectors), external geomorphic form, and stratigraphic relationship to other units (Roksandic, 1976; Vail et al., 1977). Where possible seismic facies were correlated with borehole records. Knowledge of glacial depositional systems is required to interpret the depositional environments of the seismic facies. Gustavson and Boothroyd (1987) used the Malaspina Glacier in Alaska as a modern analog for the Late Wisconsinan Laurentide Ice Sheet. The Malaspina glacier is similar in size to the lobes of the Laurentide ice sheet, with landforms that are similar in scale to those deposited during deglaciation in southern New England (Gustavson and Boothroyd, 1987). These depositional models, along with models created from mapping Late Quaternary deposits throughout New England (Koteff and Pessl, 1981; Stone and Stone, 2005) provided the basis for the seismic interpretations.

The upper surface of identified seismic facies were digitized on individual profiles in the ‘Seismic Reflectors’ section of SonarWeb (Figure 2). SonarWeb outputs reflectors as comma delineated (*.csv) text files, containing the Easting (X),

Northing (Y), Depth below towfish (Z), projected in Rhode Island State Plane Feet, relative to the North American Datum of 1983. The *.csv files were imported into Microsoft Excel, and combined into worksheets grouped by interpreted depositional environments (i.e. all of the lakefloor X,Y,Z is in the same workbook). The resulting Excel worksheets were converted into shapefiles in ESRI ArcMap v. 10.1.

Thickness and Volume of stratified deposits

The thickness of stratified deposits was calculated using Chesapeake Technologies SonarWebTM software, utilizing the ‘Seismic Reflectors Thickness’ tool, which calculates the algebraic difference between digitized reflectors. This included lakefloor deposits (varves), distal lacustrine fan, and distal delta slope deposits. Proximal lacustrine fans and delta plain deposits were not included due to limited seismic penetration.

The volume of deltas around Narragansett Bay was estimating using borehole records (Allen, 1956; Allen and Gorman, 1959; Bierschenk, 1954; Halberg et al., 1961; Johnson, 1962; Johnson and Marks, 1959) and the mapped extent (Boothroyd and McCandless, 2002, 2003; Schafer, 1961; Smith, 2010). The volume of lakefloor sediment within Narragansett Bay was determined by interpolating surfaces representing the elevation till/bedrock and moraine deposits, and the upper surface of glacial lakefloor deposits in a GIS environment. The volume of sediment contained between the surfaces was determined using the Cut/Fill tool within ESRI ArcMapTM Spatial Analyst extension. See Appendix 5 for details of interpolation and assessment of the surfaces.

Water depths and volume of Glacial Lake Narragansett

A single, continuous raster surface that reflects the isostatically uplifted water level of Glacial Lake Narragansett was created in ESRI ArcMapTM 10.1, based on the elevation of the deltas and minimum lake extent determined in Chapter 2. The interpolated lakefloor surface was subtracted from the water surface to approximate the water depth of Glacial Lake Narragansett, and the volume of the lake was estimated using the ESRI ArcMapTM v. 10.1 Spatial Analyst Cut/Fill tool.

RESULTS

Seismic facies and interpreted depositional environments

This study identified eleven distinct seismic facies in Narragansett Bay, which are discussed below. See table 1 for summary of facies.

Facies T/R: Till/Bedrock

This facies represents the stratigraphically lowest reflector, and is not penetrated by the seismic signal. Differentiating between till and bedrock in the subsurface with the seismic reflection profiler used was not possible in most instances. The topography of this reflector varies from flat to high relief; the highest relief (up to 30 m) is seen in east to west seismic lines (Figure 2), strongly controlled by the regional trend of the bedrock, with a dominate strike of NNE (Hermes et al., 1994; Murray et al., 2004; Reck and Mosher, 1988). This facies is interpreted to be bedrock, thin till over bedrock or thick till deposits. Reflectors were traced laterally to

shoreline exposures of bedrock and till (Boothroyd. and Hehre, 2007). Boreholes in the Providence River and West Passage sampled till or ‘till-like’ deposits 3 - 10 m thick, overlying metamorphosed sedimentary rocks of the Narragansett Basin (USACE, 1957).

Facies EM: End moraine.

Facies EM, is the stratigraphically lowest reflector when encountered, and has a different geomorphic orientation than facies T/R. The upper reflector is intense, with high relief, hummocky topography in a north to south survey lines. There was little penetration of the seismic signal, but where visible, the internal reflectors were chaotic. This facies was not sampled by any boreholes or cores, but is likely composed of a mixture of till and stratified material, interpreted to have been deposited as recessional end moraines. These deposits mark stillstands or fluctuations of the Laurentide Ice Sheet.

Facies IM: Ice marginal deposits

Facies IM is characterized by an extremely hummocky, intense external seismic reflector. This facies is interpreted to represent ice-marginal deposition, primarily as braided rivers flowing between the ice sheet and valley walls and/or debris flows off of the ice. Terrestrial analogs are composed mostly of stratified sand and gravel (Boothroyd et al., 2003; Stone and Stone, 2005). This unit is continuous with ice-marginal deposits in existing Quaternary maps (Boothroyd and McCandless,

2003; Smith, 2010) adjacent to steep bedrock hills along the margin of present-day Narragansett Bay.

Facies HM: Hummocky moraine

Facies HM is similar in morphology to facies IM, with a hummocky, intense external seismic reflector. Seismic penetration in this facies was limited, but occasional parabolic reflectors are interpreted to be large (> 1 m) boulders. This facies was only mapped in a wide (> 1 km) area in the West Passage, and is continuous with units mapped adjacent to Narragansett Bay (Schafer, 1961; Smith, 2010). This unit is interpreted to be fluvial sand and gravel interbedded with debris flow till, deposited around and/or on debris-covered ice. The hummocky topography is the result of burial and subsequent melting of ice blocks during deglaciation (Schafer, 1961; Smith, 2010).

Facies PF: Proximal lacustrine fan

Facies PF is stratigraphically above facies T/R. Internal acoustic reflectors, when visible, show steeply dipping or chaotic bedding. Externally, this facies has relatively high relief in north to south track lines (> 10 m total relief) with a moderate intensity external reflection (Figure 3), and is distinguished from facies T/R based on the strength of the reflector, orientation, and geomorphic form. This facies is interpreted to be composed of sand and gravel, deposited in the proximal portion of a lacustrine fan, from meltwater issuing from subglacial tunnels at the grounded margin of the ice sheet. Offsets seen in seismic reflectors immediately up ice from the fan (Figure 3) represent ice-tectonics from the fluctuating active margin of the ice sheet.

Sand and gravel reported in boreholes southwest of Greenwich Bay (USACE, 1957), are correlative with interpreted proximal lacustrine fans in seismic profiles.

Facies DF: Distal lacustrine fan

Facies DF is continuous with facies PF, and often onlaps PF and T/R (Figure 3). Internally, reflectors are well defined, and are sub-parallel to parallel. Externally, this facies fills topographic lows, is 3 - 5 m thick, and individual sedimentary packages tend to thin progressively to the south. This facies is interpreted to be composed of mostly sand, deposited in the distal portion of a lacustrine fan. This unit was probably sampled in boreholes and cores, however distinguishing this unit from sandy lakefloor deposits (Facies GLF) are not possible.

Facies GLF: Lakefloor

Facies GLF is the most ubiquitous glacial facies in the study area, is characterized by well-defined, parallel, laterally continuous reflectors that drape underlying topography and fill existing valleys (> 40 m) and is stratigraphically above facies T/R, EM, PF, DF (Figures 2 - 5). This facies is interpreted to have been deposited in a glacial lakefloor depositional environment. While the sediment is composed of laminated silt and clay (interpreted as varves), individual seismic reflectors represent groupings of sedimentary couplets rather than individual varves. This facies was sampled in boreholes and vibracores throughout Narragansett Bay (Peck and McMaster, 1991; Pickart, 1987; USACE, 1957).

Facies DS: Delta slope

Facies DS is the least common glacial depositional environment mapped. This facies is typically 5 - 10 m thick, is characterized by steeply dipping internal reflectors (10 - 20°) (Figure 4), and stratigraphically overlies facies GLF. This unit is interpreted to be composed of sand and gravel, deposited as a glacial delta. The steeply dipping reflectors represent proximal delta slope deposition. Seismic penetration was limited within portions of the deltas now submerged below present sea level along the present-day western shoreline of Narragansett Bay, and the mapped extent is largely based on the geomorphology of the area.

Facies E: Estuarine Channel

Facies E is identified by an intense basal reflector that truncates underlying units as an erosional unconformity (Figure 5), and is always stratigraphically above the units discussed previously. This unit is interpreted to represent post-glacial fluvial channels modified during Holocene marine transgression. This facies has been sampled in boreholes and cores throughout Narragansett Bay, and is composed of a variety of sediment types, ranging from gravel to silt with shells and other organic matter are common (Peck and McMaster, 1991; USACE, 1957).

Facies M: Estuarine mud

Facies M is ubiquitous throughout much of Narragansett Bay, occurring as an acoustically transparent layer that drapes the underlying units up to 15 m thick. This facies is interpreted to be estuarine mud deposited in low-energy basins (Figures 2 -5). Where sampled in boreholes (USACE, 1957), it is composed primarily of organic silt or clay, with marine shells common. Occasionally, in low-energy basins, the lower half of the unit shows a slightly darker seismic return, without a distinct seismic reflector. This could represent changes in the sediment characteristics reflecting increasing water depths during transgression (Peck and McMaster, 1991; Vinhateiro et al., 2007).

Facies NG: Natural Gas

Facies NG has a distinct seismic signature, with a dark, opaque upper seismic reflector that typically has a convex up reflection that obscures or ‘wipes out’ the underlying seismic record (Figure 5). This facies is interpreted to represent gas bubbles in the sediment. This gas is likely in the form of buried methane formed from decayed organic matter. The source of the organic matter is probably a combination of freshwater and saltwater marsh peat, post-glacial lake gyttja, and organic rich estuarine sediment. Natural gas is common in the subsurface of other glaciated estuaries (Kelley et al., 1994; Rogers et al., 2006; Ussler et al., 2003).

Facies ADM: Anthropogenic dredged material

Facies ADM is rare in Narragansett Bay. Where mapped it has a strong upper reflector, with a convex external form. Where visible, internal reflectors are chaotic. Facies ADM is stratigraphically the uppermost facies, although a thin drape (< 15 cm) of facies M may be present. This facies is interpreted to be dredged material placed adjacent to navigational channels.

Facies	Seismic characteristics	Interpretation
ADM	Bumpy, convex surface, chaotic internal reflectors. Stratigraphically overlies facies M or E	Anthropogenic dredged material
NG	Dark, opaque later with a convex upper surface. Obscures underlying seismic record	Natural gas
M	Acoustically transparent layer that drapes and fills underlying topography. Ubiquitous in low-energy basins throughout the bay	Estuarine mud
E	Distinct erosional unconformities in underlying facies. Basal reflector is usually dark	Estuarine channel
DS	Characterized by steeply dipping (10-20°) internal reflectors. Stratigraphically above and continuous with facies GLF.	Delta slope
GLF	Most common seismic facies. Well defined, parallel reflectors that drape underlying topography and fill existing valleys.	Glacial lakefloor
DF	Well defined, sub-parallel to parallel reflectors that fill underlying topography. Laterally continuous with facies PF. Can be difficult to delineate from facies GLF.	Distal lacustrine fan
PF	High relief in north to south profiles. North (up-ice) side often shows evidence of collapse. Internal reflectors steeply dipping or chaotic. Laterally continuous with facies DF	Proximal lacustrine fan
IM	High intensity surface reflector with high relief in east to west profiles. Internal reflectors chaotic. Adjacent to bedrock hills	Ice-marginal deposits
HM	High intensity external reflector with hummocky surface. Internal reflectors chaotic, with parabolic reflectors interpreted to be boulders	Hummocky Moraine
EM	High intensity surface return w/ high relief in north to south profiles. Where visible, internal reflectors are chaotic.	Recessional end moraine
T/R	High intensity surface return. Surface has high topographic relief; no internal reflectors	Bedrock or Till

Table 1: Seismic Facies of Narragansett Bay

Interpolated raster surfaces

Thickness and volume of stratified deposits

The thickest stratified deposits are located in the deepest portions of the Pre-Wisconsinan bedrock valleys now occupied by the East and West Passages, Sakonnet River and Mount Hope Bay. This study estimated that stratified deposits range from < 1 m to > 50 m (Figure 6). Stratified deposits in Glacial Lake Narragansett cover > 425 km², with a total volume of 8.7×10^9 m³ (Table 2). Similar volumes have been calculated elsewhere. The volume of seven glacial marine deltas in eastern Maine of similar size (250 km²) to those in Glacial Lake Narragansett was estimated at 4.7×10^9 m³ (Ashley et al., 1991). This estimate did not include sediment deposited as glacial marine mud, analogous to the lakefloor sediment ($> 3.5 \times 10^9$ m³) deposited within Glacial Lake Narragansett.

Delta	Area - km²	Average Thickness - m	Number of wells	Volume - m³
Narragansett Bay - lakefloor	200	Varies	Seismic profiles	3,500,000,000
Warwick Plains	51	25	20	1,275,000,000
Providence Plains	26	34	68	894,200,000
Blackstone	43	19	36	765,000,000
Riverside / Barrington North	27	19	31	513,000,000
New Meadow Neck	19	17	11	317,900,000
Potowomut	16	20	16	316,000,000
Island park	5	60	2	300,000,000
East Providence	10	21	18	210,000,000
Mill Creek	12	17	5	204,000,000
Warren River	17	10	12	170,000,000
Smith Hill	3	33	7	108,900,000
Hunt-Quonset	9	> 10	0	85,000,000
Barrington	2	30	2	45,000,000
Ten Mile River	1.5	25	3	37,500,000
Annaquatucket	0.8	15	Seismic profiles	12,000,000
Dutch Island	0.2	15	Seismic profiles	3,000,000
Total	428			8,756,500,000

Table 2: Sediment volume for deltas and lakefloor deposits in Glacial Lake Narragansett in and around present-day Narragansett Bay

DISCUSSION

Morphosequence concept

The Quaternary glacial depositional environments of the seismic facies were interpreted, and grouped into morphosequences. Morphosequences are time-equivalent groups of landforms that extend from the collapsed former ice margin at the proximal end of the deposit, with a general decrease in grain-size towards more distal portions of the sequence (Koteff and Pessl, 1981; Stone and Stone, 2005).

Traditionally, in terrestrial Quaternary mapping, morphosequences are identified using 1:24,000 scale topographic maps and are named based on the present-day watershed or geographic location. Morphosequences are correlated based on their position relative to the margin of the retreating ice sheet. This correlation is shown in Figure 7.

Ice marginal deposits not linked to individual morphosequences were mapped as undifferentiated ice-marginal deposits (Qimu). Proximal lacustrine fans (Qpf) also were not linked to an individual morphosequence. Lakefloor deposits (Qlf), which overlie older deposits, were not associated with any individual morphosequence, as deposition occurred during the entire deglaciation of Narragansett Bay. Eskers, which are a common feature on terrestrial Quaternary maps, could not be differentiated from other deposits (i.e. proximal fans) due to their limited spatial extent.

Ice margin positions and ages

Ice margins in the southern portion of Narragansett Basin were identified using a combination of proximal lacustrine fan and recessional end moraine deposits interpreted from high resolution sub-bottom seismic reflection profiles. The ice-

margins were placed along the up-ice side of recessional moraine deposits, and behind the crest of proximal lacustrine fans. Margins were correlated with previously published ice margins from adjacent areas (Boothroyd et al., 1998; Dyke and Prest, 1987; Ridge, 2003; Schafer and Hartshorn, 1965; Smith, 2010; Stone and Borns, 1986; Stone and Peper, 1982). The age of the Wolf Rocks – Whale Rock and Congdon Hills-Bonnet Point ice margins are correlated to cosmogenic beryllium (Be^{10}) exposure ages of moraines in eastern Connecticut (Balco et al., 2009; Balco and Schaefer, 2006; Balco et al., 2002) and with cold intervals in Greenland ice core records (Andersen et al., 2006; Svensson et al., 2006).

Deglaciation of Narragansett Bay

Deglaciation of what became present-day Narragansett Bay began when the southern margin of the Laurentide Ice Sheet retreated north of the Whale Rock End Moraine (QemWRK), at the entrance of the West Passage of Narragansett Bay (Figure 8, Plate 1). This moraine is interpreted to be correlative with the Old Saybrook and Wolf Rocks moraines (Figure 8) and would represent a stillstand or fluctuation of the Laurentide Ice Sheet. Cosmogenic exposure dates on the Old Saybrook Moraine indicate that the moraine was deposited between 20,300 yBP (Balco et al., 2009), and 20,550 yBP (Oakley and Boothroyd, 2012). Drainage down the present-day Pettaquamscutt River Valley began at this time, depositing a delta (QdPR) (Plate 1) that was graded to Glacial Lake Rhode Island.

The margin of the ice continued to retreat north into the present-day West Passage of Narragansett Bay, and a stillstand or fluctuation of the active ice margin

formed the Bonnet Point end moraine (QemBPT) (Figure 8, Plate 1). This topographic feature was first proposed as a moraine by Peck (1989), and Peck and McMaster (1991), and is interpreted to correlate with the Ledyard - Congdon Hills moraine. This moraine was deposited between 20,200 yBP (Balco et al., 2009), and 20,400 yBP (Oakley and Boothroyd, 2012). Subglacial drainage in the center of the present-day West Passage deposited the Dutch Island Delta (QdDI) (Plate 1). Lakefloor deposits seen in seismic reflection profiles below the delta (Figure 4) suggest this landform started as a lacustrine fan and formed a progradational delta in the manner presented by Gustavson and Boothroyd (1987). The present-day East Passage and Sakonnet River were both still occupied by ice at this time.

The Annaquatucket sequence (QimAN, QfAN, QdAN) began to form as the ice margin retreated from the till hill along the west side of the present-day lower West Passage, and drainage shifted from the Pettaquamscutt River Valley to the Hunt-Annaquatucket valley (Schafer, 1961; Smith, 2010). Meltwater from the Hunt-Annaquatucket flowed down the lower West Passage of Narragansett Bay, between the valley wall to the west and a tongue of ice in the deeper portion of the valley (Schafer, 1961). The sequence ends in a delta deposited into Glacial Lake Narragansett in the West Passage (QdAN) (Plate 1). The hummocky moraine deposits at the head of the Annaquatucket sequence (QhmaQ) extend south and east from Fox Island. These deposits are correlative with ice marginal deposits in the center of the Sakonnet River. No correlative ice-marginal or moraine deposits were mapped in the East Passage.

After retreating from the Annaquatucket sequence, drainage down the pre-Wisconsinan bedrock valley west of Narragansett Bay (Upson and Spencer, 1964) began to deposit the first in a series of very large (20 - 47 km²) deltas into Glacial Lake Narragansett. The Mill Creek Delta (QdMC) surrounds Wickford Harbor. North of the Mill Creek sequence, a stillstand or fluctuation of the ice margin is marked by the Quonset Point end moraine (QemQP) adjacent to Narragansett Bay (Schafer, 1961; Smith, 2010). Moraine deposits offshore of Quonset Point are correlative with this position, as are lacustrine fans north of present-day Conanicut Island, and ice marginal deposits around Dyer Island in the East Passage and in the Sakonnet River valley (Figure 9; Plate 1).

The Hunt-Quonset delta that extends from Wickford into Narragansett Bay was deposited when the ice retreated from the Quonset Point to the Quidnessent (QemQUI) moraine positions (Figure 9) (Schafer, 1961; Smith, 2010). Two segments of the Quidnessent moraine were mapped between Hope Island and the western shoreline of Narragansett Bay, that are now completely buried by lakefloor deposition. This ice margin is correlative with lacustrine fans east of Hope Island, ice marginal deposits around Dyer Island in the East Passage, and with the Sakonnet end moraine (QemSR) in the center of the Sakonnet River valley. This also marks the onset of deposition of a prominent set of lacustrine fans that extends from this ice margin north to the deposits at Prudence Island (QimPI) (Plate 1).

The Potowomut delta along the west side of Narragansett Bay was deposited as the ice margin retreated north from the Quidnessent position (Boothroyd and McCandless, 2003; Schafer, 1961; Smith, 2010). Deposition of the sequence of

lacustrine fans west of present-day Prudence Island continued until the margin of the ice sheet retreated to the northern end of the Potowomut morphosequence (QdPO) and ice marginal Prudence Neck deposits (QimPI). This ice margin is marked by proximal lacustrine fans south of the entrance of Greenwich Bay, ice-marginal deposits at Hog Island (QimHI) and in western Greenwich Bay (QimEG) and extends across the head of the Island Park morphosequence (QimIP and QdIP) (Plate 1).

Ice continued to retreat north from this position, and drainage down the bedrock valley west of Narragansett Bay deposited the Warwick Plains delta (QdWP). The ice-marginal Warwick Neck deposits (QimWKN) (Plate 1) were deposited after the margin of the ice retreated from the northern end of the streamlined bedrock/till hill known as Warwick Neck. These deposits are correlative with the ice marginal deposits along the eastern side of the Warren River Valley (QimWRN) (Figure 8). A prominent set of lacustrine fans in the Upper Bay are correlative also with these sequences.

A second set of lacustrine fans was mapped south of the Barrington morphosequence (QimBT) in Upper Narragansett Bay. It is unclear if these lacustrine fans extended across the dredged channel, contiguous with the set of fans further to the south. Deposition of the Warwick plains delta continued at this time, and is correlative with the Barrington delta (QdBT), Warren River delta (QdWRN) and probably the Cole River deposits (QdCRV) in present-day Mount Hope Bay (Plate 1).

North to south trending ridges comprised of till underlain by bedrock were mapped adjacent to Nayatt Point, west of Barrington and near the mouth of the Pawtuxet River. Bedrock crops out south of the Pawtuxet River, and till underlain by

bedrock was recorded in boreholes west of Nayatt Point (USACE, 1957). The bouldery area along the present shoreline of the Providence River north of Conimicut Point are interpreted to be ice marginal deposits associated with the adjacent Warwick Plains delta (Plate 1).

Natural gas obscures the seismic reflection profiles in much of the central portion of the Providence River. Where the seismic signal penetrates, lakefloor deposits were mapped throughout. Two proximal fans were mapped, one offshore of present-day Bullocks Cove and the other north of Sabin Point. Boreholes in the uppermost Providence River reported sand and gravel underlying silt and clay (USACE, 2001), and these deposits are interpreted to be proximal lacustrine fans overlain by glacial lakefloor deposits. The southern margin of the ice sheet continued to retreat north, depositing the Smith Hill delta northwest of the Providence River, and the Blackstone delta, which was deposited into an arm of Glacial Lake Narragansett in the present-day Seekonk River. Assuming an ice retreat rate of 70 m yr^{-1} (Ridge, 2004), Narragansett Bay was ice-free before 19,500 yBP, although the ice remained in the watershed until at least 19,300 yBP (Oakley and Boothroyd, 2012).

Late Pleistocene non-glacial deposits

The Conimicut Point deposits (QfCP, QdCP) (Plate 1) are markedly lower (10 m) than the projected water level recorded by the surrounding deltas (QdWP, BT, RIV, etc) (Plate 1). This is interpreted to represent deposition into a smaller, non-glacial lake in upper Narragansett Bay, probably after the onset of isostatic rebound and initial drainage of Glacial Lake Narragansett as discussed in Chapter 2. The fluvial deposits at the head of the Sakonnet passage (QfSB) probably represent drainage from the Taunton River Valley through Mt Hope Bay and down the Sakonnet River Valley around the same time. Penetration of the seismic signal in this area was very limited due to the presence of natural gas and coarse surface sediment (sand and gravel (McMaster, 1960)), but boreholes in the narrow area between Aquidneck Island and the adjacent upland east of the Island Park delta penetrated >200 feet of sand (USACE, 1957). The extent of these fluvial deposits appears to be limited to the sandy, central channel of the present-day Sakonnet River.

Extent of lakefloor deposits

The hypothesis carried throughout this work is that one large lake, Glacial Lake Narragansett, occupied much of the southern portion of Narragansett Basin and was contiguous with lakes in adjacent waters. Paramount to this is determining the continuity of lakefloor deposits in the different geographic areas within Narragansett Bay. If glacial lakefloor deposits are restricted to the deeper basins, then it could be argued that separate, smaller glacial lakes existed. Glacial lakefloor deposits are ubiquitous throughout Narragansett Bay (Figure 9), supporting the hypothesis that one

large lake occupied much of southern Narragansett Basin. Natural gas and estuarine deposits (Facies NG and E) obscure the seismic reflection for short distances (e.g. across the dredged channel at Quonset Point and in portions of the Providence River), but these gaps are typically less than 500 m. The seismic record is obscured in parts of the East Passage but silt and clay reported in boreholes from this area (USACE, 1957) are interpreted to be glacial lakefloor deposits.

The only portions of the bay where lakefloor deposits are not seen continuously on seismic reflection profiles is in the channels connecting the East Passage with Mount Hope Bay, and Mount Hope Bay with the Sakonnet River (Figure 9). The gap between the mapped lakefloor deposits in both areas is < 5 km. Mount Hope Bay and the East Passage are connected by a narrow (< 1 km), deep (> 25 m) incised channel, between two till uplands (Plate 1). Seismic penetration in this area was very limited due to coarse grained surface sediment (gravel) (McMaster, 1960). No geomorphic evidence exists to suggest that Glacial Lake Narragansett did not extend into present-day Mount Hope Bay via the East Passage.

It is unclear if the glacial lake in the present-day Sakonnet River was contiguous with the both the lake to the south in Rhode Island Sound (Glacial Lake Rhode Island), and Glacial Lake Narragansett in Mount Hope Bay. A 3 km long, 0.5 km wide channel connects the present-day Mount Hope Bay and the Sakonnet River. The favored interpretation is that an arm of Glacial Lake Rhode Island extended into the Sakonnet River valley, but was not connected with Glacial Lake Narragansett in Mount Hope Bay. The lakes would have been separated by the Island Park delta (QdIP) that originally extended across the head of the present Sakonnet River. The

present channel connecting Mount Hope Bay with the Sakonnet River was incised by the post-glacial Taunton River.

Elevation of glacial lakefloor sediment, minimum water-depths, and volumes of Glacial Lake Narragansett

If any of the lakefloor deposits are higher than the interpreted water level of Glacial Lake Narragansett, more than one lake may have existed in Narragansett Bay, and an alternative hypothesis would have to be discussed. The upper surface of lakefloor deposits digitized from seismic reflection profiles were plotted as a point cloud based on their location and elevation. The upper surface of the lakefloor deposits in each geomorphic area of the bay (i.e. East Passage, Providence River etc). These surfaces were compared to the elevation of delta plain-delta slope contacts around present-day Narragansett Bay, and the interpreted water levels of Glacial Lake Narragansett (Figure 10) (BAO Water-level chapter)). No lakefloor deposits were mapped higher than the projected water levels of Glacial Lake Narragansett, supporting the hypothesis that one large lake occupied most of present-day Narragansett Bay during deglaciation.

Lacustrine fans and subglacial drainage

The systematic northward retreat of the ice margin through Narragansett Bay is recorded by the deposition of lacustrine fans at the grounded margin of the ice sheet. The presence of lacustrine fans indicates that a significant amount of meltwater (and sediment) issuing from the ice sheet was subglacial (Shreve, 1972) (Figure 12), similar

to the present drainage of the Greenland Ice Sheet (Zwally et al., 2002). The lacustrine fans often onlap a preceding fan, indicating that the subglacial tunnels stayed open, and in the same position as the ice margin retreated north (Banerjee and McDonald, 1975), and did not reorganize each melt season in the manner presented for the Greenland Ice Sheet (Bartholomew et al., 2010) and Arctic valley glaciers (Bingham et al., 2005).

Lacustrine fans were most common in the deeper portions of the valleys, suggesting that drainage was focused by a network of subglacial channels into a subglacial tunnel (Figure 13). This agrees with hydrologic models of the Laurentide Ice Sheet, which suggest subglacial drainage was a distributed drainage system that flowed towards the bottom of valleys, forming a larger single conduit for subglacial drainage (Hooke and Fastook, 2007). This differs from other regions in the glaciated northeast. Ice tunnels were close together (spacing 100's of m) and formed coalesced fans (stratified end moraines) parallel to the ice margin prior to 14,700 yBP in coastal Maine (Dorion et al., 2001; Thompson and Borns, 1985), before switching to larger, more centralized drainages (Ashley et al., 1991). While the spacing of the seismic profiles ($< 1\text{ km}$) could be biasing the results, the seismic coverage was sufficient to map fans that were laterally continuous (parallel to the margin ice sheet). Lacustrine fan distribution similar to Glacial Lake Narragansett has been mapped in Long Island Sound (Lewis and Stone, 1991; Stone et al., 2005). The implication of this is that larger, less frequent subglacial tunnels are indicative of a warm based ice sheet with a wide ice marginal area where surface water reached the bed (Hooke and Fastook, 2007). Hooke and Fastook (2007), however, limit subglacial drainage and tunnel

formation to within 5 km of the margin of the ice, which differs than the interpretations discussed below.

Volume of sediment

To account for the volume of sediment deposited in Glacial Lake Narragansett ($8.7 \times 10^9 \text{ m}^3$) requires excavation of $> 2.5 \text{ m}$ of sediment from across the entire $3,400 \text{ km}^2$ present-day watershed of Narragansett Bay. Direct bedrock erosion did not contribute a large portion of this sediment. Colgan et al. (2002), using cosmogenic exposure dates of bedrock surfaces, suggest that total bedrock erosion during the late Wisconsinan near the southern margin of the Laurentide was $0.4 - 0.9 \text{ m}$. Applying the middle of this range (0.6 m) across the entire watershed of present-day Narragansett Bay, leaves $> 6 \times 10^9 \text{ m}^3$ of sediment unaccounted for. Till deposits mapped in southern New England are typically $< 3 \text{ m}$ thick. If the source of sediment deposited in the present-day watershed of Narragansett Bay was entirely eroded from subglacial till, deposits were 75 - 100% thicker during the advance of the ice sheet, or there were additional sources of sediment.

Based on the location of morphosequences and uncorrelated lacustrine fans throughout Glacial Lake Narragansett, multiple drainage systems were active as the ice sheet retreated. Major drainage systems were probably located in the paleo-Blackstone and paleo-Taunton River valleys, with numerous smaller drainages (Boothroyd and August, 2008). Upson and Spencer (1964) interpret deep bedrock valleys extending down the Providence River, Mount Hope Bay/Sakonnet, East Passage and West Passage (Figure 13). The interpreted course of the paleo-

Blackstone River down a pre-Wisconsinan west of upper Narragansett Bay and through the entrance of Greenwich Bay (Upson and Spencer, 1964), contradicts boreholes (USACE, 1957), seismic reflection profiles and the regional trend of bedrock in Narragansett Basin (Hermes et al., 1994; Mosher, 1983). An alternative interpretation is that the paleo-Blackstone flowed down the west side of present-day Narragansett Bay, and down the present-day Pettaquamscutt River valley (Figure 13). The paleo-Taunton River probably flowed down the bedrock valley in the Mount Hope Bay and the Sakonnet River (Boothroyd and August, 2008; Upson and Spencer, 1964). Obviously these drainages would have been active at different times as the southern margin of the Laurentide retreated north up present-day Narragansett Bay. An important note is that these valleys are coincident with the large deltas along the western shoreline of the present-day West Passage, in Upper Narragansett Bay and the Providence River.

Similar depositional processes would have been active during pre-Wisconsinan glaciations, as well as during the advance of the Laurentide during Late Wisconsinan time (Ridge, 2004). To account for the volume of sediment deposited during Late Wisconsinan deglaciation, these deposits had to have contributed sediment, although how this process would work remains enigmatic. All in place evidence of these deposits have been removed, but stratified deposits have been identified as thrust sheets in the recessional moraine at Block Island (Sirkin, 1976).

Regardless of some localized sediment sources, the immense volume of sediment deposited during deglaciation suggests that the drainage systems beneath the Laurentide Ice Sheet had to be very efficient and certainly began more than 5 km from

the ice margin, contradicting some hydrologic models of the ice sheet (Hooke and Fastook, 2007). Previous work in Maine and Scandinavia suggest that through-flowing, subglacial drainage systems can begin 150 - 170 km from the margin of the ice sheet (Arnold and Sharp, 2002; Ashley et al., 1991). The present-day Blackstone River begins 120 km north of Narragansett Bay, extending up a pre-glacial bedrock valley (Upson and Spencer, 1964), and the northern extent of this valley may have been continuous with other river valleys further to the north prior to isostatic rebound. Gustavson and Boothroyd (1987) report total sediment discharge for the Malaspina Glacier, which is similar in size to the individual lobes of the Laurentide Ice Sheet, to be 15 to 150 million $\text{m}^3 \cdot \text{yr}^{-1}$, of which, half may have been bedload (Ashley et al., 1991; Hooke et al., 1985). Cowan and Powell (1991), measured the sediment yield of McBride Glacier, which is drained by a single subglacial tunnel, to be $1.7 - 3.6 \times 10^6 \text{ m}^3 \cdot \text{yr}^{-1}$. Using this rate, the largest delta (Warwick Plains $1.2 \times 10^9 \text{ m}^3$) would have been deposited in 300 – 700 years. Based on estimated rates of ice-margin retreat this deposition occurred within < 100 years, suggesting individual drainages were at least three times larger than the present McBride drainage, and/or multiple drainages were active in larger deltas.

The average river discharge of all the temperate valley glaciers (8) in Glacier Bay National Park (including McBride) is $8.8 \times 10^6 \text{ m}^3 \cdot \text{yr}^{-1}$ (Powell, 1991). This rate of discharge would deposit the Warwick Plains delta in 135 years. The low-end estimate of Gustavson and Boothroyd (1987) for sediment discharge of the Malaspina would deposit the Warwick Plains delta in 160 years. Small deltas (i.e. Dutch Island, $3 \times 10^6 \text{ m}^3$) could be deposited in as little as one year. Taken together, this suggests

that the sediment discharge of the temperate valley glaciers in southeastern Alaska are within the same order of magnitude of individual drainages within Glacial Lake Narragansett.

Climate

The role of subglacial meltwater indicated by the prevalence of lacustrine fans, is directly related to the climate during deglaciation. Climatically, subglacial fans indicate a warm melt season with abundant melt water in sub-glacial tunnels. Ice-wedge casts and other features interpreted to be the result of permafrost suggest that the mean annual temperatures had to be below 0° C (Boothroyd et al., 1998; Boothroyd and Sirkin, 2002; Stone and Ashley, 1992). Modeling of summer climate along the southern margin of the Laurentide Ice Sheet at the last glacial maximum suggests that mean July temperatures were below freezing under the influence of northerly winds (blowing off the ice), and above freezing under the influence of southerly winds. Mean summer temperature was modeled to be 3 - 6° C (Bromwich et al., 2005).

The relatively warm temperatures of ice-free surfaces (i.e. the exposed continental shelf) adjacent to the ice sheet produced a strong thermal gradient along the margin of the ice sheet. Episodic low-pressure systems tracked along the southern margin of the ice sheet, producing extended periods of southerly wind and precipitation (rain), and the precipitation that fell on the ice would quickly reach the bed through moulins and drain via subglacial tunnels. These climatic conditions are

not dissimilar from present-day coastal Greenland, which has average summer temperature of 6°C and mean annual temps 2 - 4° C below zero (Vinher et al., 2006).

The similarities between the Laurentide and parts of the Greenland Ice Sheet are important. Future predictions of modern ice sheet behavior and response to climate warming requires an understanding of previous ice sheets. Subglacial drainage of the Greenland Ice Sheet, specifically the fact that surface meltwater transported to the base of the ice-sheet through moulins may be accelerating flow of outlet glaciers, has become a controversial topic (Bartholomew et al., 2010; Luthcke et al., 2006; Sundal et al., 2011; Zwally et al., 2002). A secondary conclusion of those studies is that as climate continues to warm, the Greenland is shifting from a polythermal to a warm-based ice sheet. As a result, the southern margin of the Late Wisconsinan Laurentide Ice Sheet may have been similar to the present-day characteristics of the Greenland Ice Sheet.

It has been proposed that freshwater draining from glacial lakes can have an impact on thermohaline circulation in the North Atlantic (Broecker, 1997; Broecker et al., 1989). Freshwater flux from draining glacial lakes had to exceed 0.1 Sv (1 Sv = $10^6 \text{ m}^3 \cdot \text{s}$) to affect thermohaline circulation (and climate) in the North Atlantic (Ganopolski and Rahmstorf, 2002; Rahmstorf, 1995, 2000). The calculated volume of Glacial Lake Narragansett ($40 \times 10^9 \text{ m}^3$) represents a minimum value. Delta progradation and lakefloor deposition was time-transgressive as the ice sheet retreated north, making it difficult to calculate an instantaneous depth and volume of the lake. Glacial Lake Narragansett would have had to drain completely in $3 \times 10^5 \text{ s}$ (107 hr) to have exceeded this flux. While probably not exceeding this threshold, Glacial Lake

Narragansett does represent a significant volume of freshwater not accounted for in existing models of freshwater flux (Licciardi et al., 1999). The volume of one lake (i.e. Glacial Lake Narragansett) in conjunction with other lakes in the region (Glacial Lakes Connecticut, Taunton, Cape Cod Bay) may become significant if they drained at approximately the same time (i.e. at the onset of isostatic rebound). If future work can constrain drainage of the lakes, it may be possible to link these events with climate records in the North Atlantic.

Patterns in the seismic record

Individual reflectors in the seismic records of lakefloor deposits show distinct patterns, with dark reflectors (more intense) at intervals of ~0.75, 1.5, and 3 m. This layering pattern may reflect climate fluctuations. Possible causes could be decadal changes in sea surface temperatures due to the Atlantic Multidecadal Oscillation (AMO) (Delworth and Mann, 2000), or increased storminess in the northeast due to the El Nino-Southern Oscillation or North Atlantic Oscillation (Hoerling and Kumar, 2000; Hubeny, 2006; Rittenour et al., 2000; Rogers, 1984). Based on limited core samples collected in the Providence River, the average thickness of individual couplets was approximately 2 cm (Oakley and Boothroyd, 2012; Pickart, 1987). If this average is representative throughout the lake, each meter of lakefloor sediment represents approximately 50 years of deposition. The dominant intervals at 0.75 m and 1.5 m would represent ~35 years and 75 years of deposition respectively. These intervals coincide with the signal of the AMO, which has a periodicity ranging from 30 - 100 yr or more (Delworth and Mann, 2000). This is thought to be the result of

variability of thermohaline circulation in the Atlantic Ocean, and could point to the link between the climate in the North Atlantic and the deglacial evolution of the Laurentide Ice sheet.

Attempts to link the thickness of varves in central New England, with the climate records of Greenland suggest that there is a link between the rate of melting of the Laurentide Ice Sheet and Western Hemisphere climate (Ridge et al., 2012). Work by Rittenour et al., (2000) in Glacial Lake Hitchcock showed a strong periodicity in the varve record at an interval of 2 - 5 years, interpreted to represent variability induced by El Nino - Southern Oscillation. Rittenour et al., (2000) also report a signal with > 40 year variability that could represent the variability induced by the AMO, but was not discussed in detail. Additionally, no mention was made of the North Atlantic Oscillation, which has been recognized from Holocene sediment records in southern New England (Hubeny et al., 2006).

CONCLUSIONS

- Quaternary (glacial) depositional environments were interpreted from seismic facies identified from 800 km of high-resolution seismic reflection profiles collected throughout Narragansett Bay. These deposits were grouped into morphosequences, and mapped in a similar manner to traditional (terrestrial) Quaternary mapping.
- The retreat of the ice-sheet up present-day Narragansett Bay was systematic with five minor stillstands or fluctuations recorded by small recessional moraines. While lakefloor deposits are ubiquitous throughout, large deltas are limited to the western and upper portions of present-day Narragansett Bay, coincident with pre-glacial bedrock valleys.
- The near continuity of glacial lakefloor deposits throughout present-day Narragansett Bay and the elevation of the deposits relative to the projected water level of Glacial Lake Narragansett support the hypothesis that one large lake occupied present-day Narragansett Bay and extended into adjacent areas during Late Wisconsinan deglaciation.
- The prevalence of lacustrine fans deposited at the margin of the ice sheet throughout the study area indicates that subglacial meltwater was dominant throughout the lake basin. The distribution of the fans suggests that subglacial tunnels remained active in the same locations during retreat, and were mostly localized to the deepest portions of pre-glacial bedrock valleys.

- The spacing of the lacustrine fans and nature of subglacial drainage indicates that the Laurentide Ice Sheet was warm-based, and that drainage was focused into a distributed drainage system that flowed from the sides towards the bottom of valleys, forming larger single conduits for subglacial drainage.
- The volume of sediment deposited around and within present-day Narragansett Bay suggests that a very efficient drainage system existed under the Laurentide Ice Sheet during deglaciation, and multiple drainages were active during deposition of larger morphosequences. The amount of excavated sediment needed to account for this volume suggests either a pre-glacial (Illinoian) source of stratified sediment, and/or that sediment was transported from well beyond the present-day watershed of Narragansett Bay.
- The climate of the Laurentide during Late Wisconsinan deglaciation does not have a direct modern analog, and arguments persist that suggest aspects of temperate glaciers (i.e. the Malaspina in Alaska) or subarctic glaciers (i.e. Svalbard) are the closest possible examples. There is some similarity between the climate of coastal Greenland and models of the Laurentide Ice Sheet in the Late Wisconsinan
- The high-resolution seismic reflection profiles of lakefloor deposits show a distinct layering with spacing that may be related to variability induced by the Atlantic Multidecadal Oscillation.

ACKNOWLEDGEMENTS

The authors were supported by the Department of Geosciences, College of Environment and Life Sciences, University of Rhode Island and funded by the Rhode Island Coastal Resources Management Council Cooperative agreement 50A00311741; The Rhode Island SeaGrant Program BayMap Project and NOAA CSC grant NA06NOS4730220. Thanks to J. Alvarez, J. Allen, E. Lentz, C. Troskosky, T. Bottenus, M. Tarasevich (University of Rhode Island, Department of Geosciences) and M. Sutherland (University of New Hampshire) for assistance in the field. M. Borrelli (Provincetown Center for Coastal Studies) and T. Smith (U.S. Geological Survey) provided helpful comments on prior drafts of this manuscript.

REFERENCES:

- Allen, W.B., 1956, Ground-water resources of the East Greenwich quadrangle, Rhode Island. Geological Bulletin, 8, Rhode Island Industrial Commission, Providence, p. 56.
- Allen, W.B., and Gorman, L.A., 1959, Ground-water resources of the East Greenwich quadrangle, Rhode Island. Geological Bulletin, 8, Rhode Island Industrial Commission, Providence.
- Andersen, K.K., Svensson, A., Johnsen, S.J., Rasmussen, S.O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Peder Steffensen, J., Dahl-Jensen, D., Vinther, B.M., and Clausen, H.B., 2006, The Greenland Ice Core Chronology 2005, 15-42 ka. Part 1: constructing the time scale: Quaternary Science Reviews, v. 25, p. 3246-3257.
- Arnold, N., and Sharp, M., 2002, Flow variability in the Scandinavian ice sheet: modelling the coupling between ice sheet flow and hydrology: Quaternary Science Reviews, v. 21, p. 485-502.
- Ashley, G.M., Boothroyd, J.C., and Borns, H., 1991, Sedimentology of Late Pleistocene (Laurentide) deglacial-phase deposits, eastern Maine: an example of a temperate marine, grounded ice sheet margin, *in* Anderson, J.B., and Ashley, G.M., eds., Glacial marine sedimentation - paleoclimatic significance: Geological Society of America Special Paper 261: Boulder, CO, p. 141-191.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., and Schaefer, J.M., 2009, Regional beryllium-10 production rate calibration for late-glacial northeastern North America: Quaternary Geochronology, v. 4, p. 93-107.
- Balco, G., and Schaefer, J.M., 2006, Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England: Quaternary Geochronology, v. 1, p. 15-28.
- Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: Quaternary Science Reviews, v. 21, p. 2127-2135.
- Banerjee, I., and McDonald, B.C., 1975, Nature of esker sedimentation, *in* Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and glaciolacustrine sedimentation, Society of Economic Paleontologists and Mineralogists Special Paper 23, p 132-154.

- Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M.A., and Sole, A., 2010, Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier: *Nature Geosci.*, v. 3, p. 408-411.
- Bierschenk, W.H., 1954, Ground-water resources of the Bristol quadrangle, Rhode Island-Massachusetts. Rhode Island Industrial Commission Geological Bulletin, 7, Rhode Island Industrial Commission, Providence.
- Binghamn, R.G., Nienow, P.W., Sharp, M.J., and Boon, S., 2005, Subglacial drainage processes at a high Arctic polythermal valley glacier: *Journal of Glaciology*, v. 51, p. 15-24.
- Boothroyd, J.C., and August, P.V., 2008, Geologic and contemporary landscapes of the Narragansett Bay ecosystem, *in* Desbonnet, A., and Costa-Pierce, B.A., eds., *Science for ecosystem based management*, Springer, 507 p.
- Boothroyd, J.C., Freedman, J.H., Brenner, H.B., and Stone, J.R., 1998, Glacial geology of south and central Rhode Island, *in* Murray, D.P., ed., *Guidebook to Field Trips in Rhode Island and Adjacent Regions of Connecticut and Massachusetts*. New England Intercollegiate Geological Conference, 90th Annual Meeting: Kingston, Rhode Island., University of Rhode Island, p. C5-1 - C5-22.
- Boothroyd, J.C., and McCandless, S.J., 2002, Quaternary geologic map of Providence and East Providence Quadrangles: Kingston, RI, Rhode Island Geological Survey.
- , 2003, Quaternary Geologic map of the East Greenwich quadrangle, including parts of the Bristol and Crompton quadrangles: Kingston, RI, Rhode Geological Survey Open File Map 2003-01.
- Boothroyd, J.C., McCandless, S.J., and Dowling, M.J., 2003, Quaternary Geologic Map of Rhode Island: Kingston, RI, Rhode Island Geological Survey STATEMAP Program.
- Boothroyd, J.C., and Sirkin, L., 2002, The Quaternary geology of Block Island and adjacent regions, *in* Paton, P., Gould, L.I., August, P.V., and Frost, A.O., eds., *The Ecology of Block Island: Kingston, Rhode Island, Rhode Island Natural History Survey*, p. 13-27.
- Boothroyd, J.C., and Hehre, R.E., 2007, Shoreline change maps for Narragansett Bay and Islands, Rhode Island: Kingston, RI, Rhode Island Geological Survey.

- Broecker, W.S., 1997, Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO₂ upset the current balance? : *Science*, v. 278, p. 1582-1588.
- Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., and Wolfli, W., 1989, Routing of meltwater from the Laurentide ice sheet during the Younger Dryas cold episode: *Nature*, v. 341, p. 318-321.
- Bromwich, D.H., Toracinta, E.R., Oglesby, R.K., Fastook, J.L., and Hughes, T.J., 2005, LGM Summer climate on the southern margin of the Laurentide Ice Sheet: Wet or Dry: *Journal of Climate*, v. 18, p. 3317-3338.
- Colgan, P.M., Bierman, P.R., Mickelson, D.M., and Caffee, M.W., 2002, Variation in glacial erosion near the southern margin of the Laurentide Ice Sheet, south-central Wisconsin, USA: Implications for cosmogenic dating of glacial terrains: *Geological Society of America Bulletin*, v. 114, p. 1581-1591.
- Cowan, E.A., and Powell, R.D., 1991, Ice-proximal sediment accumulation rates in a temperate glacial fjord, southeastern Alaska, *in* Anderson, J.B., and Ashley, G.M., eds., *Glacial marine sedimentation - paleoclimatic significance*: Geological Society of America Special Paper 261: Boulder, CO, Geological Society of America, p. 61-73.
- Delworth, T.L., and Mann, M.E., 2000, Observed and simulated multidecadal variability in the Northern hemisphere: *Climate Dynamics*, v. 16, p. 661-676.
- Denny, C.S., 1982, *Geomorphology of New England*: U.S. Geological Survey Professional Paper 1208: Reston, VA, U.S. Geological Survey
- Dorion, C.C., Balco, G., Kaplan, M.R., Kreutz, K.J., Wright, J.D., and Borns, H.W., 2001, Stratigraphy, paleoceanography, chronology and environment during deglaciation of eastern Maine, *in* Weddle, T.K., and Rettle, M.J., eds., *Deglacial history and relative sea-level changes, northern New England and adjacent Canada*: Geological Society of America Special Paper 351: Boulder, CO.
- Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J., 2002, The Laurentide and Innuitian ice sheets during the Last Glacial Maximum: *Quaternary Science Reviews*, v. 21, p. 9-31.
- Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: *Geographie physique et Quaternaire*, v. 41, p. 237-263.

- Edgetech, 1998, Full-spectrum sub-bottom profiler; technical and users manual: Milford, MA. USA, EdgeTech.
- Ganopolski, A., and Rahmstorf, S., 2002, Abrupt glacial climate changes due to stochastic resonance: *Physical Review Letters*, v. 88, p. 038501.
- Gustavson, T.C., and Boothroyd, J.C., 1987, A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: A modern analog of the southeastern margin of the Laurentide Ice Sheet: *Geological Society of America Bulletin*, v. 99, p. 187-200.
- Halberg, H.N., Knox, C.E., and Pauszek, F., 1961, Water resources of the Providence area, Rhode Island. U.S. Geological Survey Water Supply Papers 1499-A.
- Hermes, O.D., Gromet, L.P., and Murray, D.P., 1994, Bedrock Geologic Map of Rhode Island: Rhode Island Map Series No. 1: Kingston, Rhode Island, University of Rhode Island.
- Hoerling, M.P., and Kumar, A., 2000, Understanding and Predicting Extratropical Teleconnections Related to ENSO, *in* Diaz, H.F., and Markgraf, V., eds., *El Niño and the Southern Oscillation, Multiscale Variability and Regional Impacts*: New York, University Press.
- Hooke, R.L., and Fastook, J.L., 2007, Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: implications for esker formation: *Journal of Glaciology*, v. 53, p. 646-658.
- Hooke, R.L., Wold, B., and Hagen, J.O., 1985, Subglacial hydrology and sediment transport at Bondhusbreen, southwest Norway: *Geological Society of America Bulletin*, v. 96, p. 388-397.
- Hubeny, J.B., 2006, Late Holocene climate variability as preserved in high-resolution estuarine and lacustrine sediment archives [Ph.D. thesis]: Narragansett, Rhode Island, University of Rhode Island.
- Hubeny, J.B., King, J.W., and Santos, A., 2006, Subdecadal to multidecadal cycles of Late Holocene North Atlantic variability preserved by estuarine fossil pigments: *Geology*, v. 34, p. 569-572.
- Johnson, K.E., 1962, Rhode Island parts of the Attleboro, Blackstone, Franklin, Oxford and Uxbridge quadrangles. RI Water Resources Division of USGS. Ground-water Maps. Map 19.

- Johnson, K.E., and Marks, L.Y., 1959, Wickford quadrangle, Rhode Island. RI Water Resources Division of USGS. Ground-water maps. Map 1.
- Kelley, J.T., Dickson, S.M., Belknap, D.F., Barnhardt, W.A., and Henderson, M., 1994, Giant sea-bed pockmarks: Evidence for gas escape from Belfast Bay, Maine: *Geology*, v. 22, p. 59-62.
- Koteff, C., and Pessl, F., 1981, Systematic ice retreat in New England: Geological Survey Professional Paper 1179: Washington, D.C., United States Government Printing Office, p. 1-20.
- Lewis, R.S., and Stone, J.R., 1991, Late Quaternary stratigraphy and depositional history of the Long Island Sound Basin: Connecticut and New York, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, eds., *Quaternary Geology of Long Island Sound and Adjacent Coastal Areas: Journal of Coastal Research, Special Issue 11*, p. 1-23.
- Licciardi, J.M., Teller, J.T., and Clark, P.U., 1999, Freshwater routing by the Laurentide Ice Sheet during the last deglaciation, *in* Clark, P.U., Webb, R.S., and Keigwin, L.D., eds., *Mechanisms of global climate change at millennial time scales, Volume Geophysical Monograph 112*, AGU, p. 177-201.
- Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S., 2006, Recent Greenland ice mass loss by drainage system from satellite gravity observations: *Science*, v. 314, p. 1286-1290.
- McMaster, R.L., 1960, Sediments of Narragansett Bay system and Rhode Island Sound, Rhode Island: *Journal of Sedimentary Research*, v. 30, p. 249-274.
- , 1984, Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, USA: *Sedimentology*, v. 31, p. 777-792.
- McMaster, R.L., and Ashraf, A., 1973, Subbottom basement drainage system of inner continental Shelf off Southern New England: *Geological Society of America Bulletin*, v. 84, p. 187-190.
- Mosher, S., 1983, Kinematic history of the Narragansett Basin, Massachusetts and Rhode Island; constraints on late Paleozoic plate reconstructions: *Tectonics*, v. 2, p. 327-344.

- Murray, D.P., Skehan, J.W., and Raben, J., 2004, Tectonostratigraphic relationships and coalification trends in the Narragansett and Norfolk Basins, New England: *Journal of Geodynamics*, v. 37, p. 583-611.
- Needell, S.W., O'Hara, C.J., and Knebel, H.J., 1983, Quaternary geology of the Rhode Island inner shelf: *Marine Geology*, v. 53, p. 41-53.
- NOAA-NOS, 1998, Narragansett Bay Nautical Chart 13221, United States - East Coast- Rhode Island Massachusetts, National Oceanic and Atmospheric Administration.
- Oakley, B.A., and Boothroyd, J.C., 2012, Constraining the age of Glacial Lake Narragansett and the deglacial chronology of the Laurentide Ice Sheet in southeastern New England: In prep.
- Peck, J.A., 1989, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay [Masters thesis]: Kingston RI, University of Rhode Island.
- Peck, J.A., and McMaster, R.L., 1991, Stratigraphy and geologic history of Quaternary sediment in Lower West Passage, Narragansett Bay, Rhode Island, *in* Gayes, P.T., Lewis, R.S., and Bokuniewicz, ed., *Quaternary Geology of Long Island Sound and Adjacent Coastal Areas*, *Journal of Coastal Research*, Special Issue 11, p. 25-37.
- Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: *Quaternary Science Reviews*, v. 25, p. 3322-3337.
- PIC, 2008, Rhode Island E911 Uniform Emergency Telephone System, Pictometry International Corporation, 2008. Pictometric Licensed Images (Spring 2008), Rhode Island Digital Atlas, Environmental Data Center, University of Rhode Island, Kingston, RI.
- Pickart, D.S., 1987, Physical stratigraphy and geological evolution of the Providence River, Narragansett Bay, Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island.
- Powell, R.D., 1991, Grounding-line systems as second-order controls on fluctuations of tidewater termini of temperate glaciers, *in* Anderson, J.B., and Ashley, G.M., eds., *Glacial marine sedimentation - paleoclimatic significance*: Geological Society of America Special Paper 261: Boulder, CO, Geological Society of America, p. 75-93.

- Rahmstorf, S., 1995, Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle: *Nature*, v. 378, p. 145-149.
- , 2000, The thermohaline ocean circulation: a system with dangerous thresholds?: *Climatic Change*, v. 46, p. 247-256.
- Reck, B.H., and Mosher, S., 1988, Timing of intrusion of the Narragansett Pier Granite relative to deformation in the southwestern Narragansett Basin, Rhode Island: *The Journal of Geology*, v. 96, p. 677-692.
- Ridge, J.C., 2003, The last deglaciation of the Northeastern United States: A combined varve, paleomagnetic and calibrated ^{14}C Chronology, *in* Hart, J.P., and Cremeens, D.L., eds., *Geoarcheology of landscapes in the glaciated Northeast*: New York State Education Department, Albany, New York.
- , 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J., and Gibbard, P.L., eds., *Quaternary glaciations - extent and chronology: Part II: North America. Developments in Quaternary Science, Volume 2B*: Amsterdam, Elsevier, p. 163-193.
- Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B., and Wei, J.H., 2012, The new North American Varve Chronology: A precise record of southeastern Laurentide Ice Sheet deglaciation and climate: 18.2-12.5 kyr BP: *American Journal of Science*, v. In press.
- Rittenour, T.M., Brigham-Grette, J., and Mann, M.E., 2000, El Nino-like climate teleconnections in New England during the Late Pleistocene: *Science*, v. 288, p. 1039-1042.
- Rogers, J.C., 1984, The association between North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere: *Monthly Weather Review*, v. 112, p. 1999-2015.
- Rogers, J.N., Kelley, J.T., Belknap, D.F., Gontz, A., and Barnhardt, W.A., 2006, Shallow-water pockmark formation in temperate estuaries: A consideration of origins in the western gulf of Maine with special focus on Belfast Bay: *Marine Geology*, v. 225, p. 45-62.
- Roksandic, M.M., 1976, Seismic facies analysis concepts: *European Association of Exploration Geophysicists*, p. 1.
- Schafer, J.P., 1961, Surficial geology of the Wickford Quadrangle, Rhode Island: Washington, DC., US Geological Survey, Quadrangle Map GQ-136.

- Schafer, J.P., and Hartshorn, J., 1965, The Quaternary of New England, *in* Wright, J., and Frey, D., eds., The quaternary of the United States: Princeton, N.J., Princeton University Press, p. 113-127.
- Shreve, R.L., 1972, Movement of water in glaciers: *Journal of Glaciology*, v. 11, p. 205-214.
- Sirkin, L.A., 1976, Block Island, Rhode Island-evidence of fluctuation of the Late Pleistocene ice margin: *Geological Society of America Bulletin*, v. 87, p. 574-580.
- Smith, T.L., 2010, A conceptual model of the deglaciation of southern Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island
- Stone, B.D., and Borns, H., 1986, Pleistocene glacial and interglacial stratigraphy of New England, Long Island and adjacent Georges Bank and Gulf of Maine, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary glaciations in the Northern Hemisphere: New York, Pergamon, p. 39-52.
- Stone, B.D., and Peper, J.D., 1982, Topographic control of the deglaciation of eastern Massachusetts: ice lobation and the marine incursion, *in* Larson, G.J., and Stone, B.D., eds., Late Wisconsinan glaciation of New England: Dubuque, Kendall-Hunt.
- Stone, B.D., and Sirkin, L.A., 1996, Geology, *in* Veeger, A.I., ed., Hydrogeology and Water Resources of Block Island, Rhode Island: Providence, RI, U.S. Geological Survey.
- Stone, B.D., and Stone, J.R., 2005, Sedimentary facies and morphosequences of glacial meltwater deposits, *in* Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., ed., Quaternary geologic map of Connecticut and Long Island Sound basin, US Geological Survey Scientific investigations map 2784, scale 1:125,000, p. 72.
- Stone, J.R., and Ashley, G.M., 1992, Ice-wedge casts, pingo scars, and the drainage of Glacial Lake Hitchcock, *in* Robinson, P., and Brady, J.B., eds., Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts and Adjacent States, v. 2 (84th Annual meeting of the New England Intercollegiate Geological Conference): Amherst, MA, University of Massachusetts, Geology Department, Contribution 66, p. 305-331.
- Stone, J.R., Shafer, J.P., London, E.H., DiGiacomo-Cohen, M., Lewis, R.S., and Thompson, W.B., 2005, Quaternary Geologic Map of Connecticut and Long

- Island Sound Basin, U.S. Geological Survey Geologic Investigations Series Map I-2784, scale 1:125,000, 2 sheets and pamphlet. p. 1-72.
- Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P., 2011, Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage: *Nature*, v. 469, p. 521-524.
- Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Rasmussen, S.O., Röthlisberger, R., Peder Steffensen, J., and Vinther, B.M., 2006, The Greenland Ice Core Chronology 2005, 15-42 ka. Part 2: comparison to other records: *Quaternary Science Reviews*, v. 25, p. 3258-3267.
- Thompson, W.B., and Borns, H., 1985, *Surficial Geologic Map of maine: Augusta, ME*, Maine Geological Survey.
- Trimble, 2004, Trimble DSM132 DGPS Reciever Fact Sheet: Dayton, Ohio, Trimble Geomatics and Engineering Division.
- Upton, J.E., and Spencer, C.W., 1964, *Bedrock Valleys of the New England Coast as Related to Fluctuations of Sea Level: U.S. Geological Survey Professional Paper 454-M*, p. 1-31.
- USACE, 1957, *Hurricane survey interim report: Narragansett Bay Area, Rhode Island and Massachusetts: Boston, MA, Corps of Engineers, U.S Army Office of the Division Engineer*.
- , 2001, *Drilling Logs: Providence CAD Explorations, New England District of the U.S. Army Corps of Engineers*.
- Ussler, W., Paull, C.K., Boucher, J., Friederich, G.E., and Thomas, D.J., 2003, Submarine pockmarks: a case study from Belfast Bay, Maine: *Marine Geology*, v. 202, p. 175-192.
- Vail, P.R., Mitchum, R.M., Todd, R.G., and Thompson, S., III, 1977, Seismic stratigraphy and global changes in sea level, part 3: relative changes in sea level from coastal onlap, *in* Payton, C.E., ed., *Seismic stratigraphy - applications to hydrocarbon exploration*, American Association of Petroleum Geologists, memoir 26, p. 63-81.
- Vinhateiro, N.D., King, J.W., Robinson, R.S., and Reddy, C.M., 2007, Holocene stratigraphy and environmental history of a shallow water embayment in

Narragansett Bay, RI, Abstracts of papers, Estuarine Research Federation:
Providence, RI.

Vinher, B.M., Andersen, K.K., Jones, P.D., Briffa, K.R., and Cappelen, J., 2006,
Extending Greenland temperature records into the late 18th century: *Journal of
Geophysical Research*, v. 111, p. 13.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002,
Surface melt-induced acceleration of Greenland Ice-sheet flow: *Science*, v.
297, p. 218-222.

Figure 1: Shaded relief map of Narragansett Bay showing the geographic subdivisions discussed in the text and the locations of figures 2-5. EP: East Passage, WP: West Passage, SP: Sakonnet Passage, GB: Greenwich Bay, UB: Upper Bay, MHB: Mount Hope Bay, PR: Providence River, SR: Seekonk River. Inset map shows the location of sub-bottom seismic reflection profiles collected for this study.

Figure 2: A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile from the West Bay of Narragansett Bay showing facies T/R, GLF and M. See figure 1 for location

Figure 3: A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile showing facies T/R, PF, DF, GLF and M. See figure 1 for location

Figure 4: A. Sub-bottom seismic reflection profile of the Dutch Island delta, lower West Passage, Narragansett Bay. B. Interpreted seismic reflection profile showing facies DS, GLF and M. See figure 1 for location.

Figure 5: A. Sub-bottom seismic reflection profile from upper Narragansett Bay. B. Interpreted seismic reflection profile showing facies T/R, GLF, E, M and NG. See figure 1 for location

Figure 6: Thickness of stratified deposits in Narragansett Bay

Figure 7: Correlation diagram of Quaternary deposits in the southern portion of Narragansett Basin. Deposits are grouped by geographic sections of Narragansett Bay. Correlation with moraine deposits west of Narragansett Bay (Boothroyd and McCandless, 2003; Schafer, 1961; Smith, 2010) are shown on the left; uncorrelated deposits are shown on the right side.

Figure 8: Recessional ice-margins of Narragansett Bay and adjacent areas. Positions correlated with margins outside of Narragansett Bay are modified from Smith (2010). Red lines indicate the margin of the ice sheet marked by a lacustrine fan.

Figure 9: Extent of glacial lakefloor deposits throughout mapped throughout Narragansett Bay

Figure 10: The elevation of the upper surface of lakefloor sediment digitized from seismic reflection profiles throughout Narragansett Bay and the elevation of the delta plain-delta slope contact used as a proxy for water level of Glacial Lake Narragansett. Delta abbreviations: PR – Pettaquamscutt River, DI – Dutch Island, AN- Annaquatucket, IP –Island Park, PO – Potowomut, WP – Warwick Plains, BT- Barrington, RIV – Riverside, PP – Providence Plains, EPP – East Providence Plains, SH – Smith Hill, BLR – Blackstone River

Figure 11: Minimum water depths within Glacial Lake Narragansett

Figure 12: Schematic model of lacustrine fan deposition in Glacial Lake Narragansett. A: Fan deposition at the margin of the Laurentide Ice Sheet. Note meltwater from Moulin reaching the base of the ice sheet and the dominance of subglacial meltwater and density underflows (Modified from Gustavson and Boothroyd, 1987). B: Same area after the ice margin had retreated north. The 'stacked' fans suggest that the ice tunnels are staying in approximately the same location an extended period (years). Glacial lakefloor deposits have buried the entire sequence as the ice sheet retreated north.

Figure 13: Location of proximal lacustrine fans in Narragansett Bay. Dashed black lines represent the thalweg of the bedrock valleys identified by Upson and Spencer (1964). Fans likely exist in the upper East Passage and Sakonnet River, but seismic penetration was limited in these areas.

CHAPTER 5

Benthic geologic habitats of shallow estuarine environments: Greenwich Bay and Wickford Harbor, Narragansett Bay, Rhode Island, USA

Accepted for publication in the Journal of Coastal Research, 8 December, 2011

Bryan A. Oakley¹, Jonathan D. Alvarez² and Jon C. Boothroyd^{1,3}

1. Department of Geosciences, College of the Environment and Life Sciences,
University of Rhode Island, Kingston, RI, USA
2. ESS Group, Inc, 401 Wampanoag Trail, Suite 400, East Providence, RI, USA
3. State geologist, Rhode Island Geological Survey, Kingston, RI, USA

ABSTRACT

An integrated mapping approach using high-resolution side-scan sonar, surface sediment grab samples, digital aerial and orthophotography and underwater video imagery was used to map Holocene sediment cover and Late Wisconsinan glacial outcrop in two shallow embayments in Narragansett Bay, Rhode Island, USA. The use of side-scan sonar to characterize the seafloor has become common in a variety of different marine environments. Challenges remain in classifying side-scan or other acoustic data into a naming convention that is useful to scientists and managers. We characterize the benthic geologic habitats of these areas utilizing a flexible naming convention that combines information about geologic processes, morphologic form, particle size, biota, and anthropogenic impacts. Benthic geologic habitats were separated into three habitat groups (depositional environments) (Estuarine bayfloor, estuarine cove and estuarine marginal habitats), and further divided based on morphologic form, surface sediment texture, geologic features, biologic characteristics, and anthropogenic impacts. There is a general trend of decreasing grain size with increasing distance from the open water of Narragansett Bay, however, the types and distribution of facies is complicated, and this work adds to the developing sedimentary models of estuaries. The methods outlined in this paper has been successfully applied in other estuarine, lagoon and shoreface environments, providing a concise method of imaging and characterizing benthic geologic habitats on the seabed.

INTRODUCTION

The objective of this work was to understand the benthic geologic habitats and geologic processes within two important areas of Narragansett Bay and describe them with a naming convention understandable by managers and non-geologists at a scale useful in a wide variety of applications. The high-resolution of the side-scan records and aerial photographs allow for detailed delineation of map units, and identification of geologic features and anthropogenic impacts. The results of this work contribute to the overall understanding of the distribution of depositional environments in microtidal estuaries.

BENTHIC GEOLOGIC HABITATS

A habitat is a spatially recognizable area with physical, chemical and biological characteristics that are distinctly different from surrounding areas (Valentine et al., 2005). We propose that a benthic geologic habitat is a spatially recognizable area with geologic characteristics that are distinctly different from surrounding areas. Identification of these habitats is done using side-scan records in conjunction with ground-truth data and existing or estimated tidal current, wind, and wave information. The definition we propose is analogous to depositional environments, a term often used in geologic mapping. Because many non-geologists are unfamiliar with the concept of depositional environments, we adopted the term benthic geologic habitat (Boothroyd and August, 2008). It has been pointed out that referring to interpretive maps of the seafloor as ‘habitat’ maps is problematic without specific details on the association between species or populations and different areas

of the seafloor, and a better term would be ‘potential’ habitats (Greene et al., 2007). We feel that our definition of benthic geologic habitats are analogous to the ‘potential habitats’ defined by Greene et al. (2005), without any connotation of possible correlation with species or populations beyond those visible in the side-scan sonar imagery.

Challenges remain in classifying side-scan or other acoustic data into a naming convention that is useful to scientists and managers, and numerous classification schemes have been proposed (Barnhardt et al., 1998; Goff et al., 2000; Greene et al., 1999; Kennish et al., 2004; Nitsche et al., 2004; Valentine et al., 2005). These existing schemes are not applicable in complex estuarine environments, which we map at very large scales (1:10,000 or 1:5,000). Cowardin et al. (1979), which is commonly applied to estuarine and lagoon environments, uses a hierarchical approach that would classify both study sites simply as ‘Estuarine, Subtidal, Unconsolidated Bottom’, with further delineation based only on sediment texture.

Recent attempts at creating a national standard for ecological mapping (CMECS; Madden et al., 2010) were examined. We feel that the segmented nature of this largely ecologically based classification scheme, which separates the morphologic form (Geoform), surface sediment characteristics (Surficial Geology) and biological attributes (Benthic Biota) into different components is overly complicated. Our classification scheme provides a concise way to describe the morphologic form, surface sediment texture and other characteristics identifiable in side-scan sonar imagery, using a naming convention that combines information from particle size ,

geologic processes, depositional environment, and also biota and anthropogenic impacts (Boothroyd and August, 2008; Oakley et al., 2007).

The interdisciplinary nature of marine mapping makes it important to report data in a manner useful to managers and scientists in fields other than geology. Shumchenia and King (2011) simplified the benthic geologic habitats from Greenwich Bay into silty (low-energy basin and bay channel habitats) and sandy (depositional platforms and bayfloor sand sheets) geologic habitats. This grouping coincided with the broad scale assemblages of benthic macrofauna, and showed a good example of combining the spatial coverage of ‘top down’ acoustic based mapping with biologically based ‘bottom up’ information.

STUDY SITES

Narragansett Bay is a microtidal estuary located in eastern Rhode Island and southeastern Massachusetts that is an important resource for fishing, maritime transportation, tourism, recreation, shipbuilding, defense and manufacturing (Harrington, 2000). Mapping the geologic characteristics of the estuary has become a focal point of several recent projects (CRC, 2005; Stolt et al., 2011). Greenwich Bay (12 km²) and Wickford Harbor (1.6 km²), Rhode Island, two shallow, east-west trending embayments of Narragansett Bay (Figure 1) were mapped using a combination of side-scan sonar, underwater video imagery, surface sediment grab samples, high-resolution aerial photographs, and digital orthophotographs..

Greenwich Bay contains a large central basin, and four, north to south trending coves (Figure 1). Depths in the central basin range from 1 - 2 m on the shallow depositional platforms, up to 12 m at the deep channel at the entrance of Greenwich Bay. The average depth of the coves is 1 - 3 m, except where dredged channels are 2.5 - 4 m deep. The entrance to Wickford Harbor is formed by two rubble mound breakwaters with a 150 m opening reduce wave-energy in the harbor (Figure 1). The overall geomorphology is similar to that of Greenwich Bay, with relatively deeper central basins and three north to south trending coves (Figure 1). Water depths in Wickford Harbor are mostly shallower than 2 m, except for the outer harbor (4 m) and the dredged navigation channels (2 – 3 m).

Present-day Narragansett Bay lies within Narragansett Basin. The underlying bedrock is the Rhode Island Formation, a coarse to fine-grained metamorphosed sedimentary rock (Hermes et al., 1994). Narragansett Bay is located within the Late Wisconsinan glacial limit, and both study sites are underlain by a variety of sediment types, including glacial fluvial sand and gravel, glacial lakefloor silt and clay, and till. Marine water first inundated Narragansett Bay after 10,200 yBP (sea level 30 m below present) (all ages reported in calendar ages before present) (Boothroyd and August, 2008; McMaster, 1984). Greenwich Bay was flooded between 6,500 and 5,000 yBP (sea level 5 m below present), Wickford Harbor between 4,000 and 2,500 yBP (sea level 2.5 to 4 m below present) (Boothroyd and August, 2008; McMaster, 1984). Present-day Narragansett Bay is microtidal (spring tidal range 1.2 m at Newport, 1.5 m at Providence), and a mixed-energy estuary according to the classifications of Dalrymple et al. (1992) and Hayes (1979).

Greenwich Bay is bracketed by glacial deltas to the north and south (Boothroyd and McCandless, 2003). The eastern shoreline of Greenwich Bay is comprised of till, containing a mixture of gravel, sand, silt and clay, while the western shoreline is a mixture of coarse grained, ice-marginal sand and gravel (Boothroyd and McCandless, 2003). Wickford Harbor is located entirely within a glacial delta, and the deeper areas of the harbor likely represent ice-block basins, now inundated with marine water. The north to south trending coves in both sites likely formed by spring sapping, similar to those on southeast shore of Massachusetts (FitzGerald et al., 2002; Boothroyd and August, 2008), with the exception of Greenwich Cove, which may occupy the location of a collapsed ice-margin of the retreating Laurentide Ice Sheet (Boothroyd and McCandless 2003).

Both sites support commercially important shellfish, finfish, migratory birds and other aquatic wildlife essential to the ecosystem of Narragansett Bay, and are popular recreational areas for boating, kayaking, fishing, and swimming (Joubert and Lucht, 2000; Dalton et al., 2010). These factors, along with evidence of declining water quality (fish kills, disappearance of eelgrass beds and shellfish closures) led to the creation of a process by the Rhode Island Coastal Resources Management Council to create a Special Area Management Plan (SAMP) for Greenwich Bay and surrounding watershed. The types and extent of benthic geologic habitats were mapped in Greenwich Bay to assist with the creation of this plan. Mapping in Wickford Harbor was completed as part of the ongoing MapCoast project, which has a goal to map, inventory, describe, and classify sediment and subaqueous soils in Rhode Island waters shallower than 5 m (<http://www.mapcoast.org>).

METHODS

Side-scan sonar

Between 2003 and 2006, 210 km of high-resolution (500 kHz, 100 m swath width) side-scan sonar data were collected in Greenwich Bay and Wickford Harbor using an towed EdgeTech 272TD side-scan sonar system (Average vessel speed $1.8 \text{ m} \cdot \text{s}^{-1}$), spatially located using a Trimble Differential GPS with a reported accuracy $< 1 \text{ m}$ (Trimble, 2004). Side-scan records were processed using Chesapeake Technologies SonarWebTM software, and individual data files were manually bottom tracked, adjusted for variations in contrast and time-varied gain, and a slant range correction was applied to correct for the elevation of the towfish above the bay bottom (Fish and Carr, 1990). Side-scan files were combined into a single mosaic of each study site, with a pixel size of 0.3 m (ground distance). The mosaics were exported as a GeoTiff for analysis in a Geographic Information System (GIS), displayed using an inverse medium yellow-orange known as a ‘Klein’ color scheme.

Side-scan data interpretation

Side-scan records are interpreted based on the texture and intensity of the returning acoustic energy, and spatially recognizable areas with different backscatter patterns represent side-scan sonar facies. Geologic facies are sediment or rock with certain readily identifiable characteristics such as color, particle size, sorting, structure, biologic content, plus others, discernable in either the field or laboratory (Walker, 1990). Side-scan sonar facies are the geologic facies interpreted using the strength and texture of the returning sonar signal; in general, the harder (or denser) the

bottom, the stronger the return signal and the darker the side-scan sonar record (using an inverse color scheme) (Goff et al., 2000). This relationship is complicated by bed roughness, vegetation and bioturbation (Nitsche et al., 2004), and surface sediment samples and underwater video imagery were collected to aid interpretation.

Facies boundaries were manually digitized directly onto the digital mosaic at a scale of 1:1,000 (the limit of pixilation) using MapInfo™ GIS software. Identification of features too small to be resolved on the mosaics was aided using digital, ungeoreferenced ‘waterfall’ side-scan images, which have a pixel size of approximately 5 cm (ground distance). The shapefile created was imported into ESRI ArcMap v. 9.3 GIS software, projected in Rhode Island State Plane Feet, relative to the North American Datum, 1983 and polygons were assigned a facies name and symbol. Minimum polygon size was 300 m². Smaller identified features (i.e. boulders, sunken boats) were assigned a point feature.

Surface sediment samples

Surface sediment grab samples (n = 48), were collected using a Petite Ponar™ sampler. Samples were spatially located using the same DGPS utilized in the side-scan survey, and were photographed and described in the field. Selected samples were analyzed using standard sieve and pipette techniques outlined by (Folk, 1980). Additional sediment samples (24), collected by McMaster (1960) were downloaded from the United States Geologic Survey (USGS) East Coast sediment texture database (Hastings et al., 2000). Particle sizes are based on Udden (1914) and Wentworth

(1922). Sediment texture is classified using a modified version of the Shepard (1954) naming convention (Figure 2).

Underwater imagery

Limited underwater video imagery was collected in both Greenwich Bay (C. Deacutis, personal communication) and Wickford Harbor. Video imagery in Wickford was collected using a SeaViewer Sea-DropTM color digital video camera. A similar, analog system was used in Greenwich Bay. Files were played back in the lab, and qualitative observations were made regarding sediment texture, geologic features, and biologic characteristics. Visibility in both sites was poor, which reduced the field of view, and limited the usefulness of the video imagery, particularly in muddy environments. Diver collected photographs and interpreted aerial photographs (Bradley et al., 2007), provided additional ground-truth in Wickford Harbor.

Aerial photography

Vertical aerial photographs were used to delineate geologic habitats in shallow (< 2 m) subtidal areas. Polygons created by Boothroyd and Galagan (1992) were fit to orthophotographs flown in the spring and summer of 2003 (USDA-FSA, 2003; RIDOT, 2005). The original interpretation were validated against the side-scan sonar mosaic, 2003 orthophotographs and 1996 aerial photographs, and minor revisions were made as needed. The orthophotographs and vertical aerial photographs provided a visual check for interpretations, as well as clues into the presence/absence and year-to-year persistence of macroalgae seen on side-scan records in Wickford Harbor.

Naming convention of benthic geologic habitats

Benthic geologic habitats were named based on the interpreted depositional environment, abbreviated with a one to three letter acronym (Table 1), sediment texture, and a descriptor if applicable. The names and abbreviations of depositional environments were modified from those presented in Boothroyd et al. (1985) for coastal lagoons along the Rhode Island south shore, which in turn were based on units from Fisher et al., (1972) (Table 1). Grainsize is abbreviated as Gravel (g), sand (sa) and silt (si), with additional classes of fine (f) or coarse (c). Sediment containing more than 5% organic matter (dry weight) was classified as organic (o). Habitats where sediment texture was not determined were mapped as undifferentiated (u) (Table 2). Descriptors are based on characteristics seen on the side-scan imagery, and can be verified in the underwater video imagery and aerial photography. These descriptors are frequently biological characteristics (i.e. presence of macroalgae or submerged aquatic vegetation, indicated by a (v) for macroalgae, or (e) for eelgrass, but could also refer to anthropogenic or geological features. A summary of the benthic geologic habitats is shown in table 3. The key to this naming convention is the flexibility, and new depositional environments, descriptors, and additional sediment textures can be added as needed in new study areas.

RESULTS

Benthic Geologic Habitats

Benthic geologic habitats were grouped into three main geologic habitat groups (depositional environments) in both study sites, (estuarine bayfloor, estuarine cove, and estuarine marginal environments), and further divided based on morphologic form (i.e. basins, flats, tidal deltas etc.). The distribution of these habitats can be seen in figures 3 and 4. The general color scheme for is red for gravel, yellows for sand, browns for mud and brown-green or green for macroalgae or submerged aquatic vegetation. Inlet channels, dredged channels, marinas, and distributary deltas are in blue.

Estuarine Bayfloor

Boulder gravel pavement (Pvbg)

A distinct habitat composed primarily of pebbles, cobbles, and large (up to 6 m diameter) boulders was mapped at the entrance of Greenwich Bay. The boulders in this habitat are not transported, and the relatively high tidal energy (compared to the adjacent basins) inhibits the deposition of finer grained sediment.

Shell reef (Shr)

This habitat exists only in a small area of western Wickford Harbor, where it was visible in side-scan sonar records and digital orthophotographs. Field

observations show it to be comprised of intact shells and fragments of eastern oyster (*Crassostrea virginica*) with some slipper shells (*Crepidula fornicata*). This is likely not a drowned oyster reef (portions are intertidal), which would have been 1-2 m below mean lower low water (McCormick-Ray, 2005). No shell middens have been reported for this location. This probably represents the placement of dredged materials adjacent to a small dredged navigation channel.

Bayfloor sand sheets (Sssa)

Adjacent to the depositional platforms, areas of the bayfloor identified by a moderate to dark side-scan return are interpreted as bayfloor sand sheets. Sediment samples from these habitats were > 90% sand. These habitats often have tidal or wave- generated bedforms visible on side-scan or video imagery.

Low-energy basins (Leb)

The areally most extensive habitats in both Greenwich Bay and Wickford Harbor are identified by a low-backscatter, featureless side-scan return (Figure 5A) which generally indicates fine-grained sediment, and are mapped as low-energy basins. Habitats mapped as low-energy basin silt (Lebsi) have surface sediment samples with 50 - 94% silt, classified as sandy silt, silt or clayey silt. The edges of the basins are often flanked by a facies with a slightly higher backscatter (darker side-scan return) than the central part of the basins. Grain-size in these environments contained 40 - 60% silt and was classified as silty sand to sandy silt, and was mapped as low-energy basin coarse silt (Lebsic). Areas with abundant macroalgae, either attached or

drift were mapped as low-energy basin silt, vegetated (Lebsiv), and habitats with eelgrass were limited to Wickford Harbor, mapped as low-energy basin silt with eelgrass (Lebsie). Units with > 5% organic carbon were classified as low-energy basin organic silt (Lebsio).

Bay channels (Bc)

The bay channel geologic habitats encompass a variety of energy levels and grain-sizes, primarily related to variations in tidal current velocity. Bay channels connect adjacent low-energy basins, and incised channels are common in many estuarine environments (Dalrymple et al., 1992). Channel habitats range from sandy (Bcsa) in the channel connecting the inner and outer harbor in Wickford, to organic silt (Bcsio) in both Greenwich Bay and Wickford Harbor.

The descriptor, 'patches' (p) was used to describe two habitats in the bay channel in Greenwich Bay (Figure 3) (Bcsip, Bcsiop), based on features seen in the side-scan mosaic. These features are 1-5 m in diameter, with a hard (dark) side-scan return (Figure 5B). The origin of these features is enigmatic. The larger features (3-5 m) were first mapped as pockmarks caused by methane gas escape from the sediment (Boothroyd and August, 2008; Boothroyd and Oakley, 2005), which are common in other estuaries in the northeast (Kelley et al., 1994). Sub-bottom seismic reflection profiles through this habitat show none of the characteristics of pockmarks or pockmark fields (e.g. depressions, gas wipeouts) (Rogers et al., 2006). It is now thought these represent aggradations of shelled bivalves, however these were not seen in the sediment samples or limited video from this area. Given the nature of these

ground-truth methods and relatively small size of the features, a sample needs to be collected directly on an aggradation to confirm this interpretation.

Estuarine Cove

North to south trending coves extend off the central basins in both study sites.

These coves are narrow (generally less than 300 m across at the entrance); extend off the main basins < 2200 m with water depths generally less than 2 m, except dredged channels up to 4 m deep.

Low-energy basins (Leb)

Low-energy basins occupy the deeper areas of coves and have a very light side-scan return that indicates fine-grained sediment. Surface sediment samples range from sandy silt to silt or clayey silt containing 50 - 95% silt and were mapped as low-energy basins. These areas tend to be finer-grained (silt to clayey silt) with higher organic content (5 - >10%) than low-energy basins in the less protected basins of Greenwich Bay and Wickford Harbor, and were mapped as low-energy basin silt (Lebsio).

Inlet Channels (Ci, Cf, Ce, Cd)

Inlet channels at the mouth of the coves in both study sites contain natural (Ci, Cf, Ce) and dredged channels (Cd). Natural inlet channels are generally sandy (Cisa), and were further subdivided into ebb (Cesa) or flood channels (Cfsa) depending on

the horizontal segregation of tidal currents around tidal deltas (Boothroyd, 1985). Representative samples from dredged channels contained 85-90 % silt and were mapped as dredged channel silt (Cdsi).

Tidal deltas (Df, De)

A flood-tidal delta and some features of an ebb-tidal delta were mapped at the entrance of Brushneck Cove in central Greenwich Bay. The flood-tidal delta was mapped as Dfsa. Individual units within the flood-tidal delta (i.e. flood ramp) were not mapped due to the small size of the delta and the map scale (1:10,000). The only obvious features of an ebb-tidal delta were channel marginal linear bars (Decm) that flank the inlet channel. The geomorphic features of these tidal deltas, including the associated ebb and flood-channels are mapped using the terminology described by Hayes, (1975).

Estuarine marginal habitats

Estuarine marginal environments are those that are immediately adjacent to, and often continuous with similar upland environments (i.e. a sandy depositional platform extends landward to a sandy intertidal beach). This work focused on subtidal geologic habitats, although many of these features extend into the intertidal areas. These habitats were broadly classified as erosional (terraces) or depositional (platforms, distributary deltas, tidal deltas and tidal flats).

Erosional habitats

Terraces (Te)

Wave-eroded terraces have formed narrow bands of coarse-grained sediment (sand to boulders) in areas of high wave action, and are mapped as gravel erosional terraces (Teg). Erosional terraces have a dark return on side-scan records, with large cobbles and small boulders visible on both the side-scan and aerial imagery. This habitat was mapped in eastern Greenwich Bay (Figure 3), and southeastern Wickford Harbor (Figure 4). Some portions contain abundant macroalgae attached to the individual cobbles and boulders, and are mapped as vegetated gravel-erosional terrace (Tegv).

Depositional habitats

Platforms (Dp)

Depositional platforms are spatially the most extensive habitats in the marginal areas of Wickford Harbor and Greenwich Bay, (up to 500 m wide) (Figures 3, 4), distinguished by a moderately dark, generally featureless side-scan return. Tidal bedforms, wave ripples, and wave-formed bars were mapped within portions of the habitat (Figure 3). Surface sediment samples contain 80-100% sand, with sand to gravel sized shell-fragments. This habitat was mapped as depositional platform sand (Dpsa). Areas with persistent macroalgae or submerged aquatic vegetation were mapped as Dpsav.

Distributary deltas (Dd)

Triangular, fan shaped deposits have formed at the mouth of many of the tidal creeks that empty into both study sites. These small distributary deltas extend from the intertidal into shallow sub-tidal areas, and are generally composed of sand-sized material.

Tidal flats (F)

Tidal flats are common in the coves of both Greenwich Bay and Wickford Harbor, and ranged from sandy (Fsa) to muddy (Fsm). Mud flats with attached or drift macroalgae were mapped as vegetated (Fsmv). These flats fringe deeper channels or basins, and are less than 300 m wide. Water depths on these flats are typically less than 1 m at mean lower low water.

Dredged marina basins (Md)

Greenwich Bay and Wickford Harbor are prominent boating harbors. Many of the sheltered areas are developed with marinas and wharves, and portions of the tidal flats have been dredged. These areas were mapped as dredged marina basins (sand or silt), (Mdsa, Mdsi). Where the grainsize was not determined, units were mapped as undifferentiated dredged marina basins (Mdu).

Geologic features

Wave-formed bars

Large bedforms were found on the depositional platform and on the bayfloor sand sheet in Greenwich Bay (Figure 5D), identified by a moderate acoustic return with distinct bar forms (>100 m in length, crest to crest spacing 10 - 300 m). The bars do not appear to be shore connected. Most of the bars on the depositional platform in northern Greenwich Bay are sub-parallel to the shoreline although a few are oriented perpendicular to the shoreline. Wave-formed bars were not present in Wickford Harbor.

Tidal bedforms

Tidal bedforms (Figure 5C) were identified on the side-scan record in the southwest corner of Greenwich Bay (Habitats Sssa and Dpsa), in an area influenced by strong tidal-current flow. These bedforms are medium to large (crest to crest spacing 5 - 15 m) 2-D and 3-D dunes using the terminology of Ashley et al. (1990). The current velocity necessary to form the 3-D dunes is at least 80 cm s^{-1} (Boothroyd and Hubbard, 1975). Modeled and observational data suggests a height of approximately 0.6 m (Boothroyd, 1985). They appear to be ebb oriented; however, determining orientation of low-amplitude bedforms from side-scan records can be problematic.

Bedrock

Bedrock outcrops are not common in or adjacent to either study site. One small outcrop of Rhode Island Formation (Hermes et al., 1994) in the northern portion of Mill Creek in Wickford occurs as a small island, mapped as (Bdrx) (Figure 4).

Isolated boulders (within other habitats)

Isolated large boulders up to 5 m diameter crop out within the depositional platform and bayfloor sand sheet habitat throughout Greenwich Bay (Figure 5E). Boulders in Wickford Harbor were limited to some scattered boulders in the southeast portion of the harbor.

Submerged Aquatic Vegetation and Macroalgae

Drift or attached macroalgae, and rooted submerged aquatic vegetation are identifiable in the side-scan records in both study areas (Figure 6). Macroalgae was also visible in aerial photography in both sites. Common types of macroalgae in Greenwich Bay and Wickford harbor are Red algae (*Gracilaria verrucosa*, *Ceramium rubrum*, *Polysiphonia* etc.) and green Algae (*Ulva lactuca* and other spp., *Enteromorpha intestinalis*, *Codium fragile* etc.) (Villalard-Bohnsack et al., 1988; Thornber et al., 2008). The extent of eelgrass (*Zostera marina*), which is an important habitat for juvenile finfish and invertebrates, has declined dramatically in Narragansett Bay due to a deterioration in water quality (Kopp et al., 1995). Eelgrass was mapped in the low-energy basin in Wickford Harbor (Lebsie) (Figures 4, 6A, B). The presence

of eelgrass interpreted from side-scan records was confirmed by direct diver observations. No eelgrass was mapped in Greenwich Bay.

Anthropogenic features

Quahog (hard-shell clam) harvesting (rake) trails

Bottom trails resulting from harvesting quahogs (*Mercenaria mercenaria*) are clearly visible in the side-scan imagery (Figure 7A). These features are extant in a large area of the western basin and along the northern margin of the midbay channel system within Greenwich Bay (Figure 3). Quahogs are harvested using a long handled metal rake (approximately 60 cm across) known locally as a bull rake, dragged through the sediment, forming distinct furrows in the bayfloor. Some areas mapped showed no portions of the bayfloor untouched by a rake (Figure 7B). Wickford Harbor is typically closed to shell fishing, and these features were not seen.

Mooring drags

Distinct circular bottom features, 5-20 m across, appear on the sonar record throughout the mooring fields of both Greenwich Bay (Figure 7C) and to a lesser extent Wickford Harbor. These features represent bottom disturbance from the ground chain of boat moorings, which disturbs the bottom as the boat pivots around the mooring anchor. This feature is particularly prevalent in a very dense mooring field in southwest Greenwich Bay.

Marina/shoreline structure debris

Debris litters the bay floor along parts of the developed western shoreline of Greenwich Bay, and numerous pilings lay on the bayfloor, possibly the result of Hurricane Carol in 1954. Boulders mapped in the entrance channel to Wickford Harbor appear to have been part of the jetties, but could not be differentiated from glacial boulders cropping out within the surrounding bayfloor sandsheet (Sssa).

Sunken Boats

There are a number of sunken boats scattered around the study sites. Most are < 10 m in length. One unique sunken boat located in Greenwich Bay, in approximately 1 meter of water (MLLW) (Figure 7D). This large > 30 m wreck shows up in detail on the side-scan imagery. Individual wooden planks can be identified, and it appears that the sides of the wreck have collapsed outward and lay on the depositional platform.

DISCUSSION

The present distribution of benthic geologic habitats is controlled largely by the Late Wisconsinan glacial landforms and sediment characteristics. The gravel erosional terraces (Teg) in eastern Greenwich Bay fringe a headland comprised of till (Boothroyd and McCandless, 2003). These terraces form as storm waves erode of the shoreline. Boulders (up to 6 m diameter) were left behind during retreat of the headland bluffs by wave action, and likely are not transported, except perhaps during severe storm events (hurricanes). These processes would have been active during Holocene transgression, and the boulder-gravel pavement (Pvbg) adjacent to the erosional terraces in southeast Greenwich Bay formed as an erosional terrace at a lower relative sea level. Wave erosion of the till could not begin until relative sea level was < 6m below present. Applying the relative sea-level curves proposed for Narragansett Bay (Boothroyd and August, 2008; McMaster, 1984), this process began around 6,000 yBP. The boulder gravel pavement is presently impacted by breaking waves only during hurricanes and severe extra-tropical cyclones. Relatively strong tidal currents inhibit deposition of fine-grained sediment during fair-weather periods. This habitat probably marks the extent of the till headland prior to Holocene transgression, and similar habitats have been mapped around till or coarse-grained stratified uplands along the Rhode Island south shore (Klinger, 1996; Zitello, 2002; Oakley et al., 2009).

The sandy depositional platforms (Dpsa) in both study sites are interpreted to have formed from the deposition of sand eroded from the stratified glacial headlands, as the shoreline retreated due to wave action during storm events. The shoreline in

northern Greenwich Bay has retreated 20 to 30 m since 1939; the shoreline Wickford Harbor has eroded 5 to 10 m in the same period (Boothroyd. and Hehre, 2007). The wide depositional platforms (< 500 m) and bayfloor sand sheets (< 1,000 m) in eastern Greenwich Bay are forming on the now submerged sandy delta slope and eroded portions of the sandy and gravelly delta plains of glacial deltas north and south of Greenwich Bay (Boothroyd and McCandless, 2003). These deltas provide a ready source of sediment, and the original depositional slope of the delta (2 - 3 m · km based on the configuration of modern glacial deltas in Alaska) (Boothroyd and Ashley, 1975) is conducive to forming wide depositional platforms.

The bayfloor sandsheet (Sssa) (Water depth 2 - 4 m) adjacent to the modern depositional platforms would have been an active depositional platforms when relative sea level was > 2.5 m below present (prior to 2,500 yBP (Boothroyd and August, 2008; McMaster, 1984)) This habitat no longer actively exchanges sediment with the shoreline. It is unclear if the extent of the depositional platform and bayfloor sand sheet in Greenwich Bay marks the limit of the glacial delta plain, subsequently modified during Holocene transgression, or if the extent represents sand eroded from the delta slope and deposited over glacial lakefloor deposits. The depositional platform in Wickford Harbor is part of a relict spit, no longer active after the construction of the breakwaters in the 1940's.

The tidal bedforms (dunes) and shore parallel and transverse bars on the depositional platform show that these are areas of active sediment transport in both along shore and cross shore directions. The bars in Greenwich Bay likely form and are only modified during storm events. A qualitative look at the bars in aerial

imagery taken before (2003, 2006) and after (2008) the April, 2007 Patriots Day Extratropical cyclone (Maximum storm surge 1.1 m; maximum sustained wind speed $> 25 \text{ m} \cdot \text{s}^{-1}$ (NOAA, 2011)) show the bars were unchanged, suggesting modification occurs only during severe storms (hurricanes).

Low-energy basins are areally the most extensive habitats in both study areas (Figures 3, 4), occupying topographic lows in the glacial topography or channels incised into the glacial deposits. These areas are sinks for fine-grained (silt to clay) mineral and organic sediment. Fine-grained sediment has four possible sources in estuaries; fluvial input, biological production, offshore sources and shoreline erosion (Cronin, 2007). Direct fluvial input is low in both of the embayments studied here, and throughout Narragansett Bay as a whole. Major rivers draining into Narragansett Bay have been extensively dammed, and while not well quantified, models show decreasing sediment load in the Blackstone River closer to Narragansett Bay (Ji et al., 2002), and much of the river is at or close to bedrock (Upson and Spencer, 1964). One exception to this, are the small distributary deltas at the mouth of some of the tidal creeks, although exactly how much sediment is presently transported down these creeks is unclear.

Primary production is the most significant source of organic, silt-sized sediment in Narragansett Bay (Nixon et al., 1995), and the remains of decayed macroalgae and phytoplankton are deposited into low-energy basins (Granger et al., 2000). Offshore sediment was identified as a source of sediment in Chesapeake Bay; however, models of sediment transport in Rhode Island Sound suggest that this area is not a significant source of sediment for deposition in Narragansett Bay (Grilli et al.,

2010). The embayments studied here are 15 km (Wickford) and 25 km (Greenwich Bay) from the southern entrance of Narragansett Bay and active exchange of sediment between these areas and Rhode Island Sound is probably negligible.

Shoreline erosion is a significant source for silt and minor amounts of clay within Narragansett Bay as well as other estuaries (Boothroyd and August, 2008; Cronin, 2007; Marcus and Kearney, 1991). Wave action erodes the till shorelines throughout Narragansett Bay, selectively removing silt and clay from these areas, where it can be transported to, and deposited in, deeper, low-energy areas. Modern channel incision into underlying glacial lakefloor sediment was reported as an additional source for fine-grained sediment in eastern Long Island Sound (Knebel et al., 1999). Seismic reflection profiles in the channel at the entrance to Greenwich Bay shows that 1 - 3 m of estuarine mud overlies the glacial lake floor deposits suggesting that active channel incision is not occurring here. Wind-blown silt from adjacent areas likely contribute small amounts of sediment, but this process would have been more active in the recent past, when tilling of fields around Narragansett Bay was more common.

High-resolution chirp sub-bottom seismic reflection profiles indicate the low-energy basin in western Greenwich Bay contains 7 – 8 m of fine-grained Holocene sediment; in Wickford Harbor, the basins contain 2.5 – 5 m of fine-grained sediment. Published sedimentation rates for Greenwich Bay ($0.35 - 0.5 \text{ cm yr}^{-1}$) (Latimer and Quinn, 1996) suggest deposition took 1,600 – 2,500 years. This age range correlates with the Holocene inundation model of Narragansett Bay presented by Boothroyd and August (2008) and McMaster (1984), that suggest by 2,500 yBP, most of Narragansett

Bay was at roughly the present extent and configuration . Circulation models of Narragansett Bay based on acoustic Doppler current profiles suggest that southwest ‘sea-breeze’ winds may create a circulation pattern that significantly increases the residence time for water in Greenwich Bay. This may reduce transport of fine-grained material out of central Greenwich Bay (Rogers, 2008), and could produce higher sedimentation rates.

There is a general trend of decreasing grain size from east to west in both Greenwich Bay and Wickford Harbor, ranging from sand (and some gravel) along the shallow shelf areas in the eastern portions of the study sites, to fine-grained silt and silty sand in the deeper depositional basins. This trend is expected, given the general decrease in wave-energy from the open water of Narragansett Bay and towards the more protected areas. A decrease in grain size in sheltered central basins within an estuary is common in mixed energy environments (Dalrymple et al., 1992). This relationship is complicated in areas where wave action and tidal currents have produced sandy or gravelly deposits in estuarine cove and marginal depositional environments. Similar depositional environments have been mapped in other modern, mixed-energy microtidal estuaries (Biggs, 1967; Kerhin et al., 1988; Knebel, 1986, 1989; Nitsche et al., 2004). Facies distributions in these estuaries are more complicated than the models of tide-dominated or wave-dominated estuaries illustrated by Dalrymple et al., (1992) and Boyd et al. (2006). This is further complicated in glaciated estuaries, where sediment characteristics exhibit great lateral variability (Barnhardt et al., 1998; Knebel et al., 1991).

The complex lateral distribution of facies interpreted to have been deposited in estuarine environments have begun to be recognized in the rock record, by comparing modern estuarine facies with detailed outcrop analysis (Mack et al., 2003). Few facies models and assemblages of estuarine environments have been proposed that are directly applicable to the rock record (Reinson, 1992). Future work on rocks interpreted to have been deposited in an estuarine environment should consider sandy depositional platforms, which may comprise some of the sandstones in interpreted estuarine sedimentary sequences (Mack et al., 2003), and the low-energy central basins of estuaries and coastal lagoons have been recognized as potential petroleum source rocks (Putnam, 1989; El Hariri, 2008). Transgressive estuaries have a high preservation potential in incised valleys (Belknap and Kraft, 1985). Detailed mapping of the extent and distribution of facies and depositional environments within modern estuarine environments allows for a better understanding of the rock record (Reinson, 1992).

The results of this work also provided the basis for subaqueous soil mapping in both study sites, and other estuarine and coastal lagoons in Rhode Island (i.e. Stolt et al., 2011; Payne, 2007). The combined geologic and soils mapping efforts have helped agencies like the United States Department of Agriculture – Natural Resource Conservation Service to properly site research, restoration and commercial scale aquaculture.

CONCLUSIONS

- Greenwich Bay and Wickford Harbor, two embayments of western Narragansett Bay were mapped using side-scan sonar, surface sediment samples and vertical and oblique aerial photographs. The combination of techniques allowed for full coverage mapping in these shallow estuarine environments.
- These areas were mapped into benthic geologic habitats utilizing a flexible naming convention that combines information about geologic processes, morphologic form, sediment characteristics, biota and anthropogenic impacts.
- Human activities in Narragansett Bay have a considerable impact on benthic habitats. Significant bottom disturbances from shell fishing and mooring fields were identified, and debris from marina construction/destruction litters the bay floor adjacent to most of the developed shoreline.
- The Late Wisconsinan glacial landforms and sediment distribution control the distribution of benthic geologic habitats throughout the studies sites, especially in estuarine marginal environments.

- There is a general decrease in grain size from east to west correlating with a decrease of wave-energy in more protected portions of the estuary in both study sites. This is similar to other microtidal estuaries, and published estuarine models; however, the distribution of facies within these embayments is complicated, especially in estuarine cove and marginal environments. The dominant process (wave or tidal) varies spatially and temporally, especially when considering processes active during storms.
- The methods outlined in this paper has been successfully applied in other estuarine, lagoon and shoreface environments, and provides a relatively low-cost, concise method of imaging and characterizing benthic geologic habitats on the seabed.

ACKNOWLEDGEMENTS

M. Payne, USDA/NRCS provided field assistance in Wickford Harbor.
E. Shumchenia (Graduate School of Oceanography, University of Rhode Island), M. Borrelli (Provincetown Center for Coastal Studies), and 4 anonymous reviewers provided helpful comments on prior drafts of this manuscript.

The authors were supported by the Department of Geosciences, College of Environment and Life Sciences, University of Rhode Island, and funded by the Rhode Island Coastal Resources Management Council Cooperative agreement 50A00311741; The Rhode Island SeaGrant Program BayMap Project and NOAA CSC grant NA06NOS4730220

REFERENCES

- Ashley, G. M. (1990) Classification of large-scale subaqueous bedforms; a new look at an old problem. *Journal of Sedimentary Research*, 60, 161-172.
- Barnhardt, W. A., Kelley, J. T., Dickson, S. M. & Belknap, D. F. (1998) Mapping the Gulf of Maine with Side-Scan Sonar: A New Bottom-Type Classification for Complex Seafloors. *Journal of Coastal Research*, 14, 646-659.
- Belknap, D. F. & Kraft, J. C. (1985) Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. *Marine Geology*, 63, 235-262.
- Biggs, R. B. (Ed.) (1967) *The sediments of Cheapeake Bay*, American Association for the Advancement of Science Publication 83,.
- Boothroyd, J. C. (Ed.) (1985) *Mesotidal inlets and estuaries*, New York, Springer.
- Boothroyd, J. C. & Ashley, G. M. (Eds.) (1975) *Processes, bar morphology and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska*, Tulsa, OK, Society of Economic Paleontologists and Mineralogists Special Publication 23.
- Boothroyd, J. C. & August, P. V. (Eds.) (2008) *Geologic and contemporary landscapes of the Narragansett Bay ecosystem*.
- Boothroyd, J. C., Friedrich, N. E. & McGinn, S. R. (1985) Geology of microtidal coastal lagoons: Rhode Island. *Marine Geology*, 63, 35-76.
- Boothroyd, J. C. & Galagan, C. A. (Eds.) (1992) *Coastal geological characteristics, Final Report for the Narragansett Bay Project*, p. 7-25, 14 (1:24,000 scale) Quaternary geology maps with ArcInfo computer map files for 43 separate aerial photographs.
- Boothroyd, J. C. & Hubbard, D. K. (Eds.) (1975) *Genesis of bedforms in mesotidal estuaries*, New York, Academic Press.
- Boothroyd, J. C. & Mccandless, S. J. (2003) Quaternary Geologic map of the East Greenwich quadrangle, including parts of the Bristol and Crompton quadrangles. Kingston, RI, *Rhode Geological Survey Open File Map 2003-01*.

- Boothroyd, J. C. & Oakley, B. A. (2005) Benthic Geologic Habitats of Greenwich Bay, RI, in Special area management plan for Greenwich Bay and watershed. Wakefield, RI, Rhode Island Coastal Resources Management Council, 1:10,000 scale maps and side-scan sonar images.
- Boothroyd., J. C. & Hehre, R. E. (2007) Shoreline change maps for Narragansett Bay and Islands, Rhode Island. Kingston, RI, Rhode Island Geological Survey.
- Boyd, R., Dalrymple, R. W. & Zaitlin, B. A. (Eds.) (2006) *Estuarine and incised-valley facies models*, Society for Sedimentary Geology.
- Bradley, M., Raposa, K. & Tuxbury, S. (2007) Report on the Analysis of True Color Aerial Photography to Map and Inventory *Zostera marina* L. in Narragansett Bay and Block Island, Rhode Island. University of Rhode Island Environmental Data Center.
- Cowardin, L. M., Carter, V., Golet, F. C. & Laroe, E. T. (1979) *Classification of wetland and deepwater habitats of the United States*, U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC.
- Crc (2005) Greenwich Bay Special Area Management Plan. University of Rhode Island Coastal Resources Center and Rhode Island Sea Grant.
- Cronin, T. M. (Ed.) (2007) *Sediment sources and deposition in the estuary*, Reston, VA, U.S.G.S.
- Dalrymple, R. W., Zaitlin, B. A. & Boyd, R. (1992) Estuarine facies models; conceptual basis and stratigraphic implications. *Journal of Sedimentary Research*, 62, 1130-1146.
- Dalton, T., Thompson, R. & Jin, D. (2010) Mapping human dimensions in marine spatial planning and management: An example from Narragansett Bay, Rhode Island. *Marine Policy*, 34, 309-319.
- El Hariri, T. Y. (2008) Depositional environment and petrophysical studies on subsurface Devonian sediment from Faghur-1x well at North Western Desert, Egypt. *Journal of Applied Sciences Research*, 4, 65-75.
- Fish, J. P. & Carr, H. A. (1990) *Sound underwater images: A guide to the generation and interpretation of side-scan sonar data*, Cataumet, MA, American Underwater Search and Survey, Ltd.

- Fisher, W. L., McGowen, J. H., Brown, L. F. & Groat, C. G. (1972) Environmental geologic atlas of the Texas Coastal Zone—Galveston–Houston area. The University of Texas at Austin, Bureau of Economic Geology.
- Fitzgerald, D. M., Buynevich, I. V., Davis, R. A. & Fenster, M. S. (2002) New England tidal inlets with special reference to riverine-associated inlet systems. *Geomorphology*, 48, 179-208.
- Folk, R. L. (1980) *Petrology of sedimentary rocks*, Austin, TX, Hemphill Publishing.
- Goff, J. A., Olson, H. C. & Duncan, C. S. (2000) Correlation of side-scan backscatter intensity with grain-size distribution of shelf sediment, New Jersey margin. *Geo-Marine Letters*, 20, 43-49.
- Granger, S., Brush, M., Buckley, B., Traber, M., Richardson, M. & Nixon, S. W. (Eds.) (2000) *An assessment of eutrophication in Greenwich Bay. Paper no. 1*, Narragansett, RI, Rhode Island Sea Grant.
- Greene, H. G., Bizzarro, J. J., O'connell, V. & Brylinsky (Eds.) (2007) *Construction of digital potential marine benthic habitat maps using a coded classification scheme and it's application*, Canadian Geological Association Special Paper 47.
- Greene, H. G., Bizzarro, J. J., Tilden, J. E., Lopez, H. L. & Erdey, M. D. (Eds.) (2005) *The benefits and pitfalls of geographic information systems in marine benthic habitat mapping*, Corvallis, OR, Oregon State University Press.
- Greene, H. G., Yoklavich, M. M., Starr, R. M., O'connell, V. M., Wakefield, W. W., Sullivan, D. E., Mcree Jr., J. E. & Cailliet, G. M. (1999) A classification scheme for deep seafloor habitats. *Oceanologica acta*, 22, 663-678.
- Grilli, S., Harris, J., Sharma, R., Decker, L., Stuebe, D., Mendelsohn, D., Crowley, D. & Decker, S. (2010) High resolution modeling of meteorological, hydrodynamic, wave and sediment processes in the Rhode Island Ocean SAMP study area: Technical Report 6. 119.
- Harrington, M. P. (2000) The impact of Narragansett Bay on Rhode Island's industrial development: Narragansett Bay Summit 2000 White paper, Bay Summit 2000, Narragansett Bay in the new millennium. *Environment, economy and community, Providence, R.I.*, 1-43.
- Hastings, M. E., Poppe, L. J. & Hathaway, J. C. (2000) USGS East-coast sediment texture database. *U.S. Geological Survey open file report 00-350*.

- Hayes, M. O. (Ed.) (1975) *Morphology of sand accumulations in estuaries*, New York, Academic Press.
- Hayes, M. O. (1979) Barrier island morphology as a function of tidal and wave regime. IN LEATHERMAN, S. P. (Ed.) *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico*. New York, Academic Press.
- Hermes, O. D., Gromet, L. P. & Murray, D. P. (1994) Bedrock Geologic Map of Rhode Island: Rhode Island Map Series No. 1. Kingston, Rhode Island, University of Rhode Island.
- Ji, Z. G., Hamricj, J. H. & Pagenkopf, J. P. (2002) Sediment and metals Modeling in Shallow River. *Journal of Environmental Engineering*, 128, 105-119.
- Joubert, L. & Lucht, J. (2000) Wickford Harbor Watershed Assessment. College of Environment and Life Sciences and Rhode Island Cooperative Extension, University of Rhode Island Technical Report 00-03.
- Kelley, J. T., Dickson, S. M., Belknap, D. F., Barnhardt, W. A. & Henderson, M. (1994) Giant sea-bed pockmarks: Evidence for gas escape from Belfast Bay, Maine. *Geology*, 22, 59-62.
- Kennish, M. J., Haag, S. M., Sakowicz, G. P. & Durand, J. B. (2004) Side-scan sonar imaging of subtidal benthic habitats in the Mullica River-Great Bay estuarine system. *Journal of Coastal Research, Special Issue 45*, 227-240.
- Kerhin, R. T., Blakeslee, P. J., Zoltan, N. & Cuthbertson, R. (1988) The Surficial Sediments of the Chesapeake Bay, Maryland: Physical Characteristics and Sediment Budget. Maryland Geological Survey Report of Investigation 48.
- Klinger, J. P. (1996) Sedimentary environments and processes on the Charlestown-Green Hill Barrier/Headland shoreface and Misquamicut Barrier/Headland shoreface, south coast of Rhode Island:. Kingston, RI, University of Rhode Island.
- Knebel, H. J. (1986) Holocene depositional history of a large glaciated estuary, Penobscot Bay, Maine. *Marine Geology*, 73, 215-236.
- Knebel, H. J. (1989) Modern sedimentary environments in a large tidal estuary, Delaware Bay. *Marine Geology*, 86, 119-136.

- Knebel, H. J., Rendigs, R. R., List, J. H. & Bothner, M. H. (1991) Modern sedimentary environments in Boston Harbor, Massachusetts. *Journal of Sedimentary Petrology*, 61, 791-804.
- Knebel, H. J., Signell, R. P., Rendigs, R. R., Poppe, L. J. & List, J. H. (1999) Seafloor environments in the Long Island Sound estuarine system. *Marine Geology*, 155, 277-318.
- Kopp, B., Doherty, A. M. & Nixon, S. W. (1995) A guide to site-selection for eelgrass restoration projects in Narragansett Bay, Rhode Island: Report to Aquafund. Narragansett, RI, Graduate School of Oceanography.
- Latimer, J. S. & Quinn, J. G. (1996) Historical trends and current inputs of hydrophobic organic compounds in an urban estuary: the sedimentary record. *Environmental Science and Technology*, 30, 623-633.
- Mack, G. H., Leeder, M., Perez-Arlucea, M. & Bailey, B. D. J. (2003) Sedimentology, Paleontology, and Sequence Stratigraphy of Early Permian Estuarine Deposits, South-Central New Mexico, USA. *Palaaios*, 18, 403-420.
- Madden, C. J., Goodin, K. L., Allee, R. J., Cicchetti, G., Moses, C., Finkbeiner, M. & Bamford, D. (2010) *Coastal and Marine Ecological Classification Standard Version 3.1: NOAA and NatureServe*, Silver Spring, MD and Reston, VA.
- Marcus, W. A. & Kearney, M. S. (1991) Upland and coastal sediment sources in a Chesapeake Bay Estuary. *Annals of the Association of American Geographers*, 81, 408-424.
- Mccormick-Ray, J. (2005) Historical oyster reef connections to Chesapeake Bay - a framework for consideration. *Estuarine, Coastal and Shelf Science*, 64, 119-134.
- Mcmaster, R. L. (1960) Sediments of Narragansett Bay system and Rhode Island Sound, Rhode Island. *Journal of Sedimentary Research*, 30, 249-274.
- Mcmaster, R. L. (1984) Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, USA. *Sedimentology*, 31, 777-792.
- Nitsche, F. O., Bell, R., Carbotte, S. M., Ryan, W. B. F. & Flood, R. (2004) Process-related classification of acoustic data from the Hudson River Estuary. *Marine Geology*, 209, 131-145.

- Nixon, S. W., Granger, S. L. & Nowicki, B. L. (1995) An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. *Biogeochemistry*, 31, 15-61.
- Noaa-Nos (1998) Narragansett Bay Nautical Chart 13221. *United States - East Coast-Rhode Island Massachusetts*. National Oceanic and Atmospheric Administration.
- Noaa (2011) Verified water-level data at Conimicut Light (station 8452944).
- Oakley, B. A., Alvarez, J. D. & Boothroyd, J. C. (2007) Benthic Geologic Habitats of the Matunuck-Green Hill Shoreface, Rhode Island. *Geological Society of America, Abstracts with program*, 39, 70.
- Oakley, B. A., Alvarez, J. D., Brenner, H. B., Dowling, M. J., Klinger, J. P., Zitello, M. & Boothroyd, J. C. (2009) Depositional environments and sediment transport on a microtidal, wave-dominated shoreface. *Proceedings of Coastal Zone 09*. Boston, MA.
- Payne, M. K. (2007) Landscape level assesment of subaqueous soils and water quality in shallow embayments in Southern New England. *Natural Resource Science*. Kingston, RI, University of Rhode Island.
- Pic (2008) Rhode Island E911 Uniform Emergency Telephone System, Pictometry International Corporation, 2008. Pictometric Licensed Images (Spring 2008). *Rhode Island Digital Atlas*. Environmental Data Center, University of Rhode Island, Kingston, RI.
- Putnam, P. E. (1989) Geological controls on hydrocarbon entrapment within the Lower Cretaceous Cantuar Formation, Wapella Field, southeastern Saskatchewan. *Bulletin of Canadian Petroleum Geology*, 37, 389-400.
- Reinson, G. E. (Ed.) (1992) *Transgressive barrier island and estuarine systems*, St. Johns, Newfoundland, Geological Association of Canada.
- Ridot (2005) RIGIS03/04 Digital Orthophotos of Rhode Island: Chas H Sells, Inc, Rhode Island Geographic Information System, Rhode Island Department of Transportation.
- Rogers, J. M. (2008) Circulation and transport in upper Narragansett Bay. University of Rhode Island Graduate School of Oceanography.

- Rogers, J. N., Kelley, J. T., Belknap, D. F., Gontz, A. & Barnhardt, W. A. (2006) Shallow-water pockmark formation in temperate estuaries: A consideration of origins in the western gulf of Maine with special focus on Belfast Bay. *Marine Geology*, 225, 45-62.
- Shepard, F. P. (1954) Nomenclature based on sand-silt-clay ratios. *Journal of Sedimentary Research*, 24, 151-158.
- Shumchenia, E. J. & King, J. W. (2011) Comparison of methods for integrating biological and physical data for marine habitat mapping and classification. *Continental Shelf Research*, 30, 1717-1729.
- Stolt, M., Bradley, M., Turenne, J., Payne, M., Scherer, E., Cicchetti, G., Shumchenia, E., Guarinello, M., King, J., Boothroyd, J., Oakley, B., Thornber, C. & August, P. (2011) Mapping Shallow Coastal Ecosystems: A Case Study of a Rhode Island Lagoon. *Journal of Coastal Research*, 27, 1-15.
- Thornber, C. S., Dimilla, P., Nixon, S. W. & McKinney, R. A. (2008) Natural and anthropogenic nitrogen uptake by bloom-forming macroalgae. *Marine Pollution Bulletin*, 56, 261-269.
- Trimble (2004) *Trimble DSM132 DGPS Receiver Fact Sheet*, Dayton, Ohio, Trimble Geomatics and Engineering Division.
- Udden, J. A. (1914) Mechanical composition of clastic sediments. *Bulletin of Geological Society of America*, 25, 655-744.
- Upson, J. E. & Spencer, C. W. (1964) Bedrock Valleys of the New England Coast as Related to Fluctuations of Sea Level: U.S. Geological Survey Professional Paper 454-M.
- Usda-Fsa (2003) 2003 USDA-FSA National Agriculture Imagery Program (NAIP) 1:12,000 digital true color orthophotography, USDA-FSA-APFO Aerial Photography Field Office. Rhode Island Geographic Information System.
- Valentine, P. C., Todd, B. J. & V.E., K. (2005) Classification of marine sublittoral habitats, with application to the northeastern North America Region. *American Fisheries Society Symposium*, 41, 183-200.
- Villalard-Bohnsack, M., Peckol, P. & Harlin, M. M. (Eds.) (1988) *Marine macroalgae of Narragansett Bay and adjacent sounds*, Dubuque, Iowa, Kendall Hunt Publishing.

- Walker, R. G. (1990) Facies modeling and sequence stratigraphy. *Journal of Sedimentary Petrology*, 60, 777-786.
- Wentworth, C. K. (1922) A scale of grade and class terms for clastic sediments. *Journal of Geology*, 30, 377-392.
- Zitello, M. (2002) Facies configuration changes and sediment transport on the Charlestown/Green Hill Barrier shoreface. Kingston, RI, University of Rhode Island.

Table 1: Depositional environments

Depositional environments	
<i>Estuarine bayfloor</i>	
Pavement	Pv
Shell reef	Shr
Sand sheet	Ss
Low-energy basin	Leb
Bay channel	Bc
<i>Estuarine cove</i>	
Inlet channel (Flood, ebb)	Ci, Cf, Ce
Dredged channel	Cd
Flood-tidal delta	Df
Ebb-tidal delta	De
<i>Estuarine marginal</i>	
Erosional terrace	Te
Depositional platform	Dp
Depositional platform relict spit	Dprs
Distributary delta	Dd
Fringing tidal flat	F
Dredged marina basin	Md

Table 2: Sediment textures and descriptors

Descriptors	
<i>Sediment texture</i>	<i>Abbreviations</i>
Gravel	g
Sand	sa
Silt	si
Undifferentiated	u
<i>Sediment modifiers</i>	
Coarse	c
Fine	f
Organic (>5%)	o
<i>Biologic characteristics</i>	
Vegetated (macroalgae or undetermined SAV)	v
Eelgrass (<i>Zostera marina</i>)	e
<i>Side-scan features: Unverified</i>	
Patches (shell aggradations?)	p

Table 3: Benthic geologic habitats

Estuarine Bayfloor			
<i>Benthic Geologic Habitat</i>	<i>Unit</i>	<i>Color</i>	<i>Sediment textures (Modified Shepard, 1954)</i>
Pavement	Pvbg		Gravel or sandy gravel with outcropping boulders
Shell reef	Shr		Intact and fragmented shells
Sand sheet	Sssa		Sand with scattered gravel and shells (Representative sample 9)
Low-energy basin	Lebsic		Silty sand to sandy silt
	Lebsi		Silt, sandy silt, clayey silt (Representative sample 7)
	Lebsio		Silt, clayey silt. Greater than 5% organic content
	Lebsie		Silt, w/ eelgrass
	Lebsiov		Silt, organic silt w/ attached or drift macroalgae
Bay channel	Bcsa		Sand with scattered gravel and shell fragments
	Bcsic		Silty sand to sandy silt; units denoted (p) have shell aggregations (Representative sample 5)
	Bcsip
	Bcsio		Silt, clayey silt. Greater than 5% organic content, units denoted (p) have shell aggradations (Representative sample 3)
	Bcsiop
	Bcsiov		Silt, clayey silt. Greater than 5% organic content w/ attached or drift macroalgae
Estuarine Cove			
Low-energy basin	Lebsio		Silt, clayey silt. Greater than 5% organic content (Representative sample 16)
Dredged channel	Cdsi		Silty sand, sandy silt, silt, clayey silt
Inlet channel (Flood, ebb)	Cisa		Sand with scattered gravel and shell fragments
	Cfsa
	Cesa
Flood-tidal delta	Dfsa		Sand with scattered gravel and shell fragments
Channel margin linear bars	Dfcm		Sand with scattered gravel and shell fragments
Bedrock outcrop	Bdrx		Bedrock
Estuarine Marginal			
Erosional terrace	Teg		Cobble to boulder gravel
	Tegv
Depositional platform	Dpsa		Sand with scattered gravel and shell fragments (Representative sample 20)
	Dpsav
Depositional platform relict spit	Dprs		Sand with scattered gravel and shell fragments
Distributary delta	Ddsa		Sand
Fringing tidal flat	Fsa		Sand, silty sand, shells and shell fragments
	Fsm		Sandy silt to clayey silt
	Fsmv		Sandy silt to clayey silt
	Ffu		Undifferentiated (Sand to silt)
Dredged marina basin	Mdsi		Sand, Sandy silt, Silt, may be greater than 5% organic
	Mdu

Figure 1. A. Location map of Narragansett Bay, Rhode Island, USA. B. Location of Greenwich Bay and Wickford Harbor along the western shoreline of Narragansett Bay. C. Close up maps of Greenwich Bay and D. Wickford Harbor showing the location of figures 5 - 7. Bathymetric contours digitized from NOAA chart 13221 (NOAA-NOS, 1998).

Figure 2. Modified Shepard (1954) sediment classification scheme showing the percentage of sand silt and clay for samples collected in Greenwich Bay and Wickford Harbor, and includes samples collected by McMaster (1960). Representative samples are labeled and their locations shown on figure 3.

Figure 3. Benthic geologic habitats of Greenwich Bay overlain on 2003/2004 digital orthophotographs showing the locations of figures 5 and 7. See table 3 for summary of map units.

Figure 4. Benthic geologic habitats of Wickford Harbor overlain on 2003/2004 digital orthophotographs showing the locations of figure 6. See table 3 for summary of map units.

Figure 5: Selected side-scan images of geologic features. See figures 1 and 3 for location. A. Facies boundary between bayfloor sand sheet Sssa and low-energy basin organic silt (Lebsio) in southwest Greenwich Bay. B. Dark patches within the bay channel organic silt (Bcsiop). Patches are interpreted to be shell aggradations. Fuzzy area in the center of the image is the corrected nadir directly below the towfish C. Tidal bedforms on the bayfloor sand sheet (Sssa). Crest to crest spacing averages 8 m. The distinct furrow in the upper right of the image was produced by a hydraulic dredge used for collecting shellfish. D. Wave-formed bars in southeast Greenwich Bay on the depositional platform (Dpsa). E. Isolated boulders cropping out on the depositional platform sand sheet (Dpsa), Greenwich Bay.

Figure 6: Examples of macroalgae and submerged imaged using side-scan sonar. See Figure 1 for geographic locations. A. Side-scan image in central Wickford Harbor. The distinct speckled pattern on the right side of the image is Eelgrass (*Zostera Marina*). The line delineates the boundary between the eelgrass (Lebsie) and the adjacent, low-energy basin coarse silt (Lebsic). B. Photograph of the Wickford Harbor eelgrass bed collected by a diver using a still camera in the summer of 2007) (M. Cole-Ekberg, Personal Communication). The red arrow points to a representative clump of eelgrass in the side-scan image. C. Side-scan image in southwest Wickford Harbor. The blotchy pattern throughout the image is macroalgae. The feature in the upper left of the image is the shoreline. D. 2008 Digital aerial photograph of a portion of southwest Wickford Harbor (PIC, 2008). The elongated alternating pattern of attached macroalgae is shaped by tidal currents.

Figure 7. Anthropogenic impacts mapped in Greenwich Bay. See figure 1 for geographic locations. A. Trails formed by rakes dragged across the bottom during the harvesting of shellfish (*Mercenaria mercenaria*, locally called Quahogs). Scale across each rake trail is ~0.6 m. Geologic habitat is low-energy basin silt (Lebsi). Box shows the extent of figure 7B. B. Inset of figure A showing no portion of the bayfloor in this area untouched by a rake. C. Mooring drag in southeast Greenwich Bay. The circular feature in the lower right of the image is caused by the ground chain dragging along the bayfloor as the boat pivots around mooring anchor. Geologic habitat is low-energy basin silt (Lebsi). The vertical mooring chain and keel of the boat are also visible in the image. D. Shipwreck on the depositional platform (Dpsa) south of Oakland Beach in Greenwich Bay

APPENDIX 1

Supplemental figures: Chapter 1

Figure S1: Example of the National Elevation Dataset 30 m data points and National Ocean Service hydrographic survey points in the study area used to interpolate the digital terrain model. The accuracy of the interpolated hydrographic grid was assessed by randomly withholding 10% of the data points and recreating the terrain model. The difference between the elevations in the grid created using the subset data and the withheld data points was checked using the ‘Point Intersect’ feature in ESRI ArcMAP™ ‘Hawth’s Tools’ extension. The mean difference was 0.1 m, $\pm$ 0.6 m. The high standard deviation was due to outliers located near areas of high relief, specifically in the East Passage of Narragansett Bay, and between Block Island and Long Island Sound (Figure 1). Less than 0.5% of the withheld data points differed by more than 1 m from the grid. The final terrain utilized all of the data points.

Figure S2: A - Isobase surface reflecting 30 m of depression at the terminal margin of the Laurentide Ice Sheet south of Block Island, Rhode Island, with a profile of rebound of 0.85 m km^{-1} .

Figure S3: A - Isobase surface reflecting 50 m of depression at the terminal margin of the Laurentide Ice Sheet south of Block Island, Rhode Island, with a profile of rebound of 0.85 m km^{-1} .

Figure S4: A - Isobase surface reflecting 75 m of depression at the terminal margin of the Laurentide Ice Sheet south of Block Island, Rhode Island, with a profile of rebound of 0.85 m km^{-1} .

Figure S5: Isostatic rebound, relative sea level and eustatic sea level used in creation of figures S6 – S14

Figure S6: Relative sea level at 26 ka 30 m of isostatic depression at the terminal margin. Note the lack of marine inundation across the study area. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S7: Relative sea level at 21 ka 30 m of isostatic depression at the terminal margin. Note the lack of marine inundation across the study area. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S8: Relative sea level at 16.5 ka 30 m of isostatic depression at the terminal margin. Marine water may have begun to inundate the channel south of Block Island by 16.5 ka. The southern margin of the Laurentide Ice Sheet had retreated north of the study area by this time.

Figure S9: Relative sea level at 26 ka with 50 m of isostatic depression at the terminal margin. Note the marine grounded ice margin. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S10: Relative sea level at 21ka with 50 m of isostatic depression at the terminal margin. Note the inundation of the southern Rhode Island and Massachusetts shorelines and marine grounded ice margin. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S11: Relative sea level at 16.5 ka with 50 m of isostatic depression at the terminal margin. Note the inundation of much of southern New England under marine water. The southern margin of the Laurentide Ice Sheet had retreated north of the study area by this time.

Figure S12: Relative sea level at 26 ka with 75 m of isostatic depression at the terminal margin. Note the inundation of most of the southern shoreline of Long Island and Martha's Vineyard and the marine grounded ice margin. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S13: Relative sea level at 21 ka with 75 m of isostatic depression at the terminal margin. Note the inundation of most of Long Island, Block Island and Martha's Vineyard and the grounded ice margin. Extent of the Laurentide Ice Sheet modified from Dyke and Prest, (1987).

Figure S14: Relative sea level at 16.5 ka with 75 m of isostatic depression at the terminal margin. Note the inundation of much of southern New England under marine water. The southern margin of the Laurentide Ice Sheet had retreated north of the study area by this time.

APPENDIX 2

Sedimentological description of cores

Location of the cores

Seven cores were recovered from the upper Providence River (PVD-1 – PVD-8). PVD-4 was recovered, but the core was lost out of the bottom of the barrel during recovery. Cores were located in a general area 300 m south of the Port Edgewood Marina and approximately 50 to 100 m east of the Edgewood shoreline (Figure 1A). Water depths were less than 1 m MLLW. Two cores from a previous study (Pickart, 1987) were also used. The location of these cores are shown on figures 1A and 1B.

Post-glacial depositional environments

The interpretations of the post-glacial depositional environments follow those of Pickart (1987). The sand capping the cores was eroded and transported from the adjacent glacial deltas during storm events and deposited on a sandy tidal flat. The dark brown interbedded silt and sand in cores PVD-1 to PVD-5 is interpreted to have been deposited in a shallow estuarine environment, evidenced by the presence of estuarine and marine macrofossils (Pickart, 1987). The dark brown ~ 1 cm thick peat capping the varves was interpreted to have been deposited in a freshwater marsh (Pickart, 1987), although a detailed examination of these layers for identifiable macrofossils was not conducted. The thick, organic-rich, silt in core PVD-6 may represent wetland deposition in small kettle hole, however the layer was not examined for macrofossils to confirm this interpretation.

Detailed description of cores

PVD-1

PVD-1 contains 6.33 m of laminated sand, silt, and clay, interpreted to be glacial varves, representing 200 years of deposition (Figure 2). Individual couplet thickness ranges from 0.4 to 9.5 cm, with an average thickness of 2.2 cm. Overlying the varves is 1.5 cm of dark brown peat, followed by 25 cm of interbedded mottled, olive-gray silt and sand, 44 cm of moderately sorted medium to coarse sand and 35 cm of moderately sorted, medium to coarse sand with fragments of soft-shell (*Mya arenaria*) and hard-shell (*Mercenaria mercenaria*) clams.

PVD-2

PVD-2 contains 5.93 m of laminated silt and clay, interpreted to be glacial varves, representing 212 years of deposition (Figure 3). This core is capped by 14 cm of moderately sorted, medium to coarse sand with shell fragments of soft-shell (*Mya arenaria*) and hard-shell (*Mercenaria mercenaria*) clams.

PVD-3

PVD-3 contains 1.88 m of laminated silt and clay (varves) representing 68 years of deposition overlain by 25 cm of gray, partially deformed sandy couplets with thin (> 0.5 mm) silt layers. Couplet thickness ranges from 0.3 to 7.1 cm with an average thickness of 2.4 cm (Figure 4). The core is capped by 37 cm of dark brown medium sand with interbedded silt and scattered and intact shell fragments of soft-shell clams (*Mya arenaria*).

PVD-5

PVD-5 contains 3.31 m of laminated silt and clay, representing 147 years of deposition. Individual couplet thickness ranged from 0.26 cm to 7.2 cm, with an average thickness of 2.2 cm (Figure 5). The top of the varve sequence contains a 12 cm, gray, sandy couplet, and 2 cm of sand interpreted to part of a couplet, truncated by 15 cm of brown sand. The core is capped by 20 cm of moderately sorted, medium to coarse sand with shell fragments of soft-shell (*Mya arenaria*) and hard-shell (*Mercenaria mercenaria*) clams.

PVD-6

PVD-6 contains 65 cm of laminated silt and clay representing 27 years of deposition, overlain by 121 cm of highly deformed couplets. Undeformed couplet thickness ranged from 0.4 to 6.7 cm, with an average of 2.44 cm (Figure 6). 1 cm of deformed, dark brown peat caps the deformed varves, and is overlain by 67 cm of mottled olive-gray silt, 70 cm of dark brown, organic rich silt, and 220 cm of mottled olive-brown silt with isolated (> 1cm thick sandy layers). The core is capped by 44 cm of moderately sorted, medium to coarse sand with shell fragments of soft-shell (*Mya arenaria*) and hard-shell (*Mercenaria mercenaria*) clams.

EW-1

EW-1, collected by Pickart (1987), contains 266 cm of laminated silt and clay couplets (varves) representing 166 years of deposition (Figure 7). Individual couplets range from 0.3 to 7 cm, with an average thickness of 1.66 cm. This core is capped by 10 cm of moderately sorted medium to coarse sand with no visible shell fragments and 15 cm of moderately sorted, medium to coarse sand with fragments of soft-shell (*Mya arenaria*) and hard-shell (*Mercenaria mercenaria*) clams. A dark brown, 1.5 cm thick layer between the sand and varves may represent the peat seen in other cores; however, the resolution of the scanned slides did not allow for definitive interpretation of this layer.

PC-6

PC-6 was collected by Pickart (1987). The base of PC-6 contains 30 cm of moderately sorted coarse sand and gravel. Overlying this is 365 cm of laminated silt and clay couplets (varves) interpreted to represent 160 years of deposition (Figure 8) and 15 cm of highly deformed varves. Undeformed couplets range from 0.35 to 24 cm, with an average thickness of 2.28 cm. Drop stones (up to 2 cm diameter) are seen in the first four varves. The core is capped by 9 cm of dark brown to black silt.

Figure 1: Location of sediment cores in A. The Providence River, B. Pawtuxet Cove

PVD-1

Figure 2: Image from core PVD-1. Red Arrow marks the boundary of undeformed varves and deformed ice-proximal varves discussed in text. The white objects indicated by the black arrow are shell fragments. Green arrow marks the boundary between mottled silt and overlying sand. Brown arrow marks the boundary between varves and the 1 cm thick peat. Blue arrow marks the top of the varve sequence. Core depths represent depth within the recovered core sample. Deformed sections, where accurate varve measurements were not possible are noted.

PVD-2

Figure 3: Image from core PVD-2. Core depths represent depth within the recovered core sample. Blue arrow marks the boundary between the varves and overlying medium sand with shell fragments. Deformed sections, where accurate varve measurements were not possible are noted.

Figure 4: Image from core PVD-3. Red arrow marks the boundary between tan varves and gray sandy varves discussed in text. Blue arrow marks the boundary between the varves and the overlying medium sand with shell fragments. Core depths represent depth within the recovered core sample. Deformed sections, where accurate varve measurements were not possible are noted.

Figure 5: Image from core PVD-5. Red arrow marks the boundary between tan varves and gray sandy varves discussed in text. Blue arrow marks the boundary between the varves and the overlying medium sand with shell fragments. Core depths represent depth within the recovered core sample. Yellow dots are plastic disks placed 5 cm apart during imagery collection to aid in scaling images during varve analysis. Deformed sections, where accurate varve measurements were not possible are noted.

Figure 6: Image from core PVD-6. Core depths represent depth within the recovered core sample. Red arrow marks the boundary between undeformed and deformed varves. Blue arrow marks the boundary between mottled olive-gray and dark brown organic silt. Brown arrow marks boundary between dark brown organic silt and mottled olive-brown silt. Purple arrow marks the boundary between mottled silt and medium sand with shell fragments. Deformed sections, where accurate varve measurements were not possible are noted.

Figure 7: Images from core EW-1 from Pickart(1987). Blue arrow marks the brown peat layer overlying the varve sequence. Red arrow marks the base of medium sand with shell fragments that caps the core. Core depths represent depth within the recovered core sample.

Figure 8: Images from core PC-6 from Pickart(1987). IRD = Ice rafted debris seen in the first four basal varves. Red arrow marks the boundary between deformed varves and the overlying estuarine silt. Green arrows refer to thick (13 and 25 cm), sandy couplets discussed in the text. Orange arrow marks the boundary between varves and ice-marginal sand and gravel. Core depths represent depth within the recovered core sample. Deformed sections, where accurate varve measurements were not possible are noted.

APPENDIX 3

**Varve count from cores PVD-1 – PVD-6, and EW-1 and PC-6 from
Pickart (1987)**

PVD-1 Varve Count

Varve Year	PVD-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5004	1	5.703	0.312	6.016	6.016
5005	2	7.188	0.352	7.539	13.555
5006	3	5.039	0.43	5.469	19.023
5007	4	1.445	0.352	1.797	20.82
5008	5	8.438	0.781	9.219	30.039
5009	6	0.352	0.156	0.508	30.547
5010	7	1.099	0.172	1.272	31.818
5011	8	1.509	0.388	1.897	33.715
5012	9	3.319	0.366	3.685	37.4
5013	10	2.155	0.431	2.586	39.987
5014	11	0.905	0.345	1.25	41.237
5015	12	0.539	0.345	0.884	42.12
5016	13	0.453	0.28	0.733	42.853
5017	14	2.392	0.409	2.802	45.655
5018	15	0.776	0.28	1.056	46.711
5019	16	1.661	0.484	2.145	48.856
5020	17	0.865	0.398	1.263	50.119
5021	18	0.969	0.363	1.332	51.451
5022	19	3.253	0.277	3.529	54.981
5023	20	0.502	0.156	0.657	55.638
5024	21	1.436	0.346	1.782	57.42
5025	22	1.644	0.588	2.232	59.652
5026	23	1.411	0.484	1.895	61.547
5027	24	1.573	1.653	3.226	64.773
Deformed	25				
Deformed	26				
Deformed	27				
Deformed	28				
Deformed	29				
Deformed	30				
Deformed	31				
Deformed	32				
Deformed	33				
Deformed	34				
Deformed	35				
Deformed	36				
Deformed	37				
Deformed	38				
Deformed	39				
Deformed	40				
Deformed	41				
Deformed	42				
5044	43	4.022	0.57	4.592	294.613
5045	44	1.318	0.156	1.475	296.087
5046	45	2.48	0.335	2.816	298.903
5047	46	0.852	0.139	0.991	299.894

Varve Year	PVD-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5048	47	0.765	0.278	1.043	300.938
5049	48	1.678	0.33	2.009	302.946
5050	49	0.791	0.409	1.2	304.146
5051	50	1.548	0.237	1.785	305.931
5052	51	0.355	0.118	0.473	306.405
5053	52	1.258	0.247	1.505	307.91
5054	53	0.925	0.247	1.172	309.082
5055	54	1.419	0.204	1.624	310.706
5056	55	1.323	0.215	1.538	312.243
5057	56	1.351	0.126	1.477	313.721
5058	57	3.009	0.288	3.297	317.018
5059	58	1.189	0.306	1.495	318.514
5060	59	0.721	0.234	0.955	319.468
5061	60	0.847	0.27	1.117	320.586
5062	61	1.766	0.45	2.216	322.802
5063	62	1.099	0.505	1.604	324.405
5064	63	1.604	0.234	1.838	326.243
5065	64	2.239	0.55	2.789	329.032
5066	65	0.697	0.202	0.899	329.931
5067	66	1.413	0.477	1.89	331.821
5068	67	0.826	0.183	1.009	332.83
5069	68	2.642	0.275	2.917	335.748
5070	69	0.495	0.404	0.899	336.647
5071	70	1.009	0.422	1.431	338.078
5072	71	0.862	0.202	1.064	339.142
5073	72	0.294	0.257	0.55	339.693
5074	73	2.113	0.532	2.645	342.338
5075	74	0.823	0.339	1.161	343.499
5076	75	1.371	0.435	1.806	345.306
5077	76	1.306	0.29	1.597	346.902
5078	77	1.629	0.258	1.887	348.79
5079	78	1.226	0.258	1.484	350.273
5080	79	0.774	0.339	1.113	351.386
Deformed	80				
Deformed	81				
Deformed	82				
Deformed	83				
Deformed	84				
Deformed	85				
Deformed	86				
Deformed	87				
5089	88	1.402	0.855	2.256	374.884
5090	89	3.671	0.518	4.188	379.072
5091	90	3.506	0.776	4.282	383.355
5092	91	2.141	0.565	2.706	386.06
5093	92	2.101	0.522	2.623	388.684
5094	93	1.174	0.362	1.536	390.22

Varve Year	PVD-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5095	94	1.406	0.609	2.014	392.234
5096	95	5.195	0.707	5.902	398.137
5097	96	3.463	0.415	3.878	402.015
5098	97	3.098	0.463	3.561	405.576
5099	98	1.707	0.293	2	407.576
5100	99	2.488	0.317	2.805	410.381
5101	100	0.719	0.337	1.056	411.437
5102	101	0.809	0.292	1.101	412.538
5103	102	0.921	0.315	1.236	413.774
5104	103	0.674	0.404	1.079	414.853
5105	104	4.292	0.517	4.809	419.662
5106	105	2.944	0.404	3.348	423.01
5107	106	2.629	0.764	3.393	426.403
5108	Core break				
5109	Missing				
5110	Missing				
5111	Missing				
5112	Missing				
5113	Missing				
5114	Missing				
5115	Missing				
5116	107	2.677	0.548	3.226	429.629
5117	108	1.387	0.452	1.839	431.468
5118	109	1	0.452	1.452	432.919
5119	110	1.355	0.71	2.065	434.984
5120	111	0.742	0.387	1.129	436.113
5121	112	0.323	0.29	0.613	436.726
5122	113	1.129	0.355	1.484	438.21
5123	114	1.065	0.484	1.548	439.758
5124	115	1.742	0.516	2.258	442.016
5125	116	0.548	0.355	0.903	442.919
5126	117	0.774	0.258	1.032	443.952
5127	118	2.29	0.613	2.903	446.855
5128	119	1.226	0.581	1.806	448.661
5129	120	0.897	0.586	1.483	450.144
5130	121	1.724	0.379	2.103	452.247
Deformed	122				
Deformed	123				
Deformed	124				
Deformed	125				
Deformed	126				
5135	127	3.12	0.48	3.6	481.346
5136	128	1.947	0.56	2.507	483.853
5137	129	2	0.533	2.533	486.386
5138	130	0.907	0.907	1.813	488.199
5139	131	1.44	0.453	1.893	490.093
5140	132	1.333	0.56	1.893	491.986

Varve Year	PVD-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5141	133	1.484	0.258	1.742	493.728
5142	134	1.097	0.387	1.484	495.212
5143	Missing				
5144	135	4.484	0.484	4.968	500.179
5145	136	4.484	0.323	4.806	504.986
5146	137	2.935	0.355	3.29	508.276
5147	138	2	0.226	2.226	510.502
5148	139	2.258	0.29	2.548	513.05
5149	140	4.258	0.258	4.516	517.567
5150	141	0.61	0.305	0.914	518.481
5151	142	8.876	0.19	9.067	527.548
5152	143	1.276	0.229	1.505	529.053
5153	144	0.952	0.267	1.219	530.272
5154	145	0.99	0.152	1.143	531.415
5155	146	0.705	0.152	0.857	532.272
5156	147	1.812	0.562	2.375	534.647
Deformed	148				
Deformed	149				
Deformed	150				
Deformed	151				
Deformed	152				
Deformed	153				
Deformed	154				
Deformed	155				
Deformed	156				
Deformed	157				
Deformed	158				
Deformed	159				
Deformed	160				
Deformed	161				
Deformed	162				
Deformed	163				
Deformed	164				
Deformed	165				
Deformed	166				
Deformed	167				
Deformed	168				
Deformed	169				
Deformed	170				
Deformed	171				
Deformed	172				
Deformed	173				
Deformed	174				
Deformed	175				
Deformed	176				
Deformed	177				
Deformed	178				

Varve Year	PVD-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
Deformed	179				
Deformed	180				
Deformed	181				
5186	182	1.2	1.253	2.453	600.152
5187	183	0.96	1.28	2.24	602.392
5188	184	0.853	0.56	1.413	603.805
5189	185	1.893	1.093	2.987	606.792
5190	186	1.253	0.853	2.107	608.899
5191	187	1.067	0.693	1.76	610.659
5192	188	1.44	0.64	2.08	612.739
5193	189	1.36	0.72	2.08	614.819
5194	190	1.84	0.773	2.613	617.432
5195	191	0.745	0.245	0.99	618.422
5196	192	1.582	0.724	2.306	620.728
5197	193	0.908	0.469	1.378	622.105
5198	194	0.255	0.194	0.449	622.554
5199	195	0.459	0.276	0.735	623.289
5200	196	0.959	0.735	1.694	624.983
5201	197	2.14	0.222	2.36	627.343
5202	198	0.389	0.903	1.292	628.635
5203	199	0.722	1.125	1.847	630.482
5204	200	3.153	0.319	3.472	633.954

PVD-2

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
Deformed	1	7.089	0.585	7.675	7.675
Thick and sandy	2	14.675	0.234	14.909	22.584
(Uncorrelated)	3	2.416	0.286	2.701	25.285
' ' '	4	0.364	0.364	0.727	26.012
' ' '	5	0.831	0.26	1.091	27.103
' ' '	6	12.591	0.261	12.852	39.956
' ' '	7	16.523	0.364	16.886	56.842
' ' '	8	9.714	0.476	10.19	67.032
' ' '	9	6.095	0.31	6.405	73.437
' ' '	10	0.762	0.19	0.952	74.39
' ' '	11	13.884	0.58	14.464	88.853
' ' '	12	6.377	0.406	6.783	95.636
' ' '	13	12.617	0.318	12.935	108.57
' ' '	14	3.711	0.309	4.021	112.591
' ' '	15	2.907	0.165	3.072	115.663
' ' '	16	4.041	0.309	4.351	120.014
' ' '	17	4.455	0.198	4.653	124.667
' ' '	18	2.752	0.257	3.01	127.677
5042	19	3.347	0.277	3.624	131.301
5043	20	3.663	0.158	3.822	135.123
5044	21	1.698	0.226	1.925	139.826
5045	22	0.774	0.189	0.962	140.788
5046	23	0.811	0.151	0.962	141.75
5047	24	1.208	0.264	1.472	143.222
5048	25	2.321	0.208	2.528	145.75
5049	26	2.34	0.189	2.528	148.278
5050	27	0.264	0.094	0.358	148.637
5051	28	1.83	0.208	2.038	150.675
5052	29	1.245	0.17	1.415	152.09
5053	30	0.569	0.098	0.667	152.756
5054	31	0.882	0.294	1.176	153.933
5055	32	1.059	0.118	1.176	155.109
5056	33	1.49	0.431	1.922	157.031
5057	34	1.667	0.373	2.039	159.07
5058	35	0.686	0.294	0.98	160.05
5059	36	0.882	0.275	1.157	161.207
5060	37	1.922	0.392	2.314	163.521
5061	38	1.392	0.314	1.706	165.227
5062	39	1.255	0.275	1.529	166.756
5063	40	5.588	1.029	6.618	173.374
5064	41	1.814	0.784	2.598	175.972
5065	42	2.598	0.784	3.382	179.354
5066	43	2.059	0.588	2.647	182.001
5067	44	6.422	0.931	7.353	189.354
5068	45	1.176	0.392	1.569	190.923
5069	46	3.333	0.882	4.216	195.139

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5070	47	1.618	0.686	2.304	197.443
5071	48	0.539	0.441	0.98	198.423
5072	49	4.657	0.882	5.539	203.962
5073	50	0.696	0.239	0.935	204.897
5074	51	1	0.348	1.348	206.245
5075	52	0.913	0.261	1.174	207.419
5076	53	1.217	0.413	1.63	209.049
5077	54	0.587	0.217	0.804	209.854
5078	55	0.717	0.239	0.957	210.81
5079	56	1.239	0.304	1.543	212.354
5080	57	1.37	0.304	1.674	214.027
5081	58	1.435	0.391	1.826	215.854
5082	59	3.63	0.391	4.022	219.875
5083	60	4.778	0.333	5.111	224.986
5084	61	2.167	0.722	2.889	227.875
5085	62	2.222	0.722	2.944	230.82
5086	63	1.806	0.778	2.583	233.403
5087	64	2.722	0.361	3.083	236.486
5088	65	2.889	0.722	3.611	240.097
5089	66	3	0.553	3.553	243.65
5090	67	2.368	0.474	2.842	246.492
5091	68	1.421	0.395	1.816	248.308
5092	69	0.921	0.263	1.184	249.492
5093	70	1.632	0.316	1.947	251.44
5094	71	6.395	0.395	6.789	258.229
5095	72	4.692	0.923	5.615	263.844
5096	73	1.103	0.256	1.359	265.203
5097	74	1.256	0.179	1.436	266.639
5098	75	1.359	0.256	1.615	268.255
5099	76	1.333	0.308	1.641	269.896
5100	77	1.103	0.359	1.462	271.357
5101	78	1.513	0.436	1.949	273.306
5102	79	1.282	0.436	1.718	275.024
5103	80	1.974	0.513	2.487	277.511
5104	81	0.805	0.195	1	278.511
5105	82	1.878	0.707	2.585	281.096
5106	83	0.854	0.195	1.049	282.145
5107	84	2.146	0.463	2.61	284.755
5108	85	1.195	0.244	1.439	286.194
5109	86	0.805	0.366	1.171	287.365
5110	87	1.049	0.195	1.244	288.609
5111	88	0.829	0.22	1.049	289.657
5112	89	0.415	0.171	0.585	290.243
5113	90	1.366	0.171	1.537	291.779
5114	Missing				
5115	Missing				

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5116	91	2.756	0.244	2.33	297.987
5117	92	0.683	0.195	1.429	299.416
5118	93	2	0.33	1.275	300.69
5119	94	1.253	0.176	2.022	302.712
5120	95	1.077	0.198	3.714	306.427
5121	96	1.824	0.198	0.637	307.064
5122	97	3.516	0.198	0.703	307.767
5123	98	0.505	0.132	1.385	309.152
5124	99	0.462	0.242	0.967	310.119
5125	100	1.275	0.11	1.385	311.503
5126	101	0.835	0.132	4.647	316.151
5127	102	1.209	0.176	9.588	325.739
Deformed	103	2.971	1.676	8.059	333.798
Deformed	104	8.147	1.441	1.617	335.415
Deformed	105	6.765	1.294	2.728	338.142
Deformed	106	1.303	0.314	1.859	340.001
5133	107	2.341	0.386	2.486	342.487
5134	108	1.593	0.266	1.69	344.177
5135	109	2.1	0.386	1.81	345.987
5136	110	1.448	0.241	2.076	348.063
5137	111	1.424	0.386	2.148	350.211
5138	112	1.762	0.314	1.424	351.636
5139	113	1.979	0.169	7.47	359.105
5140	114	1.231	0.193	3.277	362.383
5141	Missing				
5142	115	6.988	0.482	1.711	364.093
5143	116	3.06	0.217	2.843	366.937
5144	117	1.301	0.41	1.349	368.286
5145	118	2.482	0.361	8.282	376.568
5146	119	1.133	0.217	1.667	378.235
Deformed	120	7.949	0.333	4.923	383.158
Deformed	121	1.385	0.282	0.949	384.107
Deformed	122	4.667	0.256	1.103	385.209
5151	123	0.795	0.154	1.308	386.517
5152	124	0.821	0.282	1.615	388.132
5153	125	1.077	0.231	6.545	394.678
5154	126	1.436	0.179	0.955	395.632
Deformed	127	6.227	0.318	2.705	398.337
Deformed	128	0.705	0.25	6.773	405.11
Deformed	129	2.364	0.341	3.268	408.377
Deformed	130	6.659	0.114	2.676	411.053
5165	131	2.986	0.282	1.606	412.659
5166	132	2.507	0.169	0.789	413.448
5167	133	1.465	0.141	1.972	415.419
5168	134	0.592	0.197	1.972	417.391
5169	135	1.662	0.31	2.141	419.532

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5216	180	0.716	0.746	4.727	515.758
5217	181	4.636	0.705	2.409	518.167
Deformed	182	4.159	0.568	1.773	519.94
Deformed	183	2	0.409	1.75	521.69
Deformed	184	1.455	0.318	8	529.69
Deformed	185	1.273	0.477	2.881	532.571
Deformed	186	6.524	1.476	6.81	539.381
Deformed	187	2.476	0.405	2.172	541.553
Deformed	188	5.095	1.714	4.057	545.611
Deformed	189	1.68	0.492	8.484	554.094
Deformed	190	3.279	0.779	8.934	563.029
Deformed	191	7.869	0.615	6.967	569.996
Deformed	192	8.73	0.205	1.27	571.266
Deformed	193	6.598	0.369	0.514	571.781
5229	194	1.025	0.246	1.086	572.866
5230	195	0.414	0.1	0.414	573.281
5231	196	0.943	0.143	0.557	573.838
5232	197	0.314	0.1	2.143	575.981
5233	198	0.386	0.171	1.271	577.252
5234	199	1.957	0.186	1.843	579.095
5235	200	1.086	0.186	1	580.095
5236	201	1.686	0.157	1.143	581.238
5237	202	0.743	0.257	1.897	583.135
5238	203	1	0.143	1.282	584.417
5239	204	1.675	0.222	2.325	586.742
5240	205	1.111	0.171	0.786	587.528
5241	206	2.085	0.239	1.521	589.05
5242	207	0.598	0.188	1.197	590.246
5243	208	1.265	0.256	1.385	591.631
5244	209	0.957	0.239	0.65	592.28
5245	210	1.077	0.308	0.803	593.084
5246	211	0.41	0.239	0.65	593.733
5247	212	0.547	0.256	0.803	594.536

PVD-3

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
Deformed	1	0.889	0.192	1.082	1.082
Deformed	2	1.394	0.12	1.514	2.596
Deformed	3	4.567	0.12	4.688	7.284
Deformed	4	2.548	0.168	2.716	10
Deformed	5	0.192	0.144	0.337	10.337
Deformed	6	0.673	0.096	0.769	11.106
Deformed	7	2.26	0.24	2.5	13.606
5188	8	0.601	0.168	0.769	14.375
5189	9	3.392	0.472	3.864	18.239
5190	10	1.681	0.147	1.829	20.068
5191	11	1.003	0.531	1.534	21.602
5192	12	1.947	0.649	2.596	24.198
5193	13	3.186	1.032	4.218	28.416
Deformed	14	4.897	0.885	5.782	34.198
Deformed	15	0.855	0.354	1.209	35.407
Deformed	16	3.07	1.07	4.141	39.548
5198	17	3.408	0.563	3.972	43.52
5199	18	4.648	1.718	6.366	49.886
5200	19	3.042	1.324	4.366	54.253
5201	20	1.887	0.535	2.423	56.675
5202	21	2.761	0.896	3.656	60.331
5203	22	2.267	0.841	3.108	63.439
5204	23	2.249	0.823	3.071	66.51
5205	24	2.706	0.512	3.218	69.728
5206	25	1.579	0.362	1.941	71.669
5207	26	2.368	1.02	3.388	75.057
5208	27	1.447	0.23	1.678	76.735
5209	28	2.467	0.428	2.895	79.629
5210	29	1.316	0.329	1.645	81.274
5211	30	1.48	0.296	1.776	83.05
5212	31	1.02	0.362	1.382	84.432
5213	32	2.434	0.724	3.158	87.59
5214	33	1.283	0.526	1.809	89.399
5215	34	3.224	0.362	3.586	92.985
5216	35	1.086	0.855	1.941	94.925
5217	36	5.893	0.313	6.207	101.132
Deformed	37	6.928	0.251	7.179	108.311
Deformed	38	2.915	0.282	3.197	111.508
Deformed	39	2.351	0.376	2.727	114.236
Deformed	40	1.034	0.533	1.567	115.803
Deformed	41	1.536	1.442	2.978	118.781
Deformed	42	1.747	0.278	2.025	120.806
Deformed	43	1.671	0.076	1.747	122.553
Deformed	44	1.342	0.405	1.747	124.3
Deformed	45	4.228	0.278	4.506	128.806

Varve Year	PVD-2 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
Deformed	46	0.481	0.203	0.684	129.49
Deformed	47	3.443	0.456	3.899	133.389
Deformed	48	3.316	0.278	3.595	136.984
5235	49	1.471	0.196	1.667	138.65
5236	50	0.373	0.118	0.49	139.14
5237	51	0.431	0.059	0.49	139.631
5238	52	0.745	0.157	0.902	140.533
5239	53	1.569	0.196	1.765	142.297
5240	54	0.529	0.176	0.706	143.003
5241	55	1.294	0.137	1.431	144.435
5242	56	1.392	0.098	1.49	145.925
5243	57	0.431	0.176	0.608	146.533
5244	58	2.059	0.196	2.255	148.787
5245	59	2.137	0.294	2.431	151.219
5246	60	0.436	0.095	0.531	151.75
5247	61	2.922	0.152	3.074	154.824
5248	62	1.176	0.114	1.29	156.114
5249	63	2.486	0.209	2.694	158.809
5250	64	1.025	0.152	1.176	159.985
5251	65	0.74	0.19	0.93	160.915
5252	66	0.645	0.19	0.835	161.75
5253	67	2.6	0.209	2.808	164.558
5254	68	0.398	0.114	0.512	165.071
5255	69	4.934	0.232	5.166	170.236
5256	70	2.682	0.298	2.98	173.217
5257	71	5.894	0.464	6.358	179.574
5258	72	3.113	0.364	3.477	183.051
5259	73	4.57	0.166	4.735	187.786
5260	74	0.662	0.099	0.762	188.548

PVD-5

Varve Year	PVD-5 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5107	1	2.246	0.556	2.802	2.802
5108	2	0.942	0.386	1.329	4.13
5109	3	1.039	0.217	1.256	5.386
5110	4	0.797	0.338	1.135	6.522
5111	5	1.184	0.217	1.401	7.923
5112	6	0.556	0.145	0.7	8.623
5113	7	1.498	0.314	1.812	10.435
5114	8	1.304	0.169	1.473	11.908
5115	9	1.667	0.556	2.222	14.13
5116	10	0.773	0.314	1.087	15.217
5117	11	0.894	0.242	1.135	16.353
5118	12	2.126	0.266	2.391	18.744
5119	13	1.507	0.48	1.987	20.731
5120	14	0.83	0.568	1.397	22.128
5121	15	1.31	0.524	1.834	23.962
5122	16	2.38	0.677	3.057	27.019
5123	17	0.59	0.284	0.873	27.892
5124	18	0.48	0.284	0.764	28.657
5125	19	0.961	0.24	1.201	29.857
5126	20	0.83	0.24	1.07	30.927
5127	21	1.048	0.24	1.288	32.216
5128	22	2.096	0.284	2.38	34.595
Deformed	23	1.122	2.073	3.195	37.791
Deformed	24	0.683	2.049	2.732	40.522
Deformed	25	4.732	0.951	5.683	46.205
5132	26	5.366	0.171	5.537	51.742
5133	27	2.714	0.306	3.02	57.53
5134	28	1.367	0.408	1.776	59.306
5135	29	2.143	0.531	2.673	61.979
5136	30	1	0.327	1.327	63.306
5137	31	1.898	0.286	2.184	65.49
5138	32	1.633	0.286	1.918	67.408
5139	33	1.857	0.184	2.041	69.449
5140	34	1.183	0.312	1.496	70.944
5141	Missing				
5142	35	5.201	0.223	5.424	79.359
5143	36	2.656	0.335	2.991	82.35
5144	37	1.987	0.246	2.232	84.582
5145	38	1.496	0.268	1.763	86.345
5146	39	1.562	0.179	1.741	88.086
5147	Missing	Core break			
5148	Missing	Core break			
5149	40	0.932	0.353	1.285	89.371
5150	41	1.776	0.214	1.99	91.361

Varve Year	PVD-5 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5151	42	0.882	0.214	1.096	92.457
5152	43	0.907	0.327	1.234	93.691
5153	44	1.499	0.277	1.776	95.467
5154	45	2.331	0.489	2.82	98.287
5155	46	5.977	0.313	6.291	104.578
5156	47	0.666	0.201	0.867	105.445
5157	48	2.173	0.264	2.437	107.882
5158	49	4.133	0.264	4.397	112.279
5159	50	4.505	0.279	4.784	117.063
5160	51	3.655	0.178	3.832	120.895
5161	52	0.835	0.139	0.975	121.87
5162	53	0.797	0.139	0.937	122.807
5163	54	2.203	0.266	2.468	125.275
5164	55	2.051	0.316	2.367	127.642
5165	56	0.924	0.278	1.203	128.845
5166	57	1.459	0.254	1.713	130.558
5167	58	1.168	0.266	1.434	131.992
5168	59	0.609	0.216	0.825	132.817
5169	60	1.332	0.216	1.548	134.365
5170	61	0.863	0.076	0.939	135.304
5171	62	0.241	0.063	0.305	135.609
5172	63	1.662	0.114	1.777	137.386
5173	64	0.876	0.228	1.104	138.49
5174	65	0.114	0.152	0.266	138.756
5175	66	0.584	0.203	0.787	139.543
5176	67	1.117	0.266	1.383	140.926
5177	68	1.066	0.203	1.269	142.195
5178	69	1.091	0.279	1.371	143.566
5179	70	0.228	0.076	0.305	143.871
5180	71	0.266	0.102	0.368	144.239
5181	72	1.662	0.216	1.878	146.117
5182	73	0.306	0.268	0.574	146.691
5183	74	0.625	0.281	0.906	147.597
5184	75	0.842	0.14	0.982	148.579
5185	76	0.714	0.204	0.918	149.497
5186	77	2.296	0.421	2.717	152.214
5187	78	0.191	0.332	0.523	152.737
5188	79	0.268	0.128	0.395	153.132
5189	80	1.378	0.217	1.594	154.726
5190	81	3.583	0.264	3.847	158.573
5191	82	0.444	0.278	0.722	159.295
5192	83	2.014	0.514	2.528	161.823
5193	84	2.278	0.361	2.639	164.462
Deformed	85	2.354	0.443	2.797	167.259
Deformed	86	2.063	1.152	3.215	170.474

Varve Year	PVD-5 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
Deformed	87	0.481	0.62	1.101	171.575
Deformed	88	6.637	0.584	7.221	178.796
Deformed	89	1.632	0.279	1.912	180.708
Deformed	90	1.603	0.794	2.397	183.105
Deformed	91	2.412	0.882	3.294	186.399
Deformed	92	1.793	1.63	3.424	189.823
Deformed	93	1.223	0.761	1.984	191.807
Deformed	94	0.978	0.326	1.304	193.111
Deformed	95	0.353	1.005	1.359	194.47
Deformed	96	2.091	0.819	2.909	197.379
Deformed	97	2.544	1.115	3.659	201.038
Deformed	98	2.073	0.61	2.683	203.721
Deformed	99	1.986	0.801	2.787	206.508
Deformed	100	3.308	0.733	4.041	210.549
Deformed	101	3.214	0.432	3.647	214.196
Deformed	102	0.47	0.207	0.677	214.873
Deformed	103	0.432	0.244	0.677	215.55
Deformed	104	0.752	0.508	1.259	216.809
Deformed	105	1.485	0.414	1.898	218.707
5215	106	1.184	0.827	2.011	220.718
5216	107	1.054	0.799	1.854	222.572
5217	108	3.656	0.629	4.286	226.858
5218	109	3.997	0.306	4.303	231.161
Deformed	110	2.782	0.282	3.065	234.226
Deformed	111	3.376	0.819	4.195	238.421
Deformed	112	2.455	1.697	4.152	242.573
Deformed	113	2.788	1.091	3.879	246.452
Deformed	114	3.818	0.576	4.394	250.846
Deformed	115	5.273	0.727	6	256.846
Deformed	116	4.758	0.455	5.212	262.058
Deformed	117	3.377	0.274	3.652	265.71
Deformed	118	3.998	0.418	4.415	270.125
Deformed	119	0.651	0.205	0.855	270.98
Deformed	120	1.795	0.265	2.06	273.04
Deformed	121	2.807	0.108	2.916	275.956
Deformed	122	4.151	0.096	4.246	280.202
Deformed	123	3.349	0.072	3.421	283.623
Deformed	124	5.541	0.216	5.757	289.38
5234	125	1.803	0.264	2.067	291.447
5235	126	0.481	0.156	0.637	292.084
5236	127	0.469	0.132	0.601	292.685

Varve Year	PVD-5 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5237	128	0.323	0.096	0.419	293.104
5238	129	0.526	0.096	0.622	293.726
5239	130	1.005	0.12	1.124	294.85
5240	131	0.706	0.108	0.813	295.663
5241	132	1.531	0.191	1.722	297.385
5242	133	1.041	0.239	1.28	298.665
5243	134	1.172	0.191	1.364	300.029
5244	135	1.265	0.263	1.527	301.556
5245	136	3.532	0.286	3.819	305.375
5246	137	0.573	0.119	0.692	306.067
5247	138	1.933	0.131	2.064	308.131
5248	139	2.464	0.181	2.645	310.776
5249	140	2.017	0.157	2.174	312.95
5250	141	2.114	0.193	2.307	315.257
5251	142	0.843	0.157	1	316.257
5252	143	0.783	0.145	0.928	317.185
5253	144	0.988	0.108	1.096	318.281
5254	145	1.53	0.181	1.711	319.992
5255	146	1.386	0.301	1.687	321.679
5256	147	12.244	0.317	12.561	334.24

PVD-6

Varve Year	PVD-6 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5000	1	5.47	0.14	5.61	5.61
5001	2	6.13	0.28	6.41	12.02
5002	3	1.82	0.11	1.93	13.95
5003	4	2.54	0.19	2.74	16.69
5004	5	4.50	0.19	4.70	21.38
5005	6	4.33	0.12	4.45	25.83
5006	7	3.09	0.32	3.41	29.24
5007	8	6.32	0.35	6.67	35.91
5008	9	0.60	0.20	0.80	36.71
5009	10	0.85	0.25	1.10	37.80
5010	11	1.64	0.20	1.84	39.64
5011	12	2.25	0.40	2.65	42.29
5012	13	1.25	0.21	1.46	43.76
5013	14	1.40	0.23	1.64	45.39
5014	15	0.60	0.15	0.75	46.14
5015	16	0.79	0.14	0.92	47.06
5016	17	1.37	0.23	1.60	48.66
5017	18	0.81	0.14	0.94	49.60
5018	19	1.79	0.17	1.96	51.56
5019	20	0.69	0.31	1.00	52.56
5020	21	1.19	0.25	1.44	54.01
5021	22	2.81	0.34	3.15	57.15
5022	23	0.26	0.15	0.41	57.56
5023	24	0.99	0.27	1.26	58.82
5024	25	1.79	0.56	2.35	61.17
5025	26	1.11	0.56	1.67	62.83
5026	27	1.85	1.12	2.98	65.81

Core EW-1: Pickart, 1987

Varve Year	EW-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5042	1	1.896	0.468	2.364	2.364
5043	2	0.961	0.26	1.221	3.584
5044	3	1.065	0.286	1.351	4.935
5045	4	0.987	0.286	1.273	6.208
5046	5	1.091	0.208	1.299	7.506
5047	6	1.429	0.208	1.636	9.143
5048	7	1.688	0.182	1.87	11.013
5049	8	1.61	0.156	1.766	12.779
5050	9	0.312	0.182	0.494	13.273
5051	10	1.195	0.182	1.377	14.649
5052	11	0.805	0.286	1.091	15.74
5053	12	1.091	0.26	1.351	17.091
5054	13	1.065	0.286	1.351	18.442
5055	14	0.961	0.156	1.117	19.558
5056	15	2.146	0.244	2.39	21.949
5057	16	0.878	0.366	1.244	23.193
5058	17	0.488	0.22	0.707	23.9
5059	18	0.634	0.244	0.878	24.778
5060	19	1.39	0.341	1.732	26.51
5061	20	1.22	0.244	1.463	27.973
5062	21	2.341	0.317	2.659	30.632
5063	22	1.659	0.488	2.146	32.778
5064	23	0.488	0.244	0.732	33.51
5065	24	0.951	0.317	1.268	34.778
5066	25	0.39	0.122	0.512	35.29
5067	26	1.537	0.39	1.927	37.217
5068	27	0.416	0.182	0.597	37.814
5069	28	0.623	0.416	1.039	38.853
5070	29	0.519	0.286	0.805	39.659
5071	30	0.208	0.156	0.364	40.022
5072	31	1.325	0.312	1.636	41.659
5073	32	0.545	0.286	0.831	42.49
5074	33	0.805	0.286	1.091	43.581
5075	34	0.753	0.312	1.065	44.646
5076	35	0.935	0.312	1.247	45.892
5077	36	0.623	0.286	0.909	46.801
5078	37	0.597	0.286	0.883	47.685
5079	38	0.753	0.208	0.961	48.646
5080	39	1.143	0.234	1.377	50.022
5081	40	1.247	0.286	1.532	51.555
5082	41	2.208	0.416	2.623	54.178
5083	42	2.597	0.338	2.935	57.113
5084	43	1.448	0.65	2.098	59.211
5085	44	0.92	0.663	1.583	60.794
5086	45	2.11	0.613	2.724	63.518

Varve Year	EW-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5087	46	2.767	0.651	3.419	66.937
5088	47	1.744	0.279	2.023	68.96
5089	48	3.093	0.372	3.465	72.425
5090	49	2.14	0.419	2.558	74.983
5091	50	1.465	0.186	1.651	76.634
5092	51	0.93	0.163	1.093	77.727
5093	52	1.302	0.163	1.465	79.192
5094	53	6.709	0.253	6.962	86.154
5095	54	4.734	0.177	4.911	91.066
5096	55	1.949	0.177	2.127	93.192
5097	56	1.57	0.203	1.772	94.965
5098	57	1.367	0.329	1.696	96.661
5099	58	0.861	0.278	1.139	97.8
5100	59	1.314	0.371	1.686	99.486
5101	60	1.086	0.457	1.543	101.029
5102	61	2.229	0.429	2.657	103.686
5103	62	1.371	0.2	1.571	105.257
5104	63	1.514	0.371	1.886	107.143
5105	64	2.229	0.229	2.457	109.6
5106	Missing				
5107	65	2.886	0.486	3.371	112.971
5108	66	0.886	0.457	1.343	114.314
5109	67	0.8	0.457	1.257	115.571
5110	68	0.829	0.371	1.2	116.771
5111	69	0.657	0.286	0.943	117.714
5112	70	0.384	0.219	0.603	118.317
5113	71	1.397	0.438	1.836	120.153
5114	72	0.904	0.384	1.288	121.44
5115	73	1.397	0.438	1.836	123.276
5116	74	0.575	0.274	0.849	124.125
5117	75	0.795	0.247	1.041	125.166
5118	76	1.562	0.247	1.808	126.975
5119	77	1.205	0.219	1.425	128.399
5120	78	0.849	0.329	1.178	129.577
5121	79	1.315	0.274	1.589	131.166
5122	80	2.767	0.219	2.986	134.153
5123	81	0.438	0.247	0.685	134.838
5124	82	0.493	0.137	0.63	135.468
5125	83	1.041	0.219	1.26	136.728
5126	84	0.685	0.164	0.849	137.577
5127	85	0.522	0.217	0.739	138.316
5128	86	2.457	0.239	2.696	141.012
5129	87	1.413	1.261	2.674	143.686
5130	88	2.826	1.283	4.109	147.795
5131	89	3.565	1.065	4.63	152.425
5132	90	3.213	0.247	3.461	155.886

Varve Year	EW-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5133	91	3.326	0.157	3.483	159.369
5134	92	1.506	0.202	1.708	161.077
5135	93	1.393	0.18	1.573	162.65
5136	94	0.966	0.247	1.213	163.863
5137	95	1.303	0.247	1.551	165.414
5138	96	1.416	0.157	1.573	166.987
5139	97	1.105	0.184	1.289	168.276
5140	98	0.868	0.158	1.026	169.303
5141	99	0.632	0.132	0.763	170.066
5142	100	2.474	0.211	2.684	172.75
5143	101	2.105	0.211	2.316	175.066
5144	102	0.921	0.184	1.105	176.171
5145	103	1.132	0.211	1.342	177.513
5146	104	1.079	0.211	1.289	178.803
5147	105	1.921	0.132	2.053	180.855
5148	106	0.447	0.105	0.553	181.408
5149	107	2.632	0.263	2.895	184.303
5150	108	1.132	0.184	1.316	185.619
5151	109	0.711	0.237	0.947	186.566
5152	110	0.821	0.284	1.104	187.67
5153	111	1.03	0.179	1.209	188.879
5154	112	1.06	0.164	1.224	190.103
5155	113	0.388	0.254	0.642	190.745
5156	114	2.134	0.358	2.493	193.238
5157	115	1.343	0.149	1.493	194.73
5158	116	2.075	0.269	2.343	197.073
5159	117	2.375	0.2	2.575	199.648
5160	118	2.375	0.25	2.625	202.273
5161	119	0.8	0.125	0.925	203.198
5162	120	0.55	0.325	0.875	204.073
5163	121	1.6	0.2	1.8	205.873
5164	122	1.6	0.275	1.875	207.748
5165	123	0.65	0.25	0.9	208.648
5166	124	1	0.3	1.3	209.948
5167	125	0.8	0.175	0.975	210.923
5168	126	0.325	0.325	0.65	211.573
5169	127	0.75	0.25	1	212.573
5170	128	0.725	0.35	1.075	213.648
5171	129	0.5	0.375	0.875	214.523
5172	130	1.175	0.25	1.425	215.948
5173	131	0.753	0.208	0.961	216.909
5174	132	0.571	0.26	0.831	217.74
5175	133	0.857	0.208	1.065	218.805
5176	134	1.117	0.494	1.61	220.416
5177	135	0.519	0.078	0.597	221.013
5178	136	0.286	0.156	0.442	221.454

Varve Year	EW-1 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
5179	137	0.26	0.156	0.416	221.87
5180	138	1.273	0.182	1.455	223.325
5181	139	0.26	0.156	0.416	223.74
5182	140	0.545	0.182	0.727	224.467
5183	141	0.312	0.208	0.519	224.987
5184	142	0.727	0.182	0.909	225.896
5185	143	2.026	0.286	2.312	228.208
5186	144	1.117	0.338	1.455	229.662
5187	145	0.442	0.312	0.753	230.416
5188	146	1.169	0.26	1.429	231.844
5189	147	0.286	0.26	0.545	232.39
5190	148	1.429	0.338	1.766	234.156
5191	149	1.169	0.571	1.74	235.896
5192	150	1.155	0.451	1.606	237.502
5193	151	1.352	0.563	1.915	239.417
5194	152	0.732	0.761	1.493	240.91
5195	153	2.479	0.732	3.211	244.121
5196	154	0.62	0.31	0.93	245.051
5197	155	1.662	0.479	2.141	247.192
5198	156	1.549	0.704	2.254	249.445
5199	157	2.169	0.817	2.986	252.431
5200	158	1.803	0.732	2.535	254.966
5201	159	0.761	0.451	1.211	256.178
5202	160	1.506	0.854	2.36	258.537
5203	161	1.146	0.562	1.708	260.245
5204	162	0.809	0.674	1.483	261.728
5205	163	0.989	0.742	1.73	263.459
5206	164	0.809	0.404	1.213	264.672
5207	165	1.056	0.449	1.506	266.178
5208	166	0.315	0.27	0.584	266.762

Core PC-6: Pickart, 1987

PC-6 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
1	3.65	0.36	4.00	4.00
2	15.94	1.32	17.26	21.26
3	16.73	0.83	17.56	38.81
4	0.86	0.73	1.59	40.40
5	9.76	2.64	12.39	52.80
6	1.70	0.76	2.46	55.25
7	2.76	1.76	4.52	59.77
8	2.67	0.52	3.18	62.95
9	5.51	1.31	6.82	69.76
10	5.46	0.72	6.17	75.93
11	1.58	1.21	2.79	78.72
12	2.67	0.79	3.45	82.18
13	1.48	1.05	2.52	84.70
14	0.64	0.60	1.24	85.94
15	0.48	0.31	0.79	86.72
16	2.24	1.26	3.50	90.22
17	0.45	0.93	1.38	91.61
18	0.64	0.64	1.29	92.89
19	3.10	0.36	3.45	96.34
20	3.50	0.71	4.21	100.56
21	1.60	1.59	3.19	103.74
22	0.54	0.27	0.81	104.56
23	15.42	9.42	24.85	129.41
24	7.09	5.76	12.84	142.25
25	1.11	2.16	3.27	145.52
26	1.57	4.43	6.00	151.52
27	10.49	0.30	10.79	162.30
28	3.97	0.59	4.56	166.86
29	0.39	0.66	1.05	167.91
30	2.45	0.23	2.68	170.59
31	3.65	0.19	3.84	174.43
32	0.41	0.17	0.58	175.00
33	0.23	0.12	0.35	175.35
34	0.70	3.24	3.94	179.29
35	2.17	0.52	2.68	181.97
36	3.02	0.46	3.48	185.45
37	2.30	0.50	2.80	188.25
38	0.61	0.17	0.78	189.03
39	1.59	0.19	1.78	190.81
40	2.82	0.37	3.19	193.99
41	0.74	0.17	0.91	194.90
42	0.17	0.11	0.28	195.18
43	3.64	0.36	4.00	199.18
44	2.76	0.26	3.02	202.19
45	0.83	0.38	1.21	203.40
46	0.33	0.28	0.60	204.00
47	1.53	0.22	1.76	205.76
48	1.62	0.28	1.90	207.66
49	0.74	0.20	0.93	208.59
50	0.56	0.23	0.79	209.38

PC-6 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
51	0.89	0.26	1.15	210.53
52	0.69	0.33	1.02	211.54
53	0.95	0.38	1.33	212.87
54	0.74	0.38	1.12	213.99
55	0.59	0.23	0.82	214.81
56	0.49	0.34	0.84	215.64
57	0.89	0.38	1.26	216.90
58	0.69	0.43	1.12	218.02
59	0.85	0.51	1.36	219.38
60	1.50	0.57	2.06	221.44
61	1.54	0.52	2.06	223.50
62	2.37	0.23	2.60	226.10
63	0.60	0.34	0.93	227.03
64	0.41	0.37	0.78	227.81
65	1.71	0.26	1.97	229.78
66	1.02	0.27	1.29	231.06
67	2.15	0.31	2.46	233.52
68	1.02	0.19	1.20	234.73
69	0.88	0.32	1.20	235.93
70	0.78	0.39	1.17	237.10
71	0.46	0.22	0.68	237.78
72	0.51	0.27	0.78	238.56
73	0.59	0.12	0.71	239.27
74	0.90	0.31	1.20	240.47
75	1.45	0.27	1.72	242.19
76	0.33	0.14	0.47	242.66
77	0.14	0.14	0.28	242.94
78	0.28	0.17	0.45	243.39
79	0.72	0.20	0.92	244.32
80	0.69	0.17	0.86	245.17
81	0.73	0.27	1.00	246.17
82	1.58	0.30	1.88	248.05
83	0.17	0.20	0.38	248.42
84	0.19	0.11	0.30	248.72
85	1.06	0.30	1.36	250.08
86	0.80	0.16	0.95	251.03
87	0.19	0.11	0.30	251.33
88	0.76	0.20	0.96	252.29
89	0.14	0.18	0.33	252.62
90	0.47	0.27	0.74	253.35
91	0.18	0.27	0.45	253.80
92	0.92	0.18	1.10	254.90
93	0.65	0.16	0.82	255.72
94	1.08	0.18	1.27	256.98
95	0.69	0.20	0.90	257.88
96	0.35	0.20	0.55	258.43
97	0.69	0.18	0.88	259.31
98	1.39	0.82	2.20	261.51
99	0.29	0.29	0.57	262.09

PC-6 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
100	0.31	0.25	0.55	262.64
101	2.22	0.31	2.53	265.17
102	0.74	0.18	0.92	266.09
103	11.12	0.59	11.71	277.79
104	2.59	2.53	5.12	282.91
105	5.54	2.62	8.16	291.07
106	0.65	1.01	1.66	292.73
107	1.52	0.79	2.31	295.04
108	1.61	0.93	2.54	297.58
109	1.69	1.92	3.61	301.18
110	2.82	0.54	3.35	304.53
111	1.27	0.93	2.20	306.73
112	1.13	0.39	1.52	308.25
113	1.55	0.23	1.78	310.03
114	0.76	0.45	1.21	311.24
115	0.51	0.23	0.73	311.97
116	2.93	0.43	3.35	315.32
117	1.08	0.48	1.55	316.87
118	0.38	0.28	0.65	317.52
119	0.40	0.18	0.58	318.10
120	1.75	0.45	2.20	320.30
121	2.03	0.38	2.40	322.70
122	1.43	0.43	1.85	324.55
123	0.85	0.25	1.10	325.65
124	0.23	0.13	0.35	326.00
125	0.60	0.23	0.83	326.82
126	1.13	0.60	1.73	328.55
127	0.83	0.40	1.23	329.77
128	1.10	0.36	1.45	331.22
129	1.05	0.19	1.24	332.47
130	0.27	0.15	0.42	332.88
131	0.95	0.30	1.24	334.13
132	0.82	0.22	1.04	335.16
133	0.36	0.27	0.62	335.79
134	0.56	0.27	0.83	336.62
135	0.99	0.44	1.44	338.05
136	0.58	0.27	0.84	338.90
137	0.55	0.34	0.89	339.79
138	5.93	1.03	6.96	346.74
139	0.50	0.46	0.96	347.70
140	1.22	0.27	1.49	349.18
141	0.30	0.23	0.53	349.72
142	1.74	0.34	2.07	351.79
143	0.34	0.50	0.83	352.62
144	0.18	0.41	0.58	353.20
145	0.74	0.32	1.06	354.26
146	0.25	0.32	0.57	354.83
147	0.27	0.14	0.41	355.24
148	0.55	0.21	0.76	356.00
149	0.28	0.11	0.39	356.39

PC-6 Count	Summer- cm	Winter - cm	Couplet - cm	Total - cm
150	0.66	0.21	0.87	357.25
151	0.60	0.37	0.97	358.23
152	0.60	0.34	0.94	359.17
153	0.66	0.35	1.01	360.18
154	0.20	0.32	0.51	360.69
155	0.20	0.09	0.28	360.97
156	0.27	0.16	0.43	361.40
157	0.20	0.18	0.37	361.77
158	0.89	0.57	1.45	363.22
159	0.41	0.34	0.74	363.96
160	1.38	0.30	1.68	365.64

APPENDIX 4

PALEOMAGNETIC RESULTS FROM CORES PVD-3 AND PVD-5 COLLECTED IN THE PROVIDENCE RIVER, RHODE ISLAND

Introduction

The paleomagnetic properties of glacial lakefloor sediment have been used to support regional correlation between varve sequences. Workers studying changes to the Earth's magnetic field realized that the annual nature of varves provided an ideal platform for constructing a record of paleomagnetic remanent declination and inclination (Johnson et al., 1948; Verosub, 1979a, 1979b). Declination is more useful as a correlation tool than inclination, which can be altered during deposition or by post-depositional process (compaction) (Ridge, 2003; Ridge et al., 1999; Ridge and Larsen, 1990). It was hoped that paleomagnetic information, particularly remanent declination would support a potential correlation with the North American Varve Chronology (NAVC). Ultimately, results were inconclusive and were not included in the manuscript version of chapter 3.

Methods

Paleomagnetic directional information was measured on continuous longitudinal subsamples of cores PVD-3 and PVD-5 following the procedures outlined by King and Peck (2001). Measurements of inclination, declination, and magnetization were conducted with a 2-G EnterpriseTM (WSG Inc., Sand City, CA), pass through cryogenic magnetometer at one-centimeter intervals. Progressive demagnetization with a diminishing alternating field removed magnetic overprints and subsampling disturbances. Declination and inclination were averaged over the depth range of each couplet, and converted to varve years.

Results

The remanent declination and inclination curves produced for cores PVD-3 and PVD-5 show inconsistencies somewhat expected given the level of deformation in the cores. While highly scattered, the remnant declination records in undeformed sections is 30° - 32° . Remanent inclination is less clear; values range between -60° and 120° , with clusters at 30° and 90° , and little consistency between cores (Figure 1).

Paleomagnetic Properties

The variability seen in the remanent inclination and declination records from cores PVD-3 and PVD-5 is presumably the result of coring deformation. While depositional processes can reorient grains, and cause declination to vary up to 15° (Verosub, 1979b), the consistency of declination in undeformed sections of the cores suggests that this is not a significant issue here. Previous studies have shown that regional correlation is possible using paleomagnetic records of sediment deposited in Late Wisconsinan and Holocene time (King and Peck, 2001; Ridge and Toll, 1999). The base of the paleomagnetic record in the NAVC are from varves deposited around 17,800 yBP, which is considerably younger than the interpreted age of Glacial Lake Narragansett (discussed below). Other paleomagnetic records exist from the northeastern United States and southeastern Canada for the Holocene and latest Pleistocene, but do not extend back to Late Wisconsinan time (King and Peck, 2001; St-Onge et al., 2003). Ocean Drilling Program (ODP) cores from site 1063 on the Bermuda Rise (1,500 km southwest of the study area) show a 20° westward excursion in relative declination at approximately 19,000 yBP (Lund et al., 2006), but the

distance between the sites and coarse temporal resolution of the ODP cores make any correlation with Glacial Lake Narragansett varves speculative at best. The lack of a calibrated, high-resolution, regional paleomagnetic record older than the NAVC limits the usefulness of remanent declination and inclination as a tool for constraining the age of varves deposited in Glacial Lake Narragansett.

Figure 1: Remnant inclination and declination for cores PVD-3 and PVD-5 plotted versus Glacial Lake Narragansett Varve Year. Dashed line in the declination record is the average declination in undeformed couplets.

REFERENCES

- Johnson, E.A., Murphy, T., and Torreson, O.W., 1948, Pre-history of the Earth's magnetic field: *Terrestrial Magnetism and Atmospheric Electricity*, v. 53.
- King, J.W., and Peck, J.A., 2001, Use of paleomagnetism in studies of lake sediments, *in* Last, W.M., and Smol, J.P., eds., *Tracking environmental change using lake sediments. Volume 1: Basin analysis, coring and chronological techniques*: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 371-389.
- Lund, S., Stoner, J.S., Channell, J.E.T., and Acton, G., 2006, A summary of Brunhes paleomagnetic field variability recorded in Ocean Drilling Program cores: *Physics of the Earth and Planetary Interiors*, v. 156, p. 194-204.
- Norris, M.W., and Faichney, A.K., 2002, SEG Y rev 1 Data exchange format: SEG technical Standards Committee: Society of Exploration Geophysicists.
- Pickart, D.S., 1987, Physical stratigraphy and geological evolution of the Providence River, Narragansett Bay, Rhode Island [Masters thesis]: Kingston, RI, University of Rhode Island.
- Ridge, J.C., 2003, The last deglaciation of the Northeastern United States: A combined varve, paleomagnetic and calibrated ¹⁴C Chronology, *in* Hart, J.P., and Cremeens, D.L., eds., *Geoarcheology of landscapes in the glaciated Northeast*: New York State Education Department, Albany, New York.
- Ridge, J.C., Besonen, M.R., Brochu, M., Brown, S.L., Callahan, J.W., Cook, G.J., Nicholson, R.S., and Toll, N.J., 1999, Varve, paleomagnetic and ¹⁴C chronologies for Late Pleistocene events in New Hampshire and Vermont (USA): *Geographie physique et Quaternaire*, v. 53, p. 79-106.
- Ridge, J.C., and Larsen, F.D., 1990, Re-evaluation of Antev's New England varve chronology and new radiocarbon dates of sediment from glacial Lake Hitchcock: *Geological Society of America Bulletin*, v. 102, p. 889-899.
- Ridge, J.C., and Toll, N.J., 1999, Are late-glacial climate oscillations recorded in varves of the upper Connecticut Valley, northeastern United States?: *Geologiska Föreningens i Stockholm Förhandlingar*, v. 121, p. 187-193.

Roksandic, M.M., 1976, Seismic facies analysis concepts: European Association of Exploration Geophysicists, p. 1.

St-Onge, G., Stoner, J.S., and Hillaire-Marcel, C., 2003, Holocene paleomagnetic records from the St. Lawrence Estuary, eastern Canada: centennial- to millennial-scale geomagnetic modulation of cosmogenic isotopes: *Earth and Planetary Science Letters*, v. 209, p. 113-130.

Trimble, 2004, Trimble DSM132 DGPS Receiver Fact Sheet: Dayton, Ohio, Trimble Geomatics and Engineering Division.

Vail, P.R., Mitchum, R.M., Todd, R.G., and Thompson, S., III, 1977, Seismic stratigraphy and global changes in sea level, part 3: relative changes in sea level from coastal onlap, *in* Payton, C.E., ed., *Seismic stratigraphy - applications to hydrocarbon exploration*, American Association of Petroleum Geologists, memoir 26, p. 63-81.

Verosub, K.L., 1979a, Paleomagnetism of varved sediment from western New England; variability of the paleomagnetic record: *Geophysical Research Letters*, v. 6.

—, 1979b, Paleomagnetism of varved sediment from western New England: secular variation: *Geophysical Research Letters*, v. 6, p. 245-248.

APPENDIX 5

**INSTRUCTIONS FOR COLLECTING AND PROCESSING SEISMIC
REFLECTION PROFILES**

Collecting and processing Sub-bottom seismic reflection profiles

1. Seismic reflection profiles were collected using EdgeTech DiscoverTM software, in the native *.JSF files, using an EdgeTech 216S Full spectrum seismic reflection profiles. Most profiles were collected using a linear pulse at a frequency of 2 – 10 kHz. The 216S can run frequency ranges up to 16 kHz, but this range offered less seismic penetration. The maximum calculated resolution at a frequency of 10 kHz is 15 cm (assuming the velocity of sound in water and sediment is $1,500 \text{ cm} \cdot \text{s}^{-1}$).
2. Total signal range (depth) was adjusted depending on the observed seismic penetration. Most profiles collected between 2007 - 2010 used a range of 50 – 100 m; Profiles collected prior to 2006 used a maximum range between 30 and 50 m. Analog gain was not adjusted during data collection to maximize the ability to properly post-process the profiles for maximum resolution.
3. During data collection the height of the towfish was maintained at 1 m below the sea surface. Vessel speed averaged $1.5 \text{ m} \cdot \text{s}^{-1}$. Spatial location was embedded into sub-bottom files using the serial NEMA output of a Trimble DSM-132 GPS with a reported accuracy of 1 m (Trimble, 2004).
4. The raw EdgeTech *.JSF files were translated into SEG-Y files using Chesapeake Technologies 'JSF to SEG-Y' software for compatibility with the processing software. The SEG-Y file format is a standard file format

developed by the Society of Exploration Geophysicists (Norris and Faichney, 2002).

5. Individual data files were imported into Chesapeake Technologies SonarWeb (v3.16) software for post processing. The full seismic reflection profiles were used (i.e. the records were not clipped at a depth) and the images produced for the profiles had a pixel size of 0.05 cm. Profiles were displayed using an inverse medium yellow-orange to brown known as a ‘Klein’ color scheme, named for the color of analog paper records produced by that company’s wet-paper recordings in the 1970s. We believe the inverse Klein scheme allows us to see more detail on the digital records and provide more contrast between adjacent side-scan facies than traditional grey-scale images.
6. Profiles were imported into Chesapeake Technologies SonarWeb (v3.16) as standard SEG-Y. The antenna of the DGPS used during surveying was located within 3 m of the towfish, no layback or other spatial transformation was applied.
7. Files were reoriented in SonarWeb so that the read north to south or west to east (from left to right) on the seismic profiles. Profiles were annotated with the position (Rhode Island State Plane Feet, NAD 1983), date/time and course every 1,000 pings (approximately 200 m at a survey speed of $1.5 \text{ m} \cdot \text{s}^{-1}$).

8. The course made good during data collection was calculated using a smoothing function that fits a curve to the GPS reading every 50 pings (Approximately 10 m at a survey speed of $1.5 \text{ m} \cdot \text{s}^{-1}$). This removes some of the of the small-scale boat motion without a significant change in spatial accuracy.
9. Individual profiles were adjusted for both contrast and time-varied gain to maximize contrast between seismic reflectors. Typical values for time-varied gain ranged from 5 - 20 dB down the signal with no offset. Differences in seafloor geometry and surface sediment characteristics can change the seismic penetration, even on adjacent seismic profiles, requiring file by file processing.
10. Occasional files with excess noise, typically a combination of water column interference and multiple reflections of the seafloor, were run through a digital band-cut filter between 600 and 6000 Hz. All other settings in SonarWeb were set to the default settings
11. The upper surface of identified seismic facies were digitized on individual profiles in the 'Seismic Reflectors' section of SonarWeb. Seismic facies are sedimentary packages, distinguishable from adjacent units, based on internal characteristics, (i.e. the intensity, spacing, continuity, and internal geometry of seismic reflectors), external geomorphic form and stratigraphic relationship to other units (Roksandic, 1976; Vail et al., 1977). These reflectors were

assigned a name based on the date and file number and interpreted depositional environment of the seismic facies (e.g., AG0905_6_Lakefloor) .

12. SonarWeb outputs reflectors as comma delineated (*.csv) text files, containing the Easting (X), Northing (Y), Depth below towfish (Z) projected in Rhode Island State Plane Feet, relative to the North American Datum of 1983.
13. *.csv files were imported into Microsoft Excel, and combined into worksheets grouped by interpreted depositional environments (i.e. all of the lakefloor X,Y,Z is in the same workbook).
14. Depth of the reflector below the towfish was converted to elevation below mean sea-level, by adding 1 m (to account for the 1 m towfish depth during data collection), and multiplying by -1 to produce a negative value depth. Negative values for depth are easier to work with in a Geographic Information System (GIS)
15. The Excel workbooks (sorted by interpreted depositional environments) were imported into ESRI ArcMap (Version 9.3 and later version 10.1). X,Y points were created, and exported as Shapefiles.