National Park Service
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Natural Resource Stewardship and Science

Boston Harbor Islands National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1404

ON THE COVER
Photograph of the rocky shores of Calf Island as viewed from the west towards the "Landing Cove," a sandy bay where most visitors arrive. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in 2007.

THIS PAGE
View of interbedded deposits of Cambridge Argillite (light gray layers) and intrusive diabase (brown layers) bedrock at the Boston Light, Little Brewster Island. Visitors for scale.
Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in 2007.

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2007 and a follow-up conference call in 2015 (Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Boston Harbor Islands National Recreation Area, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Figures in Appendix B illustrate these data.

The only drowned drumlin field in the United States is protected in the midst of Boston Harbor. These hills of mixed glacial sediment rest atop ancient bedrock that is part of a landmass once exotic to North America. Today, world class-coastal features attract geomorphologists to study the coastal processes at work at Boston Harbor Islands National Recreation Area. This study site has become a crucial place to investigate the potential impacts and responses to global climate change and resultant sea level rise.

Authorized on 12 November 1996, Boston Harbor Islands National Recreational Area (also known as Boston Harbor Islands National and State Park) is a landmark effort among cooperating agencies and landowners working together through the Boston Harbor Islands Partnership. The National Park Service facilitates resource management and science in order to fulfill the purpose of the national recreation area as defined in its enabling legislation "to protect the drumlin archipelago in Boston Harbor and associated natural, geologic, cultural and historic resources." The national recreation area encompasses 34 islands and former islands (now peninsulas) in Boston Harbor with more than 66 km (41 mi) of shoreline.

Boston Harbor Islands are within an ancient geologic structure—the Boston Basin. This topographically low area in eastern Massachusetts began as an extension basin within a landmass that tectonic forces pushed and pulled across ancient seas before it was accreted onto the eastern margin of North America during the Paleozoic Era, more than 252 million years ago. The fault-bounded basin had collected sediments and volcanics (geologic map units **CZca**, **Zdm**, **Zcr**, **Zvt**, **Zvm**, and **Zvp**) more than 500 million years ago that would prove less resistant to erosion than the igneous and metamorphic rocks (e.g., **Zgr** and **SOqgr**) surrounding it. When glaciers scoured the landscape during the ice ages of the Pleistocene Epoch (2.6 million to 11,700 years ago), they carved the lowland of Boston Harbor, but also left vast amounts of sediment behind to form the "whaleback" mounds called drumlins. Some areas of bedrock persisted, particularly those underlain by intrusions of resistant igneous rocks (**JZd**, **J[?]Zib**, and **J[?]Zdo**; the question mark in the map unit symbols indicates uncertainty regarding the age assignment). When global sea level rose after glacial retreat, the drumlin field was eventually drowned, and coastal processes of wave erosion, longshore transport, and barrier migration began to shape the coastal features that persist at Boston Harbor Islands today. In general, the outer islands are smaller, rockier, and windswept, whereas the inner islands are generally larger and sandier, with forested areas.

Geologic features and processes include the following:

- **Boston Harbor**. The harbor consists of extensive subtidal flats and a complex assemblage of discontinuous ridges and depressions, with several deeper navigational channels that are drowned river valleys. The modern seafloor sedimentary environments are (1) environments of erosion or nondeposition; (2) environments of deposition of clay, silt, and sand; and (3) environments of sediment reworking. The tidal range within Boston Harbor is about 3 m (10 ft) and thus vast areas of the shoreline are alternately submerged and exposed making up an intertidal zone of about 70% of the national recreation area. The most common intertidal substrates are mixed coarse particles, mixed coarse and fine particles, and reef, but bedrock and cobble substrates are also prominent.

- **Coastal Features**. The coastal features at Boston Harbor Islands, including glacial-till bluffs, sand beaches, gravel barrier beaches, retrograding barrier beach areas anchored to drumlins, spits (geomorphic map unit **Qsp**), tombolos (**Qt**), gravel ridges (**Qgr**), salients (**Qsa**), welded bars (**Qwb**), salt marshes, retreat platforms, raised sea-level terraces, and intertidal substrates and assemblages (**Qtf** and **Qib**), are important natural resources at the national recreation area. Because the islands' shorelines are dynamic, many of the coastal features are temporary and can be transitional, changing from one type to another, or physically connected.
- **Sediment Supply and Island Erosion**. Nearly 400 years ago, the harbor had more than 50 islands. Coastal processes at Boston Harbor Islands are driven primarily by wave action and slope failure operating in a regime of accelerated sea level rise. Today, rising seas, increased storm energy, and an overall lack of incoming sediments have created a sediment-starved, erosional system at Boston Harbor Islands. Understanding how sediments are moving among the islands is important to predicting what and where features may form and how the entire coastal system will respond to rising sea level and high-energy storm events.
- **Bluff Retreat**. Erosion and wave action are causing the Boston Harbor drumlins to shrink and "retreat." Many islands have one or more drumlin exposures weathering into scarps and bluffs. Bluff retreat along island coastlines is a primary slope management concern. Coastal bluff retreat is driven by waves and surface processes (e.g., storms and slope movements) in an episodic manner. Understanding how and how much the bluffs are retreating is a focus of current study. Drumlins are a local source of sediment for the islands' coastlines.
- **Glacial Features**. Ice-age glaciers affected the landscape in two major ways; they (1) carved features into the landscape, or (2) deposited mantles of sediment over the landscape. Glaciers flowing into the ancient Boston Basin excavated the current Boston Harbor before mantling it in sediment. Because of repeated glacial advances and retreats, the glacial history of the area is complex. Locally, two distinct till deposits record two separate glacial advances. Drumlins (**Qdr**), striations, and grooves indicate which direction the glaciers flowed. The islands are the only partially drowned drumlin field along a coast in the United States. Glacial deposits in the national recreation area are of two types: (1) those deposited directly by moving ice such as sand and cobble-rich glacial till, and (2) those deposited by meltwater in rivers (glaciofluvial) or lakes (glaciolacustrine).
- **Wetlands**. Wetlands are transitional areas between land and water bodies, where water frequently floods the land or saturates the soil. Saltwater, brackish, and freshwater wetlands in embayed, perched, or fringing settings occur at Boston Harbor Islands. Wetlands are also associated with geomorphic map units **Qwe**, **Qmp**, **Qk**, and **Qla**. These wetlands provide several significant functions, including (1) coastal storm surge detention and shoreline stabilization, (2) provision of fish and shellfish habitat, (3) provision of bird and other wildlife habitat, (4) surface water detention, (5) nutrient transformation whereby elements are changed from unavailable to available to plants and animals, and (6) retention of sediments. A key resource management concern is to determine whether the rate of vertical accretion of salt marsh surfaces can keep pace with predicted local sea level rise.
- **Aeolian Features and Processes**. Paleodunes formed after the latest glacial retreat contained sand and silt as remnants of a much larger aeolian dune field that blanketed the entire area. Dunes (**Qds**) are eroding away on some islands. They are not common on barriers within Boston Harbor because of the overall sediment coarseness. The scant modern dune features that remain on the landscape are significant because of the scarcity of sediment in the system. The sand composing aeolian features at Lovells Island is an unusual combination of immature composition (mineralogy: only 50% quartz) and mature grain size, sorting, and grain shape; the exact sediment source remains unknown.
- **Bedrock Exposures**. Two broad categories of bedrock exist at Boston Harbor Islands: sedimentary and igneous. The sedimentary rocks, dominated by the Cambridge Argillite (**CZca**), contain features such as rip-up clasts, thin bedding, slump folds, cross beds, and dewatering structures that indicate conditions at the time of deposition in the Boston Basin. Igneous rocks either intruded into or were intermittently erupted

within the sedimentary rocks in the recreation area. The diabase sills (**JZd**, **J[?]Zib**, and **J[?]Zdo**) of the Brewster Islands are more resistant to erosion than the Cambridge Argillite and this resistance is the reason the islands persist today. Geologic study of the Inter-Island Tunnel confirmed that the bedrock underlying most of Boston Harbor is the Cambridge Argillite.

- **Folds**. As bedrock is compressed, folds form adjacent to one another. Named folds in the bedrock beneath Boston Harbor include the Charles River syncline (U-shaped fold), Central anticline (A-shaped fold), and Wollaston syncline. The axes of these folds trend northeast-southwest.
- **Faults**. Faults in the rock accommodate movement in Earth's crust. The excavation associated with the Inter-Island Tunnel exposed a major fault zone, known as the Cathedral fault, which trends northeast-southwest across Boston Harbor. This and myriad other smaller-scale faults attest to the structural complexity within the Avalon terrane and the long geologic history of the local rocks.
- **Paleontological Resources**. Fossils are evidence of life preserved in a geologic context. Fossils known from the Cambridge Argillite (**CZca**) include microbial mats, the Ediacaran form *Aspidella*, and a variety of microfossils, including spherical forms, filaments, and colonies identified as *Bavlinella cf. faveolata*, many of which are now altered to pyrite. Some or all of these may occur in Boston Harbor Islands' rocks. Pleistocene fossils, including marine and estuarine fossils (e.g., *Mercenaria*), occur in the older glacial till composing the drumlins. Other fossils such as pollen, peat, foraminifera, ostracodes, bivalves, gastropods, sponges, stony corals, barnacles, crabs, worm tubes, and hickory nuts wash up on the coastlines or accumulate in marsh areas. Other fossils from the surrounding area may wash up on the islands' shorelines.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- **Coastal Erosion and Response to Climate Change**. The Boston Harbor Islands are diminishing in size because of coastal erosion, rising sea level, limited sediment supply, and increased human use. Research projects addressing coastal issues and sea level rise are part of the National Park Service's responsibility to help to facilitate resource management and provide guidance. Ongoing research is addressing the determination of areas of past and likely future land loss and gain, thresholds above which coastal structures will be overtopped or dismantled, and what will happen to glacial bluffs as sea level continues to rise. Target studies include drumlin bluff retreat, climate change and sea level rise, boat-wake increases, and coastal engineering structures' condition and impacts.
- **Abandoned Mineral Lands and Disturbed Lands**. For hundreds of years, humans have utilized Boston Harbor Islands by quarrying slate, removing of sediment for ballast, and a variety of military, settlement, and quarantine purposes. Artificial fill (**Qaf**) occurs as coastal engineering structures and in places like Spectacle Island. That island was reclaimed for park use through capping of a municipal landfill then topping with clean fill from the harbor tunnel associated with Boston's "Big Dig," and finally covered with topsoil and planted. Some of debris may contain hazardous material such as asbestos. Asbestos-tile remediation associated with past military installations is needed on Gallops, Outer Brewster, and Great Brewster islands.
- **Paleontological Resource Inventory, Monitoring, and Protection**. Paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation. The park lacks a field-based paleontological resource survey. Such a survey could provide detailed, site-specific descriptions and resource management recommendations for all paleontological resources.
- **Seismic Activity Hazards and Risks**. Boston Harbor Islands National Recreation Area is not located near a seismic zone; however, the potential for large earthquakes exist. Within the next 100 years, a magnitude-5.0 or greater earthquake has a 0.04 to 0.06 probability (4% to 6% "chance") of occurring. In such an urban setting, should a large earthquake occur, damage to infrastructure would be significant.
- **Loss of Aeolian Features**. Dunes on Lovells Island and the south end of Thompson Island are reducing in size and extent. Quantitative measurements of this reduction are needed to understand where and how sand is moving through the dune system and to beginto investigate methods of dune stabilization.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Geologists from the Massachusetts Geological Survey, University of New Hampshire, and Boston University developed the source maps and reviewed GRI content.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix C provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

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The GRI program partially funded the field work associated with the completion of the maps used as sources for the GRI GIS data.

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Figure 1. Map of Boston Harbor Islands National Recreation Area. National Park Service map available at http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=BOHA.

Geologic Setting and Significance

This chapter describes the regional geologic setting of the recreation area and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

Boston Harbor Islands National Recreation Area was authorized as a unit of the National Park System on 12 November 1996, incorporating the Boston Harbor Islands State Park and additional lands. The Boston Harbor Islands Partnership manages 34 islands and peninsulas (former islands) in Boston Harbor across Norfolk, Plymouth, and Suffolk counties in Massachusetts, east of Boston (fig. 1). The islands and peninsulas are owned or administered by eight federal, state, municipal, and non-profit agencies. The National Park Service facilitates resource management and visitor programs across the national recreation area. The islands (table 1) are an archipelago of drumlins and the only drumlin field along a coast in the United States (National Park Service 2002; FitzGerald et al. 2011). Drumlins formed during the ice ages when glaciers flowed over the landscape shaping "whaleback" hills. Many are now partially submerged in Boston Harbor, creating islands. Drumlins are described in detail in "Glacial Features." In 2015, more than 490,000 people visited this recreation area adjacent to the Boston metropolis.

The extent of exposed land within the recreation area fluctuates with the ebb and flow of the ocean's tides. At high tide, approximately 599 ha (1,482 ac) is exposed and more than 1,241 ha (3,067 ac) is exposed at low tide. The national recreation area encompasses 66 km (41 miles) of shoreline (Curdts 2011).

The national recreation area extends seaward 18 km (11 mi) from downtown Boston. Boston Harbor is in the eastern portion of Massachusetts Bay, which is part of the Gulf of Maine. Massachusetts Bay encompasses about 2,100 km^2 (800 mi^2) stretching between Cape Ann in the north and Cape Cod Bay to the south. The oceans, bays, estuaries, and tidal rivers of Boston Harbor were part of the inspiration for an initiative for a strategic plan to foster the conservation of ocean park resources (National Park Service, Northeast Region 2007; National Park Service 2008).

The Boston Harbor Islands stretch from Thompson Island in western Boston Harbor south into Quincy Bay and Hingham Bay and east towards the greater Massachusetts Bay and the Atlantic Ocean. The Graves is the easternmost point in the national recreation area. In general, the outer islands are smaller, rockier, and windswept, whereas the inner islands are generally larger and sandier, with forested areas.

Geologic Setting

Boston Harbor is the submerged area of the Boston Basin, which is a significant topographic and geologic feature of the Avalon terrane. The Avalon terrane is among a series of terranes accreted to eastern Massachusetts (fig. 2; Zen et al. 1983; Robinson and Kapo 2003). A terrane is a group of rocks with similar characteristics and geologic history that formed somewhere other than their present location. Terranes are often associated with continent-scale plate tectonic forces that displace, squeeze, or rip apart large bodies of rock across distances ranging from a few to thousands of kilometers. Hundreds of millions of years ago (fig. 3), the rocks of the Avalon terrane (and many other terranes) were accreted to (pushed onto) the eastern edge of North America during orogenies (mountain-building events) that ultimately created the Appalachian Mountains. Individual terranes move along massive faults (fig. 4). For example, the Bloody Bluff fault (named for a location in Minute Man National Historical Park, Massachusetts) denotes where the Avalon terrane was subducted under (pushed obliquely beneath) the Nashoba terrane. Molten material that would cool to become granites intruded into the older rocks during the Ordovician and Devonian periods (see fig. 3; Robinson and Kapo 2003).

The bedrock of the Avalon terrane is many hundreds of millions of years old. The oldest rocks on the GRI geologic map are Precambrian granitic plutonic rocks (geologic map unit **Zgr**), volcanic rocks (**Zvp**, **Zvm**, and **Zvt**), and metamorphosed (altered by high temperature, pressure, and/or fluids) sedimentary rocks (**Zcr**, and **Zdm**) (see figs. 3 and 5; Thompson et al. 2011). Within the recreation area, much of the bedrock is mapped as the Cambridge Argillite (**CZca**), which is metamorphosed sedimentary rocks originally deposited

Table 1. Boston Harbor Islands characteristics and features.

Island/ Peninsula	Size* and Highest Elevation	Management Focus	Wetlands	Habitats	Geologic Features	Intertidal Substrates**
Bumpkin	25 ha (62 ac) 21 m (70 ft)	Managed landscape	Estuarine	Beaches, open fields	Drumlin, gravel beaches, gravel spit	Boulders, gravel, mixed coarse particles, mixed coarse and fine particles
Button	47 ha (116 ac) 3 m (10 ft)	Natural features	Estuarine	Sparse trees, grassy areas	Glacial till, bedrock outcrops, mudflats, sandy areas	Not mapped by Bell et al. (2002)
Calf	14 ha (35 ac) 12 m (38 ft)	Natural features	Marine, estuarine	Grassy, shrubby areas, beaches	Bedrock with thin regolith, saltwater marsh (composed of Spartina)	Cultural, boulders, mixed coarse, mud, peat, bedrock, shells
Deer	107 ha (265 ac) >30 m (100 ft)	Specific uses, managed landscape, and visitor services	Estuarine, palustrine, marine	Shrubby areas, tidal flat shorelines	Recontoured drumlin, tidal flats	Not mapped by Bell et al. (2002)
Gallops	20 ha (50 ac) 24 m (79 ft)	Managed landscape	Estuarine	Former ornamental gardens	Drumlin, gravel beaches	Boulders, mixed coarse, sand
Georges	21 ha (53 ac) 15 m (50 ft)	Historic preservation and visitor services	Estuarine	Mowed turf, large trees, former gardens	Recontoured drumlins, steep slopes	Boulders, cobble, gravel, mixed coarse, bedrock
Grape	41 ha (101 ac) 21 m (70 ft)	Managed landscape	Estuarine, palustrine	Forest, beaches, shrubby areas	Drumlins, marshy lowlands, bedrock outcrops (on beach), tidal sand spits	Boulders, cobble, mixed coarse, mixed coarse and fine, mud, peat, bedrock
The Graves	0.7 ha (1.8 ac) 5 m (15 ft)	Historic preservation	None	Bare rock, aquatic areas	Bedrock outcrops	Not mapped by Bell et al. (2002)
Great Brewster	28 ha (68 ac) 32 m (105 ft)	Managed landscape	Palustrine, marine	Salt marsh, tidal pools, former gardens	Drumlins, sand spit, marsh	Boulders, cobble, gravel, mixed coarse, bedrock
Green	7 ha (17 ac) 14 m (45 ft)	Natural features	Marine	Shrubby, rocky areas, nesting sites	Bedrock outcrops	Not mapped by Bell et al. (2002)
Hangman	2 ha (6 ac) 1 m (3 ft)	Natural features	Estuarine	Rocky areas, beach	Pebbly beach, bedrock (granite, slate) outcrops, former quarries	Boulders, gravel, mixed coarse, mixed coarse and fine, peat, bedrock
Langlee	3 ha (8 ac) 12 m (40 ft)	Natural features	Estuarine	Beaches, shrubby areas, large trees, grassy areas	Bedrock (Roxbury Conglomerate) outcrops, steep cliffs, sandy beaches, tidal mudflat, glacial till	Mixed coarse, mixed coarse and fine, peat, bedrock
Little Brewster	3 ha (7 ac) 5 m (18 ft)	Historic preservation	None	Mowed turf	Bedrock with thin regolith, steep bluffs	Boulders, mixed coarse, bedrock
Little Calf	2 ha (7 ac) 6 m (20 ft)	Natural features	Marine	Bare rock, bird nesting areas	Bedrock outcrops	Not mapped by Bell et al. (2002)
Long	91.1 ha (225.2) 29 m (95 ft)	Historic preservation, managed landscape, and visitor services	Estuarine, palustrine	Former gardens, wetlands, pine groves	Drumlins, freshwater marsh, saltwater marshes, tidal flats	Boulders, gravel, mixed coarse, mixed coarse and fine, sand
Lovells	49 ha (120 ac) 24 m (79 ft)	Managed landscape, historic preservation	Estuarine, palustrine, marine	Pine groves, beaches, wet meadow, sand dunes	Gravel beaches, dunes, saltwater wetlands, drumlins, rocky shoreline, gravel beach	Boulders, gravel, mixed coarse, sand
Middle Brewster	>5.5 ha (13.6 ac) 16 m (52 ft)	Natural features	Marine	Bare rock, bird nesting areas, sparse vegetation	Bedrock outcrops, freshwater marsh	Not mapped by Bell et al. (2002)

Table 1. Boston Harbor Islands characteristics and features, continued.

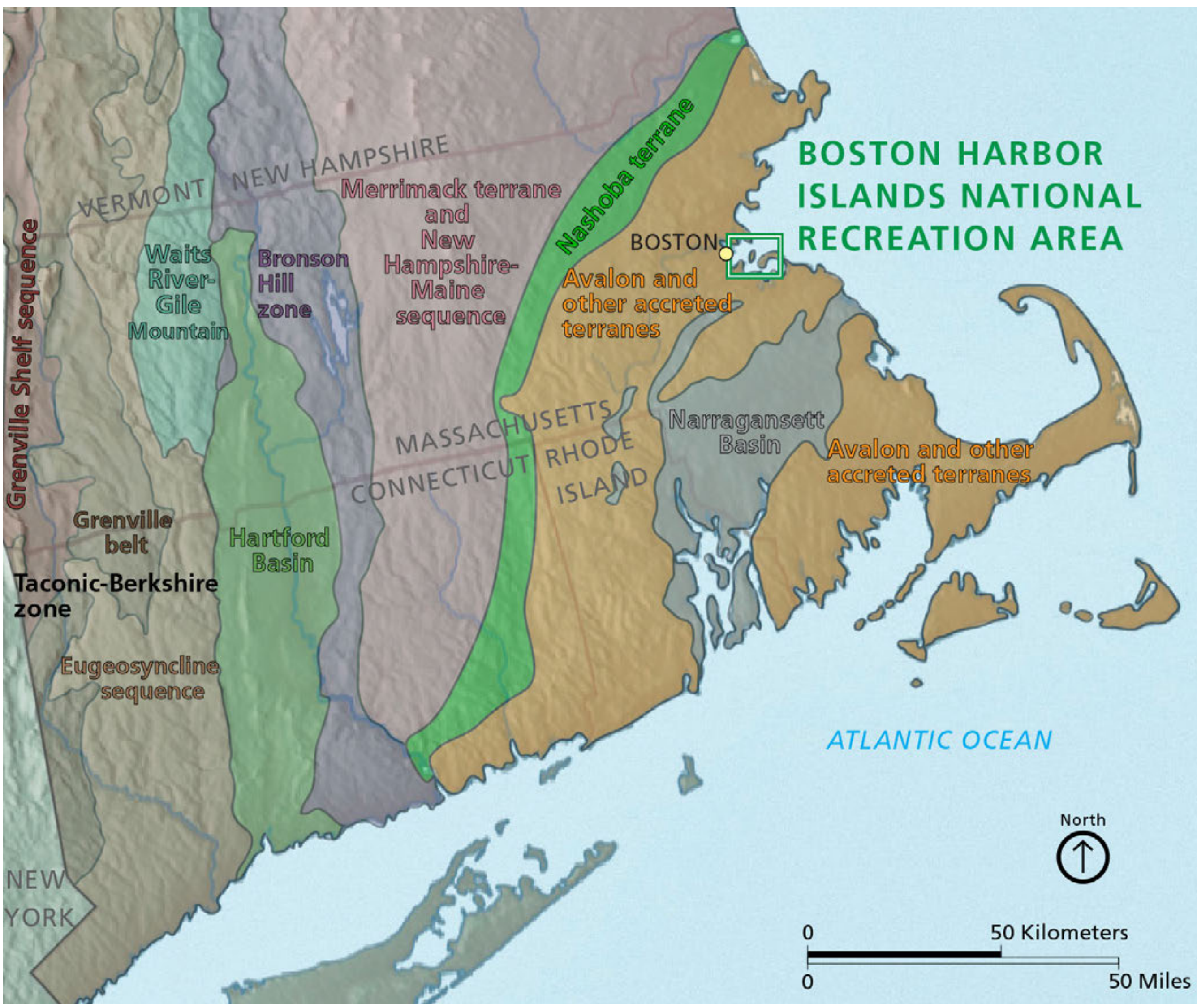
Island/ Peninsula	Size* and Highest Elevation	Management Focus	Wetlands	Habitats	Geologic Features	Intertidal Substrates**
Moon	>18.5 ha (45.7 ac) 30 m (98 ft)	Historic preservation,	Estuarine	Meadows, hardwood forest	Drumlins, tidal mudflats	Not mapped by Bell et al. (2002)
Nixes Mate	<0.4 ha (1 ac) 0 m (0 ft)	None applicable per island's small size	None	Subaquatic	Rocky flats, sand spit (at low tide), quarried areas	Not mapped by Bell et al. (2002)
Nut	>8.3 ha (20.5 ac) 3 m (10 ft)	Managed landscape, natural features	Estuarine	Manicured park, shrubby areas	Riprapped shoreline	Not mapped by Bell et al. (2002)
Outer Brewster	>8.1 ha (20.1 ac) 24 m (78 ft)	Natural features	Marine	Rocky areas, waterbird nesting areas, shrubby areas, rough fields	Bedrock outcrops (e.g., Pulpit Rock), fertile regolith, steep cliffs, quarried areas, spring, pond	Boulders, mixed coarse, bedrock
Peddocks	117 ha (288 ac) 24 m (80 ft)	Historic preservation, visitor services, managed landscape, natural features	Estuarine, palustrine, estuarine	Marshes, coastal forests	Headlands, tombolos, coastal ponds, saltwater marshes, freshwater marshes, gravel spits	Cultural, reef, cobble, gravel, mixed coarse, mixed coarse and fine, peat, sand, shells
Raccoon	>1.5 ha (3.6 ac) 9 m (30 ft)	Natural features	Estuarine	Rocky beaches	Bedrock outcrops, gravel beaches, rocky slopes	Cultural, mixed coarse, mixed coarse and fine, mud, peat, bedrock, sand, shells
Ragged	>1.7 ha (4.1 ac) 9 m (30 ft)	Natural features	Estuarine	Shrubby areas, former gardens, tidal flats	Bedrock (Roxbury Conglomerate) outcrops, gravel beaches, tidal mudflats	Not mapped by Bell et al. (2002)
Rainsford	>8.7 ha (21.6 ac) 15 m (49 ft)	Managed landscape	Estuarine	Meadows, hardwood and shrub forests	Drumlins, bluffs, bedrock outcrops, rocky shorelines, sandy cove	Boulders, cobble, gravel, mixed coarse, bedrock
Sarah	>1.9 ha (4.6 ac) 9 m (30 ft)	Natural features	Estuarine	Nesting areas, shrubby areas	Bedrock (Roxbury Conglomerate) outcrops, glacial till, sand beaches, boulders, mudflats	Not mapped by Bell et al. (2002)
Shag Rocks	>0.5 ha (1.3 ac) 8 m (26 ft)	None applicable per island's small size	None	Subaquatic vegetation	Bedrock outcrops	Not mapped by Bell et al. (2002)
Sheep	>1.3 ha (3.2 ac) 3 m (10 ft)	Natural features	Estuarine	Grassy areas, shrubby areas	Eroded drumlin, gravelly shore	Mixed coarse, mixed coarse and fine, peat, shells
Slate	>5.1 ha (12.7 ac) 10 m (32 ft)	Natural features	Estuarine	Grassy areas, shrubby areas	Bedrock (slaty) outcrops, glacial till, rocky shoreline, mudflats, quarry, Boston Blue Clay exposures	Boulders, cobble, mixed coarse, mixed coarse and fine, peat, bedrock, shells
Snake	>1.2 ha (3.0 ac) 3 m (10 ft)	Natural features	None	Nesting areas	Salt marsh, beach, mudflats	Not mapped by Bell et al. (2002)
Spectacle	46 ha (114 ac) 54 m (176 ft)	Visitor services and managed landscape	Estuarine	Forest, meadows	Two former drumlins (now reclaimed, managed landscapes on top of a landfill), former landfill over sand spit	Reef, boulders, mixed coarse, bedrock, sand

Table 1. Boston Harbor Islands characteristics and features, continued.

Island/ Peninsula	Size* and Highest Elevation	Management Focus	Wetlands	Habitats	Geologic Features	Intertidal Substrates**
Thompson	>68.8 ha (169.9 ac) 24 m (78 ft)	Managed landscape, natural features, and species uses	Estuarine, palustrine	Forest, shrubby areas, meadows, salt marsh, former orchards, mowed grass	Drumlins, gravel spits, saltwater marsh, wetland, sand spit, mudflats	Cultural, reef, boulders, gravel, mixed coarse, mixed coarse and fine, mud, peat, sand
Webb Memorial Park	>14.6 ha (36.0 ac) 12 m (40 ft)	Managed landscape	Estuarine	Mowed grass, shrubby areas, wetlands	Three drumlins, marsh	Not mapped by Bell et al. (2002)
Worlds End	>111.0 ha (274.3 ac) 43 m (140 ft)	Managed landscape	Estuarine, palustrine	Salt and freshwater marsh, former gardens, woodlands	Gravel beaches, ledges, cliffs, marsh, four drumlins, glacial till, bedrock outcrops, sandy coves, ponds	Boulders, gravel, mixed coarse, mixed coarse and fine, mud, peat, bedrock, sand, shells

*Size includes upland and intertidal areas; **See "Boston Harbor: Intertidal Substrates" for details.

Sources: Bell et al. (2002). In addition Peter Rosen (Northeastern University, coastal geologist, written communication, 24 May 2016) provided information for this table. Further information about each island is available at http://www.nps.gov/boha/historyculture/facts-intro.htm and http://www.nps.gov/boha/learn/nature/wetlands.htm.



along a shallow marine extensional basin transitioning to a continental shelf more than 570 million years ago (Morell et al. 2004; Joe Kopera, Massachusetts Geological Survey, geologist, written communication, 7April 2016). The bedrock is mapped prominently on Slate, Calf, Little Calf, Rainsford, Moon, Outer Brewster, Middle Brewster, and Little Brewster islands, and the Worlds End peninsula (Thompson et al. 2011). The Cambridge Argillite is part of the Boston Bay Group of metasedimentary and volcanic rocks (**CZca**, **Zdm**, **Zvm**, and **Zcr**) that accumulated in the Boston Basin. Hundreds of millions of years ago the Boston Basin was a lowland (like today) that formed when the underlying rocks were rifted (pulled) apart and moved down along faults (Billings 1976; Thompson et al. 2011). Faults separate the Boston Bay Group from older, harder granites (e.g., the Quincy Granite [**SOqgr**]) (FitzGerald et al. 2011; Thompson et al. 2011) and crisscross the Boston Basin complicating the correlation of rocks within the Avalon terrane (Kopera 2011). Diabase dikes and sills, **J(?)Zib** and **JZd**, such as those visible on Calf Island, later intruded the metasedimentary rocks within the basin and in some cases melted the sediments immediately adjacent to them (Ross and Thomspon 2012). The dikes and sills are the youngest bedrock geologic map units (Thompson et al. 2011). Some of them may have intruded while the argillite was still wet sediment, while others may have formed much, much later as the supercontinent Pangaea was being pulled apart, forming the Atlantic Ocean between what is now North America and Europe (see "Geologic History"). The metamorphosed sedimentary rocks of the Boston Bay Group are softer than the surrounding granites and igneous rocks, making them more prone to erosion, and, therefore, creating the present-day topographic low that forms Boston Harbor (Joe Kopera, Massachusetts Geological Survey, geologist, written communication, 7 April 2016).

Much more recently, during the Pleistocene ice ages, glaciers advanced repeatedly from the Arctic over New England to ultimately cover more than a third of North America. Glaciers are significant agents of landscape change, eroding some areas and depositing sediments elsewhere, for example, in drumlins, outwash, and till mapped as **Qdr**, **Qgfd**, and **Qmrt** (see "Glacial Features") (FitzGerald et al. 2013). It was much easier for glaciers to erode the softer Boston Bay Group rocks, forming a topographic low that is now submerged beneath Massachusetts Bay, than to erode the surrounding granitic plutonic rocks (Kaye 1976; Zen et al. 1983; FitzGerald et al. 2011).

Following the most recent glacial retreat about 15,000 years ago (Colgan and Rosen 2001), wind and waves shaped and eroded the glacial deposits to create the features on the GRI geomorphic map: dune systems (**Qds**), gravel ridges (**Qgr**), inlets (**Qi**), intertidal bars (**Qib**), lagoons (**Qla**), overwash terraces (**Qot**), salients (**Qsa**), spits (**Qsp**), tombolos (**Qt**), tidal channels (**Qtc**), tidal flats (**Qtf**), and welded bars (**Qwb**) within Boston Harbor Islands National Recreation Area. On some of the larger islands, interior wetlands (**Qwe**) and marsh ponds (**Qmp**) are mapped. Geomorphic map units overlap in many cases and are mapped as multiple units (e.g., **Qgr+Qot+Qwb**).

Artificial fill (**Qaf**) records the most recent chapter of geologic history—human use and alteration of the islands (FitzGerald et al. 2013). As described in "Geologic Significance and Connections" and "Abandoned Mineral Lands and Disturbed Lands," colonial agriculture, coastal engineering, and quarrying altered sedimentation patterns and changed the shorelines of many islands (Jones and Fisher 1990). Modern human activities such as shipping and recreational boating, other recreational uses, and coastal engineering continue to shape the islands.

Geologic Significance and Connections

The islands of Boston Harbor Islands National Recreation Area have a rich human history. More than 60 sites on the islands preserve evidence of American Indian use reaching back thousands of years (Luedtke 2000), and for this reason 21 of the islands comprise the Boston Harbor Islands Archeological District on the US National Register of Historic Places. Human history includes occupation and land use, connections to the history of geology, historic coastal engineering practices. The ecosystems and habitats of the islands are also connected to the underlying geology.

Figure 2 (facing page). Map of geologic provinces of Massachusetts, Rhode Island, and Connecticut. Boston Harbor Islands National Recreation Area is part of the Avalon terrane—one of a series of accreted terranes added over millions of years to the eastern edge of North America. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after information from Zen et al. (1983) and Robinson and Kapo (2003). Shaded relief base map courtesy of Tom Patterson (National Park Service).

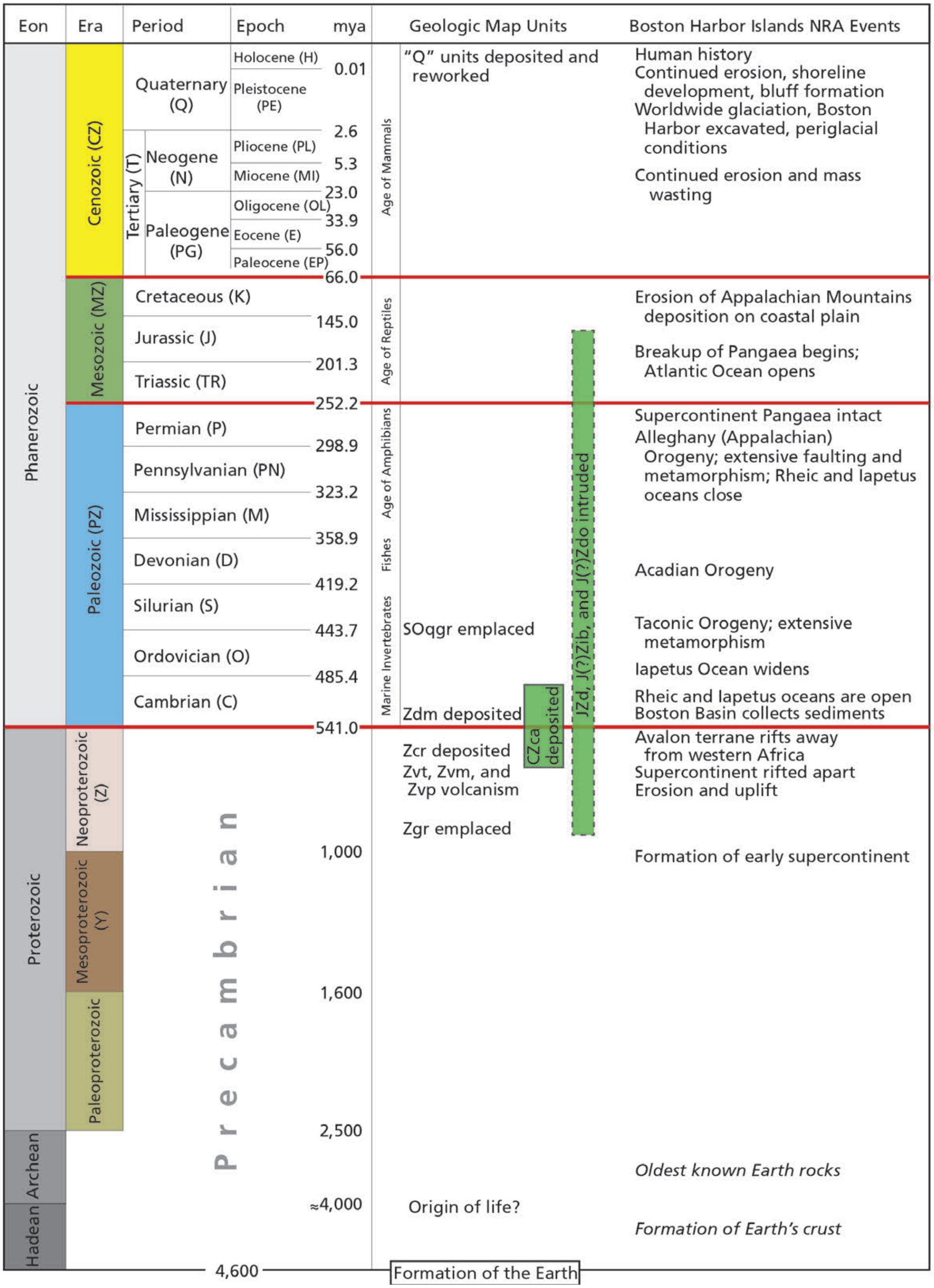


Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). Green bars indicated a period of deposition or emplacement and the associated geologic units; dashed boundaries indicate uncertain timing of intrusion of particular units. The "Alleghany Orogeny" is sometimes referred to as the "Alleghenian Orogeny." National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

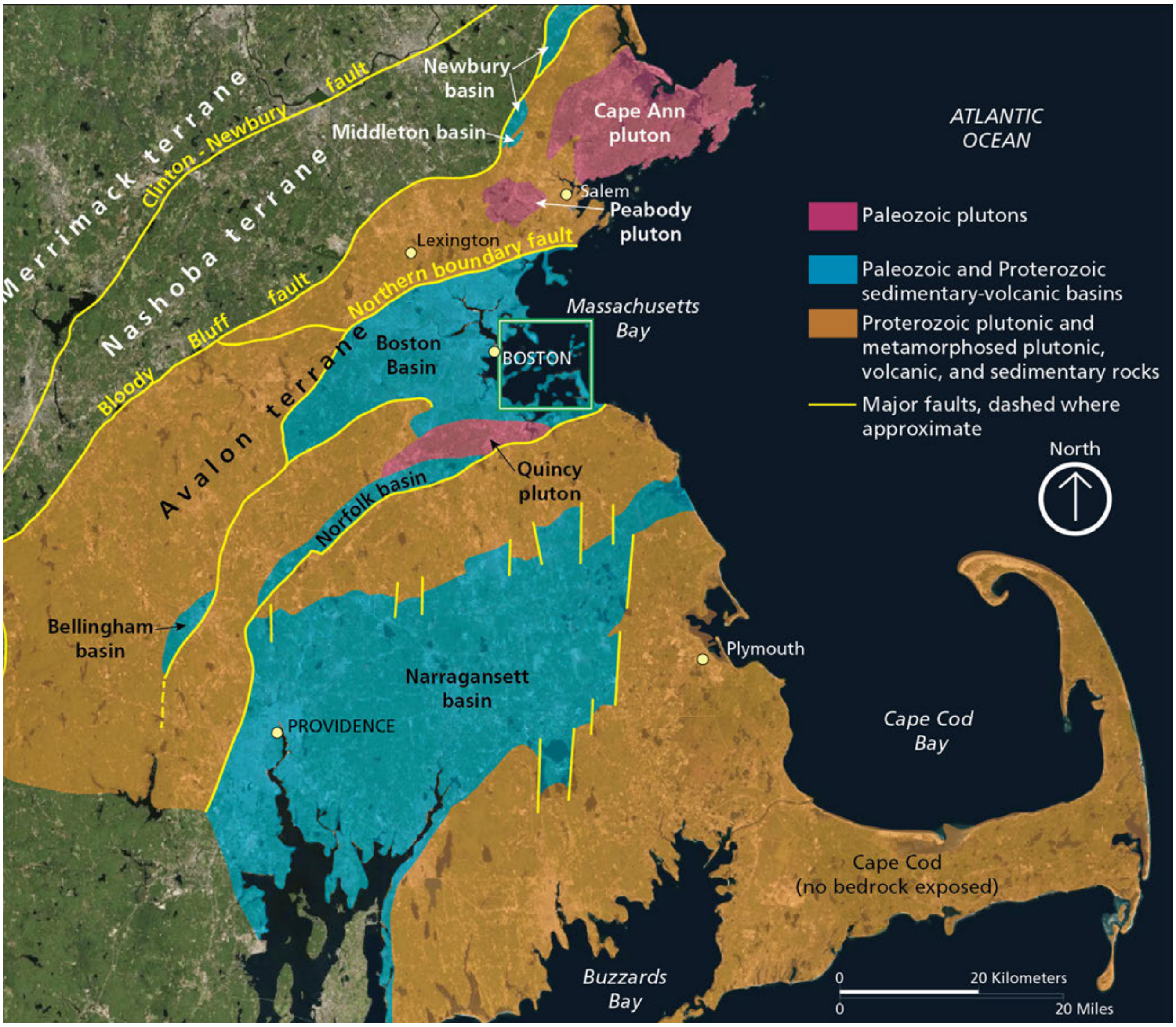


Figure 4. Map of major bedrock features of the Avalon terrane and Narragansett Basin. Boston Harbor Islands National Recreation Area (green box) is in the Avalon terrane—one of a series of accreted terranes added over millions of years to the eastern edge of North America more than 300 million years ago. Preferential erosion of the softer metasedimentary rocks in the Boston Basin created a lowland for Boston Harbor. Major faults (bold yellow lines) denote the boundaries of terranes and the Boston Basin. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 1 from Goldsmith (1991) using ESRI World Imagery basemap, accessed 28 April 2014.

Human Occupation and Land Use

The human history has many connections to the geologic history. Pollen samples collected from Grape Island indicate the presence of an established forest community, habitable by humans, in the Boston Harbor area by 9,000 years before present (Jones and Fisher 1990). A projectile point discovered on Long Island is evidence of Archaic period use of the island (8,000 to 1,000 years before common era [BCE]) (Barber 1984; Luedtke and Rosen 1993). By 4,000 to 3,000 BCE, American Indians were at least seasonally using the islands as indicated by stone and native copper tools; a human skeleton dated to 4,100 radiocarbon years before present was discovered in the recreation area (Barber 1984; Humphrey et al. 1993; Tweet et al. 2010). At that time, sea level was lower and many of the modern islands were not yet surrounded on all sides by water (Luedtke and Rosen 1993; Luedtke 2000). On Long Island, shell middens and worked flakes of rhyolite (a volcanic rock) were discovered along with hickory

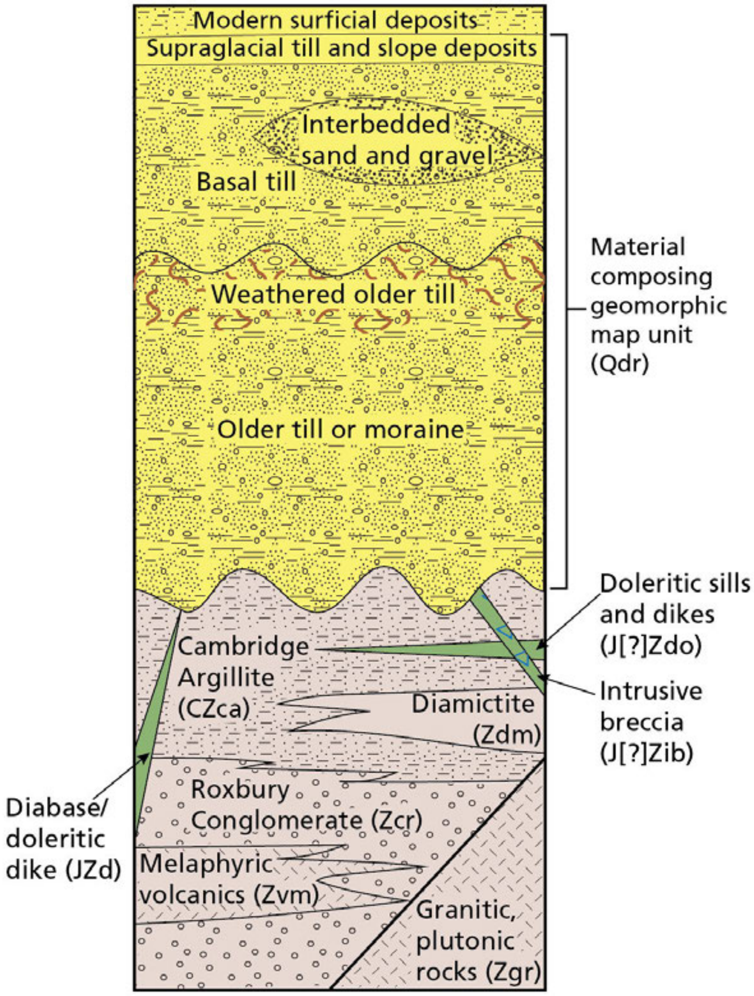


Figure 5. Onshore stratigraphic section. Wavy contacts between units represent unconformities or periods of erosion or nondeposition. Section is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 from Knebel et al. (1992), figure 4 from Rosen et al. (1993), and information from Thompson et al. (2011).

nuts and vertebrate bones that were probably left there between about 2,000 and 1,000 years ago (Leudtke and Rosen 1993; Tweet et al. 2010). The rhyolite was likely sourced nearby in the form of beach cobbles or glacial erratics, which are boulders transported by glaciers and deposited far from their original location (Luedtke and Rosen 1993). Some flakes at Bass Point were red and gold jasper (Luedtke and Rosen 1993). On mainland Massachusetts, near Saugus, American Indians quarried Saugus "jasper," actually rhyolite as jasper is a form of quartz, for tools and trade material (Hollander and Hermes 1999; Kopera 2011). The reddish, buff-colored stone was extremely fine grained (smooth) and made exceptional tool and projectile point material (see GRI report for Saugus Iron Works National Historic Site by Thornberry-Ehrlich 2015). Clay deposits of Boston Blue Clay may have also been a local resource (Luedtke 2000; Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016).

Shell middens on Grape Island are evidence of occupation from at least 1,525 years before present to about 890 years before present (Jones and Fisher 1990). The middens suggest abundant shellfish as a major source of food. Small farms may also have contributed food on some islands (Luedtke and Rosen 1993). About 890 years before present, sediment had accumulated to such a degree that Hingham-Hull Bay was cut off from the open ocean, altering circulation patterns and causing a decrease in shellfish abundance and a shift in the diets of the inhabitants (Jones and Fisher 1990).

In the early 1600s, the Pilgrims were the first Europeans to see the harbor dotted with protective, buffering islands (Barber 1984; Luedtke 2000). Captain Miles Standish explored many of the islands including Thompson Island in 1621 (Barber 1984). The area that would become Boston offered many advantages based on the geologic setting: (1) a safe harbor created by erosion of the relatively soft Boston Bay Group metasedimentary rocks, (2) drumlin and bedrock islands in the harbor to buffer the sea and offer locations for strategic fortifications, (3) three glacier-carved hills (or the "Trimountain" of Copp's, Beacon, and Fort hills) that provided a settlement place for the Puritan, and (4) the artesian spring and well water on the Trimountain. Trimountain was in fact an early name for the historic heart of Boston, the "city on a hill," where today's park headquarters are located (Dave Woodhouse, Woodhouse Geosciences, geologist, email, August 2007).

European settlers also made use of the stone resources of the Boston Harbor Islands. Rocks for ballast material were sourced from the islands (Seaholes 2009). Hangman, Nixes Mate, Slate and Outer Brewster islands were among the areas quarried for stone. Buildings in

Charlestown contain stone quarried from the islands. Slate Island's name comes from its slaty outcroppings of Cambridge Argillite (**CZca**; Seaholes 2009; Thompson et al. 2011).

From their position between Boston and the Atlantic Ocean, the Boston Harbor Islands have served as significant strategic trade and military locations. Thompson Island housed a trading post (ca. 1626) for exchange of goods and furs between Europeans and American Indians (Barber 1984). Many islands still retain the remnants of historic forts and weapon outposts. Fort Warren, on Georges Island, was a Civil War prisoner-of-war camp. Fort Warren, Fort Standish (on Lovells Island), and Fort Strong (on Long Island) controlled the navigational approaches to Boston Harbor—President Roads, The Narrows, and Nantasket Roads (Flora 2002). From the perch overlooking President Roads at Long Island, American revolutionary troops fired cannons at the British fleet in 1776. Nut Island was a munitions plant in the mid-1800s. The south face of Princes Head at Peddocks Island was a testing ground for munitions developed at Nut Island; blasting likely exacerbated slope retreat and shore erosion there (Rosen and FitzGerald 2004; Thornberry-Ehrlich 2008). Long Island housed a succession of military and municipal installations including Civil War–era Camp Wrightman (a major conscript camp during the Civil War) and Fort Strong, coastal artillery emplacements, and Cold War–era missile batteries (Luedtke and Rosen 1993; Flora 2002). Outer Brewster—the largest bedrock outcrop in Boston Harbor—housed the World War II–era coastal fortification Battery Jewell, which included a desalinization operation (Flora 2002).

The isolation afforded by the islands also made them places to house people "cast off" by society. For example, in 1675, during "King Philip's War" the Massachusetts Bay Colony relocated Indian "praying towns" to Deer Island and probably to Peddocks Island, Long Island, and one of the Brewster Islands. Long Island was a quarantine area for yellow-fever sufferers. Small pox victims were housed on Nut and Rainsford islands. Immigrants were quarantined on Rainsford and Deer islands (Flora 2002; Thornberry-Ehrlich 2008; Wagenknecht et al. 2009). Some of these involuntary island inhabitants carved graffiti into the Cambridge Argillite (**CZca**) bedrock of several islands. According to legend, the eroded Nixes Mate, an island named for previous owner and convicted pirate, Captain Nix, is sinking as a testament to the Captain's innocence (Colgan and Rosen 2001)

While protecting the harbor, the islands also formed a potentially dangerous impediment to passing ships and boats, and lighthouses and other navigation aids are an important part of their history. Boston Light on Little Brewster Island is the oldest lighthouse in the United States. It was constructed in 1716, destroyed in 1776 by the evacuating English, and rebuilt by Americans in 1783 (Colgan and Rosen 2001). Other lighthouses are located at The Graves, Deer Island, and Long Island. Numerous shipwrecks occurred throughout the harbor. Some ships fell victim to storms and rocks in the harbor. Others, such as the famous USS *Niagara* (ca. 1855), were purposely scuttled in the harbor when they were no longer useful. These wrecks are targets for underwater archeological preserves (Maio et al. 2007). The website http://bostonshipwrecks.org/ lists at least 73 known shipwreck locations within Boston Harbor dating back to about 1614.

The natural, scenic beauty of Boston Harbor Islands inspired famous landscape architect Frederick Law Olmsted to design a residential landscape on Worlds End, which is one of the peninsulas within the recreation area. The success of the multi-entity Boston Harbor Islands Partnership now provides a model for other natural preservation and restoration efforts elsewhere (Thornberry-Ehrlich 2008).

History of Geology

Boston Harbor Islands also play significant roles in the history of geology. The first use of the term "drumlin," originally termed "lenticular hills," in the United States was applied to the drowned drumlin field in Boston (Hitchcock 1841; Rosen 2007). Additionally, one of the first government topographic maps on which the relief was shown by contours alone was made in 1846 covering an area in Boston Harbor (Evans and Frye 2009). Geologist William B. Rogers observed a "species of fault known as horizontal heave" (Rogers 1857, p. 218) in slate on Governors Island (now part of Logan International Airport). Those features were important to the then-new discussion of how metamorphic cleavage planes (aligned minerals in a metamorphic rock along which it breaks more easily) formed. The classic description of a deltaic sequence was developed by Gilbert in the 1880s using exposures on Thompson

Island (Thornberry-Ehrlich 2008). His model was widely accepted for all deltas until the 1950s, and it remains a type (reference) location for lake deltas (see "Glacial Features"). The coastal features and processes provided a field laboratory for geologists such as D. W. Johnson in the early 20th century (e.g., Johnson and Reed 1910). In the 1960s, Kaye and Barghoorn assembled one of the first records of sea level change in Boston Harbor based in part on features they saw at the islands (Kaye and Barghoorn 1964). Salt marshes provided material for carbon-14 dating, which geologists used to develop hypotheses regarding glacial rebound and the direct impacts of glaciations on global sea level (see "Coastal Erosion and Response to Climate Change"). The Roxbury Conglomerate (geologic map unit **Zcr**) or "Roxbury Puddingstone" is the state rock of Massachusetts (Colgan and Rosen 2001).

Historic Coastal Engineering

Humans have tried to control the natural coastal erosion of the Boston Harbor Islands for nearly 200 years (Leudtke and Rosen 1993). The first seawall was started in 1825 by the US Army Corps of Engineers (USACE) to protect Georges Island. Coburn et al. (2010) lists at least 51 coastal engineering projects within the national recreation area encompassing more than 10 km (6 mi) of seawalls, 8.5 km (5.1 mi) of revetments, six groin areas, and 400 m (1,300 ft) of toe protection (see also FitzGerald et al. 2011). The suite of coastal engineering structures spanning many decades is of historical value in its own right. It also illustrates the evolution of coastal engineering in response to (1) an increase in the understanding of geotechnical principles, (2) more advanced materials becoming available, and (3) a growing demand for more substantial structures and deeper water in the face of increased marine traffic (Rosen and Vine 1995). The earliest seawalls consisted of "cobb cribs" in which a wood framework was floated into position and filled with rocks (commonly glacial cobbles eroding from the shoreline). Local cobble sources were soon exhausted, but these structures needed continual repair, so other sources had to be found (Rosen and Vine 1995). The widespread use of cut stone by the 1830s made possible vertical stone seawalls with fewer supports (Leudtke and Rosen 1993). In the mid-1800s, coastal engineering became more of a science, and engineers recognized the importance of the fill material behind the wall to reduce lateral forces and promote drainage (Leudtke and Rosen 1993). For example, the seawall at North Head on Long Island is a transitional design constructed in 1870. The wall was built to promote drainage with a cement foundation and backing, a cut-granite facing, and a riprap toe backfilled with porous material (Vine and Rosen 1992; Luedtke and Rosen 1993). The extreme tidal and storm conditions at Boston Harbor forestalled the extensive use of concrete in seawalls until the 20th century. Modern structures use steel sheet piling (Rosen and Vine 1995).

Many of the 19th-century stone seawalls in Boston Harbor are still extant. Some coastal engineering features are part of geomorphic map unit **Qaf** (FitzGerald et al. 2013). However, their structural integrity is compromised by a variety of factors, including sinkholes forming landward of the walls; the walls settling into the extensive glaciomarine clays, glacial tills, and alluvial sands on the floor of Boston Harbor; voids caused by the winnowing away of fine-grained material; shifting stones or loss of chinking; hole-boring organisms; and natural weathering and decay of the structure. A seawall at Gallops Island protects cultural resources; the erosion associated with this structure is the subject of a current study. A similar situation regarding exists at Rainsford Island. There, tracking shoreline retreat is a research need (GRI conference call participants, 7 April 2015). Techniques for evaluating and repairing the historic structures in lieu of replacing them are concerns facing engineers today (Rosen and Vine 1995). This requires a thorough understanding of the construction, history, and condition of the structure. Rosen and Vine (1995) provided a guide for evaluating and potentially restoring historic seawall structures.

Ecosystem and Habitat Connections

The coastlines at Boston Harbor Islands vary from bedrock outcrops to sandy beaches and host diverse coastal features (see "Coastal Features") that support myriad habitats. Flora (2002) included the intertidal/freshwater wetlands as "critical habitats" at Boston Harbor Islands National Recreation Area (see "Wetlands"). The intertidal areas and salt marshes provide nesting and breeding habitat for water birds, in addition to a rich assemblage of macroalgae (seaweed), vascular plants, invertebrates, fishes, and mammals (Bell et al. 2002). Rocky offshore deposits at the base of bluffs provide lobster habitat (Thornberry-Ehrlich 2008). The Cambridge Argillite (**CZca**) at Little Brewster Island supports at least 25 species of lichen (Foley 2005). In addition to nesting seabirds and harbor seals, more than 200 species of birds and three state-listed plants occur within the recreation area (Boston Harbor Islands State of the Park Report, draft in preparation). Bell et al. (2002) provided an inventory of intertidal habitats, including GIS-based habitat maps. Inventories of plants, birds, amphibians, reptiles, and mammals at Boston Harbor Islands National Recreation Area are available at the Northeast Temperate Network inventory website: http://science.nature.nps.gov/im/units/netn/inventory/inventory.cfm.

The geologic and glacial histories and setting of the islands strongly influenced the types of soils that developed, and in turn, the types of plants. Soil resources are not covered in this geologic report, but an NPS soil resources inventory product for Boston Harbor Islands National Recreation Area is available at https://irma.nps.gov/App/Reference/Profile/2170701.

Geologic Features and Processes

These geologic features and processes are significant to the recreation area's landscape and history.

Boston Harbor Islands consists of drowned drumlins ("whaleback" mounds of glacial deposits) and bedrock knobs linked by tombolos (sand spits that connect two islands) and modified by other coastal features. These islands are the highest points of a submerged landscape. As such, coastal features and processes are predominant in Boston Harbor Islands National Recreation Area.

Coastal resources are in the transition between terrestrial (on land) and marine (under water) environments. Coastal environments—shaped by waves, tides, and wind—include tidal flats, estuaries, dunes, beaches, and barriers (Bush and Young 2009). The National Park Service manages 85 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 mi) of shoreline (Curdts 2011) of which Boston Harbor Islands National Recreation Area encompasses about 66 km (41 mi) (Curdts 2011; National Park Service 2015c). FitzGerald et al. (2011) prepared island-by-island shoreline characteristic maps in a GIS format for the national recreation area (table 2). Categories include beach type, coastal engineering structures (some of geomorphic map unit **Qaf**), bluff stability, and other coastal features (e.g., salients, marshes, and bedrock).

Part of Boston Harbor Islands National Recreation Area's stated purpose is to preserve and protect a drumlin island system within Boston Harbor—the only drumlin field in the United States along a coast (National Park Service 2015a). These significant resources, along with associated natural, cultural, and historic resources offer incredible educational and recreational opportunities, as well as a natural haven within sight of the Boston metropolitan area. Listed on the national recreation area's 2009 strategic plan was the desire to identify surficial and bedrock geologic features and key points of geologic interest across the Boston Harbor Islands by 2016 (National Park Service 2009).

During the 2007 scoping meeting (see Thornberry-Ehrlich 2008) and 2015 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Boston Harbor
- Coastal Features
- Sediment Supply and Island Erosion
- Bluff Retreat
- Glacial Features
- Wetlands
- Aeolian Features and Processes
- Bedrock Exposures
- Folds
- Faults
- Paleontological Resources

Boston Harbor

Boston Harbor is a more than 130-km^2 (50-mi^2) estuary system where saltwater from the Atlantic Ocean entering Massachusetts Bay mixes with the freshwater from eight primary watersheds: Quincy Bay, Inner Harbor, Winthrop Bay, and the Charles, Mystic, Weymouth, Weir, and Neponset rivers (Flora 2002). This rich system provides a nursery for marine organisms, water filtration, flood control, and abundant wildlife habitat (National Park Service 2015e).

Boston Harbor is part of a larger structural basin, the Boston Basin, which has been a topographic low for hundreds of millions of years (see "Geologic Setting and Significance"). Now the waters of Boston Harbor cover the eastern part of the basin.

The harbor is roughly divided into inner and outer portions (fig. 6). Together, the Inner and Outer harbors contain 290 km (180 mi) of shoreline (National Park Service 2015e). The Inner Harbor has been modified by humans by dredging and filling of estuaries and coastal wetlands, as well as coastal engineering structures (geomorphic map unit **Qaf**). Natural processes still predominate in the Outer Harbor, which has been less modified by human activities (Colgan and Rosen 2001).

The submerging of Boston Harbor after the most recent glacial retreat about 15,000 years ago (and subsequent sea level rise) created an excellent example of a "drowned" glacial landscape with dozens of drumlins and other glacial features that has been modified by ongoing sea level changes over the past 15,000 years (see "Glacial Features"; Colgan and Rosen 2001). Completely submerged drumlins are now reduced to

Table 2. Boston Harbor Islands shoreline characteristics.

Island	Dock	Relic pier	Revetment/riprap	Groin	Seawalls good or new	Seawalls poor	Eroding bluffs 3–10 m (10–33 ft)	Eroding bluffs <3 m (10 ft)	Eroding bluffs >10 m (33 ft)	Stable bluffs 3–10 m (10–33 ft)	Stable bluffs <3 m (10 ft)	Stable bluffs >10 m (33 ft)	Sandy beaches	Boulder beaches	Pebble/cobble beaches	Bedrock	Dune	Overtopping or gravel ridges	Salients	Embayed marshes	Enclosed marshes	Fringe marshes
Bumpkin	Y	N	N	Y	N	N	Y	Y	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y
Button	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	N	Y	N	N	N	Y
Calf	N	N	N	N	Y*	Y*	N	Y	N	N	N	N	N	Y	Y	Y	N	Y	N	Y	Y	Y
Deer	N	N	N	Y	Y*	Y*	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Gallops	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N
Georges	Y	N	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	N	N	Y	N	N	N	N
Grape	Y	N	N	N	N	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	Y	Y
The Graves	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N
Great Brewster	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	N	N	N	N	N	N	N
Green	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N
Hangman**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	N	N	N	N	N
Langlee	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	Y	N	Y	N	Y
Little Brewster	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N
Little Calf	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N
Long	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y
Lovells	Y	Y	Y	Y	Y	N	Y	N	Y	N	N	N	Y	Y	Y	N	Y	Y	Y	N	Y	N
Middle Brewster	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N
Moon	N	N	Y	N	Y	N	Y	Y	N	N	N	N	Y	Y	Y	Y	N	Y	N	N	N	Y
Nixes Mate	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N
Nut	Y	N	N	N	Y	N	N	N	N	Y	N	N	Y	N	N	N	N	N	N	N	N	N

Table 2. Boston Harbor Islands shoreline characteristics, continued.

Island	Dock	Relic pier	Revetment/riprap	Groin	Seawalls good or new	Seawalls poor	Eroding bluffs 3–10 m (10–33 ft)	Eroding bluffs <3 m (10 ft)	Eroding bluffs >10 m (33 ft)	Stable bluffs 3–10 m (10–33 ft)	Stable bluffs <3 m (10 ft)	Stable bluffs >10 m (33 ft)	Sandy beaches	Boulder beaches	Pebble/cobble beaches	Bedrock	Dune	Overtopping or gravel ridges	Salients	Embayed marshes	Enclosed marshes	Fringe marshes
Outer Brewster	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	N	N	N	N	N	N
Peddocks	Y	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	N
Raccoon	N	N	N	N	N	N	N	N	N	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	N	Y
Ragged	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	N	N	N	N	N
Rainsford	N	N	Y	N	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y	N	N	Y	N	N	N	Y
Sarah	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N
Shag Rocks	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N
Sheep	N	N	Y	N	N	N	N	Y	N	N	N	N	Y	Y	Y	N	N	Y	N	N	N	Y
Slate	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	Y	N	Y	N	Y
Snake	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	Y
Spectacle	Y	N	Y	N	Y	N	N	Y	N	Y	N	N	Y	Y	Y	N	Y	N	N	N	N	Y
Thompson	Y	N	Y	N	N	N	Y	Y	N	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y
Webb Memorial Park	N	N	Y	N	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	N	Y	N	Y	N	Y
Worlds End	N	N	Y	Y	N	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y

Sources: FitzGerald et al. (2011), Coburn et al. (2010), and Marc Albert (Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016).

For more information about coastal engineering structures, refer to Table 5.

Y = "yes" (feature is present on island); N = "no" (feature is not present on island)

* = These islands have seawalls as documented by Coburn et al. (2010), however their condition was not listed.

** = Hangman Island was not mapped by FitzGerald et al. (2011). Information for this island was inferred based on aerial imagery.

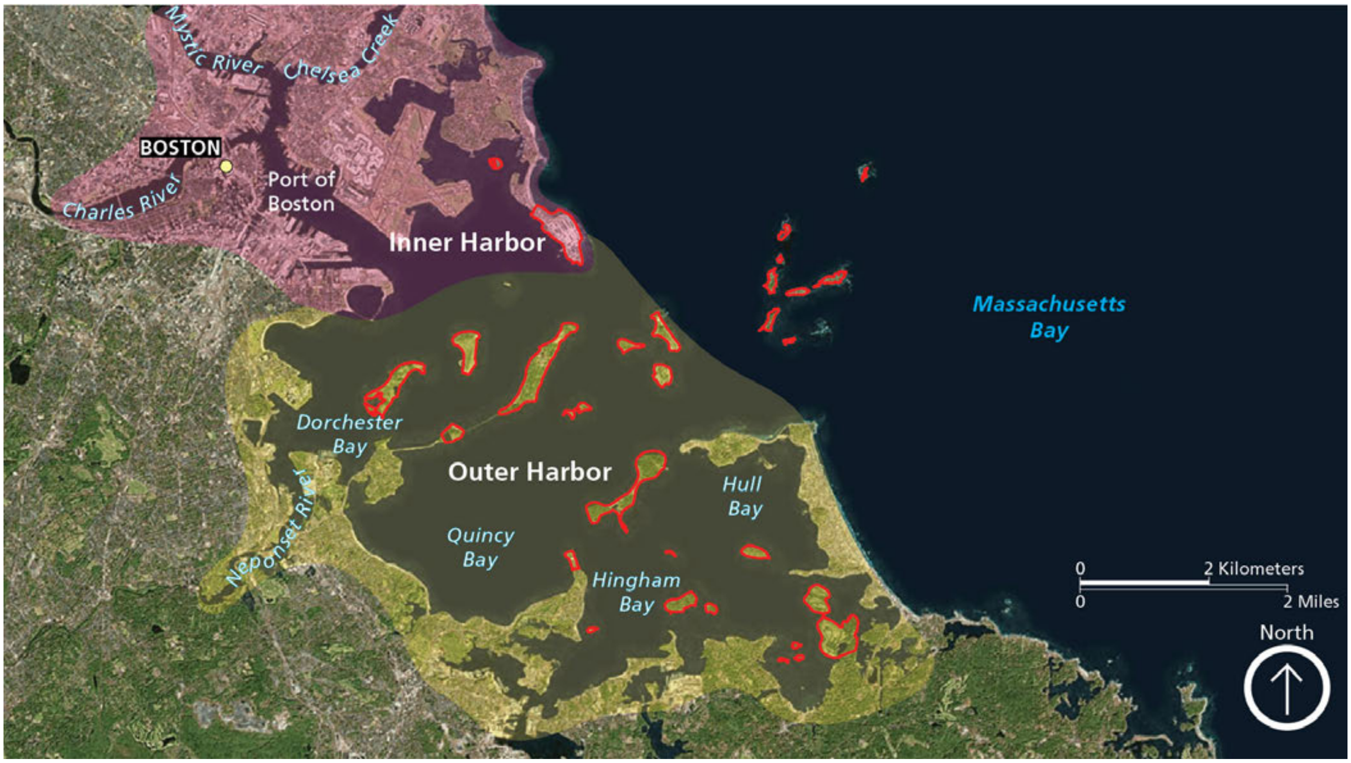


Figure 6. Map of Inner and Outer Boston Harbor. The islands and portions of peninsulas outlined in red on the figure represent Boston Harbor Islands National Recreation Area. The national recreation area is mostly in the Outer Harbor (yellow area), though some NPS lands are in the Inner Harbor (north of the Outer Harbor) and Massachusetts Bay (beyond the Outer Harbor). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap, accessed 31 December 2015.

only remnant deposits of lag boulders (e.g., Rams Head) (FitzGerald et al. 2011).

The National Park Service developed a strategic plan to integrate ocean and coastal park management in the NPS Northeast Region and address all facets of park management to (1) establish a seamless network of ocean parks, sanctuaries, refuges, and reserves; (2) discover, map, and protect ocean parks; (3) increase technical capacity for ocean exploration and stewardship; and (4) engage visitors and the public in ocean park stewardship (National Park Service, Northeast Region 2007). More information is available from the following website http://www.nps.gov/boha/learn/management/upload/BOHA_2016_strategicplan.pdf.

The harbor floor is largely composed of glacial deposits such as till, outwash, and younger glaciomarine clays (e.g., Boston Blue Clay) (Kaye 1982; Knebel et al. 1992; Luedtke and Rosen 1993). Topographically, Boston Harbor consists of extensive subtidal flats (less than 4 m [13 ft] deep), and a complex assemblage of discontinuous ridges and depressions. Deeper water areas (greater than 10 m [30 ft]) only occur at the two main harbor entrances—President Roads and Nantasket Roads (Knebel et al. 1991; Knebel and Circé 1995). Infrequent dredging maintains the active shipping channel in the Inner Harbor. Sediment is transported into the harbor from a variety of sources including rivers on the mainland, erosion of glacial deposits on the islands, landward bottom currents flowing from Massachusetts Bay, and organic debris settling from the water column (Knebel and Circé 1995).

Knebel et al. (1991) categorized the modern sedimentary environments distributed across the estuary, inner shelf, and basin settings of Massachusetts Bay as (1) environments of erosion or nondeposition comprising bedrock, glacial drift, coarse lag deposits, and other areas of strong bottom currents; (2) environments of deposition of clay, silt, and sand in areas of weak bottom currents; and (3) environments of sediment reworking (erosion and deposition across a relatively small area) in areas with variable bottom

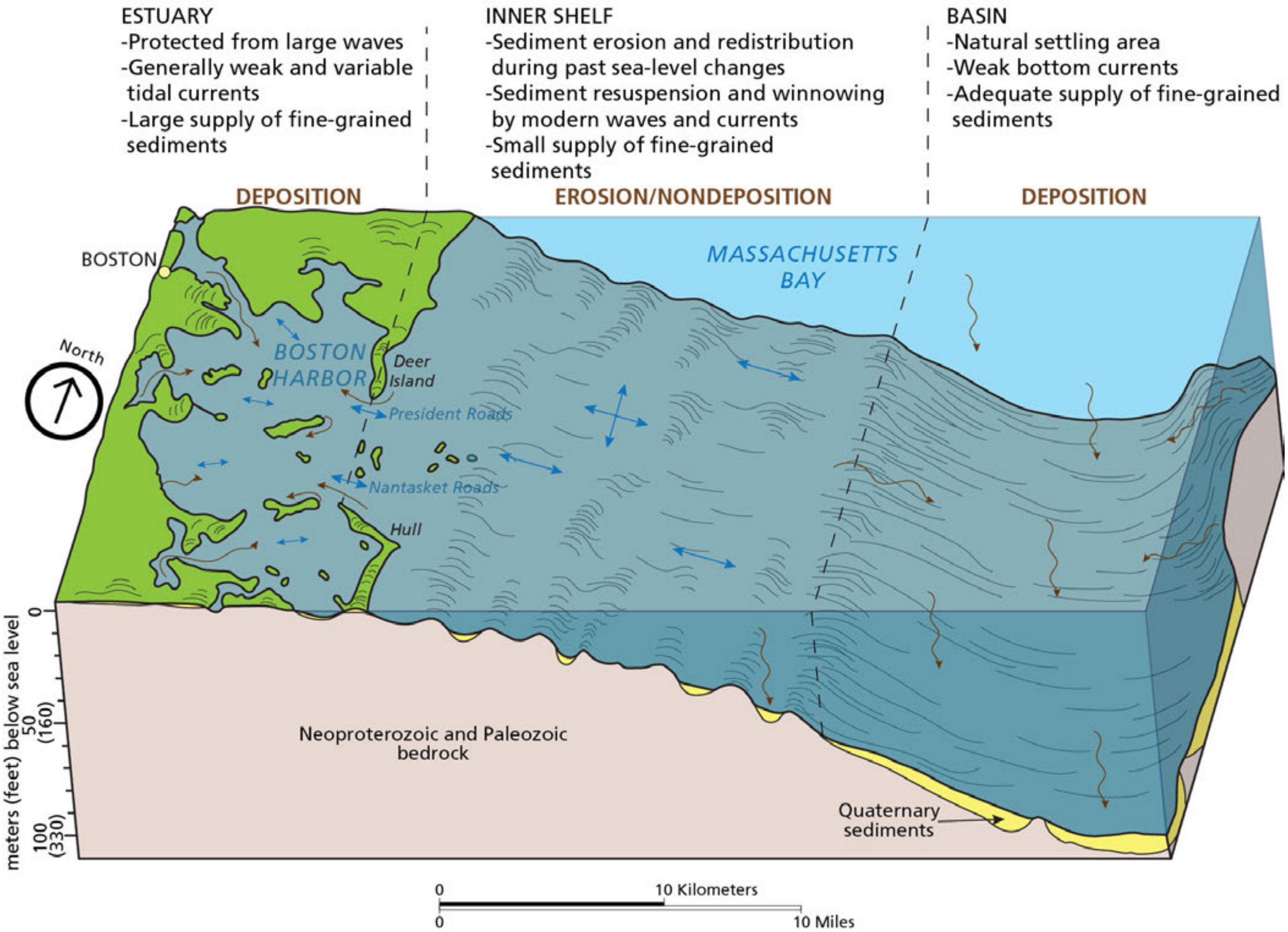


Figure 7. Diagram of sedimentary environments in Boston Harbor and Massachusetts Bay. In contrast to the erosional regime of the islands themselves, the subaqueous area around Boston Harbor Islands is largely depositional in nature. Fine-grained sediments come from mainland fluvial sources, some tidal currents, and a small amount from the islands themselves. Blue arrows indicate tides and wave directions, brown arrows indicate sediment sources. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 12 in Knebel and Circé (1995).

currents (fig. 7). Areas of nondeposition in the harbor are limited around the Boston Harbor Islands; they occur atop submerged ridges and knolls, along the southern mainland shore, and within large tidal channels (Knebel et al. 1991; Knebel and Circé 1995). Areas of deposition occur across extensive subtidal flats and in low-lying areas away from the main tidal channels. In areas of nondeposition, fine-grained sediments are eroded away leaving the seafloor covered by coarse "lag deposits" or in some places bedrock exposures (Knebel et al. 1991, 1992). Areas of sediment reworking are common in the northern third of the harbor and tend to be uncorrelated with bottom topography. More than 29% of the harbor floor has reworked sediment cover (Knebel and Circé 1995).

As an estuary protected from ocean waves, Boston Harbor is primarily an area of deposition where fine grained sediments accumulate. More than 51% of the harbor floor experienced long-term deposition of mainly dark, organic-rich sandy and clayey silts (Knebel et al. 1991; Knebel and Circé 1995). However, large storms (nor'easters) have the capacity to scour fine sediments from the harbor and back out into Massachusetts Bay (Fitzgerald 1980; Knebel and Circé 1995).

Intertidal Substrates

Boston Harbor is part of the Bay of Fundy–Gulf of Maine tidal system and has a tidal range of about 3 m (10 ft) (Rosen et al. 1993; National Oceanographic and

Atmospheric Administration 2015). This results in vast areas of shoreline being alternately submerged at high tide and exposed at low tide to create an intertidal zone encompassing about 420 ha (1,040 ac) (Mitchell et al. 2006). The tides are also a major contributor to the wave dynamics and currents flowing around the Boston Harbor Islands. The intertidal zone—the area between the reaches of high and low tide—contains a diversity of habitats, including bedrock outcrops; tide pools; sandy barrier beaches; mud and sand flat; salt marshes; and rock, cobble, and/or gravel beaches (Bell et al. 2002; National Park Service 2015c). Where and how intertidal habitats form depends on a variety of factors such as wave activity, orientation and location of the island, and the island's geologic composition and geomorphology (see bulleted list below). A gradient of wave energy and exposure ranges from low energy and low exposure on the protected and sheltered islands within the Inner Harbor to the higher wave energy settings of the Outer Harbor and beyond into Massachusetts Bay. Based on tidal currents and wave patterns, the highest rates of erosion and sediment transport occur along the northeast-facing shorelines, and sediment accumulation tends to occur on the southern shores or in areas sheltered between islands (National Park Service 2015d; Peter Rosen, Northeastern University, coastal geologist, written communication 24 May 2016).

According to Bell et al. (2002) intertidal substrates at Boston Harbor Islands include

- bedrock: at least 50% of surface area is bedrock.
- boulders: at least 75% of ground surface cover is rocks between 26 cm (10 in) and 3 m (9 ft) in diameter.
- hardpan: a hard, impervious layer composed chiefly of clay. This glaciofluvial clay is known as Boston Blue Clay and has been observed on Thompson, Grape, Snake, and Slate islands (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). It was not found at Boston Harbor by Bell et al. (2002).
- cobble: an unstable surface dominated by at least 75% of ground surface cover rocks that are less than 26 cm (10 in) but greater than 6.4 cm (2.5 in) in diameter.
- mixed coarse: heterogeneous continuum of rocks, boulders, cobbles, gravel, shell, and sand
- gravel: at least 75% of the ground surface cover is small rocks or pebbles, 2 to 64 mm (0.08 to 2.5 in) in diameter
- sand: at least 75% of the ground surface cover is sand
- shells: at least 75% of the ground cover is shells
- mixed coarse and fine: heterogeneous assemblage of rocks, boulders, and coarse and fine particles
- mud: at least 75% of the ground surface cover of silt and clay, commonly mixed with organic material
- peat: includes ground surface cover of peat, sawdust, wood chips, leaf litter, and other detritus
- cultural: at least 75% of ground surface cover is anthropogenic, including discarded tires, docks, bulkheads, logs, pilings, or oyster cultures.
- reef: carbonate mound-like features (e.g., oyster and mussel bars)
- seep: continually wet substrate, saturated with groundwater

The three most abundant substrates at Boston Harbor Islands, based on total area, are mixed coarse, mixed coarse and fine, and reef (Bell et al. 2002). These substrates in turn support a diverse array of intertidal habitats at Boston Harbor Islands. A 2002 inventory of the intertidal habitats for 20 of the islands (1) highlighted the importance of these areas, (2) identified natural resources management issues, and (3) made suggestions for long-term monitoring and research needs (Bell et al. 2002; National Park Service 2015c). Many of these areas are considered wetlands (see "Wetlands").

Bedrock intertidal areas on Green, Outer Brewster, and Calf islands were chosen for ongoing monitoring of the rocky intertidal habitat by the Northeast Temperate Network (Long and Mitchell 2015). Some objectives of the monitoring program are to determine changes in intertidal zone widths, to track any changes in zonation with sea level rise, and to establish correlations between ice scouring and storms on the vegetation (Mitchell et al. 2006). Monitoring barnacles, mussels, kelp, and algae should help establish baseline data from which to inform adaptive management practices in the face of changes such as rising sea level or contamination (Long and Mitchell 2015).

Sediment Supply

In contrast to the overall Boston Harbor setting where deposition is the predominant process, sediment supply in the harbor's island system is limited, and island shorelines are eroding (see "Sediment Supply and Island Erosion"). Islands that are composed of glacial till and other unconsolidated deposits provide a source of sediment and typically display eroding cliffs, spits, and beaches (e.g., Great Brewster, Thompson, Long, Grape, Bumpkin, Rainsford, Georges, Lovells, and Peddocks islands, as well as Worlds End) (Bell et al. 2002). Islands that are primarily composed of bedrock are more geomorphologically stable and provide little sediment to the intertidal and subtidal areas (e.g., Outer Brewster, Little Brewster, Calf, and Langlee) (Bell et al. 2002; National Park Service 2015c). Waves and currents rework and transport sediment from sources (islands) to sinks (intertidal substrates). This process tends to winnow away the fine-grained (e.g., sand, silt, and clay) component leaving coarse gravel (granules, pebbles, cobbles, and boulders), and even bare bedrock behind.

Coastal Features

Coastal features at Boston Harbor Islands form atop the various intertidal substrates (see "Intertidal Substrates") and above the high tide line. Most sediment accumulation on the coast is associated with areas where currents of longshore sediment transport converge, commonly caused by refraction of oncoming waves around an island. Generally low-energy, longshore waves rework glacial sediments, which accumulate atop preexisting topography to form myriad coastal features characteristic of the Boston Harbor Islands (Rosen and Leach 1987; Rosen and FitzGerald 2004). Such features include eroded glacial-till bluffs, a variety of beach types, spits (geomorphic map unit **Qsp**), tombolos (**Qt**), salients (**Qsa**), welded bars (**Qwb**), gravel ridges (**Qgr**), retreat platforms, raised sea-level terraces, and intertidal bars, inlets, and tidal flats (**Qi**, **Qtf** and **Qib**, respectively; see also "Intertidal Bars, Inlets, and Tidal Flats") (Thornberry-Ehrlich 2008; FitzGerald et al. 2013).

Because these coastal features are composed of unconsolidated sediment, their locations and morphologies change. Coastal geologists and geomorphologists are studying these changes to better understand the features of Boston Harbor Islands, as well as how these features will respond to rising sea level and high-energy storm events. For example, scientists are trying to determine why tombolos are forming and if glacial till exposures and flat, offshore terraces support tombolo formation. Some tombolos are forming along topographically higher areas in the basement materials with less influence from modern coastal processes (Luedtke and Rosen 1993). Salients such as those on Thompson Island may be forming because of their location where local waves converge with an availability of sediment from longshore currents (Thornberry-Ehrlich 2008).

A potential Geoscientist-In-the-Parks ("GIP"; see http://go.nps.gov/gip) project could be to take photographs of coastal features with annotation to document these features for use in interpretation and resource management.

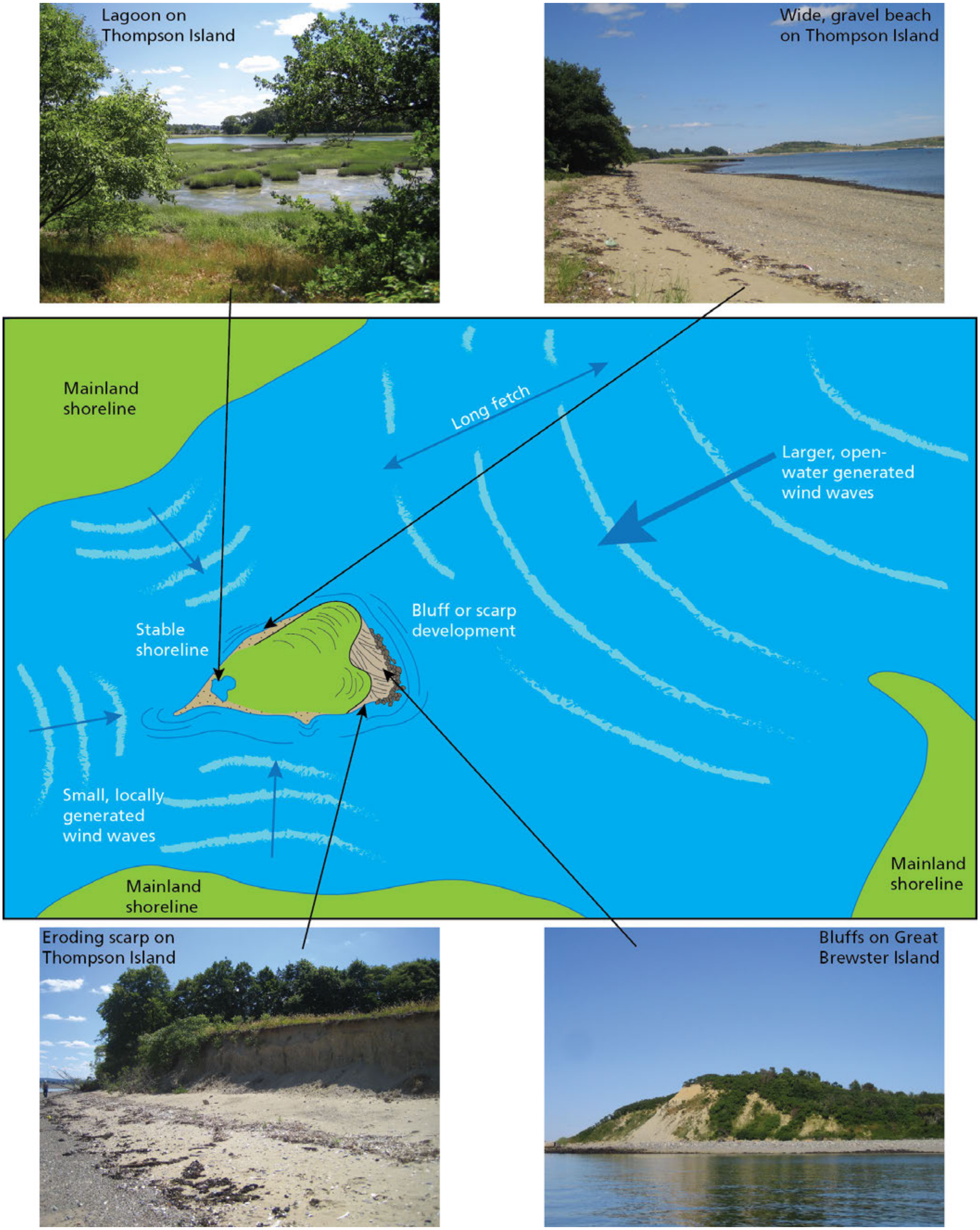
Glacial Till Bluffs (Eroding Drumlins)

Glacial till bluffs occur where wave action and surface runoff have eroded drumlins to form a steep, mostly unvegetated slope along the shoreline (see "Glacial Features"). Notable examples of these bluffs occur at Long, Peddocks, Thompson, Gallops, and Great Brewster islands. Bluff height depends largely on the size and orientation of the original drumlin, the degree to which the drumlin has been eroded, and the local wave setting. About 61% of bluffs are between 3 and 10 m (10 and 33 ft) in height; however, bluffs on Great Brewster Island are the highest in the harbor at more than 30 m (100 ft) high (FitzGerald et al. 2011). Bluffs on Peddocks Island reach 23 m (75 ft) high. The bluffs typically take on one of two morphologies—planar (without considerable gullying) or irregular (incised with rills and/or gullies)—based on the mechanism of bluff retreat (see "Bluff Retreat"; Himmelstoss et al. 2006).

Beaches

Wave energy and sediment source determine what type of beach forms along a shoreline. The beaches of Boston Harbor Islands are mixed sediment beaches because the primary source of sediment comes from the erosion of drumlins, which consist primarily of till (a heterogeneous mixture of different sized boulders, cobbles, and gravel in a matrix of sand, silt, and clay) (see "Glacial Features"; FitzGerald et al. 2011). Beaches that are particularly well developed occur at Long, Rainsford, Lovells, Moon, Peddocks, Thompson, Spectacle, Langlee, and Gallops islands (Flora 2002; FitzGerald et al. 2011).

The most common beaches of the islands are pebble/cobble (42%). Boulder and sandy beaches are less


Lagoon on Thompson Island
Wide, gravel beach on Thompson Island
Mainland shoreline
Long fetch
Larger, open-water generated wind waves
Bluff or scarp development
Stable shoreline
Small, locally generated wind waves
Mainland shoreline
Mainland shoreline
Eroding scarp on Thompson Island
Bluffs on Great Brewster Island

common (30% and 28%, respectively) (FitzGerald et al. 2011). Pebble/cobble beaches dominate, but variations are common across any given beach. Typically, boulder beaches have fetches of 1,500 m (4,900 ft) or more; they are most common in the north and northwest reaches of most islands (fig. 8; FitzGerald et al. 2011). Boulder beaches form under high energy settings where finer-grained materials are washed away (see "Bluff Retreat"). Sandy beaches form in lower energy settings wherein a longshore supply of sand collects or was deposited in a handful of protected coves along the southern and western shorelines of Boston Harbor Islands (e.g., Lovells and Thompson islands). Beaches can transition from one type to another. High-energy waves (storms) move sand from the beach to offshore, leaving cobble-covered or bare-bedrock surfaces. Retrograding barrier beaches are those that are migrating landward as a result of rising sea level.

Sand Spits, Tombolos, Gravel Ridges, Welded Bars, and Salients

Commonly mapped together at Boston Harbor Islands, sand spits (**Qsp**), tombolos (**Qt**), gravel ridges (**Qgr**), welded bars (**Qwb**), and salients (**Qsa**) can be transitional (i.e., change from one to another over time) or physically connected.

Sand spits are elongate "fingers" of sand that typically develop on the leeward sides of islands. In Boston Harbor, sand spits are well developed on Long and Peddocks islands. The sand spits on these islands formed along with welded bars (**Qwb**) in the sheltered space between two islands (see island maps in Appendix B; FitzGerald et al. 2013). At Peddocks and Lovells islands, the alignment of sand spits (**Qsp**) is controlled by preexisting glacial topography in lower energy settings and by dominant wave approach directions in higher energy settings (Rosen and FitzGerald 2004). In areas where the sediment supply is available (e.g., from longshore sources), regressive barrier spits (mapped as **Qsp**) are forming (Rosen and FitzGerald 2004).

If a sand spit extends all the way to another island, connecting the two, it forms a tombolo (**Qt**). Tombolos formed at Peddocks, Calf, Grape, and Rainsford islands, connecting once-smaller islands (see island maps in Appendix B; FitzGerald et al. 2013). Along the eastern shore of Thompson Island, sediment movement is toward both the north and south, representing the influences of dominant southwest and northeast winds. Typically, tombolos are forming at areas often on the leeward side of an island where dominant wave directions converge, the resulting accumulation of sediment may connect headlands together (**Qt**) whereas some remain as spits (**Qsp**) or salients (**Qsa**) (Rosen and Leach 1987; Bolbrock et al. 2009; FitzGerald et al. 2013). Tombolos were not mapped as standalone features by FitzGerald et al. (2013). They were mapped in various combinations with lagoons (**Qla**), welded bars (**Qwb**), overwash terraces (**Qot**), wetlands (**Qwe**), and tidal channels (**Qtc**). Tombolos and associated features occur at Peddocks, Calf, Grape, and Rainsford islands (FitzGerald et al. 2013).

Gravel ridges (**Qgr**) are wave-built accumulations of gravel, coarse sand, and shell fragments that occur in high-energy environments and are commonly overtopped during storm events. Gravel ridges are typically related to the onshore movement of pebbles and cobbles up the beach face. This results in the formation of a transgressive (landward-migrating) barrier spit consisting of a single asymmetrical ridge and a series of gravel overwash lobes projecting behind the barrier. Sometimes migrating overwash channels may form (Luedtke and Rosen 1993). Emerging ridges are associated with the presence of a salt marsh (**Qwe** and **Qla**) or other ridges towards an island's core, whereas intertidal gravel bars (**Qib**) are associated with intertidal lagoonal muds (**Qtf**) towards an island's core (Rosen and Leach 1987; FitzGerald et al. 2013). In the second scenario, the intertidal gravel bar approaches high water, but does not rise above it. The storm ridges form the emergent parts of gravel spits associated with longshore sediment supply. Overtopping of the ridges occurs during storms, but gravel overwash channels can resemble tidal inlets (**Qi** and **Qtc**) as a semi-permanent feature migrating in the downdrift direction along the spit. This results in a continuous delta-fan deposit

Figure 8 (facing page). Schematic of wave types and shoreline morphologies with accompanying photographs. Waves reshape the shorelines at Boston Harbor Islands. Where islands are exposed to the longer fetch across the harbor mouth, larger, higher-energy waves create bluffs and scarps (see fig. 11). Smaller waves refract back from the adjacent mainland shorelines. These tend to collect sediment as depositional features (e.g., beaches, salients, and spits). Photographs (taken in July 2007) and graphic by Trista Thornberry-Ehrlich (Colorado State University) after a figure presented by Rosen (2007).

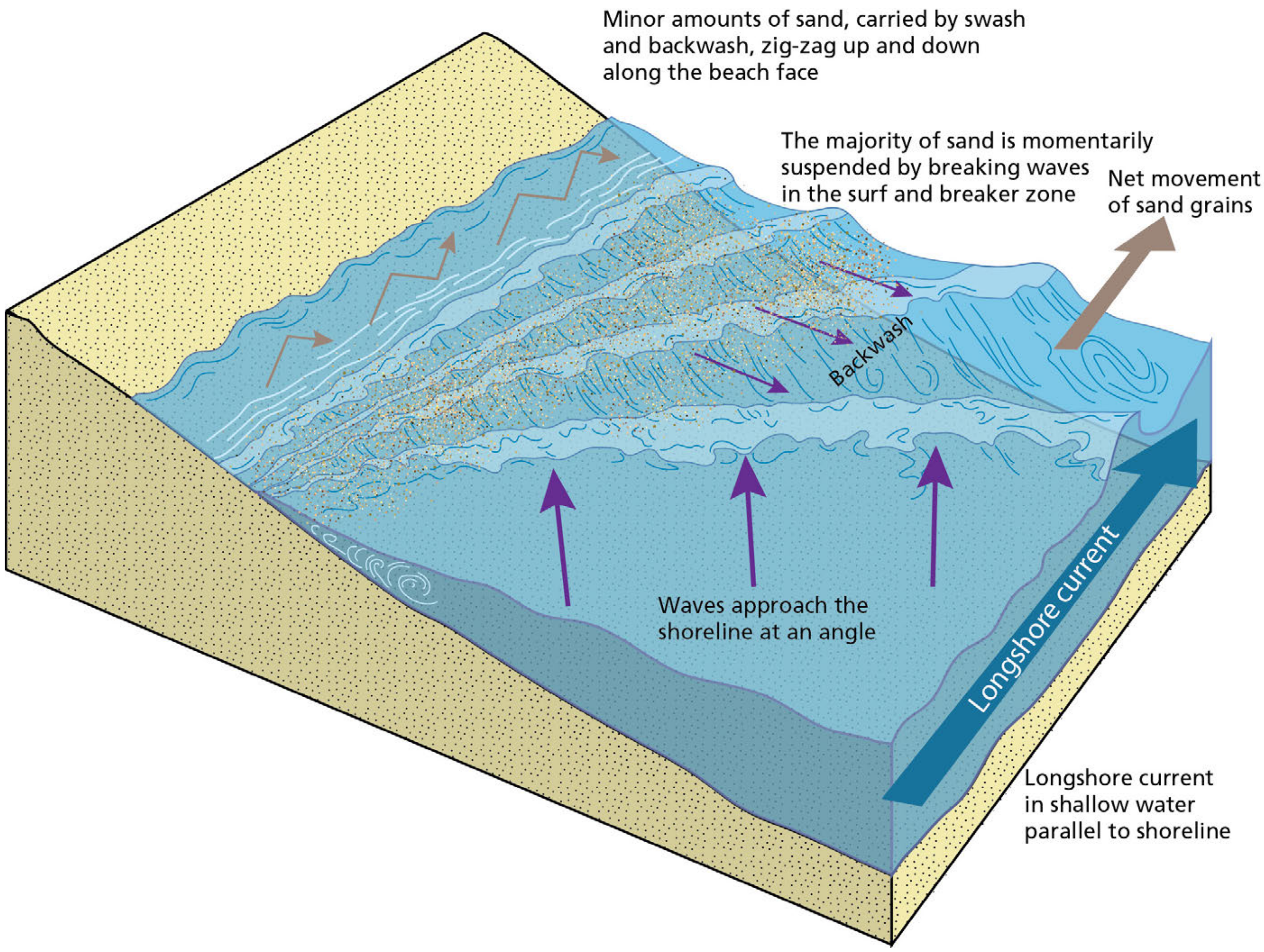


Figure 9. Diagram of longshore drift. Waves refract as they move onshore, and most of the longshore transport of sand occurs as the sand is temporarily suspended by breaking waves in the surf and breaker zone. Sand grains are transported by waves and longshore currents and deposited in sheltered areas and leeward sides of the islands. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using Capital Regional District graphics at https://www.crd.bc.ca/education/in-your-community/geology-processes/coastal-sediment and http://robcroslinggeoblog.blogspot.com/2011_10_01_archive.html and information from Peter Rosen and Duncan FitzGerald (Northeastern University and Boston University, respectively, coastal geologists, written communication, 24 and 25 May 2016).

(e.g., overwash terrace, **Qot**) landward of the spit (i.e., gravel over sand sequences (Rosen and Leach 1987; FitzGerald et al. 2013).

At Boston Harbor Islands, gravel ridge accumulations tend to form between two drumlins or joined ("welded") to one side of a drumlin. Sheltered areas behind gravel ridges may contain marshes (FitzGerald et al. 2013). Gravel ridges occur on Calf Island and prominently on the south side of Grape Island, southwest side of Peddocks Island, and southwest side of Thompson Island (FitzGerald et al. 2013; Marc Albert, Boston Harbor Islands National Recreation Area, resource stewardship program manager, written communication, 31 May 2016).

Welded bars (**Qwb**) are spits, tombolos, or gravel ridges that are joined, or "welded," to headlands at both ends, such as two drumlins and/or bedrock islands. Welded bars bind the two ends together (FitzGerald et al. 2013).

Salients (**Qsa**) are deposits of sediment that protrude from the shoreline. sometimes their formation results in associated offshore bar; however, this is not necessarily common in Boston Harbor (Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016). The type, composition, orientation, and sheer numbers of salients make Boston Harbor Islands a premier research site for these features. Salients may move alongshore in response to sediment supply and wave direction. Rates of salient migration vary from stable to 0.6 m (2.0 ft) per year (FitzGerald et al. 2011). Where the longshore transport rate is relatively constant and equal on both sides, salients are relatively stable (Bolbrock et al. 2009). Where a slightly dominant longshore transport rates exists or where the sediment supply varies, salients migrate to form "traveling headlands" such as those on Peddocks and Lovells islands (see fig. 9 and island maps in Appendix B; Rosen and FitzGerald 2004; Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016). One of the largest salients in the harbor is migrating southward from the northern end of Lovells Island (see island map in Appendix B; Rosen and FitzGerald 2004). Other examples of salients are south of Thompson Island (see island map in Appendix B) and along the southwest shore of Long Island (FitzGerald et al. 2013).

Boulder Retreat Platforms

At Boston Harbor Islands, some of the coastal landforms are controlled by the primary sediment source. Where eroding drumlins (**Qdr**) provide the sediments (e.g., Long, Lovells, and Peddocks islands), sediment-starved beaches and boulder retreat platforms with boulder lag deposits generally develop.

Boulder retreat platforms, which form primarily by wave action, are relatively flat terraces (planar surfaces) with a veneer of gravel and boulders. The gravel and boulders are "lag deposits" in that they remain after finer grained sediment has been washed away. The boulders may also form a "pavement" that protects the underlying till deposits from further wave erosion. They are landforms created during bluff retreat (see "Bluff Retreat"), and often extend offshore to the original extent of the drumlin (FitzGerald et al. 2011). Boulder retreat platforms may also have gravel spits (**Qot** and **Qgr**) connecting the drumlins that are frequently inundated by waves (Rosen and FitzGerald 2004).

Raised Sea Level Terraces

Raised sea-level terraces are features that formed during periods of higher sea level. They are flat terraces "perched" well above the high tide line. At Boston Harbor Islands, raised sea-level terraces are notable at Squaw Rock and the south side of Thompson Island (Thornberry-Ehrlich 2008). Dating of these terraces is a research need at Boston Harbor Islands to understand the temporal context for when sea level was higher in order to better understand the islands' response to modern rising seas (Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016).

Intertidal Bars, Inlets, and Tidal Flats

Some coastal features at Boston Harbor Islands are directly linked to or accommodate tidal flow, including intertidal bars, inlets, and tidal flats. Intertidal bars (geomorphic map unit **Qib**) are linear accumulations of sediments whose exposure depends on the tidal stage. They are submerged at high tides and are subaerially exposed at low tide. Commonly intertidal bars extend offshore of salients (**Qsa**). At Boston Harbor Islands, intertidal bars form where sediments converge, or where a core of sediment (glacial till or lag) existed. Notable examples occur offshore of Great Brewster, Bumpkin, Grape, and Thompson islands (see island maps in Appendix B; FitzGerald et al. 2013).

Inlets (**Qi**) are the direct channels for tides to flow between marshes or lagoons and the open water of Boston Harbor. Inlets have distinct geomorphological and sedimentological characteristics associated with tides flowing in and out thus transporting sediments both directions. Inlets may include a main ebb channel, channel margin linear bars, swash bars and platforms, marginal flood channels, or ebb tidal deltas (fig. 10; FitzGerald 1996). An inlet area was mapped on the southwestern corner of Thompson Island (see island map in Appendix B; FitzGerald et al. 2013), and tidal inlets also occur on the east side of Thompson Island and on Peddocks Island (FitzGerald et al. 2013; Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016).

Tidal flats (**Qtf**) are broad level areas that contain fine sediments and are flooded at high tide and exposed at low tide. Examples of **Qtf** occur in the GRI GIS data mapped at Snake, Thompson, and Peddocks islands (see island maps in Appendix B; FitzGerald et al. 2013).

Sediment Supply and Island Erosion

Since their drowning during the past 4,000 years, the Boston Harbor Islands have eroded and some have

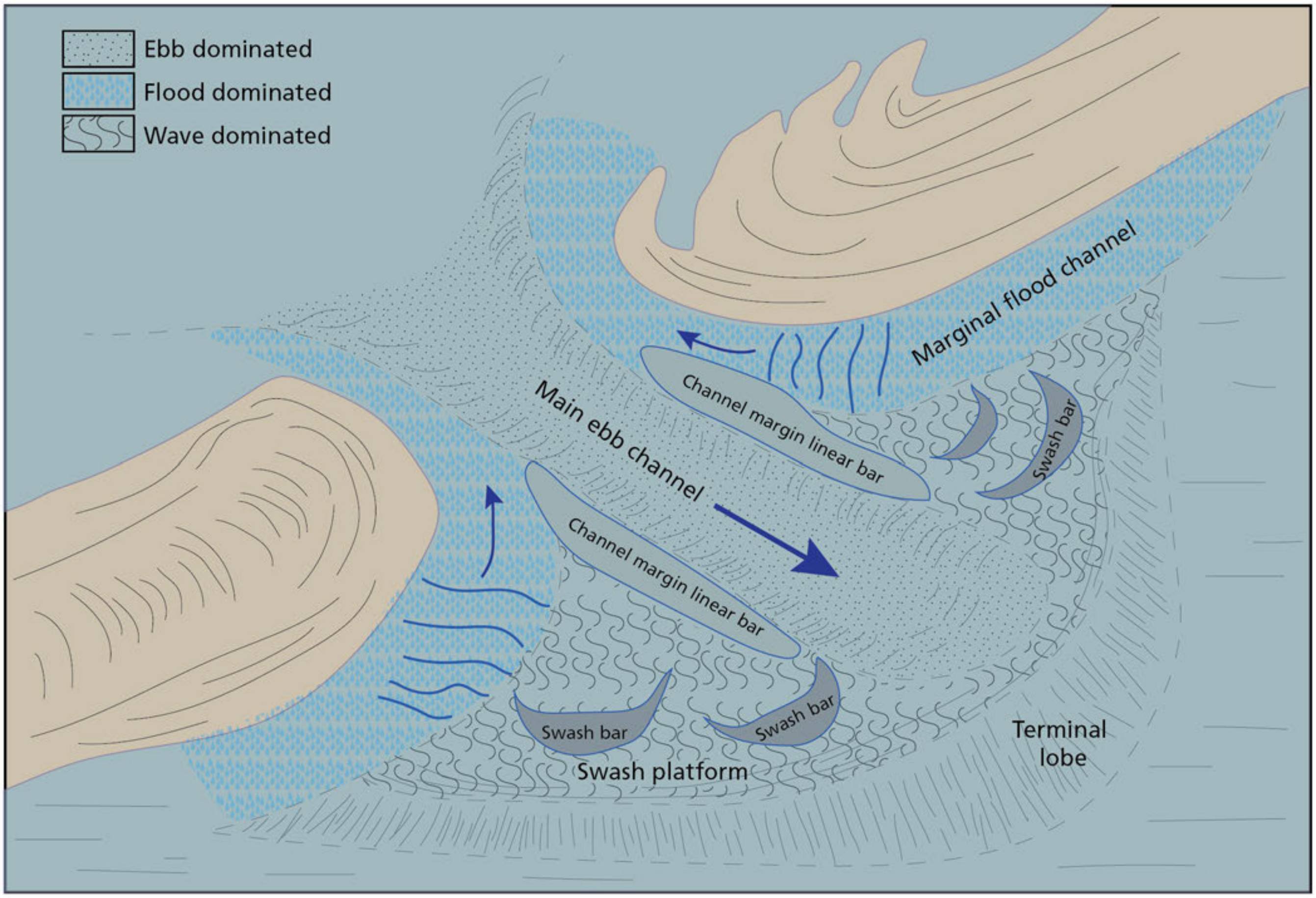


Figure 10. Illustration of ebb-tidal inlet features. Ebb tides flow in the opposite direction as flood tides. At Boston Harbor Islands, this flow would be from the tidal flat or inlet area out towards the open harbor. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 1 in FitzGerald (1996).

disappeared (Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016). The coastal processes driving erosion are natural, although human activities have greatly altered them since Europeans arrived about 400 years ago. Issues associated with coastal erosion are discussed in "Coastal Erosion and Response to Climate Change."

All of the coastal features associated with the islands (see "Coastal Features") resulted from the erosion, transportation, and/or deposition of sediments. Overall, the coastal system at Boston Harbor Islands National Recreation Area is sediment starved, meaning a net loss of sediment is occurring and the coastlines are eroding. The depositional landforms associated with the islands have developed primarily from sediment taken from the drumlin islands. Other features, including other types of glacial deposits (geomorphic map units **Qdr**, **Qgfd**, **Qtcb**, and **Qmrt**) of some of the islands, local rivers, offshore shoals (remnant deltaic sand deposits), and the enclosures of the harbor—Winthrop Beach to the north and Nantasket Beach to the south (see fig. 1)—have contributed little to the sediment supply (Rosen and Leach 1987; Thornberry-Ehrlich 2008; FitzGerald et al. 2013; Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016). Bluff retreat is a major process by which the drumlins are eroding.

When the European settlers first explored Boston Harbor nearly 400 years ago, they counted more than 50 islands (Thornberry-Ehrlich 2008). Since then, erosion, coastal processes, and sea level rise, as well as anthropogenic activities, such as dredging, ferry and boat operation, construction, quarrying, and coastal engineering, have reduced that number to less than 35 (Gontz et al. 2007; Thornberry-Ehrlich 2008; FitzGerald et al. 2011). During colonial time, Sheep Island was 10 ha (25 ac) but now encompasses less than 1.3 ha (3.2 ac). Princes Head is nearly submerged (Thornberry-

Ehrlich 2008). Nixes Mate, formerly known as Nubble Island, covered 5 ha (12 ac) but is today little more than a channel marker with a distinctive black and white buoy (Flora 2002). Using aerial photography, Jones et al. (1991) recorded a net rate of shoreline erosion between 1938 and 1977 as 0.15 m (0.49 ft) per year for seven islands within Boston Harbor (Spectacle, Gallops, Georges, Great Brewster, Lovells, Rainsford, and Long islands). An example of anthropogenic alteration is the filling of shallow waters around the East Boston shoreline and subsequent construction of Logan Airport, which created continuous land in an area that formerly included four islands (Noddle, Governors, Apple, and Bird) (Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016). As a possible response to erosion, Smith and FitzGerald (1994) studied potential offshore sand and gravel sources for shoreline nourishment, but such extraction could create offshore sinks and possibly change the wave refraction patterns into the harbor, which has the potential to alter erosion/deposition regimes already in place.

Bluff Retreat

The unconsolidated glacial deposits that make up the drumlins (see table 1) are erodible. Since their shaping by ice age glaciers, drumlins have been exposed after the glaciers receded and submerged by rising sea level. As a result, the drumlins at Boston Harbor Islands have been eroding via a process known as "bluff retreat." Today, many drumlins have multiple exposures forming eroding scarps. Bluff retreat along island coastlines, and the associated effects on island resources and facilities, is the primary slope management concern at the recreation area (Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, conference call, 7 April 2015). Hazards and risks associated with bluff retreat (slope movements) in Boston Harbor Islands National Recreation Area are described in "Geologic Resource Management Issues". Human activities can speed up or slow down the rate of slope movements and thus bluff retreat. The sediment eroding from the drumlins is an important source of sediment in a sediment-starved system such as Boston Harbor (see "Sediment Supply and Island Erosion").

Coastal bluff retreat is a natural process that is episodic (Hapke et al. 2011) and driven by waves and surface processes (e.g., storms and slope movements). Slope movements occur on time scales ranging from seconds to years (see fig. 11). Slope movements are characterized by the downslope transfer of soil, regolith, and/or rock under the influence of gravity. In the national recreation area, soil creep is a particular type of slope movement; it is influenced by soil saturation, freeze/thaw cycles in soil, and undercutting by wave erosion at the base of slopes (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016).

Himmelstoss et al. (2006) compared 13 bluffs on four of the Boston Harbor Islands to reveal variability in their height and lateral extent, as well as document the dominant mechanisms of bluff retreat. Two processes cause bluff retreat and yield distinct bluff morphologies: (1) wave attack undercuts the bluff and results in slumping, yielding planar (ramp-like) bluff slopes, and (2) subaerial processes such as rainfall and surface erosion create irregular slopes characterized by rills and gullies (fig. 11; Himmelstoss et al. 2006). These processes work in tandem. Each slump delivers a pile of gravel-rich sediment to the shoreline. That material then protects the base of the bluff from further wave erosion, stabilizing the bluff until the slumped material erodes away. In the meantime, other processes (e.g., rainfall) modify the slope and slump into a gullied morphology (see fig. 11; Kaye 1967a; Rosen and FitzGerald 2004; Himmelstoss et al. 2006). These processes create four phases of drumlin bluff retreat influenced by bluff height, slope morphology, and orientation of the bluff with respect to the long axis of the drumlin and its crest, as well as the local wave setting. The four phases are (1) initial formation of bluff, with retreat dominated by wave-notching and slumping; (2) rill and gully development as bluff heights exceed 10 m (33 ft) and slumped sediment at the base of the bluff inhibits wave attack; (3) resurgence of wave notching and slumping as bluff heights decrease; and (4) final development of boulder-rich "lag deposits" that remain after fine-grained sediments are removed by wave action and the drumlin is completely eroded away (Himmelstoss et al. 2006).

An eroding drumlin face creates higher and higher bluffs as it retreats toward the crest of the drumlin. Some of the highest bluffs occur on the northeast ends of Long, Lovells, and Peddocks islands (Rosen and FitzGerald 2004). Lower bluffs are typically more subject to slumps. Higher bluffs experience more gullying (Rosen and FitzGerald 2004; Himmelstoss et al. 2006). Transitional bluffs exhibit characteristics of

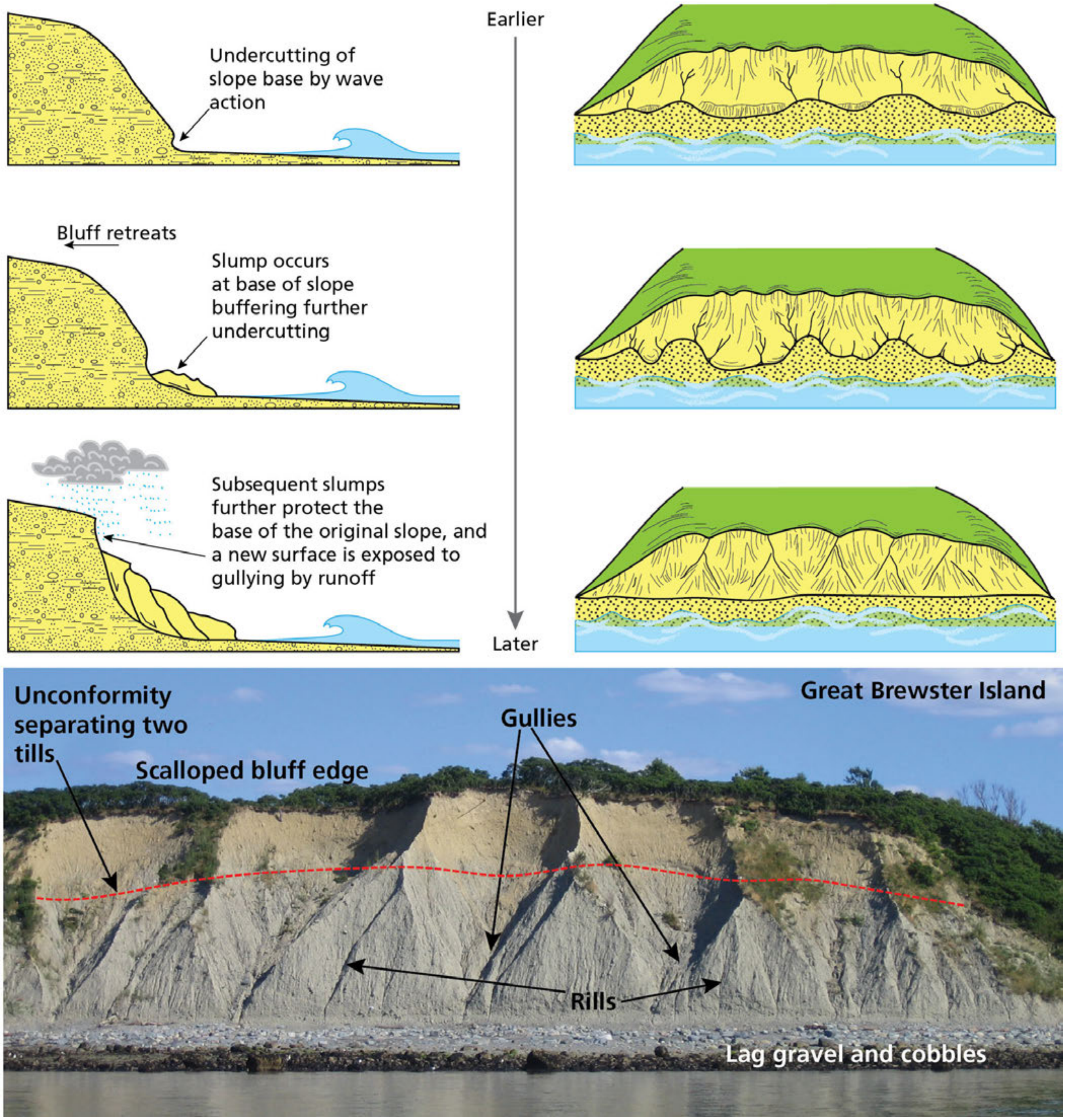


Figure 11. Schematic of slope erosion processes through time. Wave action is constantly undermining the base of the glacial till bluffs at Boston Harbor Islands. The slope eventually fails, forming a slump. The slump temporarily protects the slope base from wave action. Rain and groundwater runoff incise the slumped slope that eventually matures into a gullied bluff face. Waves incise the toe of the slumps. Exposures of glacial tills at Great Brewster Island show the gullied slopes above the lag gravel and cobbles, which were left behind after waves carried away the finer-grained material. Photographs (taken in July 2007) and graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 3 in Himmelstoss et al. (2006), with information from Peter Rosen (Northeastern University, coastal geologist, written communication, 24 May 2016).

both slope morphologies (i.e., slumping and gullying) (Himmelstoss et al. 2006). Slopes eroding primarily by wave attack and slumping are retreating at an average rate of 0.21 m (0.69 ft) per year), whereas those retreating via gullying do so at 0.13 m (0.43 ft) per year. By comparison, average rates presented by Kaye (1967a) were 0.10 m (0.34 ft) per year.

The most rapid retreat occurs along drumlin shorelines exposed to northeast storms, referred to as "nor'easters" (Rosen and FitzGerald 2004). As part of a study on boat wake impacts, FitzGerald et al. (2011) measured drumlin (geomorphic map units **Qdr** and **Qgfd**, locally) bluff retreat at 12 sites on Thompson, Spectacle, Moon, Long, Lovells, Peddocks, Bumpkin, and Grape islands, as well as Webb Memorial State Park over five years (2004–2008). They found that 80% of the bluffs are stable, and 20% are eroding rapidly. The average rate of horizontal retreat was 0.2 m (0.7 ft) per year. Areas of Lovells Island retreated as much as 3 m (10 ft) in five years, but showed no clear, quantifiable relationship between retreat rates and bluff height or elevation of the bluff base above mean sea level. Their results indicated (1) very little retreat but steepening at Bumpkin and Grape islands, the southern end of Long Island, the northern edge of Moon Island, East Head at Peddocks Island, and southeastern Webb Memorial State Park; (2) continuous parallel slope retreat at the eastern wide of Long Island, southern Moon Island, eastern Thompson Island, and western Lovells Island, which had the highest rates in the study area; and (3) mixed results from a pier construction and wave blocks at Spectacle Island.

Bluff retreat data by FitzGerald et al. (2011) revealed the need for refinement of the bluff retreat model presented by Himmelstoss et al. (2006). Additional factors to consider when determining erosion rates include secondary controlling factors such as seasonality of slumping and the impact of site-specific wave processes in the intertidal zone (FitzGerald et al. 2011). A thorough knowledge of the initiation dynamics (at the microscale) of slumping and other mechanisms causing glacial bluff retreat may help to manage the balance between natural processes and protection of cultural resources and visitor access (Peter Rosen, Northeastern University, coastal geologist, email, 7 April 2015). Such a study could be a potential project for a Geoscientists-in-the-Parks participant (see http://go.nps.gov/gip).

As part of a larger, cooperative effort to understand marsh evolution and sedimentation processes in the Boston Harbor Islands (see "Wetlands"), Hapke et al. (2011) presented an analysis of historical, volumetric sediment loss from the bluffs at Thompson, Long, Peddocks, and Lovells islands. Ground-truth information, sediment sampling, onsite characterization, and the digital comparison of light detection and ranging (LiDAR) surfaces, digital terrain models (DTMs), and historical surfaces were all techniques employed by this study to provide an evaluation of sediment influx potential. The highest, long-term (56-year) sediment loss rates (expressed as volume lost per unit area for a period of time) were measured on Long Island at -0.24 and -0.14 m^3/m^2/year (-0.79 and -0.46 ft^3/ft^2/year). The highest, short-term (13-year) rates were at Peddocks Island at -0.46 and -0.31 m^3/m^2/year (-1.51 and -1.02 ft^3/ft^2/year). Overall, larger volumes of material are being lost to the intertidal system along the south and east portions of the Boston Harbor Islands. Drumlin composition may also play a role because the most readily erodible bluffs supply substantial marsh substrates. The lower erosion rates associated with seawalls and riprap could also impact marsh adaption and migration in response to sea level rise (Hapke et al. 2011).

Repeat photogrammetry may provide an application for accurately determining net bluff retreat and sediment loss. Photogrammetry uses photographs to extract three-dimensional information from a series of well-placed images. The NPS Geologic Resources Division (GRD) has acquired equipment and software to develop a photogrammetric data program to support parks and regions in the resource management areas of protection, research, mitigation, restoration, inventory, monitoring, interpretation, and planning. See http://go.nps.gov/grd_photogrammetry for more information.

Glacial Features

Glacial features such as drumlins define the landscape of Boston Harbor Islands National Recreation Area. Massive ice sheets repeatedly advanced from the Arctic during Pleistocene glaciations (ice ages) ending approximately 10,000–12,000 years ago. Those glaciers scoured and reshaped the landscape of the northeastern United States, including Boston Harbor Islands National Recreation Area (fig. 12).

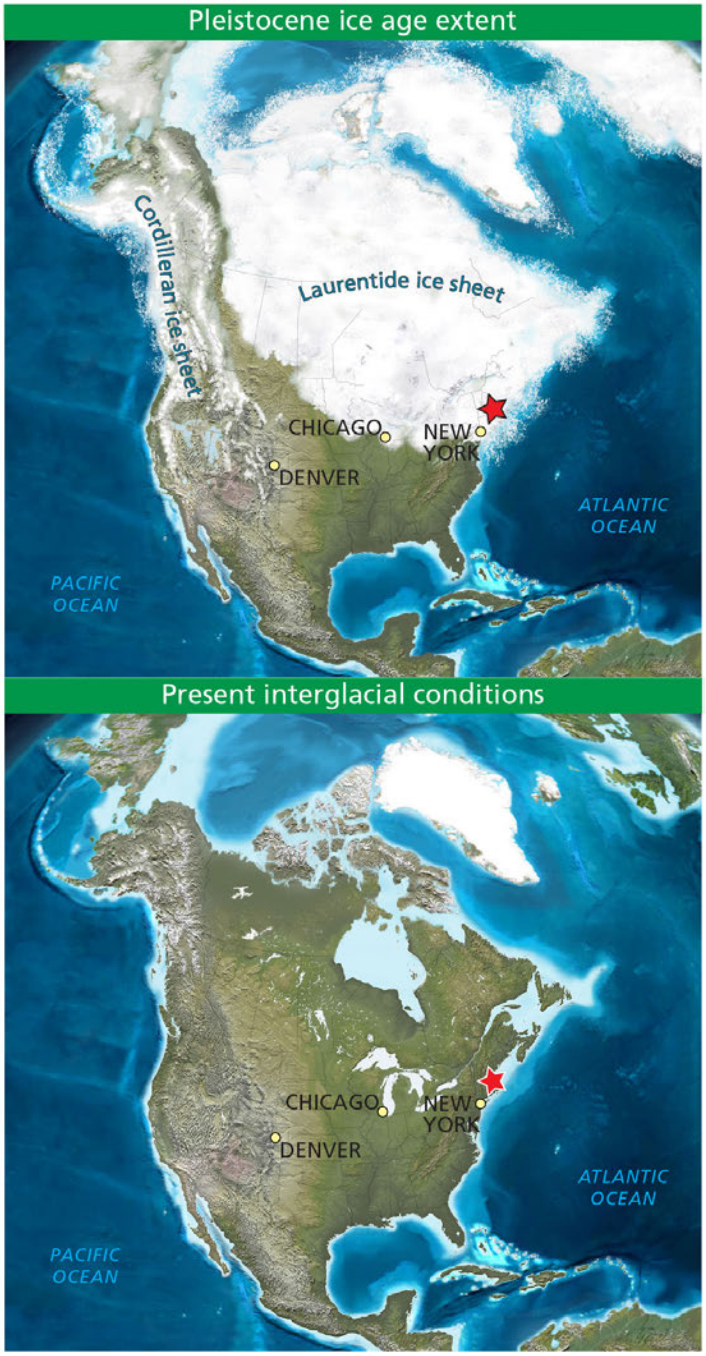


Figure 12. Maps illustrating ice age and interglacial conditions. Nearly half of North America was covered by sheets of ice during the ice age glaciations of the Pleistocene Epoch (2.6 million–11,700 years ago). Relative sea level dropped during glaciations (note the width of Florida). Boston Harbor Islands National Recreation Area is denoted by a red star. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html.

The two major categories of glacial features are (1) those created by glacial ice and (2) those deposited by rivers flowing beneath or out of glaciers, referred to as "glaciofluvial," or deposited in lakes near glaciers, referred to as "glaciolacustrine." In addition, "glaciomarine" features are those that form where glaciers or glacial sediments were deposited in the ocean. See figure 13 for schematic illustrations of these deposits and features.

The most recent ice age (called the "Wisconsinan") completely covered Boston Harbor with ice; the southernmost terminus of Wisconsinan glaciers was Long Island, New York (see fig. 12). In the Boston Harbor area, the ice was approximately 150 to 300 m (500 to 1,000 ft) thick. The glaciers carried vast amounts of sediment that were dumped as the ice melted. The sediment was then reworked by streams and lakes that also formed as the ice melted. The sediment-rich system left sorted channel, floodplain, and delta deposits across the area, as well as glacial till. At the coast, glaciomarine clays were deposited as seawater flooded the low-lying areas (Kaye 1982). The thickness of the glacial deposits that overlie the bedrock at Boston Harbor Islands reaches up to 90 m (300 ft) (Masterson et al. 1996). Because of repeated glacial advances and retreats, the glacial history of the area is complex as each glacial advance tends to obscure or obliterate much of the evidence left by the previous advance and retreat.

Within the recreation area, deposits and features associated with glacial ice include till, moraines, drumlins, kettles, grooves, striations, and glacial erratics as identified by Thompson et al. (2011) (see "Deposits and Features Created or Carved by Ice" and fig. 13). Glaciofluvial deposits and features include kames, eskers, braided streams, deltas, lake deposits, and outwash fans; glaciolacustrine deposits generally form broad plains where the underlying sediments are fine-grained and rhythmically deposited, and commonly contain erratics dropped from icebergs (see fig. 13 and "Glaciofluvial and Glaciolacustrine Deposits").

Deposits and Features Created or Carved by Ice

Glacial till is composed of gravel, cobbles, and boulders in a matrix of finer-grained material and is derived from sediment occurring both beneath and within the glacial ice. The till is left behind when

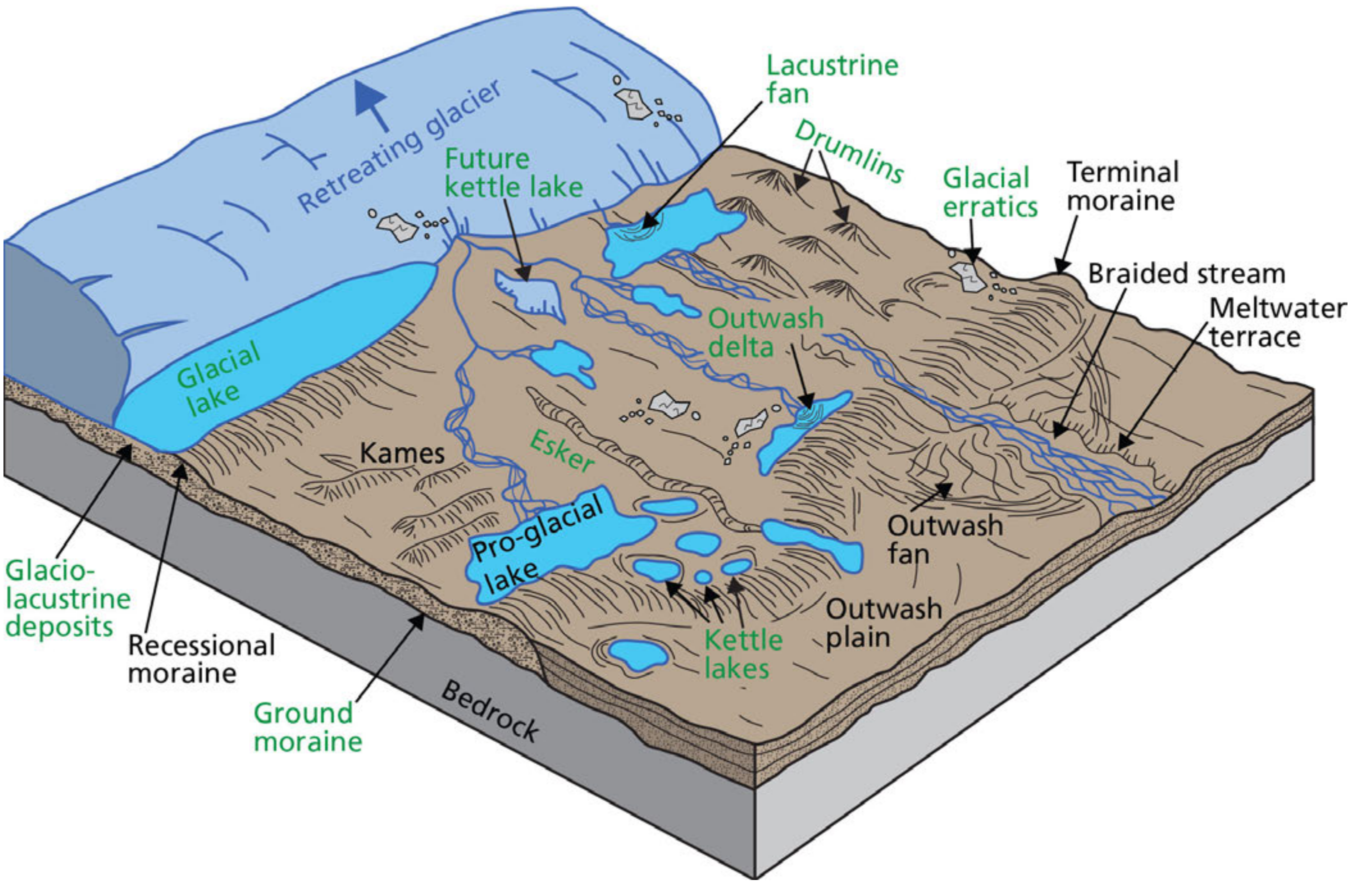


Figure 13. Diagram of general glacial features. Glacial features that occur within Boston Harbor Islands National Recreation Area are labeled in green. The national recreation area contains both depositional (e.g., moraines and glacial erratics) and erosional (e.g., drumlins) features. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

a glacier melts (e.g., till-covered bedrock; map unit **Qtcb**). In some places, the till beneath the ice is infused with water on account of large hydrostatic pressure caused by the overlying thickness (>1 km [0.6 mi]) of the glacial ice. As the glacier advances, the till, having become plastic-like as a result of the addition of water, is deformed into upside down, spoon-shaped deposits called drumlins (**Qdr**) (FitzGerald et al. 2013; Duncan FitzGerald and Peter Rosen, Boston University and Northeastern University, respectively, coastal geologists, written communications, 24 May 2016). Till that was redistributed by Earth surface processes was mapped as marine-reworked till (**Qmrt**) at Boston Harbor Islands (FitzGerald et al. 2013).

When examined up close, two distinct till deposits record two separate glacial advances (these two tills are not separated in the GRI GIS data). Because subsequent glacial advances often obliterate the records of previous advances, the two tills are uncommonly preserved. In addition, they are separated by a long nonglacial interval (Newman et al. 1990; Thornberry-Ehrlich 2008). The younger, upper brown till was deposited during the latest Wisconsinan advance. It overlies a weathered, older gray till, deposited during an earlier glacial advance, possibly “Illinoian” (Newman et al. 1990) or an earlier Wisconsinan advance as suggested by marine microfossils (Orton and Colgan 2001). A weathered surface, characterized by truncated clay-filled fractures and chemically altered clay layers, or a marine clay layer separates the two tills (Newman et al. 1990). The older till is compact, faintly stratified (layered), has some horizontal fissility (tendency to break along planes of weakness), and contains marine fossil shell fragments. Also, it has cobble- to boulder-sized clasts that exhibit more striations than those in the younger till. The younger till lacks marine shell fragments, is less compact, is faintly stratified, and contains more boulders than the lower/older till; the boulders are

Figure 14 (left). Photographs of glacial erratics, striations, and grooves. Glacial erratics are large rocks transported on or within glacial ice that are then dumped some distance from its source outcrop. In general, erratics rest on bedrock of a different lithology. Erratics occur throughout the Boston Harbor area, such as these on bedrock of the north shore of Button Island. Rocks entrained in glacial ice scratched striations into the bedrock on Button Island and gooves into the bedrock at Middle Brewster Island. Blue arrows in the glacial grooves indicate direction of glacial movement, which is toward the southeast. Top and bottom photographs are figures 43 and 11, respectively, in Thompson et al. (2011). Middle photograph provided by Peter Thompson (University of New Hampshire) in 2015. Images annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

within sand and gravel lenses (Newman et al. 1990; Newman and Mickelson 1994). The two tills are most visible at Long and Great Brewster islands (see fig. 11). The contact between the two tills is best revealed at Long and Peddocks islands where the deposits are quite thick (Newman et al. 1990; Thornberry-Ehrlich 2008). On the northeast-facing side of Great Brewster Island, the lower till is approximately 30 m (100 ft) thick and is covered by another 30 m (100 ft) or so of younger till (Colgan and Rosen 2001). The younger till drapes over the previously eroded older till (see "Glacial Features"; Newman and Mickelson 1994). The upper till is absent at Moon, Lovell, and Rainsford islands (Newman et al. 1990).

Some till forms moraines or drumlins (see "Glacial Features"). Moraines are ridges of till that mark the edges of a glacier. At Boston Harbor Islands, some of the longshore spits may be composed, at least in part, of glacial moraine deposits (Thornberry-Ehrlich 2008).

Glacial erratics are large rocks that fell onto the glacier's surface, were transported some distance, and then were dumped on the landscape as the glacier retreated (fig. 14). Erratics are composed of rock different from that upon which they came to rest. They occur throughout New England (Thornberry-Ehrlich 2008) and are usually composed of local bedrock. Outer Brewster Island has a notable exception—a red, volcanic rock of unknown origin (Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). The presence of some large boulders may not be erratics, but simply large blocks weathered from glacial till (Peter Rosen and Duncan FitzGerald, Northeastern University and Boston University, respectively, coastal geologists, written communication, 24 and 25 May 2016).

Kettles are depressions that formed where retreating glaciers left blocks of ice that were later buried by outwash sediments and then melted to form depressions. If they intersect groundwater, they can form kettle ponds (Peter Rosen, Northeastern University, coastal geologist, 24 May 2016) (see “Wetlands”). Excellent examples of mapped kettles (geomorphic map unit **Qk**) occur at the southwestern end of Thompson Island in glacial outwash sediments (geomorphic map unit **Qgfd**) and form the core of a lagoon-wetland complex (**Qla** and **Qwe**) connected to the open water with tidal inlets (**Qi**), channels (**Qtc**), and tidal flats (**Qtf**) (FitzGerald et al. 2013; GRI conference call participants, 7 April 2015).

Glacial striations (scratches on bedrock; see fig. 14) occur on several Boston Harbor Islands, notably Little Brewster, Middle Brewster, Green, Button, Grape, and Slate islands (Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). The bedrock striations formed as the sediments entrained at the bottom of a glacier gouged the underlying rock as the glacier moved over it. The regional striations record a predominantly north-south ice motion, but with a range in azimuth orientations from east to southeast (Thornberry-Ehrlich 2008; Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). Variations in striation orientation suggest that flow transitioned from east-southeast flow to south-southeast flow during the most recent glaciation (Colgan and Rosen 2001). This spread of orientations supports the idea of different glacial flow directions crossing the harbor at different times as suggested by the two-till drumlin deposits (Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015) (see “Glacial Features” and “Geologic History”).

Drumlin Field

Drumlins (geomorphic map unit **Qdr**) are elongated, linear, “whaleback” hills formed when a glacier flowed over a mass of sediment (commonly glacial till) or bedrock. Their orientation indicates the direction of glacial flow (Stokes et al. 2011; FitzGerald et al. 2013). Drumlins are incredibly diverse in terms of composition, internal structure, and evidence of deformation. Also, their origin is enigmatic, controversial, and a subject of much study (Stokes et al. 2011). Drumlin composition is divisible into five basic types: (1) mainly bedrock, (2) part bedrock/part till, (3) mainly till, (4) part till/part sorted sediments, and (5) mainly sorted sediments (Stokes et al. 2011). At Boston Harbor Islands, the drumlins are primarily composed of till with some having bedrock cores.

Boston Harbor Islands National Recreation Area has part of the only submerged or partially drowned drumlin field along a coast in the United States and those features are one of the features noted in the recreation area’s enabling legislation (National Park Service 2002; FitzGerald et al. 2011). Other examples of drowned drumlin fields occur in Nova Scotia, Ireland, and Germany. The drumlins in the recreation area are among the more than 200 drumlins that make up the entire drumlin field in the Boston Basin and form the backbone of the inner islands within Boston Harbor (Newman and Mickelson 1994; Himmelstoss et al. 2006). Notable mainland drumlins in this field include Beacon Hill, Dorchester Heights, and the hills on the Hull peninsula (Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016).

The average trend of the harbor drumlins is about 110° with the steeper side (opposite the flow direction) facing northwest, and their height and length are about 30 m (100 ft) and 0.4 km (0.2 mi), respectively (Newman and Mickelson 1994; FitzGerald et al. 2011). The number of drumlins on the individual islands varies with at least 28 total within the national recreation area’s boundaries. Long Island is composed of eight east- to southeast-trending drumlins (Newman et al. 1990). Peddocks Island has a series of five different drumlins connected by tombolos (see “Coastal Features”). A marshy lowland connects the two large drumlins of Grape Island (Flora 2002). Compound drumlins (mounds composed of two or more drumlins) occur at Long and Great Brewster islands (Thornberry-Ehrlich 2008; Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). The recreation area also contains “bedrock drumlins” (e.g., the bedrock at Grape Island has a drumlin-like morphology) or at least drumlins with a knobbed bedrock core (e.g., the thin layer of till over a bedrock protrusion at Green Island or the bedrock high beneath Long Island) (Colgan and Rosen 2001; Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). For most of

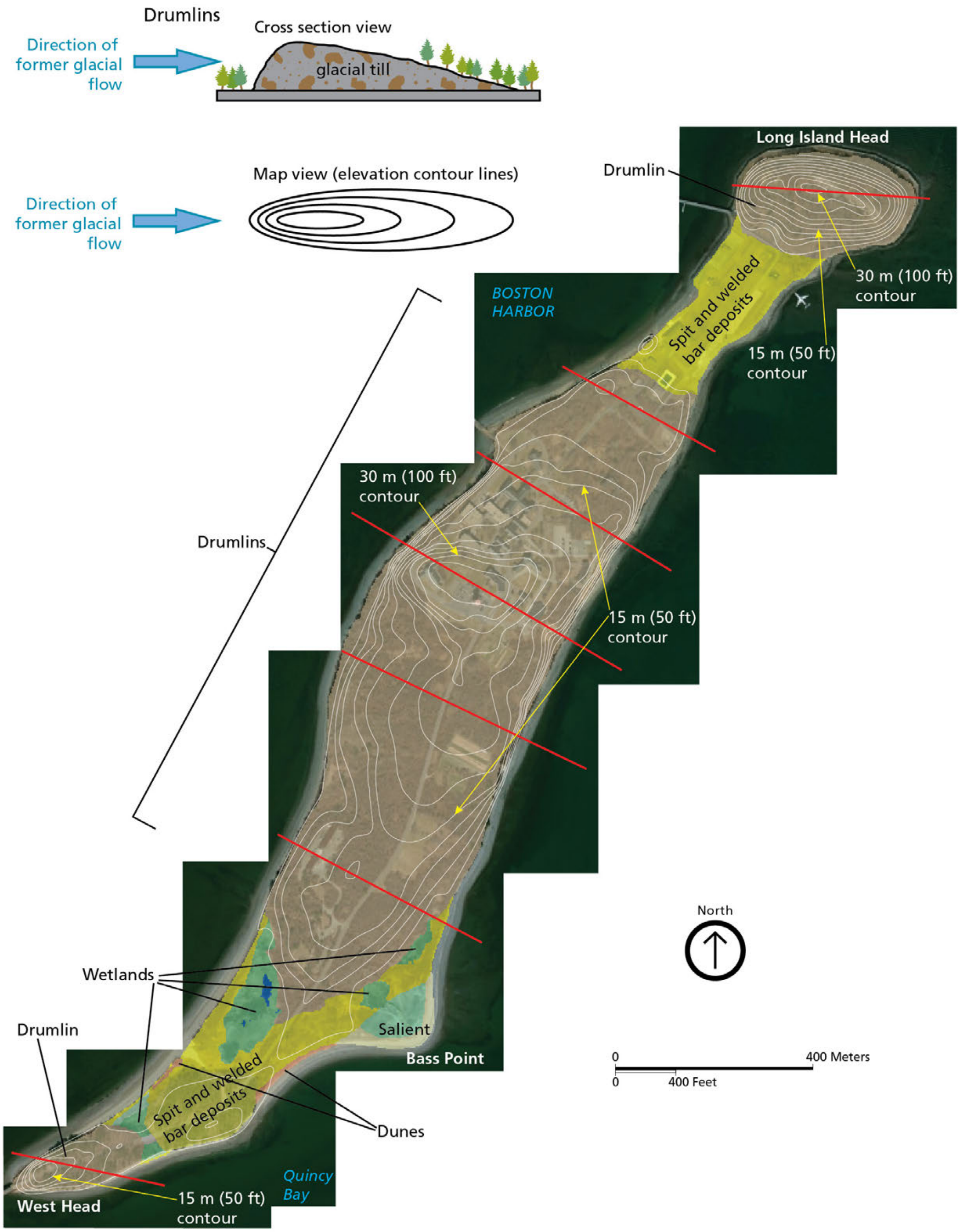


Figure 15. Schematic of drumlin formation and map of land features of Long Island. Drumlins are low, smoothly rounded, elongate oval hills that are formed by the movement of a glacier atop previously deposited glacial till. The long axis of the drumlin is parallel to the direction of glacial ice movement. Drumlin locations in Boston Harbor Islands National Recreation Area are indicated in the GRI GIS data as geomorphic map unit Qdr. The topography, marked by white lines on the figure, has a contour interval of 3 m (10 ft). Red lines indicate the approximate locations of the long axes of seven drumlins that are joined by spits and bars. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using US Geological Survey topographic coverage and ESRI World Imagery basemap, accessed 15 June 2015.

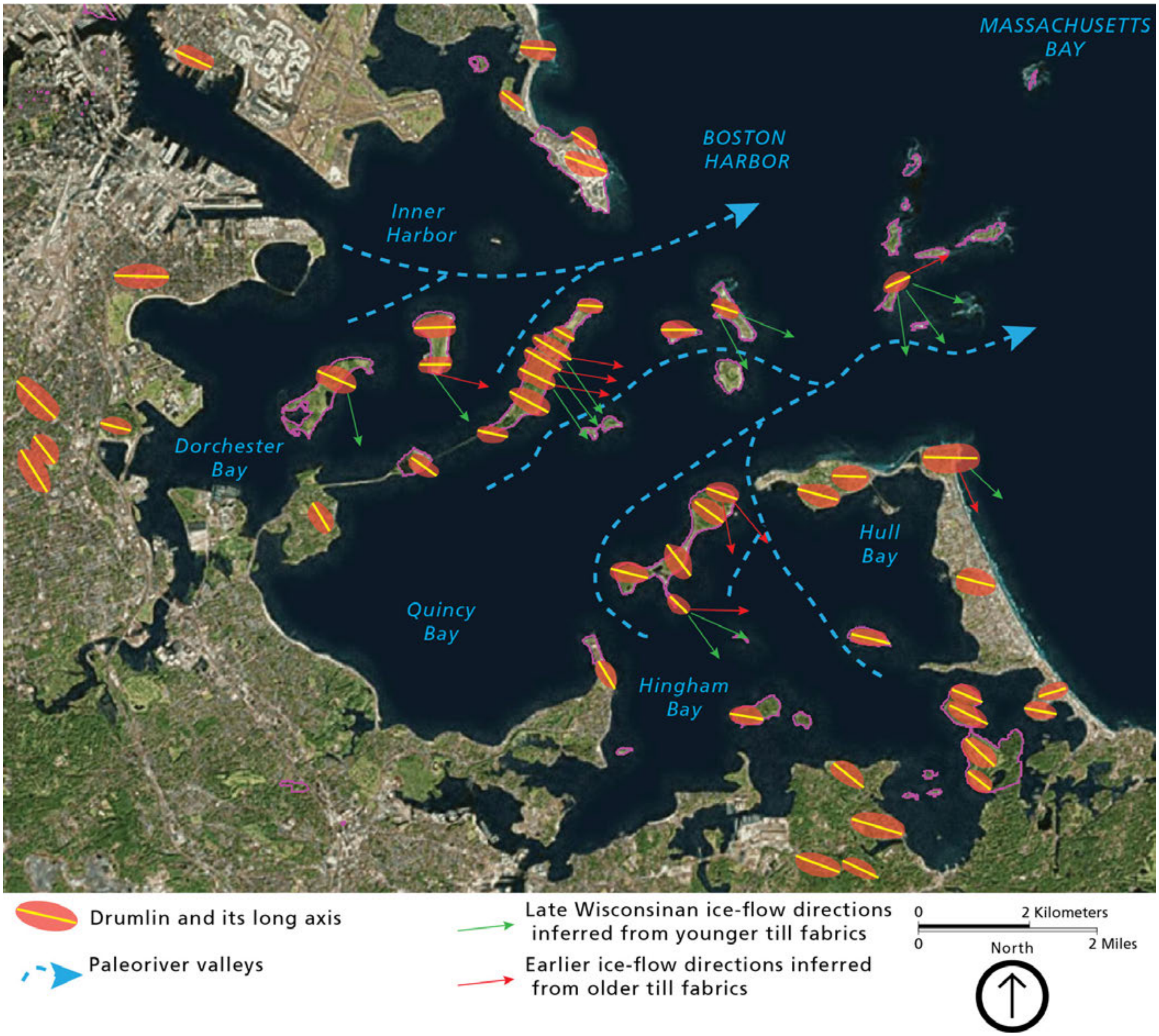


Figure 16. Map of drumlin orientations in the Boston Harbor area. Fabrics present in the two glacial tills at Boston Harbor that make up the drumlin fields record different ice flow orientations corresponding to at least two different glacial till depositional events. An older, more east-west direction (red arrows) is overprinted by a younger, more southeast direction (green arrows). Paleoriver valleys of major rivers (dashed blue arrows) are also indicated. Pink outlines indicate the boundary of Boston Harbor Islands National Recreation Area. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 4 in Newman and Mickelson (1994) using GRI GIS data and ESRI World Imagery basemap, accessed 28 April 2015.

the islands, the bedrock is beveled flat beneath the thick till deposits (Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015).

Because of their internal structures are exposed via shoreline erosion at Boston Harbor Islands, the drumlins provide an excellent field study location for geologists. Studying drumlins provides essential data for determining ice-flow directions (fig. 15) and subglacial processes that are difficult to visualize beneath modern ice sheets (Stokes et al. 2011). Storm-wave erosion maintains the detailed stratigraphic sections of the drumlins at Long, Peddocks, Great Brewster, and Rainsford islands (Newman and Mickelson 1994). Many of the drumlins at Boston Harbor Islands contain two distinct till units—the lower, older one

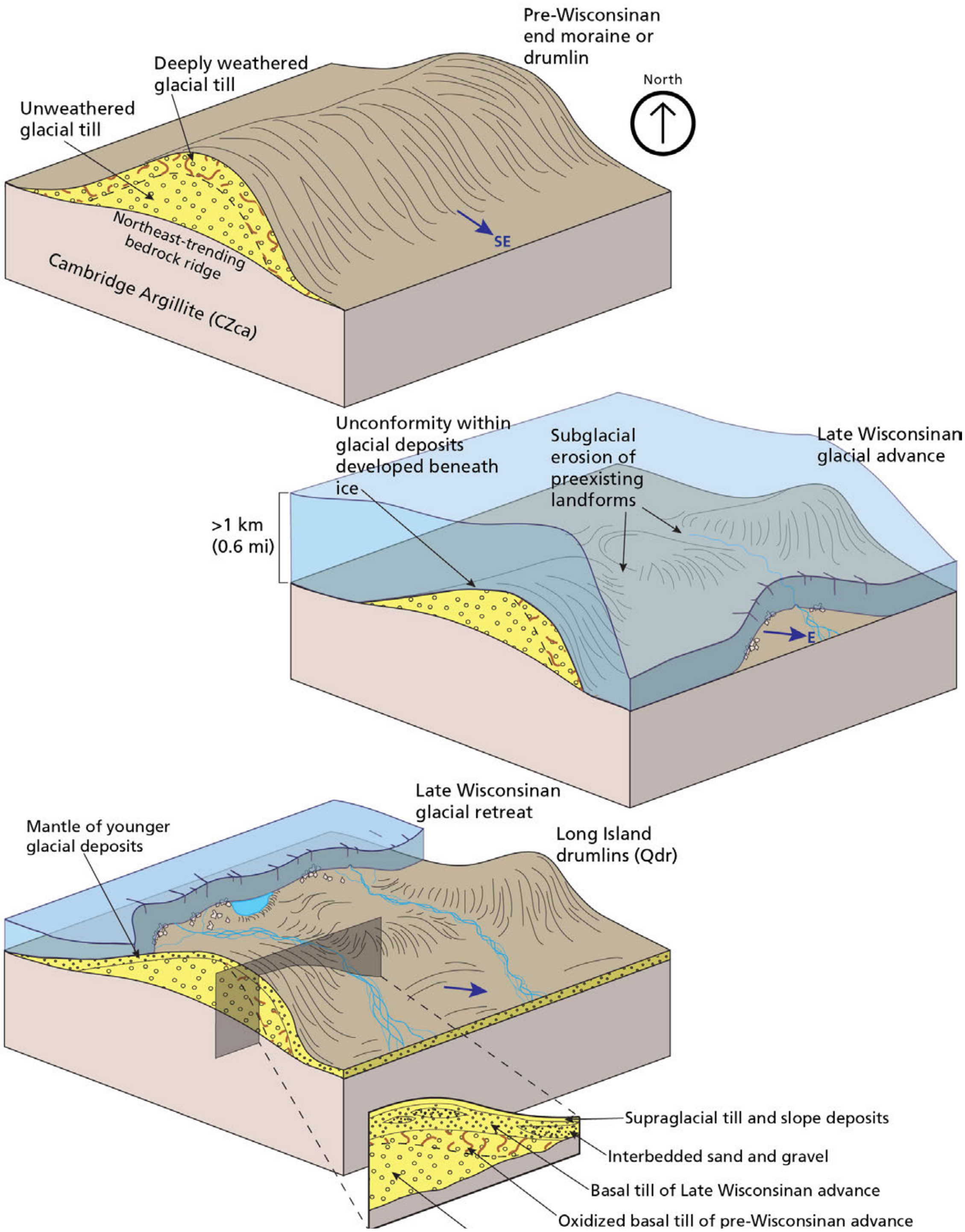


Figure 17. Schematic of drumlin formation at Long Island. A pre-Wisconsinan glacier flowed southeastward across Boston Harbor depositing till atop a northeast-trending bedrock ridge. After the glacier retreated, the deposit was deeply weathered. When another glacier advanced over the area in the late Wisconsinan, the earlier surface was eroded by ice, forming the drumlin core and removing vast amounts of the weathered till. This created an unconformity (erosional surface). During Wisconsinan glaciation and retreat, more till was deposited atop the drumlin core and produced the final drumlin shape. Subglacial ice or ice-marginal fluvial deposits (sands and gravels), supraglacial till, and slope deposits now cover much of the land surface at Boston Harbor Islands. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figures 5 and 6 in Newman and Mickelson (1994), with information from Peter Rosen and Duncan FitzGerald (Northeastern University and Boston University, respectively, coastal geologists, written communication, 24 and 25 May 2016).

being much more weathered than the upper, younger one—separated by an erosional surface. At Long Island, an exposure of the two tills indicates the preserved weathering profile of the lower till is thicker beneath the axes of the drumlins and is either thin or missing in the areas between drumlins. This suggests that glacial erosion and streamlining of the older till deposits took place after weathering had altered the surface and before subsequent deposition of the overlying till (figs. 16 and 17; Newman and Mickelson 1994). Stokes et al. (2011) provided a compilation of observations of drumlin composition and internal structure worldwide to provide insight on drumlin genesis, as well as techniques to investigate, sample, and interpret drumlin sediments.

According to Newman and Mickelson (1994), geologists have used three basic mechanisms for drumlin formation. The first is that drumlins form by the accretion of basal till beneath glacial ice. This involves contemporaneous deposition, deformation, and shaping of till into the characteristic streamlined drumlin shape. The second mechanism focuses on the importance of erosion in the formation of drumlins. This mechanism is supported by stratified (worked by water and/or wind) sand and gravels or drumlin-shaped bedrock cores in some drumlins. The third hypothesized mechanism is that of a glaciofluvial origin. This mechanism suggests that massive flows of water beneath the ice created bed forms that have the characteristic drumlin shape or that the shapes were carved in the basal ice of the glacier by flowing water to be later filled with sediment. The weathered surface between the two tills at Boston Harbor indicates that the second mechanism, glacial erosion, was an important process in drumlin formation (Newman and Mickelson 1994).

Glaciofluvial and Glaciolacustrine Deposits

In places where glacial till was not deposited, thin, glacial deltaic and outwash deposits mantle bedrock. Glaciofluvial channel deposits record the locations of outwash channels and occur on Thompson Island (geomorphic map unit **Qgfd**; labeled as "glacio-fluvial" in GRI GIS data) (Jones et al. 1981; Peter Rosen, Northeastern University, coastal geologist, conference call, 7 April 2015). The deltaic deposits formed as sediment-laden water flowing from melting glaciers and outwash streams reached glacial lakes and dumped the suspended sediment load. These deltas have characteristic assemblages, consisting of bottomset beds that are farthest from the glacier's position, angled foreset beds that cover the bottomset beds, and (3) topset beds that cover the entire sequence (fig. 18). As glacial ice melted and retreated farther northward, the delta was left as a relict, and the whole sequence repeated itself. Deltaic deposits on Thompson Island (geomorphic map unit **Qgfd**) provide textbook examples of "classic" or "Gilbert" delta formation (see "Geologic Significance and Connections") (Thornberry-Ehrlich 2008; FitzGerald et al. 2013).

Eskers are long, narrow, sinuous, steep-sided ridges composed of irregularly stratified sand and gravel (fig. 19). They were deposited by streams flowing between ice walls or in an ice tunnel beneath a glacier. They were left behind, more or less intact, when the glacier melted. An esker occurs within a marsh (kettle) area on Thompson Island (Thornberry-Ehrlich 2008). Great Esker Park, outside of Boston Harbor Islands National Recreation Area near Weymouth, Massachusetts, provides an excellent example of a braided esker that is also one of the largest in the Boston area (Colgan and Rosen 2001; Gosselin et al. 2010).

Paleoriver Channels

Because of the vast quantities of water stored as glacial ice during a major ice age, global sea level is lowered. During these periods of low sea level, major rivers along the east coast of the United States carved vast canyons through the sediments of the Coastal Plain (a physiographic province consisting of a broad belt of gently dipping, sedimentary rocks along the US eastern seaboard). When the glaciers melted, releasing the water, sea level rose and the river channels were inundated. Local river channels, such as the Charles, Chelsea, Mystic, Fore, Back, Weir, and Neponset, are now drowned, forming estuarine tidal rivers (Gontz et al. 2010; Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). Drowned channels tend to be filled with layered sands, and separated by flat, submarine terraces, which support some local accumulations of sediment (see "Coastal Features") (Thornberry-Ehrlich 2008; Gontz et al. 2010; Peter Rosen, Northeastern University, coastal geologist, conference call, 7 April 2015). Once filled with sediment, these channels become "paleochannels" that record the past locations and fluvial events (e.g., flooding) of former rivers. Dredging and infilling disrupt the stratigraphy of the recent geologic record, including paleochannels, throughout Boston Harbor (Gontz et al. 2010).

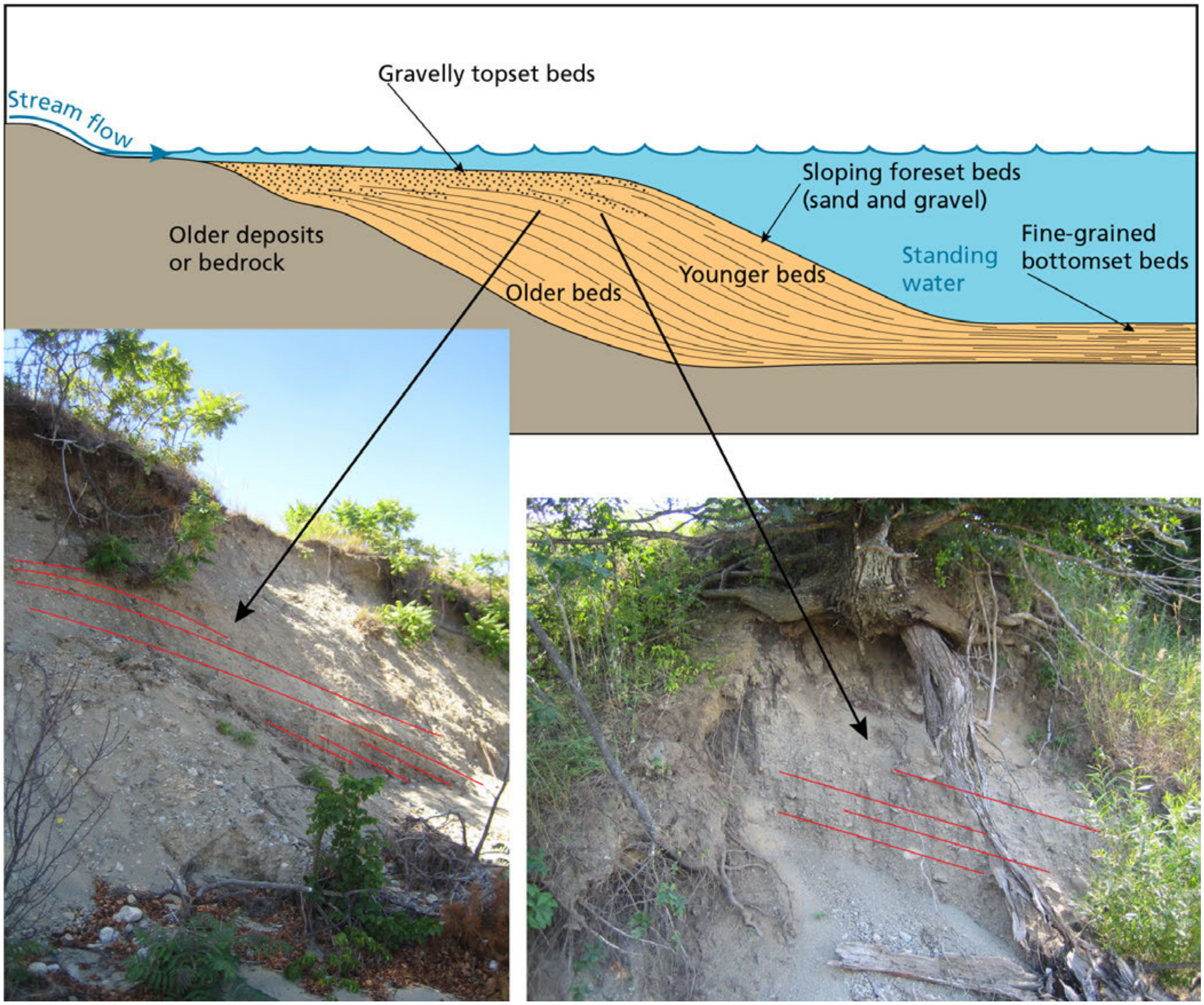


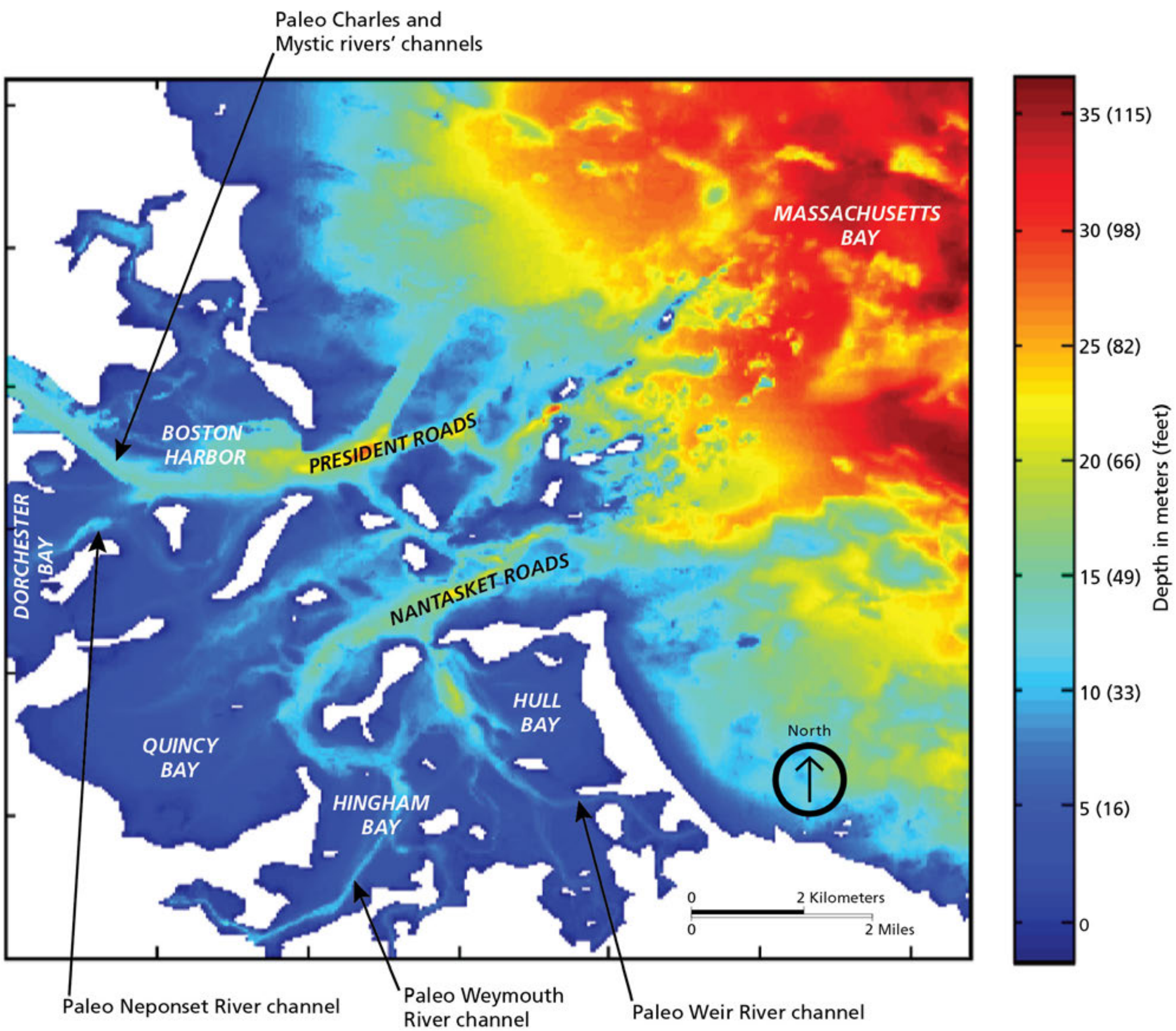
Figure 18. Diagram of Gilbert delta characteristics and deltaic deposits at Thompson Island. Deltaic deposits are characterized by the presence of topset, foreset, and bottomset beds. Topset and foreset beds develop when high energy flows enter a lower–energy water environment. As the water's velocity drops, the sand and gravel that were transported along the bed of the channel as bedload come to a stop, resulting in deposition. The deposits accumulate in layers at an incline along the floor of the lake or sea. As time passes, subsequent deposition occurs on top of the previous foreset beds, creating topset beds. Fine-grained material such as mud and silt remains in suspension longer, and settles out in nearly horizontal layers farther from shore in the lower energy environment, creating bottomset beds. Red lines on the graphic indicate sloping, gravel-rich foreset beds. Photographs (taken in July 2007) and graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after a figure by Tvelia (date unknown) and information provided by Peter Rosen (Northeastern University, coastal geologist, written communication, 24 May 2016).

The former Neponset River channel incised into the glaciomarine sediments, such as the Boston Blue Clay, in Dorchester Bay. In places, the former channel reaches 5 m (16 ft) in depth. The lack of erosion on the channel banks suggests flooding and filling were relatively quiet-water events (Gontz et al. 2010).

In Dorchester Bay, the former Neponset River channel generally underlies the present navigational channel, portions of which were dredged prior to 1990 to a depth of 4 m (13 ft) below mean low water (Gontz et al. 2007; Gontz et al. 2010). The former channels of the Charles and Mystic rivers are also correlative with modern navigation channels and major tidal channels (fig. 20; Luedtke and Rosen 1993; Peter Rosen, Northeastern University, geologist, email, August 2008).

Figure 19 (left). Photograph of an esker at Thompson Island. The esker is a sinuous ridge of slightly sorted and stratified glacial deposits left by a stream flowing within or beneath a glacier. Yellow arrow indicates the axis of the ridge and a likely paleoflow direction of the glacial stream. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in July 2007.

Figure 20 (below). Bathymetric map of Boston Harbor. Former channels of major Pleistocene rivers are now deep areas within Boston Harbor and underlie some of today's navigational channels. Modern dredging has obscured this pattern in passages such as President Roads. Spatial resolution is 30 m (100 ft). Graphic is figure 14 from FitzGerald et al. (2011) using data provided by the US Geological Survey, annotated by Trista Thornberry-Ehrlich (Colorado State University).



Wetlands

Wetlands encompass much of the area within Boston Harbor Islands National Recreation Area; they have been documented on more than 516 ha (1,276 ac) (Tiner et al. 2003). As such a significant component of the national recreation area, wetland health is a primary resource management concern (see "Coastal Erosion and Response to Climate Change"). Wetlands are transitional areas between land and water bodies, where water periodically floods the land or saturates the soil. The term "wetlands" includes wet environments such as marshes, swamps, and bogs. They may be covered during tide cycles, most of the year, or be wet only seasonally. They can be vegetated or nonvegetated (Tiner et al. 2003). Refer to the NPS Wetlands website, https://www.nps.gov/subjects/wetlands/index.htm, for additional information. The NPS Water Resources Division (https://www.nps.gov/orgs/1439/index.htm) is the primary contact for technical and policy assistance regarding wetlands.

Tiner et al. (2003) completed a wetlands inventory for the recreation area as part of the National Wetlands Inventory (NWI) Program. Wetland systems are listed by island on table 1. In Boston Harbor Islands National Recreation Area, the wetlands provide several significant functions, including (1) coastal storm surge detention and shoreline stabilization, (2) provision of fish and shellfish habitat, (3) provision of bird and other wildlife habitat, (4) surface water detention, (5) nutrient transformation whereby elements are changed from unavailable to available to plants and animals, and (6) retention of sediments.

Wetlands are associated with several geomorphic map units presented in the GRI GIS data, including kettles (**Qk**), lagoon (**Qla**), marsh pond (**Qmp**), tidal flat (**Qtf**), and wetlands (**Qwe**). These units are also mapped in combination with one or more other geomorphic units including tombolos (**Qt**), welded bars (**Qwb**), overwash terraces (**Qot**), and salients (**Qsa**) (see Geomorphic Map Unit Properties Table, in pocket; FitzGerald et al. 2013).

Figure 21. Photographs of wetlands at Boston Harbor Islands. Many wetland types exist within the national recreation area and vary by salinity (saltwater, brackish water, and freshwater), as well as their position relative to the shoreline (e.g., fringing, embayed, or perched). Gravel ridges (Qgr) may separate a marsh from the open ocean on some shorelines. In the top photo, a recurved spit at the south side of Thompson Island is a gravel ridge that separates an embayed salt marsh (formerly a fringe marsh) from the open harbor. Also on Thompson Island, a freshwater kettle wetland (lower photograph) remains in a sheltered, inland location. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in July 2007.

Boston Harbor wetlands are classified into at least three primary systems (1) marine (saltwater), (2) estuarine (brackish water), or (3) palustrine (freshwater) marshes (fig. 21; table 1; Tiner et al. 2003; FitzGerald et al. 2013; National Park Service 2015f). All of these can be somewhat transitional, depending in part on connectivity with marine water. Connectivity includes fully exposed and open to the ocean, embayed areas continuously connected to the ocean, areas not continuously connected to the ocean but subject to occasional overwash, and fully freshwater (no ocean input) wetlands. Wetlands can also be termed embayed, perched, or fringing. Embayed wetlands form in sheltered areas that extend landward of the shoreline. Perched wetlands occur away from shoreline and other large sources of water. Fringing wetlands occur along or parallel to the shoreline, commonly on the seaward edge of narrow barriers or gravel ridges. Hapke et al. (2011) described fringing marshes as rare habitats with Boston Harbor Islands being one of the few locations in the northeast United States that hosts a series of them.

Marine (saltwater) wetlands are exposed to waves and currents of the open ocean with water regimes controlled in large part by the ebb and flow of the tides. Marine wetlands composed about 22% of the total wetland area inventoried by Tiner et al. (2003; table 1). Bell et al. (2002) listed salt marshes as a habitat of particular concern in need of protection. The largest saltwater marsh system is at Thompson Island (Hughes et al. 2010). Types of marine wetlands include rocky shore, aquatic bed, reef, and unconsolidated shore.

Estuarine (brackish water) wetlands are the predominant wetland system in the recreation area, accounting for 76% of the wetland area surveyed (Tiner et al. 2003). They occur in shoreline areas of the majority of the Inner Harbor, Quincy Bay, and Hingham Harbor portions of the recreation area (table 1). They may also be found in enclosed, low-lying areas adjacent to the shoreline that are periodically breached by saltwater or where saltwater percolates through the adjacent sediments. Types of estuarine wetlands include unconsolidated shore, emergent, aquatic bed, reef, and rocky shore (National Park Service 2015f).

Palustrine (freshwater) wetlands are much less common than the other wetland types within Boston Harbor Islands National Recreation Area. They compose only 2% of the total inventoried wetland area (Tiner et al. 2003). Their salinity level (from ocean-derived salts) is less than 0.5 parts per thousand. They are limited to a few small areas of freshwater marsh or ponds including the "ice pond" at Worlds End (table 1; Tiner et al. 2003; National Park Service 2015f; Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016). Though small, they may provide vital amphibian and reptile habitats (National Park Service 2015f). Types of palustrine wetlands include emergent, unconsolidated shore, forested, scrub-shrub, and unconsolidated bottom (Tiner et al. 2003).

The formation, occurrence, longevity, and resilience of the wetlands at Boston Harbor Islands National Recreation Area are poorly understood (Hapke et al. 2011). A key concern is to determine whether the rate of vertical accretion (rate at which organic and inorganic sediment increases the elevation of the marsh floor) can keep pace with projected local sea level rise (Hughes et al. 2010; Hapke et al. 2011). The National Park Service is currently participating in a cooperative effort to study marsh evolution and sedimentation processes in the Boston Harbor Islands (Hapke et al. 2011).

Aeolian Features and Processes

Aeolian processes refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by aeolian deposition include dunes, loess, and sand sheets. Features created by aeolian erosion include desert pavement, yardangs, and ventifacts. The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian, provides additional information.

Within Boston Harbor Islands National Recreation Area, dunes are present, although not nearly as extensive as they were more than 10,000 years ago after ice-age glaciers retreated from the area. As described in "Glacial Features," glacial ice covered the Boston Basin repeatedly during the ice ages of the Pleistocene Epoch. After the glaciers retreated, the landscape was devoid of stabilizing vegetation. The unstable and unconsolidated sand and silt left by the glaciers were picked up by the wind, transported, and deposited elsewhere to create sand dunes (fig. 22) and loess (windblown silt) deposits. Dunes eventually blanketed much of the Boston Basin, and indeed much of New England.

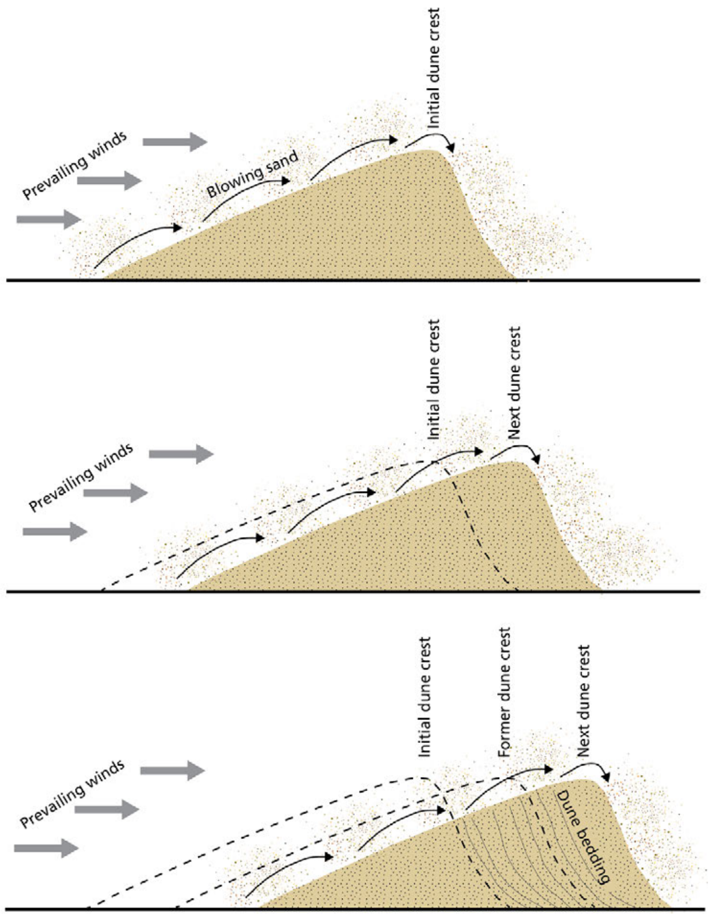


Figure 22. Schematic of aeolian sand transportation and dune movement. Prevailing winds transport sand grains up the dunes, depositing them in cascades down the steep side. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from Bagnold (1941).

Over time these periglacial dunes were buried by other deposits, removed by erosion, or stabilized by vegetation so that today they are uncommon features in the recreation area. Dunes on today's landscape are modern dunes that formed in the few areas of the national recreation area with significant sand supplies. They likely resulted from the erosion of sandy glacial deposits (FitzGerald et al. 2013; Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). Because the overall sediment supply (see "Sediment Supply and Island Erosion") is extremely limited, significant dune formation is unlikely. Modern dunes are somewhat stabilized by vegetation (FitzGerald et al. 2013). The reduction in size of the dunes, particularly at Lovells Island, is a resource management issue (see "Loss of Aeolian Features").

Most (70%) of the dunes within the Boston Harbor Islands occur on Lovells Island. Dunes also occur at the southern ends of Thompson Island (downdrift of the classic Gilbert delta deposit), Spectacle Island (as ornamental, anthropogenic dunes), Long Island, and at Nantasket Beach (beyond recreation area boundaries) (Rosen and FitzGerald 2004; Hatten et al. 2006; FitzGerald et al. 2011; Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). Dune systems (**Qds**) were mapped individually or in combination with salients, spits, and/or welded bars on Lovells and Long islands.

The largest, most robust dune system in the national recreation area is along the southern and western shores of Lovells Island, where the sand is an unusual combination of immature composition and mature grain size, sorting, and grain shape (Rosen and FitzGerald 2004; Hatten et al. 2006; Thornberry-Ehrlich 2008; FitzGerald et al. 2013; Peter Rosen, Northeastern University, coastal geologist, conference call, 7 April 2015). This unusual association makes it challenging to determine the exact source of the sand. Normally, immature ("young") dune sand has a high feldspar and rock-fragment content because over time feldspars and rock fragments weather away before quartz grains. The high non-quartz content in the sand of the largest dune system implies the sand has not been transported far from its source and/or has not been exposed to weathering for very long. Mature grain size, sorting, and grain shape are characterized by (1) relatively consistent, fine grains; (2) a high level of grain sorting; and (3) polished, rounded grains resulting from longer exposure to abrading wind transport. Sedimentological and mineralogical data such as fining grain sizes and an increasing percentage of quartz with distance suggest the sediment composing the dunes at Lovells Island could be coming from two directions: (1) southward from the north end of the island (and former Rams Head), and (2) westward around the southern tip of the island (Hatten et al. 2006).

Bedrock Exposures

Bedrock is the solid, older rock that underlies the younger unconsolidated coastal and glacial deposits of the Boston Harbor Islands. Bedrock is mapped on 20 islands and may also be exposed on three other islands (tables 1 and 6; Thompson et al. 2011).

Bedrock can be composed of three main classes of rock: sedimentary, igneous, or metamorphic. All three are present in the national recreation area. Sedimentary rocks form from the consolidation of rock or mineral fragments. Igneous rocks form by the cooling of molten material. Metamorphic rocks are those that have been altered by high temperature, high pressure, and/or fluids. In the recreation area, the sedimentary rocks have been metamorphosed.

Bedrock is mapped using formal geologic formations, which take their names from geographic features (e.g., towns, islands, and mountains) that are near their type locality. A type locality is a place with exposures are extensive enough to show all the mappable features of the formation, including the rock type, color, texture, thickness, and other distinguishing features such as depositional structures (e.g., cross beds) and the characteristic manner in which a formation weathers (e.g., forms cliffs or dissolves). Type localities are searchable at the US Geological Survey's online database: https://ngmdb.usgs.gov/Geolex/search.

Although no formal type locations occur within the national recreation area, many of the islands have excellent exposures of Precambrian rocks with notable features (figs. 23 and 24; Thornberry-Ehrlich 2008). Thompson et al. (2011) provided a comprehensive, island-by-island guide to the bedrock geology of each of the Boston Harbor Islands with visible outcrops.

Layers of rock are referred to as "conformable" where they are found to have been deposited without significant interruption or erosion. Although some rock columns may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable layers. Breaks in conformable layers are called "unconformities" and each unconformity represents a period when deposition ceased or where erosion removed layers of previously formed rocks. Because unconformities may be widespread across a large region, they can be useful for correlating rock units and tectonic history over great distances. The national recreation area contains a well-documented unconformity between the base of the Boston Bay Group sediments (geologic map units **CZca**, **Zdm**, **Zvm**, and **Zcr**) and older granite (**Zgr**) exposed on Rocky Neck and Worlds End (Thornberry-Ehrlich 2008; Thompson et al. 2011).

Sedimentary Rocks

The three main types of sedimentary rocks are clastic (fragments of rock), chemical (precipitated from solution), and organic (primarily consisting of the remains of living things). All of the sedimentary bedrock within Boston Harbor Islands National Recreation Area is clastic and was deposited in the Boston Basin between 595 million and 550 million years ago (see "Geologic History"). All of the sedimentary rocks in the recreation area have been metamorphosed.

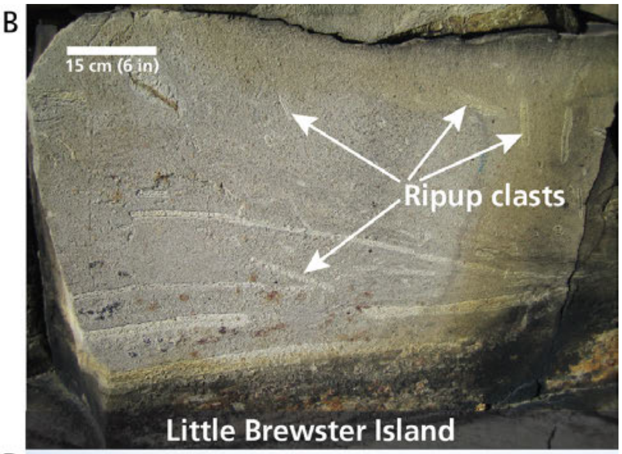
Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Clastic sedimentary rocks are named after the size of clasts, and clast size is indicative of the energy of a depositional environment (table 3).

The clastic Cambridge Argillite (geologic map unit **CZca**) is part of the Boston Bay Group of rocks and is the most common bedrock unit within Boston Harbor Islands National Recreation Area. Argillite is a slightly metamorphosed fine-grained mudstone or shale (see table 3). Unlike mudstone and shale, argillite is very well indurated ("cemented") and typically lacks fissility or cleavage, meaning it does not break easily into layers. However, a slate-like cleavage is well developed on Slate Island and Rainsford Island, and quarries took advantage of the easily separated rocks (fig. 25; Thompson et al. 2014). Sedimentary bedding (mapped offshore as observation, observed extent, and trend lines [inferred trend of bedding] in the GRI GIS data) is well preserved and shows geologic structures (see "Folds" and "Faults"). Thin layers, rip-up clasts (thin, broken pieces of mud torn off a surface), and evidence of rapid deposition (i.e., no significant sorting of grain sizes or bedding) suggest that some of the argillite was deposited by submarine landslides or debris flows, which also can create diamictites (**Zdm**), or by turbidity currents, which create turbidites (Thompson et al. 2014). A turbidity current is a bottom-flowing current laden with suspended sediment that may be associated with submarine landslides or debris flows. Slump folds—a type of soft-sediment deformation—within the Cambridge Argillite (**CZca**) suggest that deformation occurred within the layers before they became solid rock (Thornberry-Ehrlich 2008; Thompson et al. 2014). Outcrop-scale slump folds are visible at Rainsford and Slate islands (Thompson et al. 2014). Other sedimentary structures include cross beds (inclined beds at angles

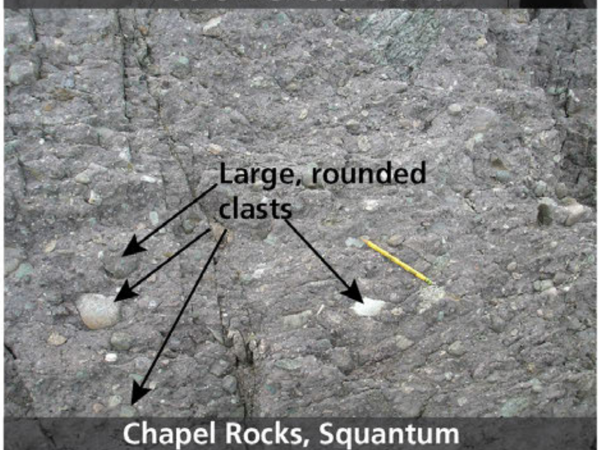
A


Middle Brewster Island

B


15 cm (6 in)
Ripup clasts
Little Brewster Island

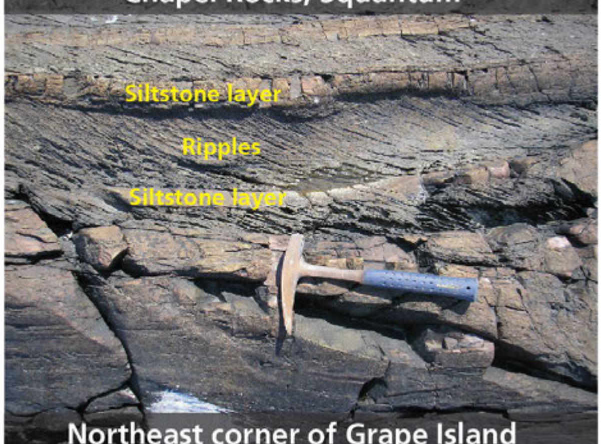
C


Large, rounded clasts
Chapel Rocks, Squantum

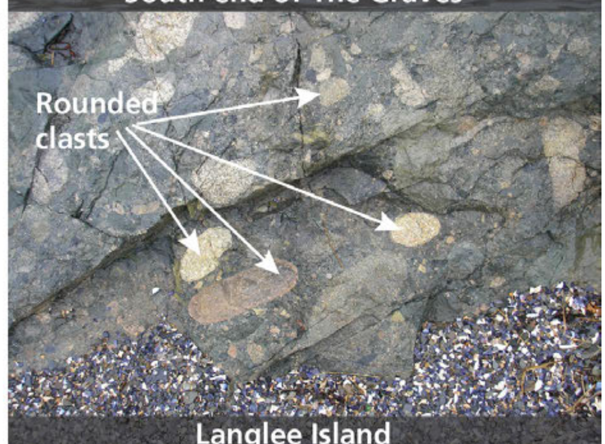
D


Dike
South end of The Graves

E


Siltstone layer
Ripples
Siltstone layer
Northeast corner of Grape Island

F


Rounded clasts
Langlee Island

G


Jumbled matrix
Middle Brewster Island

H

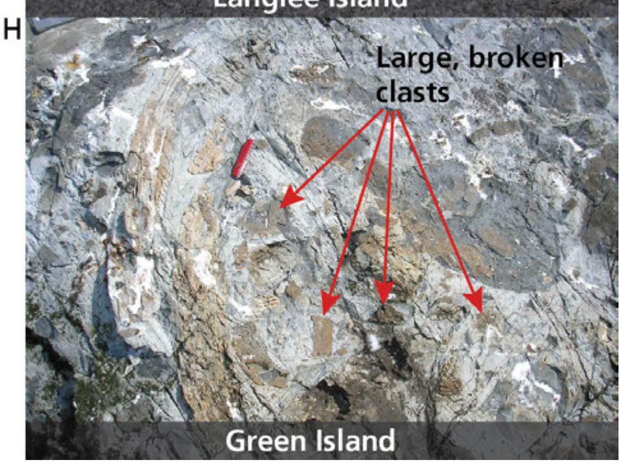

Large, broken clasts
Green Island

Figure 23 (facing page). Photographs of bedrock types and features. The bedrock at the national recreation area and in the vicinity contains the following features: (A) Soft-sediment deformation slumps (red lines) within the Cambridge Argillite (geologic map unit CZca. (B) Ripup clasts within the Cambridge Argillite. (C) Diamictic conglomerate wherein clasts “float” in the argillite matrix exposed outside Boston Harbor Islands National Recreation Area. (D) An east-to-west–trending dike (edged by red lines) cutting across a dolerite sill (J[?]Zdo). (E) Siltstone layers and ripple beds in the Cambridge Argillite (CZca). (F) Roundstone conglomerate (Zcr) with myriad clast types. (G) Volcanic breccia within a glacial erratic. (H) Intrusive breccia (J[?]Zib) that formed from local melting of argillite against a diabase sill, which then intruded across the unbrecciated sill. J[?]Zib is included in the GRI GIS data as a deformation area layer. Pencil and rock hammer for scale. Photographs A, C, D, E, F, and H are figures 9, 1, 27, 37, 44, and 25, respectively in Thompson et al. (2011), photograph G was provided by Peter Thompson (University of New Hampshire) in 2015, and photograph B (and all annotation) by Trista L. Thornberry-Ehrlich (Colorado State University).

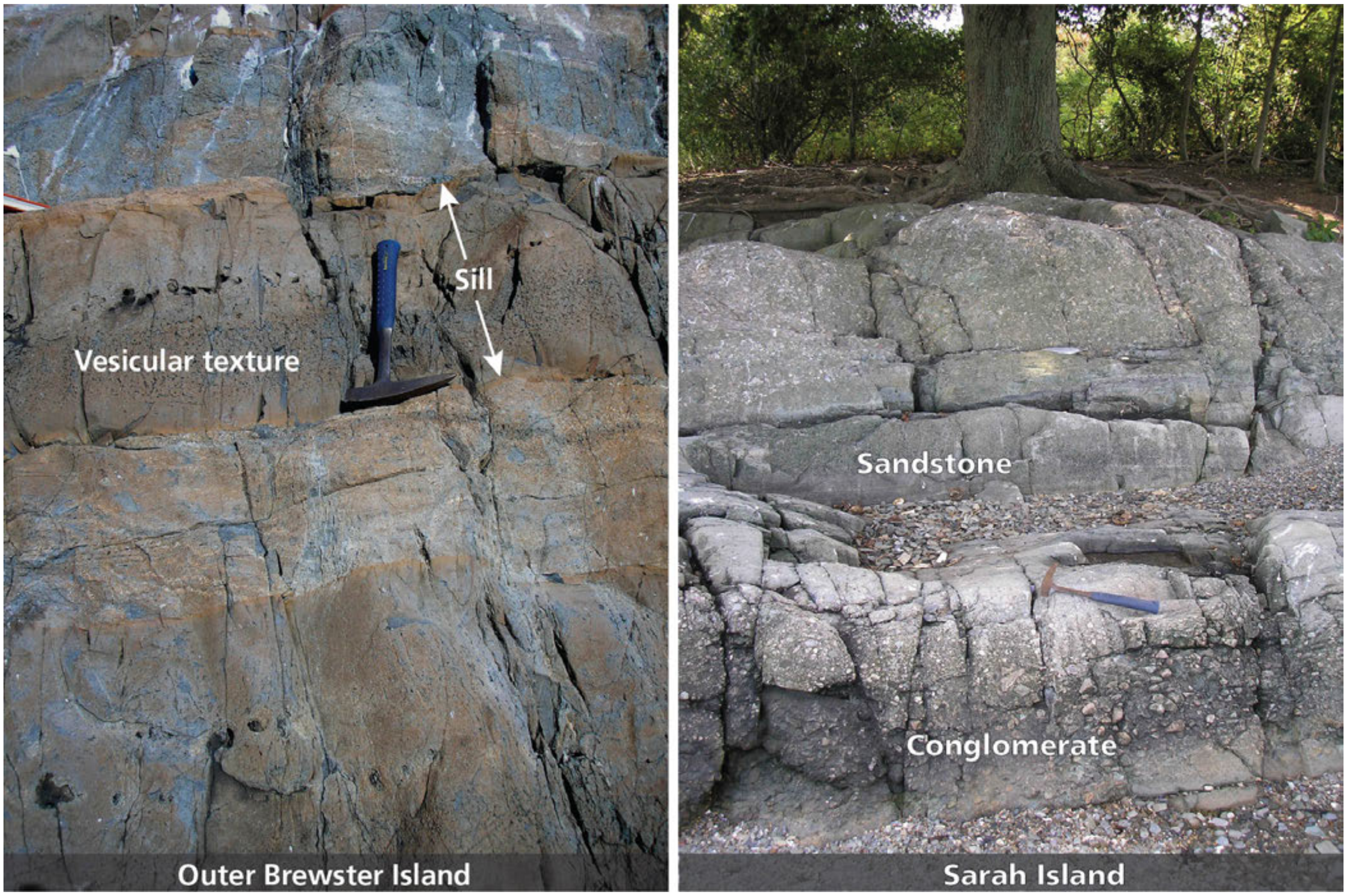


Figure 24. Photographs of volcanic and sedimentary bedrock. A basalt sill with chilled margins and a vesicular (containing cavities made by gas bubbles) middle intrudes older dolerite (geologic map unit J[?]Zdo) at Outer Brewster Island. Roxbury Conglomerate (Zcr) is exposed on the east end of Sarah Island where it is interbedded sandstone and coarser-grained pebble conglomerate. Photographs are figures 13 and 11 in Thompson et al. (2011) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

to general layering; can indicate deposition by flowing water or wind) and dewatering structures (wrinkles or corrugations in the layering) (Thompson et al. 2014). Cambridge Argillite crops out (is exposed) on Calf, Little Brewster, Middle Brewster, Outer Brewster, Grape, and Slate islands, and Worlds End (Skehan 2001; McMenamin et al. 2007). The coring and excavation associated with the construction of the Inter-Island Tunnel between Nut Island and the Deer Island wastewater treatment plant cut through almost continuous layers of Cambridge Argillite and provided important information about the lithology of the rock formation (Thompson et al. 2011).

The other common sedimentary bedrock unit within the harbor area is the Roxbury Conglomerate (**Zcr**);

Table 3. Clastic sedimentary rock classification and characteristics.

Rock Name	Clast Size	Depositional Environment	Boston Harbor Islands Example
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	The energy of depositional environments ranges from high (fast-moving water) for conglomerate to low (slow or stagnant water) for claystone.	Roxbury Conglomerate (Zcr)
Sandstone	1/16–2 mm (0.0025–0.08 in)		Layers within Roxbury Conglomerate (Zcr)
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)		Layers within Cambridge Argillite (CZca)
Claystone	<1/256 mm (0.00015 in) [smaller]		Layers within Cambridge Argillite (CZca) and diamictite (Zdm)

Note: Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Figure 25. Photograph of slaty cleavage. Slate was quarried from the south shore of Slate Island; image was taken near the old slate quarry. Slaty cleavage is a fabric that develops as rocks are squeezed and heated during low-grade metamorphism. The rocks break apart along distinct planar, closely spaced surfaces. Rock hammer for scale. Photograph is figure 35 in Thompson et al. (2011).

this unit is also part of the Boston Bay Group. It crops out at Sarah, Langlee, and Ragged islands, as well as Worlds End (Thompson et al. 2011).The Roxbury Conglomerate is much coarser grained than the Cambridge Argillite. The conglomerate contains layers of melaphyric volcanics (**Zvm**; see "Igneous Rocks" section). Also referred to as "Roxbury Puddingstone," (resembles a Christmas pudding) the Roxbury Conglomerate is the state rock of Massachusetts (Colgan and Rosen 2001). Some of the best exposures of the conglomerate and associated sandstones and argillite are on the small islands in Hingham Harbor and on Rocky Neck at Worlds End (Thompson et al. 2011).

Diamictite (**Zdm**) is a clastic sedimentary rock that contains a wide range of particle sizes. As mapped by Thompson et al. (2011), it includes pebbles and cobbles (like conglomerate) in a surrounding matrix of mudstone. Diamictite occurs as layers within Cambridge Argillite (Thompson et al. 2014). Poorly sorted, clast-rich layers within diamictite were once interpreted as lithified (hardened) till called "tillite." Now many geologists interpret this diamictite (or conglomerate) to be a deep-marine debris flow (Colgan and Rosen 2001; Thompson et al. 2011). Exposures of these layers occur at Squantum Head, southwest of Moon Island (Colgan and Rosen 2001). Within the recreation area, diamictite is exposed on Moon Island and is also mapped near Rocky Neck on Worlds End (Thompson et al. 2011).

Igneous Rocks

Igneous rocks formed from molten material. Where molten material cools and solidifies at Earth's surface, extrusive ("volcanic") igneous rocks form. Where molten material cools beneath the surface, intrusive ("plutonic") igneous rocks form. Igneous

Table 4. Volcanic rock classification and characteristics.

<table>
<tr><th>Rock Name</th><th>Silica (SiO_2)*</th><th>Viscosity</th><th>Explosiveness</th><th>Rock Formations in the Park</th></tr>
<tr><td>Rhyolite</td><td>>72%</td><td rowspan="6">Viscosity decreases from rhyolite (higher viscosity; thicker) to basalt (lower; more fluid)</td><td rowspan="6">Explosiveness decreases from rhyolite (more explosive) to basalt (less explosive)</td><td>Not mapped</td></tr>
<tr><td>Rhyodacite</td><td>68%–72%</td><td>Not mapped</td></tr>
<tr><td>Dacite</td><td>63%–68%</td><td>Dacite sills intrude the argillites on Grape and Slate Island</td></tr>
<tr><td>Andesite</td><td>57%–63%</td><td>Not mapped</td></tr>
<tr><td>Basaltic andesite</td><td>53%–57%</td><td>Just to the west on the part of Houghs Neck called Rock Island, basaltic andesite was formerly quarried</td></tr>
<tr><td>Basalt</td><td><53%</td><td>Melaphyric volcanics (Zvm)</td></tr>
</table>

*From Clynne and Muffler (2010).

rocks are classified by texture (grain size, shape, orientation), as well as the percentage of major minerals (quartz, alkali feldspar, and plagioclase) present in the rock (table 4). Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks (table 4). The term "silicic" refers to rocks with higher amounts of silica. The percentage of silica influences many properties of magma, including viscosity and explosiveness. In general, lavas with more silica are more viscous and explosive (table 4). Both volcanic and plutonic rocks are mapped in the recreation area.

Layers of volcanic ash are present within the Cambridge Argillite (geologic map unit **CZca**) (Thompson et al. 2011). Those layers have been radiometrically dated and indicate that the argillite is younger than 570 million years old (Thompson et al. 2007). Other volcanic rocks mapped in the national recreation area and included in the GRI GIS data are tuff (**Zvt**), melaphyric volcanics (**Zvm**), and porphyritic volcanics (**Zvp**). Tuff is consolidated ("cemented") volcanic ash and larger fragments. With respect to melaphyric volcanics (**Zvm**), "melaphyric" was used by Crosby in the 1890s when they originally described the unit. The term is now obsolete for describing a dark-colored porphyritic basalt. "Porphyritic" refers to igneous rocks with visible crystals surrounded by a "glassy" matrix. Basalt is the type of lava that flows from volcanoes in Hawaii (see the GRI report about Hawaii Volcanoes National Park by Thornberry-Ehrlich 2009).Volcanic rocks were mapped only on the mainland and only in the recreation area at Rocky Neck on Worlds End. These rocks erupted from volcanoes about 570 million years ago in an extensional setting during deposition of the Boston Bay Group sediments (**Zcr** and **CZca**; see "Geologic History").

Plutonic rocks mapped in the Boston Harbor Islands area include the oldest and youngest bedrock, granitic plutonic rocks, undifferentiated (**Zgr**) and diabase/dolerite dikes and breccias (**JZd**, **J[?]Zib**, and **J[?]Zdo**), respectively. The only island in the national recreation area made of granite (Dedham Granite?) is Button Island, in Hingham Harbor (Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016). The Quincy Granite (**SOqgr**) is also a locally quarried plutonic rock; blocks of Quincy Granite are visible in many breakwaters throughout the Boston Harbor Islands (Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016). Diabase intruding into the Cambridge Argillite (**CZca**) is visible at Slate Island and near Boston Light on Little Brewster Island (Thornberry-Ehrlich 2008). At Calf Island, diabase sills intruded the argillite and older sills. Sills form as molten rock intrudes parallel or concordant with adjacent rock layering. At this location, chilled margins (areas of finer crystal sizes where molten material contacted the surrounding "country rock") and areas where the surrounding rock partially melted record the intrusive relationships (Ross and Thompson 2012). Distinctive features in the igneous rocks include vesicles (cavities made by gas bubbles) preserved in the formerly liquid basalt and columnar joints, or polygonal contraction shapes which formed in the sill as it cooled (e.g., Devil's Postpile National Monument in California; Thompson et al. 2014). On the southeast tip of Calf Island, "pillows" (typically indicative of underwater eruptions) of diabase indicate rapid cooling upon extrusion into the mudstones (Thompson et al. 2014). The chemistry of the igneous rocks suggests some contact melting and incorporation of the Cambridge

Argillite country rock (Martin and Thompson 2012). The "Bedrock Map Unit Properties Table" (in pocket) provides more details of these rock units.

The diabase sills of the outer islands, and the Brewster islands in particular, are more resistant to erosion and weathering than the Cambridge Argillite (**CZca**). This resistance is the reason the Brewster islands persist today after the glaciation of the area in the Pleistocene Epoch (Peter Thompson, University of New Hampshire, geologist, email, 7 April 2015).

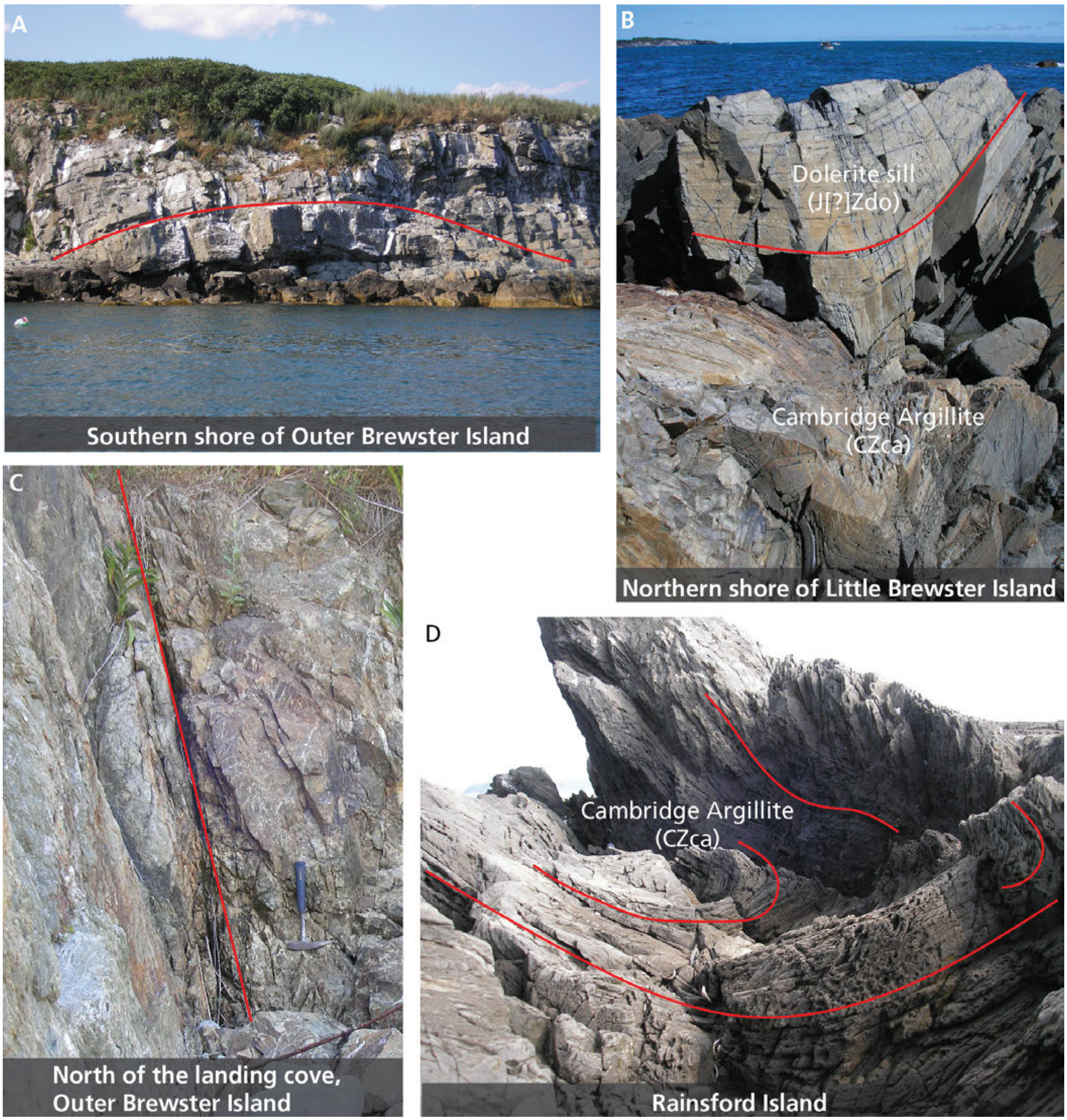


Figure 26. Photographs of folds and fault at Boston Harbor Islands. Red lines indicate the nature of the structure. (A) Broad, open anticline. (B) Synclinal fold within argillite (CZca) and an intruding dolerite sill (J[?]Zdo). (C) Trace of a small fault. (D) Isoclinal slump folds in argillite (CZca). Photographs are figures 15, 8, 16, 43 and 28 in Thompson et al. (2011) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Folds

Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation (fig. 26). The two primary types of folds are anticlines which are “A-shaped” (convex) and synclines which are “U-shaped” (concave). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently “plunge” meaning the fold axis tilts. Isoclinal folds have parallel limbs. As bedrock is compressed, anticlines and synclines form adjacent to each other, as in the bedrock beneath Boston Harbor. Folds mapped in Boston Harbor deform bedrock and formed during the orogeny that created the Appalachian Mountains or much less likely, the deformation associated with the pulling apart of Pangaea (see “Geologic History”; Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016).

Folds occur at multiple scales from regional features kilometers long and across, to outcrop-scale features centimeters or meters across such as slump folds in the Cambridge Argillite (geologic map unit **CZca**; see “Bedrock Exposures”). From north to south, the northeast–southwest-oriented Charles River syncline, Central anticline, Brewster syncline, and Wollaston syncline are regional scale folds identified in the GRI GIS data. Outcrop-scale folds are mapped on Calf Island (syncline on the eastern side) and Outer Brewster Island (paired anticline and syncline parallel to the long axis of the island). These smaller fold structures are also within intrusive doleritic sills and dikes (geologic map unit **J[?]Zdo**) (Thompson et al. 2011). Because the fold deforms both the Cambridge Argillite (**CZca**) and the intruding dikes and sills, it must have occurred during a compressional event after the igneous intrusions (Thompson et al. 2014).

Faults

A fault is a fracture in rock along which rocks have moved. The three primary types of faults are normal faults, reverse (thrust) faults, and strike-slip faults (see figs. 26 and 27). The latter two types were mapped within Boston Harbor Islands National Recreation Area and are part of the GRI GIS data. Faults are classified based on motion of rocks on either side of the fault plane as described in figure 27. Thrust faults are reverse faults with a low angle (<45°) fault plane. Décollements, or detachment faults, are very low angle (nearly horizontal) reverse faults with large displacement (kilometers to tens of kilometers). Like the folds in the national recreation area, faults are ancient (hundreds of millions of years old). They likely formed during the orogeny that created the Appalachian Mountains or

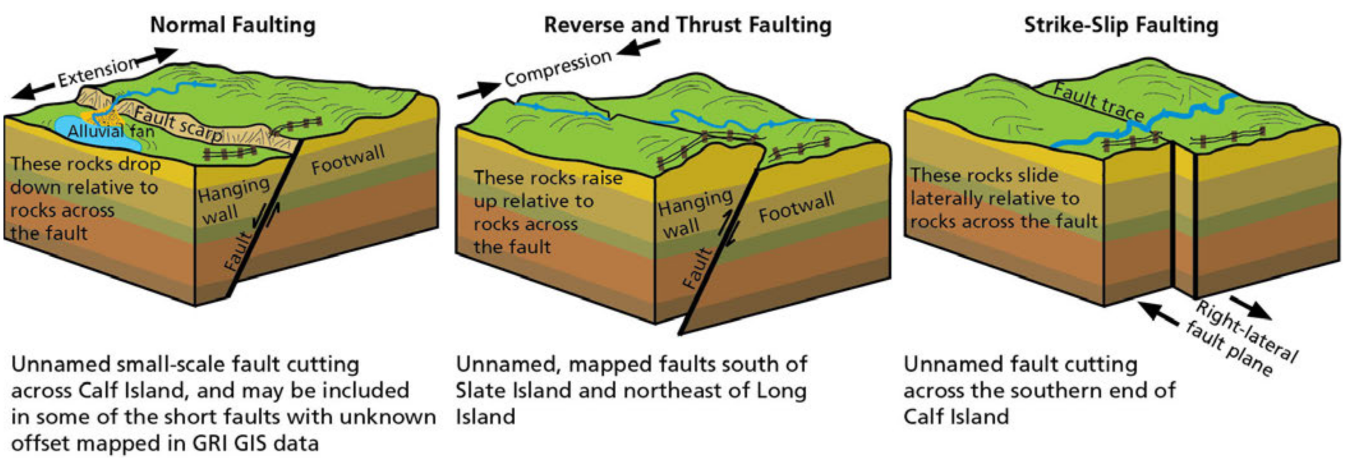


Figure 27. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral fault, as illustrated above. When movement is to the left, it is a left-lateral fault. A strike-slip fault between two plate boundaries is called a transform fault. Features (e.g., streams and fences) on the surface are intended to demonstrate the response to the type of fault movement illustrated and is not meant to necessarily reflect features at Boston Harbor Islands. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

the deformation associated with the pulling apart of Pangaea (see "Geologic History"). These ancient faults are not likely to be active, but seismic activity is possible in the Boston Harbor region (see "Seismic Activity Hazards and Risks").

The coring and excavation associated with the Inter-Island Tunnel exposed the Cathedral fault, a major fault zone trending northeast-southwest across Boston Harbor. This was one of the most important geologic discoveries from that project (Ferguson et al. 1997; Thompson et al. 2014; Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). Geophysical data associated with the Inter-Island Tunnel project are included in the GRI GIS data.

The Cathedral fault was mapped between Rainsford and Peddocks islands and is shown in the GRI GIS data; however, the fault is not labeled as the "Cathedral fault" in the data (Thompson et al. 2011). Thompson et al. (2014) mapped the fault with steep offset and the upthrown block to the south. A 120-m- (400-ft-) thick zone of altered, "rotten" rock marks the Cathedral fault and presented engineering challenges to the Inter-Island Tunnel construction. The concrete "cathedral" constructed to support the tunnel through this stretch is the fault's namesake (Thompson et al. 2014).

Other named faults in the Boston Harbor area include the Mt. Hope and Neponset faults. They are nearly parallel on the southwestern shore of Boston Harbor beyond the national recreation area's boundaries. Their offset is unknown. In addition, the Rock Island fault cuts across much of the southern edge of the harbor and separates the rocks of the Cambridge Argillite (geologic map unit **CZca**) from the Roxbury Conglomerate (**Zcr**) and melaphyric volcanics (**Zvm**). It skirts the southern end of Raccoon Island and cuts across Webb Memorial State Park (Thompson et al. 2011). Bathymetric lineaments (included in the GRI GIS data as geologic line features) may trace the offshore expression of faults (Thompson et al. 2011).

In addition to the named faults, there are many smaller faults included in the GRI GIS data for Boston Harbor Islands National Recreation Area. Most of the faults in the GRI GIS data are designated as unknown offset/displacement because the fault movement was difficult to determine in the field and/or from the source maps. These faults are mapped within the national recreation area's boundaries at Calf, Hangman, Slate, and Raccoon islands, as well as Worlds End and Webb Memorial State Park (Thompson et al. 2011). Some faults have documented displacement direction and can be classified. For example, a left-lateral strike slip fault (relative movement across the fault is to the left; see fig. 27) cuts across the southern end of Calf Island, juxtaposing a diabase sill (**J[?]Zdo**) and Cambridge Argillite (**CZca**). A vertical fault trends north–south offshore of the northern side of Rainsford Island. A thrust fault separates melaphyric volcanics (**Zvm**) from Cambridge Argillite (**CZca**) south of Slate Island on the mainland (Thompson et al. 2011). A reverse fault is submerged just off the northeastern shore of Long Island. Faults with steep offset bound an upthrown block of rock or "horst" across the center of Calf Island. This structure exposes Cambridge Argillite (**CZca**) below a diabase sill (**J[?]Zdo**). Today, the horst underlies a low-lying marsh area (geomorphic map units **Qla**, **Qwe**, **Qot**, **Qtc**, **Qwb**, and **Qgr**; FitzGerald et al. 2013; Thompson et al. 2014). This low-lying "sag" may one day be inundated by the sea dividing it into two islands (Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015).

Geology classes from Boston area colleges and universities have been coming for many years to Rocky Neck at Worlds End in Hingham to map the interesting pattern of tilted fault blocks. The number of faults throughout the Boston Harbor area attests to the deformation and movement of rocks over long periods of time (see "Geologic History").

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009; Tweet et al. 2010). Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of February 2017, 266 parks, including Boston Harbor Islands National Recreation Area, had documented paleontological resources in at least one of these contexts. All fossils are nonrenewable, and resource management issues are discussed in the next chapter. The NPS Fossils and Paleontology website, http://go.nps.gov/fossils_and_paleo, provides more information. Tweet et al. (2010) presented a summary of known paleontological resources and those with the potential for discovery at Boston Harbor Islands National Recreation Area.

Fossils from the recreation area include soft-bodied organisms hundreds of millions of years old from the Cambridge Argillite (**CZca**) and a diverse assemblage of mostly marine organisms from Pleistocene rocks and sediments up to tens of thousands of years old. Fossils within the Cambridge Argillite and are more than 540 million years old (see fig. 3; Thompson et al. 2007; Thompson et al. 2011). According to Tweet et al. (2010), which cited Bailey (2005) and McMenamin et al. (2007), fossils of the Cambridge Argillite include microbial mats, the Ediacaran form *Aspidella*, and a variety of microfossils, namely spherical forms, filaments, and colonies identified as *Bavlinella cf. faveolata*, many of which are now altered to pyrite (the brass-colored metallic mineral also known as "fool's gold"). The "Ediacaran biota" are part of a group of soft-bodied organisms, the structure and relationships of which are unknown (Tweet et al. 2010). Similarly, the microfossils are commonly described as "acritarchs," a nebulous group of fossil forms that are commonly classified together because they cannot be identified as anything else. The group briefly flourished before the evolution of hard body parts—the event that marks the beginning of the Cambrian Period (Tweet et al. 2010). Ring fossils occur in numerous locations throughout the islands (Thompson et al. 2014). Fossils resembling raindrop impressions (small dimples) have been noticed in the bedrock of Grape, Slate, Raccoon, and Middle and Outer Brewster islands, typically occurring along bedding planes (McMenamin et al. 2007; Thornberry-Ehrlich 2008; Tweet et al. 2010; Peter Thompson and Joe Kopera, University of New Hampshire and Office of the Massachusetts State Geologist, respectively, geologists, conference call, 7 April 2015).

Much younger fossils are also present within the recreation area. Pleistocene fossils include terrestrial, marine, and estuarine plants, invertebrates, and vertebrates from the older glacial till that makes up the drumlins (geomorphic map unit **Qdr** and **Qtcb**) (Colgan and Rosen 2001; Orton and Colgan 2001; Rosen and FitzGerald 2004; FitzGerald et al. 2013). Pleistocene marine fossils are known from glacial till deposits on Peddocks Island (Tweet et al. 2010; Peter Thompson, University of New Hampshire, geologist, conference call, 7 April 2015). Other islands with documented fossils include Calf, Deer, Georges, Great Brewster, Long, Lovells, Moon, and Nut; bivalves and gastropods dominate the shell types (Tweet et al. 2010). Other fossils wash up on the coastlines or accumulate in marshes (Qmp and Qwe). Pleistocene fossils include foraminifera, ostracodes, bivalves, gastropods, sponges, stony corals, barnacles, crabs, worm tubes, hickory nuts, fish, reptiles, birds, dogs, deer, and other mammals (Crosby and Ballard 1894; Luedtke and Rosen 1993; Colgan and Rosen 2001). The marine microfossils in the older glacial till indicate warmer-than-present, shallow-marine or estuarine paleoenvironments (Orton and Colgan 2001). Fossil assemblages from the salt marsh on Calf Island include pollen and peat (dated to between 840 and 860 CE), as well as anthropogenic charcoal that document environmental conditions prior to and after European settlement (Jones and Fisher 1990; Patterson et al. 2005).

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2007 scoping meeting (see Thornberry-Ehrlich 2008) and 2015 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Coastal Erosion and Response to Climate Change
- Abandoned Mineral Lands and Disturbed Lands
- Paleontological Resource Inventory, Monitoring, and Protection
- Seismic Activity Hazards and Risks
- Loss of Aeolian Features

National Park Service management policies instruct managers to protect natural geologic features and processes. The long-term vital signs monitoring plan for the National Park Service Northeast Temperate Network includes the following geology-related indicators for the Boston Harbor Islands: (1) climate, (2) shoreline geomorphology, (3) forest soil condition, (4) rocky intertidal communities, (5) wetland communities (vegetation), (6) visitor usage, (7) land cover/ecosystem cover, and (8) land use (Mitchell et al. 2006). Of these, climate; rocky intertidal communities; wetland communities, specifically salt marsh vegetation; land cover/ecosystem cover; and land use are currently being monitored. Monitoring the remaining vital signs is subject to funding availability. Park staff members are also working on a Natural Resource Condition Assessment and State of the Park report. Both of those publications should be used to inform geologic resource management.

Boston Harbor Islands National Recreation Area is one of more than 120 parks close to the coast that are vulnerable to coastal threats such as sea level rise, lower lake levels, salt water intrusion, and inundation during coastal storms (Beavers et al. 2016). The NPS Geologic Resources Division Coastal Geology website, http://go.nps.gov/grd_coastal and NPS Climate Change-Coastal Adaptation website, https://www.nps.gov/subjects/climatechange/coastaladaptation.htm, provide additional information.

The recently published NPS Coastal Adaptation Strategies Handbook (Beavers et al. 2016) summarizes the current state of NPS climate adaptation and key approaches currently in practice or considered for climate change adaptation in coastal areas in order to guide adaptation planning in coastal parks. The chapters focus on policy, planning, cultural resources, natural resources, facility management, and communication/education. The handbook highlights processes, tools and examples that are applicable to many types of NPS plans and decisions. One chapter includes a case study of Hurricane Sandy response and recovery strategies including changes to infrastructure. Another chapter features practical coastal infrastructure information including cost per unit length of constructed features (including seawalls, beach nourishment, and nature-based features).. Case studies in Schupp et al. (2015) illustrate the many ways that the National Park Service is implementing adaptation strategies for threatened resources in individual parks. Many additional resources are available for managing coastal resource management issues; they are detailed in "Coastal Erosion and Response to Climate Change."

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. *Geological Monitoring* is available online at http://go.nps.gov/geomonitoring.

Coastal Erosion and Response to Climate Change

Coastal processes at Boston Harbor Islands are driven primarily by wave action and bluff retreat operating in a regime of accelerated sea level rise (Himmelstoss et al. 2002; Caffrey 2014). Processes include tombolo formation, migrating landforms (e.g., spits and barriers; see "Coastal Features"), and bluff retreat and slumping

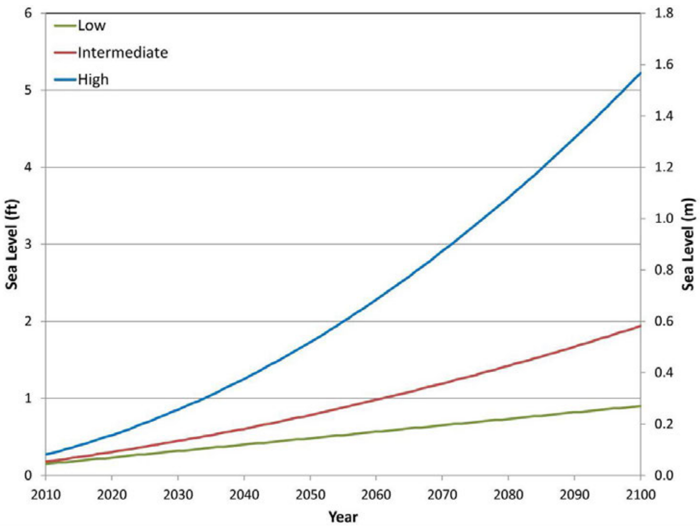


Figure 28. Graph of projected rate of sea level rise for Boston. Sea level data downscaled to Boston, Massachusetts indicate that the projected rate of rise (using US Army Corps of Engineers [ACOE] and Intergovernmental Panel on Climate Change [IPCC] data) is locally higher than the global average under most climate change scenarios. Graphic is figure 1 in Caffrey (2014).

(see "Sediment Supply and Island Erosion"). Migrating landforms and shoreline erosion are caused by wave action (storm waves and local wind waves), boat wakes, and variations in sea level, which has risen 1 m (3 ft) during the past 1,500 years or 0.3 m (1 ft) in the last 100 years (Donnelly 2006).

Bluff retreat is a mostly a natural process at Boston Harbor Islands. However, as climate changes and sea level rises (fig. 28), it is likely that bluff retreat will accelerate (Vaux et al. 2012; Caffrey 2014). In addition, increased wave energy from boats, coastal engineering structures, and vegetation degradation can all exacerbate bluff retreat (FitzGerald et al. 2011; Hapke et al. 2011). Coastal erosion associated with boat wakes is discussed in a subsequent section. Coastal engineering considerations are also discussed in the next section.

Coastal erosion and sea level rise were listed by Shriver et al. (2004) as a high threat with management concern for the national recreation area. The primary impacts to Boston Harbor Islands National Recreation Area from sea level rise and storm surge vulnerability were listed by Caffrey (2014):

- Increasing sea levels may lead to loss of land and critical habitat (e.g., geomorphic map units such as **Qot**, **Qsa**, **Qib**, **Qsp**, **Qt**, and **Qtf**).
- Increased erosion and/or accretion across the coastline by storms coupled with shorelines adjusting to new mean sea levels.
- Rising groundwater tables and possible saltwater intrusion due to rising sea levels.
- Increased risk of high intensity storm events.
- Potential loss of nearby freshwater ecosystems as sea levels rise.

Climate Change Context

Davey et al. (2006) identified climate change as a dominant factor driving the physical and ecological processes affecting the Northeast Temperate Network, including Boston Harbor Islands National Recreation Area. In general, climate models for the northeastern United States show an increase in climate-related hazards such as heat waves, intense storms, sea level rise, coastal flooding, and river flooding (Melillo et al. 2014). Climatic conditions have shifted beyond the historical range of variability over the past century, especially in terms of extreme warm temperatures and extreme wet precipitation events; "extreme" refers to conditions exceeding 95% of a historical range (Monahan and Fisichelli 2014). Temperatures in the Northeast increased by nearly 1.1°C (2°F) since 1895 or 0.14°C (0.26°F) per decade (Melillo et al. 2014; Fisichelli 2014). Mean annual temperature is projected to rise 1.7 to 2.2°C (3 to 4°F) in the Boston Harbor area by 2050 (Kunkel et al. 2013; Fisichelli 2014).

Precipitation predictions pose greater uncertainty. Between 1958 and 2010, the northeast region experienced more than a 70% increase in the amount of precipitation falling in heavy storms (Kunkel et al. 2013; Melillo et al. 2014). The two primary storm types occurring at Boston Harbor Islands are infrequent hurricanes from the south and "nor'easters," which track east of Cape Cod and Nova Scotia. A nor'easter in 1978 created record tides of 1.72 m (5.64 ft) above the mean tide elevation (FitzGerald et al. 2011). Because strong northeast winds are typical of nor'easters, easterly facing shorelines are most vulnerable to their effects; the greatest local impacts occur at the mouth of and just inside Boston Harbor (FitzGerald et al. 2011). Wind events were listed by Shriver et al. (2004) as a high threat with management concern for the national recreation area.

Warmer ocean temperatures and more frequent heavy-precipitation events contribute to sea level rise and can lead to more severe flooding and coastal erosion at Boston Harbor Islands (Fisichelli 2014; Caffrey 2014). Based on hurricane modeling, storm surge has the potential to inundate much of the low-lying area (fig. 29; Caffrey 2014). Research into climate-change impacts on nor'easters and extratropical storms is not as advanced as is that for hurricanes. Boston Harbor Islands National Recreation Area has identified this as needed research and Project Management Information System (PMIS) proposals are in review for more support (Amanda Babson, NPS Northeast Region, oceanographer, written communication, 4 April 2016).

Bluff Retreat Hazards and Risks

As discussed in "Bluff Retreat," slope movements are contributing to the loss of land on many of the Boston Harbor Islands where bluffs composed of glacial till are retreating. Storms contribute to triggering slope movements so more slope movements may be an outcome of the increased number (and intensity) of storms resulting from climate change. In addition, bluff retreat slope movements are a common type of geologic hazard. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see also Holmes et al. 2013).Resource management attention with regards to slope movements is currently focused on the coastal areas and bluffs (GRI conference call participants, 7 April 2015). For future development planning, slope vulnerability assessments on the islands would be a useful data set (Thornberry-Ehrlich 2008). In the Geological Monitoring chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of movement, (2) movement causes and triggers, (3) geologic materials in slope movements, (4) measurement of movement, and (5) assessment of slope movement hazards and risks. In addition, Highland and Bobrowsky (2008) completed a "landslide handbook" that may be of use for resource manager in understanding landslides at the national recreation area. Also, the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

FitzGerald et al. (2011) recommended vegetation as the most effective means of stabilizing bluffs. Plant roots increase a slope's integrity, and vegetation decreases surficial erosion by reducing overland flow during precipitation events. Consequently, conservation of vegetation on and above all bluffs is critical, and revegetation would benefit some areas such as the prominence in Webb Memorial State Park.

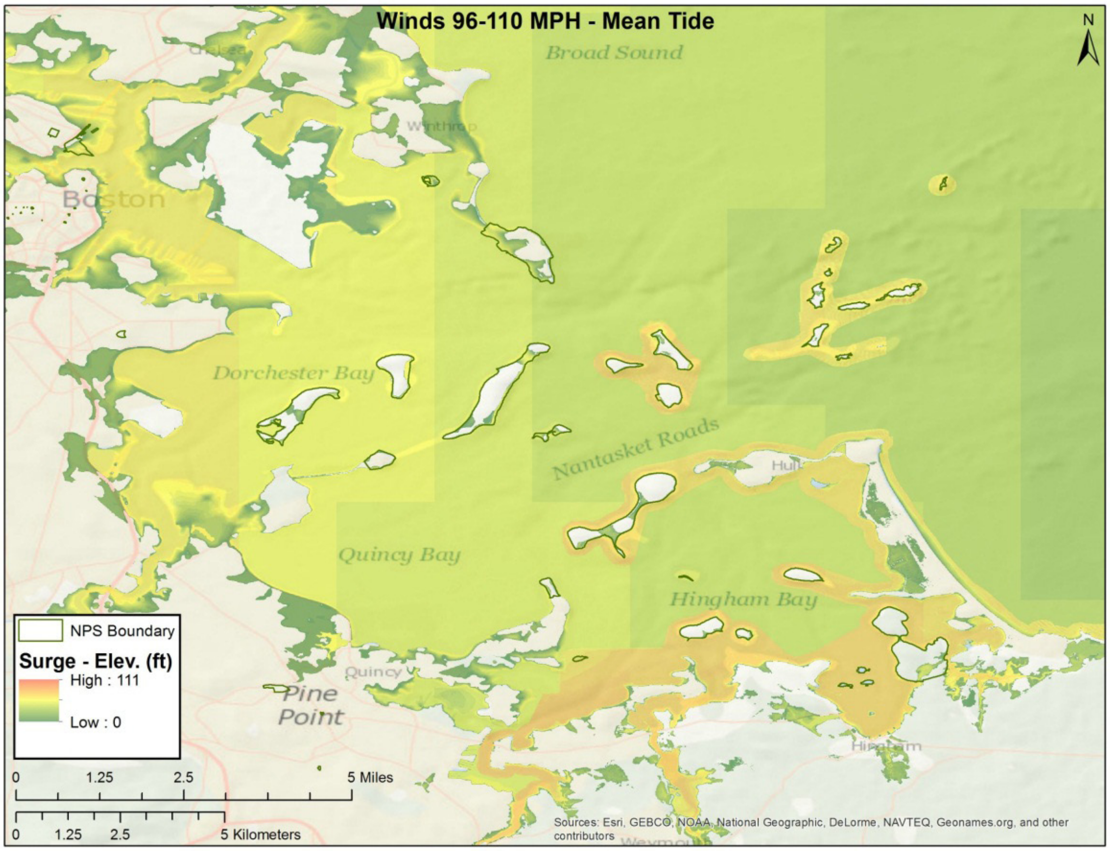
Bluff retreat issues need to be considered on a bluff-by-bluff basis and include adjacent areas, which may rely on the eroding bluff as a sediment source, and any cultural resource that may be at risk. Nourishing cobble and boulder beaches could prove helpful in areas of critical importance (FitzGerald et al. 2011).

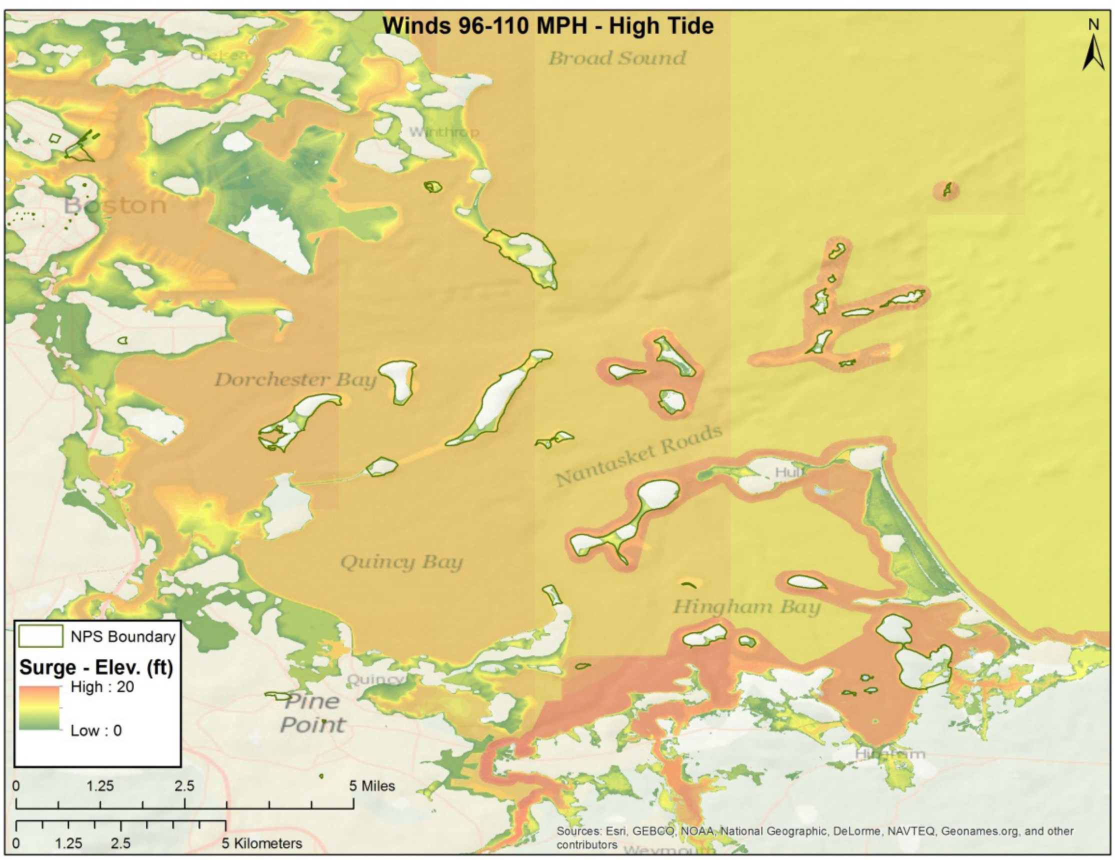
Tools for Managing and Monitoring Coastal Resources as Climate Changes

Effective planning and resource management of climate change response must be based in a comprehension of past dynamics as well as a realization that the future conditions may shift beyond the historical variability range (Fisichelli 2014). A variety of tools are available (or being developed) to assist NPS resource managers with better understanding a variety of climate change–related issues, including sea level rise and storm surge projections, impacts to salt marsh sedimentation, impacts to cultural resources and coastal assets, and the national recreation area's boundary that may shift with changing shorelines.

Sea Level Rise and Storm Surge Projections

The estimated amount of sea level rise and storm surge varies depending on the model used. However, most models show higher sea levels and an expectation for more intense storms in the future. Sea level is rising around Boston Harbor Islands National Recreation Area (see citations in Caffrey 2014). Sea level in New England has risen approximately 0.3 m (1 ft) since 1900 (Melillo et al. 2014). The rate of rise at the Boston tide gauge (the nearest long-term gauge to the national recreation area) is 0.28 m (0.86 ft) per century (National Oceanic and Atmospheric Administration 2013; Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016). Sea-level


Winds 96-110 MPH - Mean Tide
N
Broad Sound
Winthrop
Boston
Dorchester Bay
Nantasket Roads
Hull
Quincy Bay
Hingham Bay
Quincy
Pine Point
Hingham
NPS Boundary
Surge - Elev. (ft)
High : 111
Low : 0
0 1.25 2.5 5 Miles
0 1.25 2.5 5 Kilometers
Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors


Winds 96-110 MPH - High Tide
N
Broad Sound
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Boston
Dorchester Bay
Nantasket Roads
Hull
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Hingham Bay
Quincy
Pine Point
Hingham
NPS Boundary
Surge - Elev. (ft)
High : 20
Low : 0
0 1.25 2.5 5 Miles
0 1.25 2.5 5 Kilometers
Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

projections by the year 2100 for Boston, Massachusetts, range from 0.27 m (0.90 ft) to 1.59 m (5.22 ft)—greater than the global average rate predictions (see fig. 29; US Army Corps of Engineers 2013; Caffrey 2014). A new sea level rise curve, based on coring work done within Boston Harbor, is forthcoming. These data will be combined with a sediment elevation table (Zoe Hughes, Boston University, coastal geomorphologist, conference call, 7 April 2015). Storm surges will increase with sea level.

As documented by Caffrey (2014), Boston Harbor Islands National Recreation Area has not been directly in the path of any hurricane-strength storms over the last century; however, it has been within 16 km (10 mi) of two hurricane paths (the strongest was Hurricane Bob in 1991). Storms are expected to intensify over the next century. At least one Saffir-Simpson category-2 hurricane should be expected to travel up to the recreation area by 2100. As described in "Climate Change Context," nor'easter storms are prevalent in the Boston Harbor area. Their impact is intensified by the northeast exposure of the harbor mouth (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016).

The National Oceanic and Atmospheric Administration maintains an extreme water levels record for Boston, Massachusetts, at http://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=8443970. These data may provide a point of reference when examining projections of sea level rise and storm surge impacts.

The NPS Geologic Resources Division (GRD) and Climate Change Response Program (CCRP) are developing sea level rise and storm surge data that park managers can use for planning purposes over multiple time horizons (Caffrey 2014). Caffrey (2014) presented storm surge elevations for mean and high tides. Most of the islands in the Outer Harbor and Hingham Bay could receive surge as high as 6 m (20 ft). One of the most vulnerable areas was the Spectacle Island visitor center with a potential surge of 5.9 m (19.3 ft). The applicability of this study may be somewhat limited on a local scale because storm surges will not be the same across shorelines that face different directions and with different shoreline characteristics. For example, the Spectacle visitor center is on the more protected west side of the island (Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016).

The University of Rhode Island is computing inundation risk from sea level rise and storm surge using high-accuracy geodetic control (National Park Service 2015b). This work involves using geodetic GPS technology to establish a GIS-based foundation that can be used in the future to map elevation and monitor island change. This study established backbone locations (monuments or benchmarks) on recreation area islands and peninsulas (data include 99 sites on 15 islands) to support GPS surveys and chosen critical sites. Data from this study are served at a project website (http://www.edc.uri.edu/monumentation).

The National Park Service created a website with projected sea level rises of 60 cm (2 ft), 1 m (3 ft), and 2 m (6 ft) and modeling of sea, lake, and overland surges from hurricanes (SLOSH) for "sentinel sites" in the Northeast Region, including Boston Harbor Islands National Recreation Area, http://www.arcgis.com/apps/OnePane/basicviewer/index.html?appid=e004f38e68634a178d61b239f3cd98b3; data are available at https://irma.nps.gov/DataStore/Reference/Profile/2216861 (scroll for "Boston Harbor" products) (Amanda Babson, NPS Northeast Region, oceanographer, conference call, 7 April 2015). These data may indicate the areas at most risk of inundation from rising seas and storm surges.

The national recreation area's 2009 strategic plan identified completion of a coastal resource vulnerability assessment across the Boston Harbor Islands by 2016 as a goal (National Park Service 2009). Hammar-Klose et al. (2003) completed a coastal vulnerability index (CVI) assessment for nearby Cape Cod National Seashore; one has not yet been completed for Boston Harbor Islands National Recreation Area. CVIs use tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea level

Figure 29 (facing page). Maps of projected storm surge elevations for category 2 hurricanes. Top image shows mean tide conditions. Lower image shows high tide conditions (i.e., higher storm surge elevations). A category 2 storm at high tide would inundate the Spectacle Island visitor center with up to 3.7 m (12.1 ft) of water. Category 1 and 2 hurricanes are probable over the next century as storm strengths increase as a result of climate change. Graphics are figures 2 and 3 in Caffrey (2014) prepared using NOAA SLOSH data.

rise to create a relative measure of the coastal system's vulnerability to the effects of sea level rise. The CVI provides data for resource management and facilities planning. The US Geological Survey CVI website (https://woodshole.er.usgs.gov/project-pages/nps-cvi/) provides more information about coastal vulnerability.

Salt Marsh Sedimentation and Wetland Health

As detailed in "Wetlands," wetlands serve many vital functions in the overall ecosystem of the islands. Wetland condition is a primary resource management concern, but their formation, occurrence, longevity, and resilience are not well understood. Therefore, more study of all the wetland resources within the national recreation area is warranted.

Wetlands are among the most low-lying areas in Boston Harbor Islands National Recreation Area; rising seas threaten their very existence because salt marshes must accrete vertically at the same rate as rising sea level. In Boston Harbor, salt marshes cannot migrate landward with rising water levels because steep shoreline slopes commonly inhibit them (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). Sediment supply to the salt marshes is the only factor that could foster sufficient vertical accretion slopes (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016).

A cooperative project among Boston University, Northeastern University, and the National Park Service is studying salt marsh sedimentation (geomorphic map units **Qwe**, **Qla**, and **Qmp**; see "Wetlands") and using models to determine areas of land loss and gain, determine which threshold coastal structures will be overtopped or dismantled, and what will happen to glacial bluffs as sea level continues to rise (Zoe Hughes, Boston University, conference call, coastal geomorphologist, 7 April 2015). Recreation area staff members are very interested in this project. However, some aspects of this project are not slated to begin until fall 2018.

Cultural Resources and Coastal Assets

NPS Policy Memorandum 14-02 (Jarvis 2014) identifies specific foci for adaptive research and management activities related to cultural resources and provides guidelines for decision making to avoid impairment of these resources in the face of climate change. The NPS Coastal Adaptation Strategies Handbook (Beavers et al. 2016) summarizes NPS guidance and strategies for cultural resources adaptation. While this GRI report was in final review, the Cultural Resources Climate Change Strategy was published (Rockman et al. 2016).

The summary report from the Preserving Coastal Heritage workshop (National Park Service 2014) identified and described seven climate change adaptation options for cultural resources: (1) no active intervention, (2) offset stresses, (3) improve resilience, (4) manage change, (5) relocate/facilitate movement, (6) document and release, and (7) interpret the change. Melnick et al. (in preparation) and Rockman et al. (2016) have expanded these options to apply them specifically to cultural landscapes. Melillo et al. (2014) focused on three types of options to adapt to rising sea level: (1) protect (e.g., building levees or installing riprap), (2) accommodate (e.g., raising structures or using wetland restoration), and (3) managed retreat (e.g. allowing areas to be exposed to flooding by removing coastal protection. Other useful references for climate change impacts on cultural resources include Rockman (2015), Morgan et al. (2016), and Rockman et al. (2016).

The National Park Service developed *Adapting to Climate Change in Coastal Parks: Estimating the Exposure of FMSS-Listed Park Assets to 1 m of Sea level rise* (Peek et al. 2015). This report includes the geospatial location and approximate elevation of more than 10,000 assets in 40 coastal parks, including 143 assets in Boston Harbor Islands National Recreation Area. Information was derived from the NPS Facilities Management Software System (FMSS) and supplemented with other datasets, collaboration with park staff, and field visits to locate assets. Assets were characterized based on their overall exposure to a long-term, 1 meter rise in sea level and associated storm vulnerability, and were categorized as having either high exposure or limited exposure to sea level rise impacts. At Boston Harbor Islands National Recreation Area, 143 assets were identified; 54 were considered at "high exposure" to 1 m of sea level rise and 89 were considered at "low exposure" (Peek et al. 2015).

Boundary Issues, Beach Nourishment, and Other Coastal Resource Monitoring

Additional reference manuals that guide coastal resource management include NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction, which can provide insight for managers in parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: Beach Nourishment Guidance (Dallas et al. 2012) for planning and managing nourishment projects.

Park managers working to develop additional monitoring protocols for coastal resources can contact their Inventory and Monitoring network and/or consult existing standard operating procedures such as those defined in Bush and Young (2009) in the *Geological Monitoring* chapter about coastal features and processes. Bush and Young (2009) described the following methods and vital signs for monitoring coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion.

Boat Wake Impacts on Coastlines

Boston Harbor is the oldest continually active major port in the western hemisphere (Flora 2002). Boat use of all types is extensive and includes commuter and NPS ferries, commercial fishing vessels, and recreational boats (FitzGerald et al. 2011). As regional mass transit and island-access demands increase, large and fast ferries are a common facet of the transportation infrastructure (FitzGerald et al. 2011). Higher speeds produce larger wakes, which form steeper breaking waves at the shoreline (FitzGerald et al. 2011). The larger ferries produce wake approximately four times greater in height and 16 times more energy than natural waves (FitzGerald et al. 2011). Boat traffic was listed by Shriver et al. (2004) as a high threat with management concern for the national recreation area.

New and rapidly retreating erosional scarps have formed in areas thought to be low-energy areas (usually sheltered from the natural wave system) of the Boston Harbor Islands. To determine if these scarps were related to increased boat wakes, FitzGerald et al. (2011) investigated the impacts of increased ferry and other vessel traffic as part of a larger effort to understand geomorphology and retreat rates at Boston Harbor Islands. They combined climatological data, hydrodynamic measurements (wave climate, wakes, and currents), suspended sediment measurements, and rates/profiles of bluff retreat in areas sited along the major ferry routes at Thompson, Spectacle, Moon, Long, Lovells, Peddocks, Bumpkin, and Grape islands, as well as Webb Memorial State Park. Their results revealed boat wakes have the potential to enhance wave energy. Bluffs at Thompson Island are especially susceptible. Other areas have likely reached a state of equilibrium with the increased energy regime created by boat wakes. Any change in ferry activity (e.g., faster speeds or infrastructure development) would likely cause morphological changes to shorelines (FitzGerald et al. 2011).

FitzGerald et al. (2011) recommended several sites for remediation consideration: the eastern shore and bluffs on Thompson Island, the western shore on Spectacle Island, and the northeastern bluff on Lovells Island. Their action items included adding boulders to the existing cobble and boulder beaches at Thompson and Spectacle islands. Also, a breakwater structure offshore at Lovells Island could reduce wave energy without removing or inhibiting longshore transport of sediment; however, more investigation into the impacts of such a structure is advised. Furthermore, resource managers should consider the impact of natural and boat wake energy when planning coastal engineering efforts and transportation infrastructure. Reduced speed limits and "no-wake" zones could help reduce wake energy in targeted areas (FitzGerald et al. 2011).

Coastal Engineering Structures Preservation and Erosion

Boston Harbor Islands have a long history of costal engineering efforts in an attempt to curb coastal-erosion processes and landform change (fig. 30; see "Geologic Significance and Connections"). None of the islands is completely surrounded by coastal structures (FitzGerald et al. 2011). Coburn et al. (2010) identified a total of 51 coastal engineering projects, including 11 groins, two jetties, 14 revetments, 18 seawalls, one beach nourishment episode, and five dredging projects (table 5). According to the coastal study by FitzGerald et al. (2011), 85% of the seawalls, 94% of the revetments, 84% of groins, and 80% of riprap areas are in good condition. The most degraded areas are those with the most exposure and large fetches, that is, Peddocks, Rainsford, Georges, Gallops, Great Brewster, Bumpkin, Sheep, and Thompson islands, as well as some parts of Worlds End and Lovells Island (Bourne Consulting Engineers 2009; FitzGerald et al. 2011). The seawalls on Gallops, Georges, Great Brewster, Peddocks, and Rainsford islands are in poor condition (FitzGerald

Figure 30. Photographs of coastal engineering structures. Clockwise from top left is (1) a granite seawall with downtown Boston in the background from Lovells Island, (2) riprap armoring the north shore of Spectacle Island, (3 and 4) rapid erosion around a failed coastal engineering structure at Lovells Island. Top left photograph is figure 3 in Thompson et al. (2011). Top right photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken July 2007. Bottom two photographs by Allen Gontz (University of Massachusetts, Boston), taken April 2015.

et al. 2011; Vaux et al. 2012). Some of these structures are considered historic, however, and although they are not effective at preventing erosion, preservation, restoration, and/or reconstruction of them is of some interest (Peter Rosen, Northeastern University, coastal geologist, conference call, 7 April 2015). Future projects in the national recreation area may include restoring historic seawalls and revetments on several islands. They stand as examples of early applications of coastal engineering in the United States; in some cases, they are more than 150 years old (see "Geologic Significance and Connections"). Despite this interest, no specific project is currently in place, and resource management would need to consider any actions on a case-by-case basis. The protection of island resources and park facilities would likely take precedence over a particular historic engineering structure (Marc Albert, Boston Harbor Islands NRA and Saugus Iron Works National Historic Site, resource stewardship manager, conference call, 7 April 2015).

Nordstrom and Jackson (2016) presented case studies on northeast Lovells Island and north Thompson Island to illustrate problems and opportunities involved in removing protective structures where the rationale for their construction has changed. The former is a seawall that once protected Fort Standish; the latter is a seawall outboard of a ropes course and recreational area. Removing these structures may cause complex reactions in the sedimentary dynamics of the area but

Table 5. Coastal engineering structures at Boston Harbor Islands.

Island/ Peninsula	Seawalls	Breakwater	Revetment	Jetty	Groins	Riprap
Bumpkin	No	No	No	No	Yes, material unknown	No
Calf	Yes, material unknown	No	No	No	No	No
Deer	Yes, granite and concrete	No	No	Yes, split stone	Yes, stone	No
Gallops	Yes, granite	No	Yes, rubble	Yes, stone	No	No
Georges	Yes, material unknown	No	Yes, material unknown	No	Yes, stone	Yes
Great Brewster	Yes, granite and concrete	No	Yes, material unknown	Yes, stone	Yes, material unknown	No
Long	Yes, granite	No	Yes, material unknown	Yes, stone	No	Yes, rubble-stone apron
Lovells	Yes, granite	Yes, material unknown	Yes, material unknown	Yes, material unknown	Yes, material unknown	Yes, rubble-stone apron
Moon	Yes, stone	No	Yes, stone	No	No	Yes, material unknown
Peddocks	Yes, material unknown	No	No	No	Yes, material unknown	No
Rainsford	Yes, granite	No	Yes	No	No	No
Sheep	No	No	Yes	No	No	No
Spectacle	Yes, granite and concrete	No	Yes, stone	No	No	Yes
Thompson	No	No	Yes, stone	No	No	No
Worlds End	No	No	Yes, stone	No	Yes, material unknown	Yes, boulders

Sources: Bourne Consulting Engineering (2009); Coburn et al. (2010); FitzGerald et al. (2011).

is projected to ultimately lead to the greater supply of sediment to adjacent beach areas and a return to natural conditions. Nordstrom and Jackson (2016) also presented a valuable discussion of management considerations for coastal engineering structures.

Because of its status as a recreation area and part of the Boston Harbor Islands Partnership, visitor safety and access to the islands are resource management priorities. Shoreline access features and the coastal engineering structures associated with them can interfere with vegetation and natural coastal processes such as longshore drift (Thornberry-Ehrlich 2008). The access dock for Spectacle Island changed the local sedimentation patterns, which increased erosion along the adjacent marina and beach. Shoreline erosion below the supports for the former bridge between Moon and Long islands prompted the introduction of stabilizing engineering structures.

In 1978, the Commonwealth of Massachusetts adopted policies concerning the protection, development, and revitalization of coastal resources within the state. As stated in the NPS Management Policies 2006 (§ 4.8.1.1; see also Appendix C of this GRI report and Coburn et al. 2010), "the Service will comply with the provisions of Executive Order 11988 (Floodplain Management) and state coastal zone management plans prepared under the Coastal Zone Management Act of 1972." The Massachusetts Office of Coastal Zone Management (CZM) website (http://www.mass.gov/eea/agencies/czm/) documents their management policies, as well as provides links to programs such as the StormSmart Coasts (http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/). This program area provides information, strategies, and tools to help address the challenges of coastal erosion, flooding, storms, sea level rise, and other climate change impacts. The program also promotes effective, science-based management of coastal landforms, such as beaches and dunes. The Massachusetts Coastal Infrastructure Inventory and Assessment Project is developing a GIS database to include information for each coastal engineering structure such as location, ownership, type, material, height, condition, length, elevation, and priority rating (Bourne Consulting Engineers 2009). Detailed, site-by-site descriptions, photographs, and other information relevant to Boston Harbor Islands National Recreation Area are available at http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/ (see PDFs under "Boston Harbor"). The inventory for Massachusetts was completed in 2009 and is now in the process of being updated (Rebecca Haney, Massachusetts Office of Coastal Zone Management, coastal geologist, conference call, 7 April 2015). An NPS-specific coastal engineering inventory report was developed for Boston Harbor Islands National Recreation Area by Coburn et al. (2010). That report provided a summary of the coastal engineering projects including coastal structures such as seawalls, dredge and fill projects (e.g., inlets), beach nourishment, and dune construction projects. The report included historic data, imagery, cost, and a discussion of impacts (where available and appropriate); it accompanies a Geographic Information Systems (GIS) database. FitzGerald et al. (2011) presented GIS-based maps of coastal engineering structures with notes of overall condition. Coburn et al. (2010) recommended a study to evaluate the direct, secondary, and long-term cumulative impacts of coastal engineering projects on coastal processes and coastal habitats within a coastal national park. Boston Harbor Islands National Recreation Area would be a prime candidate for such a study. Park managers are encouraged to contact the NPS Geologic Resources Division for additional information.

Abandoned Mineral Lands and Disturbed Lands

For hundreds of years, the Boston Harbor Islands have been shaped by human activities. Coastal engineering structures are just one example. Resource management issues associated with coastal engineering structures are described in a previous section of this report. Other land-use practices disturbed the landscape and may require mediation and/or restoration. Such uses include stone quarrying (features could now be considered abandoned mineral lands), construction, trash dumping, and wastewater treatment.

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the NPS takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources. Possible AML features may include adits, prospects, shafts, structures, open pits, tunnels, waste rock piles, mills, wells, and landform modifications such as service roads, drainage diversions, and drill pads.

Quarrying has occurred on many islands. As of September 2016, however, no AML sites or features from Boston Harbor Islands National Recreation Area have been added to the NPS AML database (see Burghardt et al. 2014 for summary). The history of utilizing the rocks of the Boston Harbor Islands begins well before the colonial period. For example, a rhyolite (fine-grained volcanic rock) boulder at Long Island was flaked for tool material by American Indians (Luedtke and Rosen 1993). Colonial era quarrying of slate in the Cambridge Argillite (geologic map unit **CZca**) occurred on Hangman Island and the northwest side of Slate Island in colonial times (see fig. 25; Snow 1971; Seaholes 2009; Thompson et al. 2014). Diabase(**J[?]Zdo**) was extracted from the Austin quarry on Outer Brewster Island. Arthur W. Austin wanted to excavate a canal-shaped harbor on the island and sent much of the quarried stone to the mainland (Snow 1971; Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016). Some of this quarried stone is visible on building exteriors in Charlestown, Massachusetts. Quarrying of argillite occurred to such an extent on Nixes Mate that the island was reduced from a sheep pasture to a single buoy indicating submerged land. The last known quarry activity was in 1980. Quarry features are still visible on Outer Brewster and Slate islands. In addition to quarrying for building stone, rocks of the Boston Harbor Islands were removed in great quantities to be used as ballast for ships. For example, the Boston Marine Society reported in 1846 that approximately 62,000 tons of stone and gravel were taken annually from the Harbor Islands. This contributed to early and ongoing erosion concerns on islands such as Bird Island (Seaholes 2009).

AML features pose a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals, some of which may be protected under the Endangered Species Act or state species listings. Resource management of AML features requires an accurate inventory and reporting, which identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources. The NPS AML website, http://go.nps.gov/aml, provides further information. All AML features should be recorded in the servicewide AML database; the NPS Geologic Resources Division can assist park managers.

Other Disturbed Lands

Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by development, including facilities, military bases, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use. Some of these features may be of historical significance, but most are not in keeping with the mandates of the National Park Service.

Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities. Restoration activities return a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline.

Ongoing projects seek to assess and conserve cultural resources of the islands with respect to their location relative to coastal hazard zones and predicted sea level rise (Wagenknecht et al. 2009; Maio and Gontz 2009). Relocating cultural resources may be a management option; for example, Revolutionary War era cemeteries on Long Island are being relocated (Thornberry-Ehrlich 2008; Maio and Gontz 2009).

Historic land use was not always conducive to future ecological health or visitor safety. Artificial fill (geomorphic map unit **Qaf**, locally) makes up much of the Boston area's substrate. Spectacle Island, in addition to functioning as a municipal landfill from 1912 to 1959, was a deposition site for more than 2,300,000 m^3 (3,000,000 yd^3) of nonhazardous tunnel construction debris as part of revitalizing the island for park uses (Flora 2002). This material from the "Big Dig" raised the island 24 to 30 m (80 to 100 ft). Some of the original landfill material contained hazardous material such as asbestos (a fibrous mineral used as an industrial material that can cause lung damage if disturbed and inhaled). For the first several years after the island opened to visitors, the caretaker at Spectacle Island picked up asbestos debris there, which appears as beige or black squares and/or triangles (fig. 31; GRI conference call participants, 7 April 2015). Asbestos was used in some military buildings dating back to World War II. Asbestos-tile remediation is needed on Gallops, Outer Brewster, and Great Brewster islands (Vaux et al. 2012). Gallops Island has fill material and is now closed because of asbestos debris littering the beach. Part of the national recreation area's 2009 strategic plan was to have Gallops Island reopened to the public by 2016 (National Park Service 2009) but remediation is ongoing, and the target date for reopening has been pushed back (Marc Albert, Boston Harbor Islands NRA, resource stewardship program manager, written communication, 31 May 2016). On the northern end of Peddocks Island, the abandoned structures of Fort Andrews pose lead paint and asbestos issues (Flora 2002). Long Island also has significant fill material. Another possible project is to restore trash dumps on Rainsford Island (Thornberry-Ehrlich 2008; Maio and Gontz 2009).

Other disturbed features at the national recreation area include old wells and storage tanks. Several islands have unused open wells that are a safety and contamination hazard (Vaux et al. 2012). Remediation and/or replacement of underground storage tanks occurred on Great Brewster and Thompson islands (Vaux et al. 2012). As part of the national recreation area's 2009 strategic plan was the outcome to reduce solid waste that must be removed from the islands by 40% and to establish a parkwide materials management system for unwanted materials being brought off the islands by 2016 (National Park Service 2009).

Deer Island has a large wastewater treatment facility. In 1985, a court ruling stated that the then-malfunctioning plant was violating the 1972 Clear Water Act and led to the formation of the 15-year Boston Harbor Project, which modernized facilities and improved water and sediment quality throughout the harbor (Vaux et al. 2012). Now, Deer Island Treatment Plant treats Boston's wastewater before discharging the effluent into

Figure 31. Photograph of asbestos debris on Spectacle Island beach. Asbestos from dumping and landfill activities frequently washes up on several beaches at Boston Harbor Islands, including the swimming beaches flanking either side of the visitor center and ferry dock at Spectacle Island. Informative signage is in place about the appearance and hazards posed by asbestos about 300 m (980 ft) from the swimming beach. Inset image shows an aerial view of the beach and ferry dock. National Park Service photographs presented as part of a PowerPoint presentation in 2009.

Massachusetts Bay (Flora 2002). An offshore sewage tunnel extends nearly 13 km (8 mi) into the harbor.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix C). As of February 2017, Department of the Interior regulations associated with the act were being finalized. National Park Service regulations stipulate that fossils may be collected in parks only for scientific or educational purpose pursuant to a National Park Service–approved research and collection permit (Brunner et al. 2009). Unauthorized fossil collecting may be taking place within the recreation area (Thornberry-Ehrlich 2008; Joe Kopera, Massachusetts Geological Survey, geologist, written communication, 7 April 2016) although additional investigation is needed to confirm. According to Brunner et al. (2009), stopping unauthorized fossil collection along park shorelines is particularly difficult because of regulatory confusion (e.g., determining fossil from modern seashells, which may be collected at some parks), jurisdictional confusion (e.g., park boundary changes with tides), enforcement difficulty (e.g., remote and vast areas are hard to patrol), and public perception (e.g., people see fossil collection as traditional and fail to see the harm).

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a park-specific survey has not yet been completed for Boston Harbor Islands National Recreation Area, a variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance.

Tweet et al. (2010) provided a thorough literature synopsis of the known and potential fossil resources at Boston Harbor Islands National Recreation Area and provided the following guidance about managing the paleontological resources:

- Park staff should be encouraged to observe exposed sedimentary rocks and loose sediments for fossil material while conducting their usual duties.
- Staff should photodocument and potentially monitor any occurrences of paleontological resources that may be observed in situ.
- Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts.
- Future archeological excavations or infrastructure developments should consider scheduling site monitoring by a trained paleontologist in order to document and protect fossil resources.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. Brunner et al. (2009) recommend the following strategies to manage coastal fossil collecting issues: (1) provide more outreach, education, and interpretation; (2) exploit servicewide survey and guidance, (3) consider and incorporate social science data; (4) encourage and support more fossil monitoring and data collection by scientists, amateur collectors, local fossil clubs, and students, and (5) revise National Park Service regulations.

Seismic Activity Hazards and Risks

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Many earthquakes in New England are attributed to glacial rebound rather than active tectonic forces (Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016).

Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety.

Boston Harbor Islands National Recreation Area is not located near an active seismic zone. The potential for large earthquakes is low but does exist because ancient faults cut through the harbor (see "Faults"). The US Geological Survey's earthquake probability maps (https://geohazards.usgs.gov/eqprob/2009/) indicate a 0.04 to 0.06 probability (4% to 6% "chance") of a

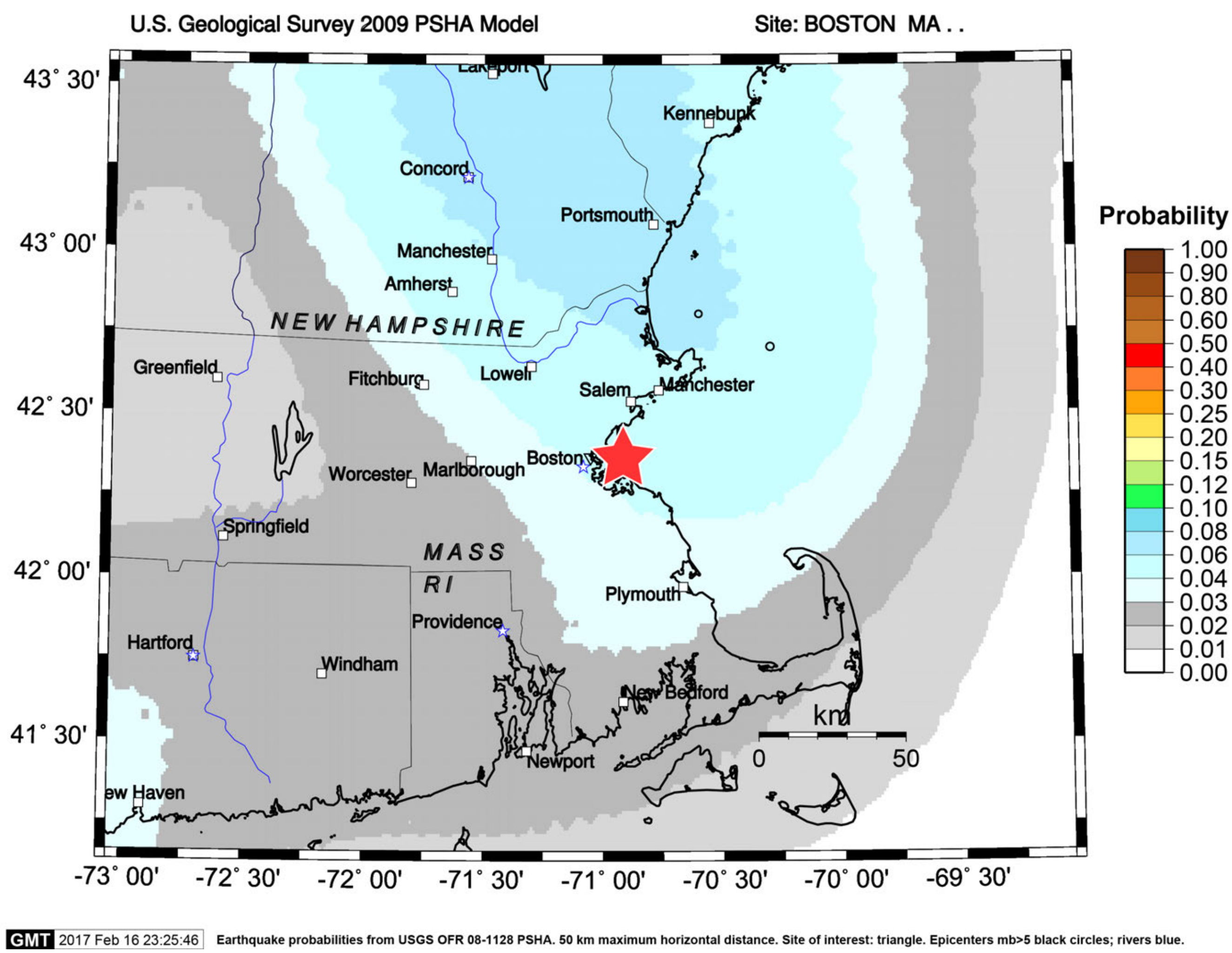


Figure 32. Map of earthquake probability with magnitude greater than 5.0 (moderate earthquake). This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Boston Harbor, Massachusetts (red star). Graphic was generated by the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php).

magnitude-5.0 or greater earthquake occurring within the next 100 years (fig. 32) (Peterson et al. 2008). Small earthquakes (between magnitude 2 and 3) occasionally take place, but most of these events are imperceptible by humans. These typically occur along northwest trending faults in the Nashoba terrane, west of Boston Harbor.

Historically, several large earthquakes have affected the Boston Harbor Islands. The 1755 earthquake near Cape Anne had an estimated magnitude of 6.4. Shaking was strong enough to ring bells, topple chimneys and weather vanes, and damage stone walls across an area stretching between Portland, Maine, to Hartford, Connecticut. If such an even were to occur today, the damage estimate would cost billions of dollars (Thornberry-Ehrlich 2008). The 2011 Virginia earthquake caused major damage in an area that was likewise considered to be relatively inactive.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. The nearest seismic station is at the Weston Observatory (http://www.bc.edu/research/westonobservatory/). Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring), and the US Geological Survey Earthquakes Hazards website (https://earthquake.usgs.gov/) provide more information.

Loss of Aeolian Features

Dunes are an important "sink" of limited amounts of sand in the sediment-starved Boston Harbor system (Peter Rosen, Northeastern University, coastal geologist, written communication, 24 May 2016). The dunes on Lovells Island (geomorphic map unit **Qds**) are reducing in size whereas the dunes on the south end of Thompson Island are actively accumulating sand (Peter Rosen and Duncan FitzGerald, Northeastern University and Boston University, respectively, coastal geologists, written communication, 24 and 25 May 2016). For resource managers, a critical need is to recognize if any reduction in dune size is a natural outcome of a sediment-starved system or if human activities are contributing to the loss of the resource. Native vegetation is commonly planted as a method of stabilizing dunes.

Park managers working to develop additional monitoring protocols for dunes and other aeolian features can contact their Inventory and Monitoring network and/or consult existing standard operating procedures such as those defined in the *Geological Monitoring* chapter about aeolian features and processes by Lancaster (2009). The following methods and vital signs were defined for monitoring aeolian resources: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape.

The rocks within and around Boston Harbor Islands span more than 600 million years, from the Proterozoic Eon to the present (see fig. 3). The geologic history of Boston Harbor Islands National Recreation Area is recorded by (1) Precambrian and Paleozoic metamorphic and igneous rocks formed and deformed during the early construction of the Avalon terrane, (2) deformation and accretion of the terrane onto North America during the formation of the supercontinent Pangaea at the end of the Paleozoic Era, (3) Mesozoic igneous rocks that intruded the area as Pangaea rifted apart, (4) ice age (Pleistocene) glacial deposits, and (5) post-glacial (Holocene) coastal deposits. These geologic events and the resulting rocks and deposits formed the landscape that has made Boston Harbor Islands an ideal location for myriad human uses over the past few hundred years.

Proterozoic Eon (2.5 Billion to 541 Million Years Ago): Formation of the Avalon Terrane and Its Detachment from Gondwana

Throughout Earth's history continents have drifted, collided, rifted apart, and recombined, culminating in the landmasses that persist today (figs. 33 and 34). Most of New England is composed of blocks of Earth's crust that originated elsewhere and then accreted onto the edge of North America. Such blocks are referred to as "terranes." The details regarding the origin, formation, and timing of assembly of individual terranes are a subject of much debate and current research (Skehan 2001).This summary discusses the basics of the Avalon terrane which underlies Boston Harbor.

The sedimentary and igneous rocks that would become the Avalon terrane formed during the Neoproterozoic Era, more than 600 million years ago. The rocks were originally located along the west coast of a massive continent called Gondwana at mid-latitudes south of the equator (Thompson et al. 2007, 2014). Antarctica, South America, Africa, Madagascar, Australia, and other smaller landmasses in existence today were once part of Gondwana. Paleomagnetic signatures in the Avalon terrane indicate the Boston area was attached to, or located near, what is now West Africa as part of Gondwana (Thompson et al. 2007; Tweet et al. 2010). Gondwana was separated from Laurentia (proto-North America) by the Iapetus Ocean.

At that time, the west coast of Gondwana was similar to the modern Andes Mountains of South America. A subduction zone was fueling volcanoes and creating an immense amount of molten material that would later cool into plutonic rocks (fig. 35A) (Hepburn et al. 1993; Skehan 2001; Linnemann et al. 2007; Tweet et al. 2010). The porphyritic volcanics (**Zvp**), melaphyric volcanics (**Zvm**), and tuff (**Zvt**) in the national recreation area record these ancient volcanoes. The plutons are now mapped as granitic plutonic rocks, undifferentiated (**Zgr**) (Thompson et al. 2011). The mountains created by this compressional setting and subduction zone are called the Avalonian Mountains.

Marine basins along the coast of Gondwana, including what geologists now call the Boston Basin, collected submarine sediments (fig. 35B) (Hepburn et al. 1993; Skehan 2001). The Boston Basin was the center of deposition for the Boston Bay Group, including the Roxbury Conglomerate (**Zcr**) and the Cambridge Argillite (**CZca**) with diamictite interlayers (**Zdm**) (Thompson et al. 2011, 2014). At first, during the Neoproterozoic Era, the basin collected coarse conglomerates including pebbles of volcanic rocks, quartzite, and granites. As sedimentation proceeded, the composition changed to finer-grained argillites dominated by sandstones, quartzites, and siltstones (Lenk et al. 1982; Kaye 1980; Kopera 2011). As the basin rapidly subsided and deepened, slumping within the soft sediments occurred, and deep marine density flows (i.e., submarine landslides) deposited turbidites across the basin floor burying microbial mats (Smith and Socci 1987, 1990; Bailey and Bland 2000; Bailey 2005). Deposition in the Boston Basin continued into at least the early Cambrian Period as the Cambridge Argillite (**CZca**) accumulated (Goldsmith 1991; Thompson et al. 2007, 2011).

By about 550 million years ago, pieces of Gondwana broke apart and were moved west across the Iapetus Ocean toward Laurentia. A marine basin called the Rheic Ocean formed between the rocks of the Avalon and other terranes and what remained of Gondwana (fig. 35B) (Coleman 2005; Linnemann et al. 2007).

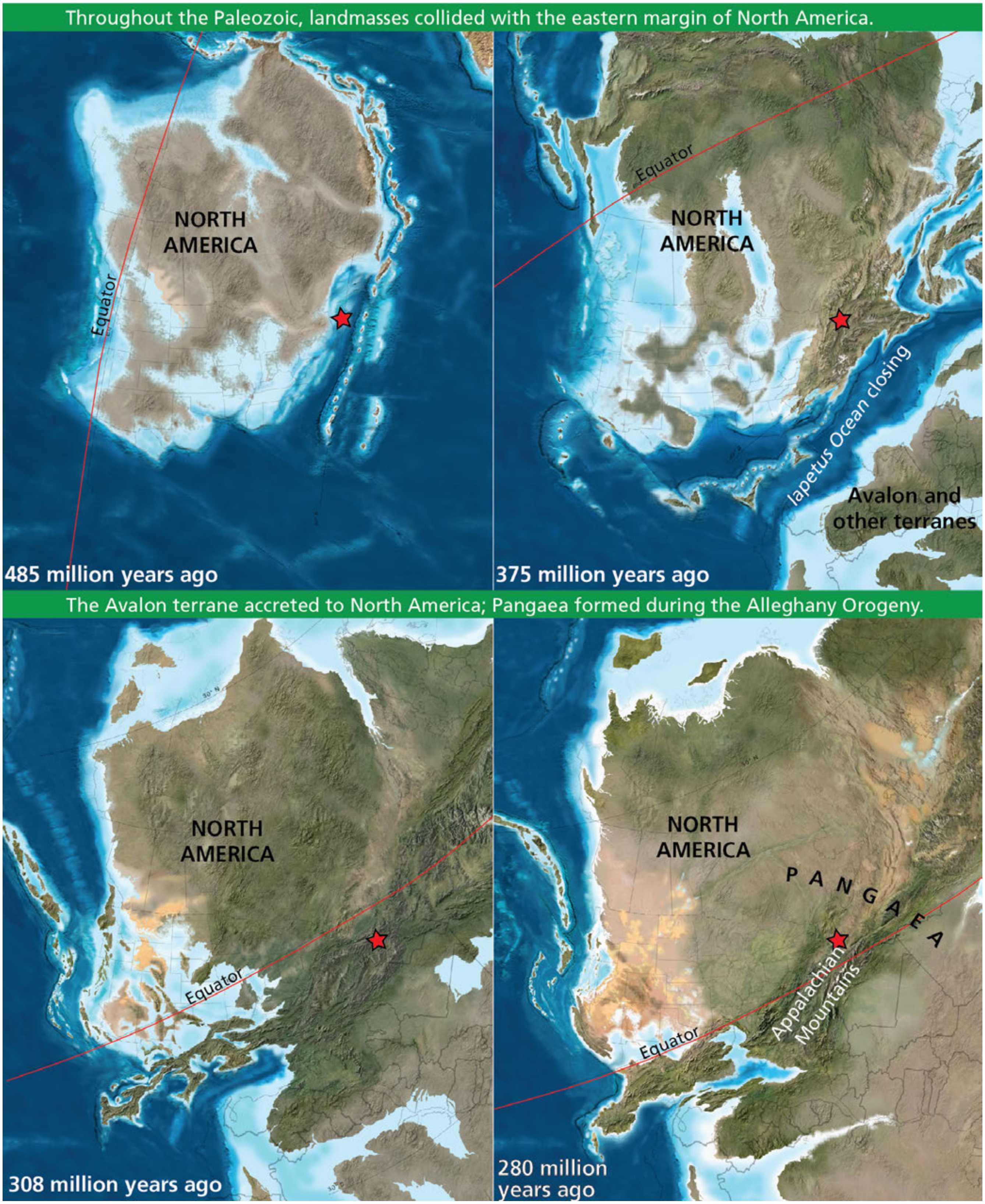

Throughout the Paleozoic, landmasses collided with the eastern margin of North America.
NORTH AMERICA
Equator
485 million years ago
NORTH AMERICA
Equator
Iapetus Ocean closing
Avalon and other terranes
375 million years ago
The Avalon terrane accreted to North America; Pangaea formed during the Alleghany Orogeny.
NORTH AMERICA
Equator
308 million years ago
NORTH AMERICA
PANGAEA
Appalachian Mountains
Equator
280 million years ago

Figure 33 (facing page). Paleogeographic maps of North America during the Paleozoic Era. Red star indicates the location of Boston Harbor Islands National Recreation Area. The approximate location of the equator is denoted by a red line. During the Ordovician Period, 485 million years ago, the Boston Harbor Islands area was dominated by open marine settings as a volcanic arc was approaching the eastern margin of North America. During the Devonian Period (375 million years ago), the Iapetus and Rheic oceans were closing as other landmasses collided with North America during the Acadian Orogeny. The Avalon terrane was one of several terranes accreted to the margin of North America during the Paleozoic orogenies. During the Pennsylvanian Period (308 million years ago), the Alleghany Orogeny formed the Appalachian Mountains. The Appalachian Mountains reached their highest elevation during the Alleghany Orogeny. At 280 million years ago, nearly all the continental crust in existence was sutured together to form Pangaea. Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems; available online: http://cpgeosystems.com/paleomaps.html) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

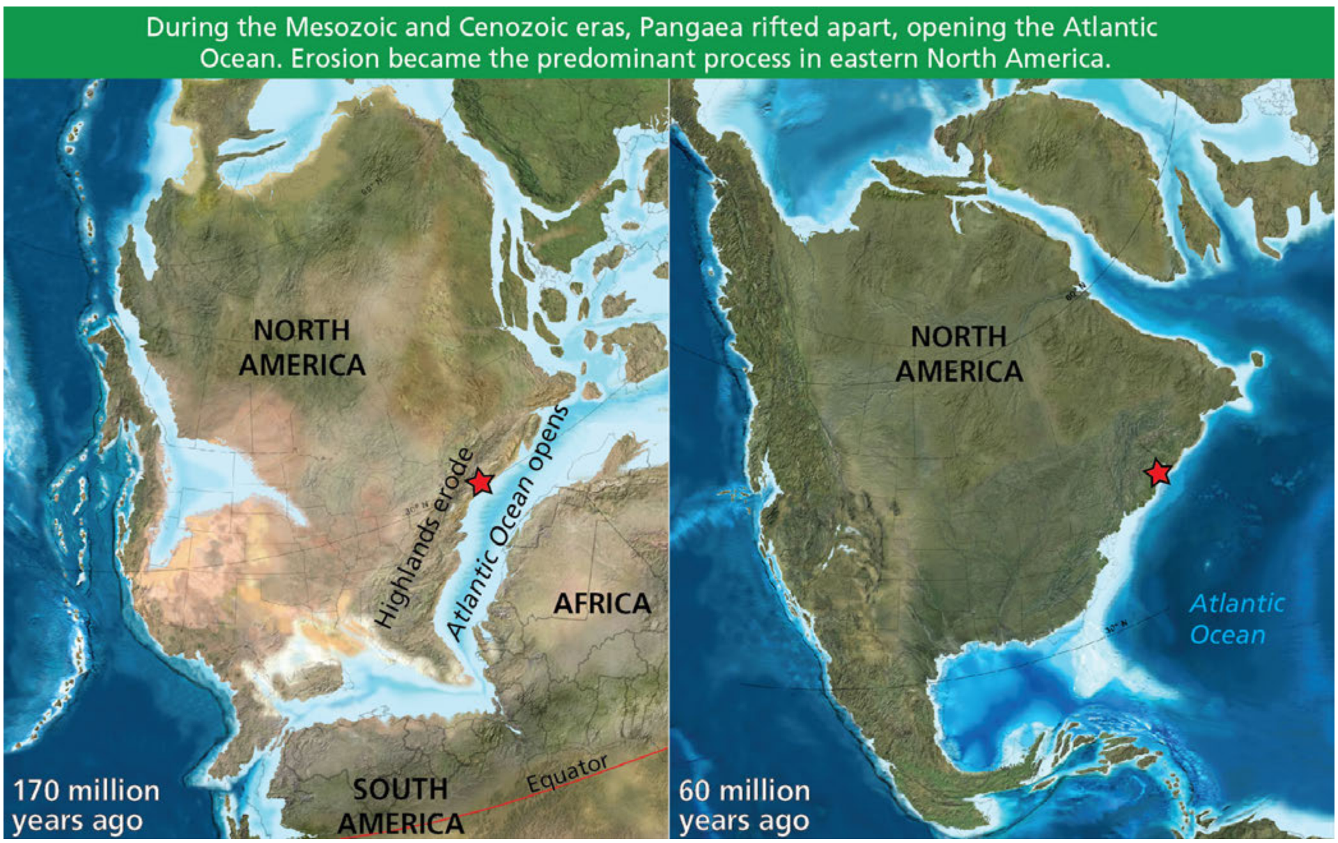
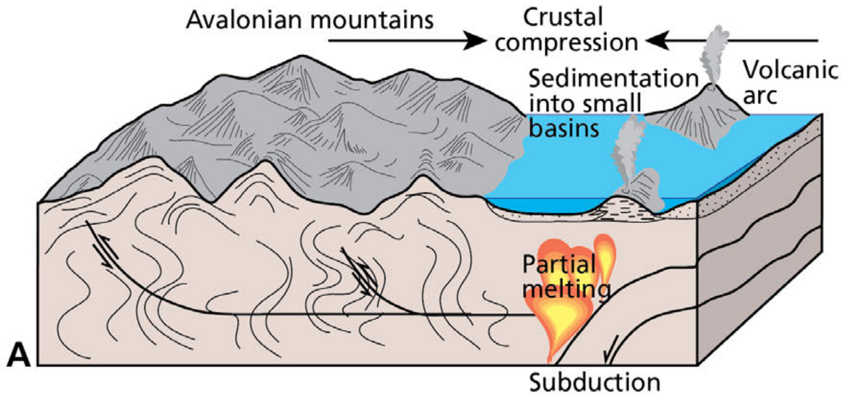
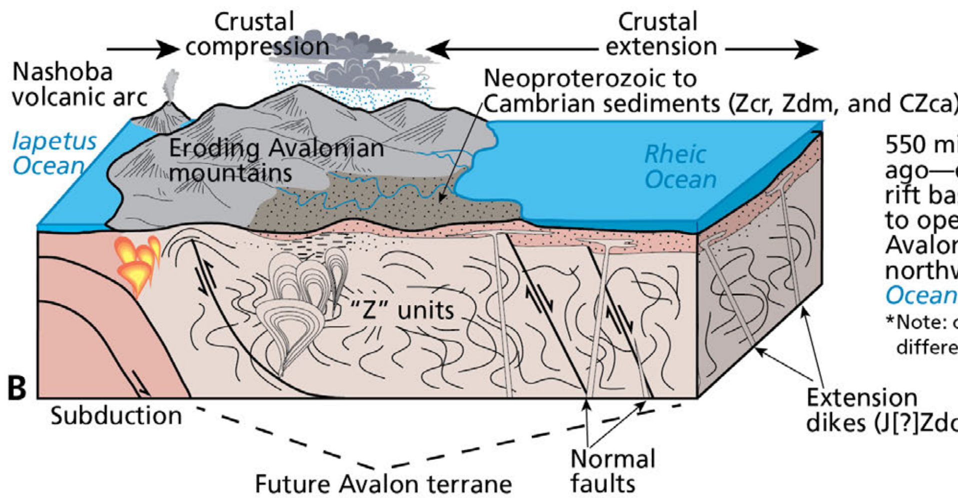


Figure 34. Paleogeographic maps of North America during the Mesozoic and Cenozoic eras. Red star indicates the location of Boston Harbor Islands National Recreation Area. The approximate location of the equator is denoted by a red line. By the Jurassic Period of the Mesozoic Era (170 million years ago), the supercontinent had broken up and roughly the continents that exist today drifted away from North America as the Atlantic Ocean spread. Throughout the rest of the Mesozoic Era and into the Cenozoic Era, the Boston Harbor Islands area was relatively tectonically quiet. Erosion lowered the mountains and built the Coastal Plain toward the widening Atlantic Ocean. The coastline continued to evolve to resemble its current shape. Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems; available online: http://cpgeosystems.com/paleomaps.html) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

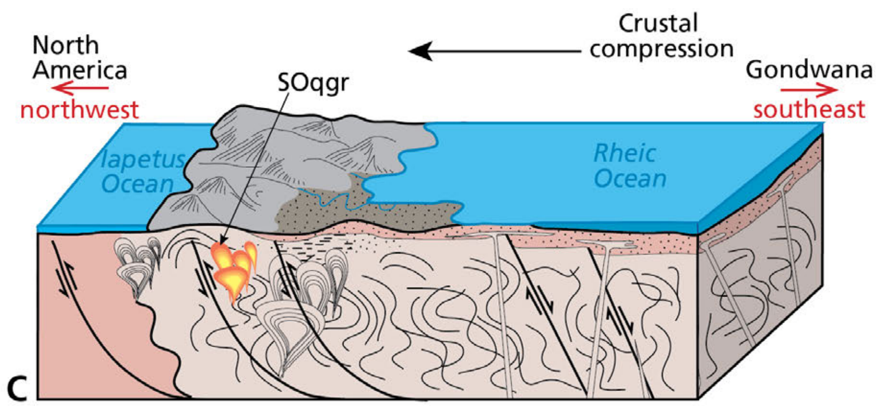


610 million years ago—the Avalonian Orogeny involved a subduction zone where partial melting of the downgoing plate led to igneous intrusions and volcanism above; extensive deformation and metamorphism took place. Interlayered sediments and volcanic deposits collected in the basins.



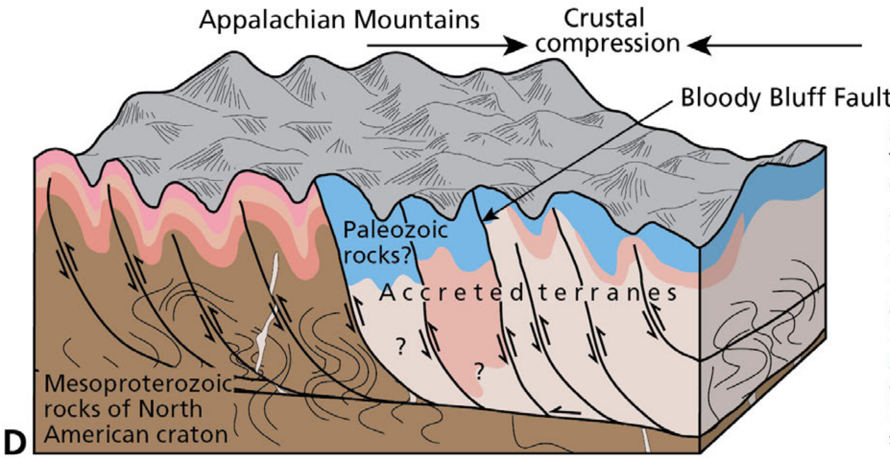
550 million to 500 million years ago—extension of the crust caused rift basins such as the Boston Basin to open and collect sediments; Avalon terrane rifts away from northwestern Gondwana; *Rheic Ocean* began to open.

*Note: colors in cross section represent different periods of geologic time.



378 million years ago—Avalon and associated terranes are pushed between the shrinking *Rheic* and *Iapetus oceans*, traveling northwestward to eventually collide with North America; internal deformation and crustal melting caused local emplacement of Quincy Granite (SOqgr) into the Avalon terrane.

Figure 35 A–C. Schematic graphics illustrating the evolution of the Boston Harbor Islands National Recreation Area landscape. Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich, with information from Hepburn et al. (1993), Skehan (2001), Coleman (2005), Linneman et al. (2007), Thompson et al. (2007), and Kopera (2011).



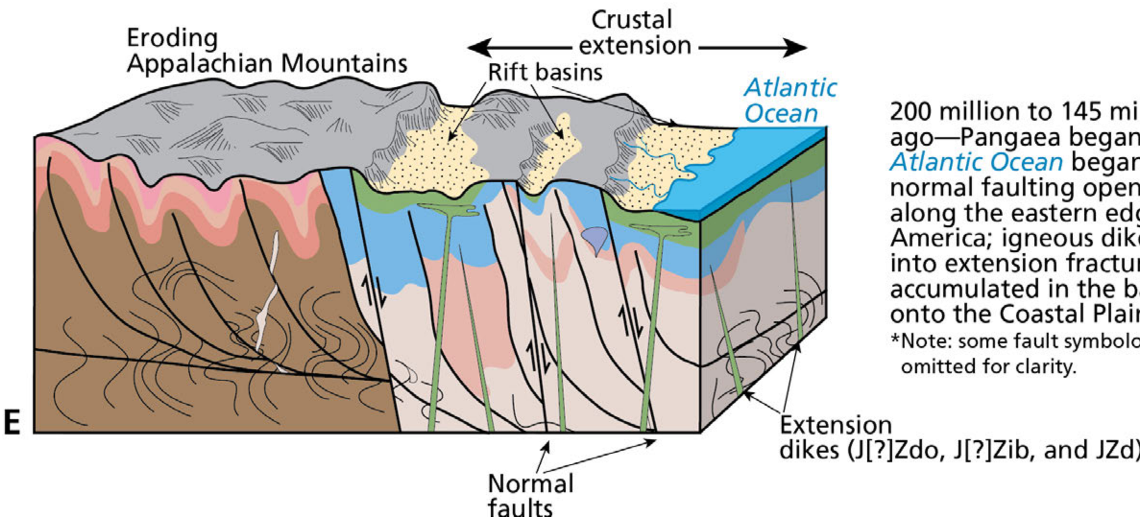


Figure 35 D–E. Schematic graphics illustrating the evolution of the Boston Harbor Islands National Recreation Area landscape, continued. Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich, with information from Hepburn et al. (1993), Skehan (2001), Coleman (2005), Linneman et al. (2007), Thompson et al. (2007), and Kopera (2011).

Paleozoic Era (541 Million to 252 Million Years Ago): Mountain Building, Terrane Accretion, and the Formation of a Supercontinent

Over hundreds of millions of years, the Avalon terrane, other terranes, and eventually the rest of Gondwana collided with Laurentia in a serious of collisions that would ultimately culminate in the creation of the Appalachian Mountains and the supercontinent Pangaea. In northeastern North America, these collisions are known as the Taconic, Acadian, and Alleghany orogenies (mountain-building events).

The Taconic Orogeny began during the Ordovician Period approximately 488 million to 440 million years ago (see fig. 3). It involved the collision of volcanic island arcs with the eastern margin of what would become North America. Because the Avalon terrane was not part of North America at that time, no trace of this orogeny occurs within the rocks of Boston Harbor Islands National Recreation Area.

By the Middle Devonian Period, about 375 million years ago, landmasses were converging again along the eastern seaboard of ancient North America, and the Iapetus oceanic basin continued to shrink as the African continent was approaching. This marked the onset of the Acadian Orogeny, an event focused in New England and recorded by folds, faults, and igneous intrusions (see fig. 3) (Epstein and Lyttle 2001). Similar to the Taconic Orogeny, the Acadian Orogeny (fig. 35C) involved landmass collision, mountain building, and regional metamorphism (Means 1995).

Approximately 325 million to 265 million years ago, Gondwana collided with the North American continent during the Alleghany Orogeny (fig. 35D, see fig. 3). This closed the Iapetus and Rheic ocean basins and was the last major orogeny to contribute to the formation of the Appalachian Mountains.

Taconic, Acadian, and Alleghany orogenies sutured Earth's landmasses together into a supercontinent called Pangaea (fig. 35D) (Levin 1999; Skehan 2001; Tweet et al. 2010). Geologists hypothesize that the Avalon terrane accreted to North America during the Acadian Orogeny, approximately 375 million years ago (e.g., Coleman 2005), or during the Alleghany Orogeny, between 325 million and 265 million years ago (e.g., Skehan 2001).

Quincy Granite (**SOqgr**) intruded into the rocks of Avalon terrane sometime after about 500 million years ago but before 400 million years ago. The many faults, folds, deformed areas (see GRI GIS folds and faults data layers and sections of this report), the brecciated melt zone on Green Island ("Deformation Areas" layer in the GRI GIS data), and the myriad intrusions suggest a long history of internal deformation and change within the terrane prior to its accretion. Geochemical signatures within some of the igneous dikes and sills (**JZd** and **J[?]Zdo**) suggest a subduction zone and island-arc origin as part of this history, but the timing of such an event is unknown (Thompson et al. 2014). The Boston Harbor sills were deformed presumably by Alleghany orogenic folding (Thompson et al. 2012, 2014). The Cathedral fault then cut through the fold structures in Boston Harbor (Thompson et al. 2012, 2014). Regardless of how, or exactly when, it arrived, by some point in the late Paleozoic Era, the Avalon terrane had collided with the eastern margin of Laurentia (proto-North America) and was near the center of Pangaea (figs. 33 and 35D).

Mesozoic Era (252 Million to 66 Million Years Ago): Pangaea Rifts Apart and the Appalachians Erode

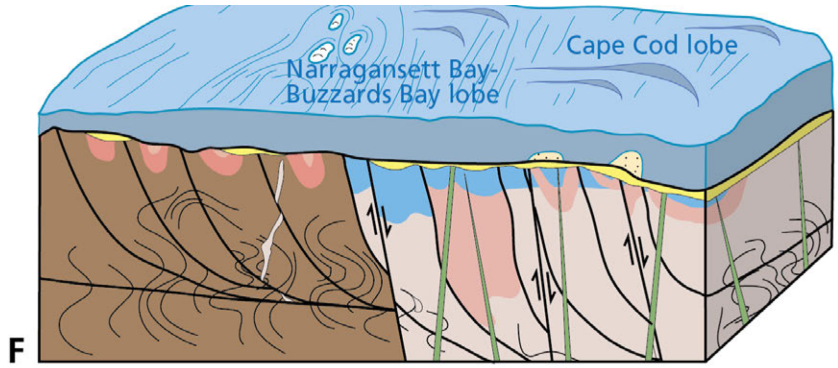
Pangaea was not to last. During the Triassic and Jurassic periods, rifting pulled what would become Africa and South America apart from North America to form the Atlantic Ocean and Gulf of Mexico (fig. 35E, see fig. 3). Intrusions of molten magma were again forced upwards. Some of these intrusions may be the less altered, undeformed diabase and doleritic sills and dikes (**JZd**) that occur throughout the recreation area (Kaye 1980; Thompson et al. 2011; Peter Thompson, University of New Hampshire, geologist, written communication, 25 March 2016). Continental rifting formed many basins along eastern and southern North America at the base of the Appalachian Mountains. Steeply dipping normal faults formed the boundaries of these basins, which quickly filled with sediment eroded from the surrounding mountains. Great portions of the once Alps-like Appalachian Mountains eroded into much lower features; other areas were buried by younger sediments of the Coastal Plain that were derived from the weathering mountains.

Weathering and erosion dominated the relatively quiet geologic history of the Boston Harbor Islands area throughout the Mesozoic Era and most of the following Cenozoic Era (see fig. 3). Rivers transported sediments worn from the highlands to build the Coastal Plain towards Massachusetts Bay and the Atlantic Ocean. Because different types of rocks are more or less resistant to erosion, some areas eroded faster than others. The hard granites, quartzites, and metamorphic rocks surrounding the Boston Basin were more resistant to erosion than the sedimentary rocks within the basin and remained as highlands on the basin's rim.

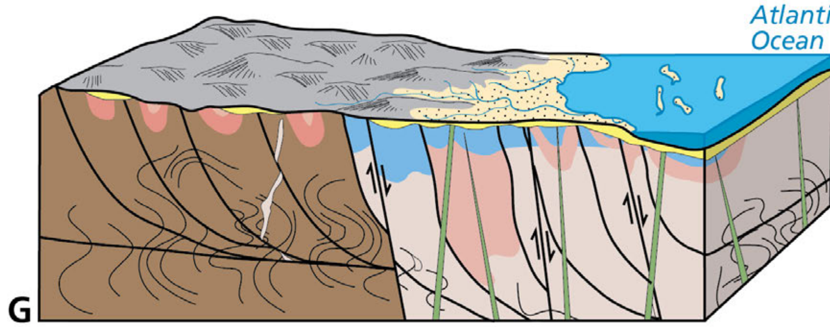
Cenozoic Era (66 Million Years Ago to Present): Ongoing Weathering, Glaciations, and Modern Landform Development

With the exception of glacial and surficial deposits from the past 2 million years, any rocks deposited since the breakup of Pangaea are now eroded from the Boston Harbor Islands National Recreation Area (Masterson et al. 1996). In other words, no rocks younger than the Jurassic Period occur in the national recreation area (see fig. 3). Weathering and erosion were likely the most important earth-surface processes prior to glaciation (Kaye 1967b; Colgan and Rosen 2001).

The Boston Harbor Islands area was greatly affected by glaciers descending south from the Arctic periodically during the Pleistocene Epoch (between 2.59 million and 12,000 years ago) (fig. 35F, see figs. 3 and 12). The glacial history of the Boston area is complex with stratigraphic evidence pointing to at least five glacial ice advances and three major marine transgressions (indicative of glacial ice retreat/melting) (Riegler 1981). Boston is located near the meeting place of two glacial lobes of a continental ice sheet—the Narragansett Bay-Buzzards Bay lobe to the west and the Cape Cod Bay lobe to the



145 million to 15,000 years—*Atlantic Ocean* continued to widen; continental margin became passive; earth surface processes wore away the highlands and removed vast amounts of material from the landscape; glacial processes during the Pleistocene Epoch carved Boston Harbor and deposited the glacial till into drumlins.

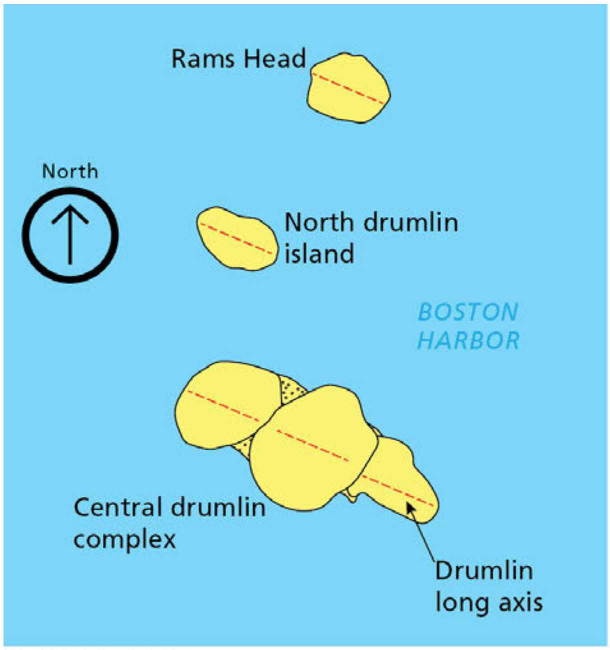


Past 10,000 years—glaciers retreated; the land surface rebounded; coastal processes began to form the shorelines of Boston Harbor Islands processes during the Pleistocene Epoch; fluvial systems such as the Neponset, Charles, and Mystic rivers developed.

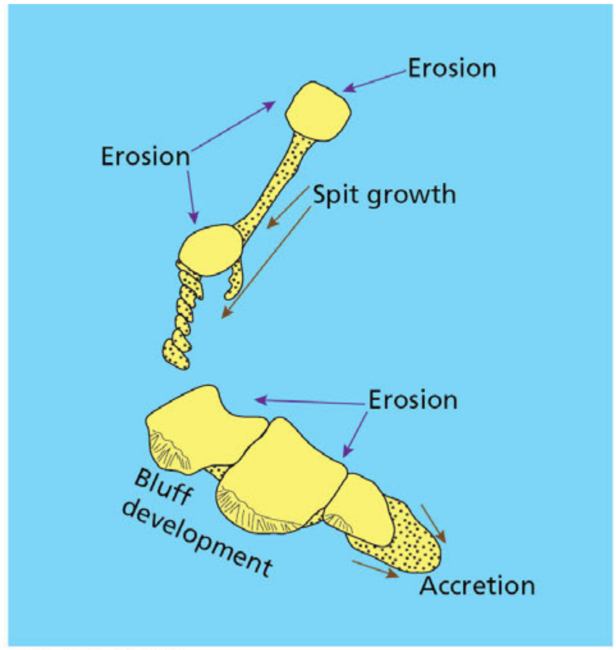
Figure 35 F–G. Schematic graphics illustrating the evolution of the Boston Harbor Islands National Recreation Area landscape, continued. Graphics are not to scale. Figure 36 shows more detail of island development and change. Graphics by Trista L. Thornberry-Ehrlich, with information from Hepburn et al. (1993), Skehan (2001), Coleman (2005), Linneman et al. (2007), Thompson et al. (2007), and Kopera (2011).

east (Skehan 2001). The area was also near the coast, and glaciers and glacial deposits develop differently depending on whether the ice was atop land or water (Kaye 1976; Tweet et al. 2010). For a time, the sea was in contact with the retreating glacier (Knebel et al. 1992). In these submarine settings, glaciomarine clay called the Boston Blue Clay was deposited across the area with significant input from rock flour–laden glacial meltwater in addition to other outwash and glaciofluvial deposits (**Qgfd**) (Knebel et al. 1992; Rosen et al. 1993; Rosen and FitzGerald 2004; FitzGerald et al. 2013). As part of an early Wisconsinan, Illinoian, or an even earlier glacial advance, a thick glacial till was deposited across Boston Harbor; it is now deeply weathered and is the "lower till" of drumlins (**Qdr**) (Newman et al. 1990; Colgan and Rosen 2001; FitzGerald et al. 2013). Erosion by an eastward-flowing, late Wisconsinan ice sheet shaped the asymmetrical cores of the Boston Harbor drumlins cutting into the weathered surface of the lower till (Newman and Mickelson 1994). At this time, sea level was approximately 20 m (60 ft) lower than present in Boston Harbor and the prominent upper till was deposited over the "drumlinized" lower till (Kaye 1978; Jones and Fisher 1990; Newman and Mickelson 1994). Deposition of the upper till occurred during the retreat of the glaciers from the harbor area, and the orientation of the drumlins (**Qdr**) changed slightly as a result of changes in ice-flow direction (Newman and Mickelson 1994).

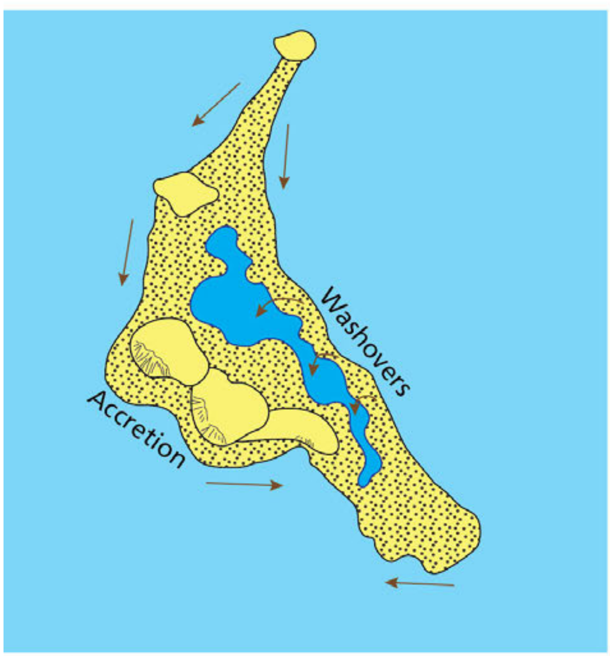
The history of sea-level change in Boston Harbor, starting with the end of the Pleistocene Epoch, is complex. The amount of water contained in continental ice sheets is immense, and glaciations coincide with global sea level lows. In general, when the ice melts, that water is released back into the oceans, and sea level rises. However, land that was previously depressed by glaciers simultaneously rises up as part of a process called "isostatic rebound." When the glaciers retreated



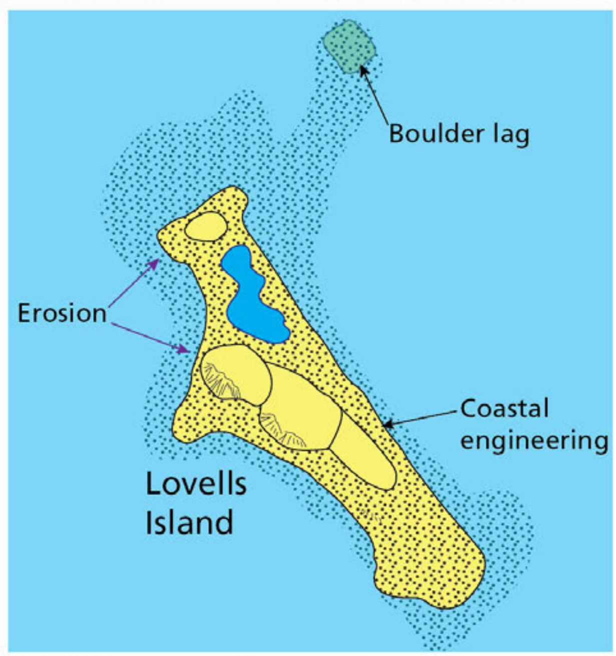
A. 5,000–4,000 years ago
Boston Harbor drumlin field was flooded, erosion of drumlins commenced, and waves and currents began to modify new shorelines.



B. 3,000–2,000 years ago
Sea level stabilized and Rams Head eroded extensively as a result of its exposure to oncoming waves. Erosion provided sediment to a mostly subtidal spit connecting with the north drumlin island. Local winds developed bluffs on the southwest side of the central drumlin complex.



C. 2,000–1,000 years ago
Erosion nearly leveled Rams Head where sediments contributed to two spits that connected the north drumlin with the central drumlin complex, enclosing a small pond and marsh system that began infilling with washover sediments. Accretion added to the southwestern side of the island.



D. 1,000 years ago to present
The north and northwest sides of the island eroded under the onslaught of storm waves. Sand was transported to the leeward side of the island. Dunes and salients developed on the southwest side of the isalnd. Steep gravel beaches formed on the eastern side of the island.

Figure 36 (facing page). Model of the evolution of Lovells Island. The story at Lovells Island is similar to the other drumlin-cored islands at Boston Harbor Islands National Recreation Area. As sea level rose, erosion of the glacial drumlins began to supply sediments for the development of coastal features. As sea level stabilized, shorelines continued to evolve and approach their modern configuration. Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich after figure 8 in Rosen and FitzGerald (2004).

from the Boston area, beginning more than 15,000 years ago, the land surface was so depressed from the incredible weight of the ice sheets that sea level was at least 22 m (72 ft) higher than its present elevation (Knebel et al. 1992; Colgan and Rosen 2001).

About 12,000 years ago, local isostatic rebound outpaced global sea level rise and caused the local relative sea level to drop about 43 m (141 ft) below present levels (Knebel and Circé 1995; Colgan and Rosen 2001). Eventually, global sea level rise began to outpace isostatic rebound, and relative sea levels rose in the Boston area. By about 10,000 years ago, sea level had risen to22 m (72 ft) below present level (Knebel et al. 1992). At this time, fluvial channels were cut into the upper glacial deposits, creating an unconformity (erosional surface); the channels subsequently filled with fluvial and estuarine sediments, creating paleochannels (Knebel et al. 1992).

During subsequent sea level rise, the harbor sediments were reworked by waves and currents (Knebel et al. 1992). By approximately 6,000 to 4,500 years ago (fig. 36A), the area was under water and collecting marine sands and muds atop the unconformity, followed by subtidal laminated muds (Knebel et al. 1992; Rosen et al. 1993; Rosen and FitzGerald 2004).

Sea level rise rates slowed considerably about 3,000 years ago, tidal flats (**Qtf**, **Qi**, **Qib**, and **Qtc**) and saltwater marshes (**Qwe**, **Qla** and **Qmp**) developed, and the drumlin shorelines began to be modified by coastal processes (figs. 36B and 35G). Sediments were moved around the shorelines forming the characteristic coastal features such as welded bars (**Qwb**), salients (**Qsa**), tombolos (**Qt**), spits (**Qsp**), overwash terraces (**Qot**), marine-reworked till (**Qmrt**), inlets (**Qi**), and intertidal bars (**Qib**) (Rosen and Leach 1987; Luedtke and Rosen 1993; Rosen et al. 1993; Hughes et al. 2010; FitzGerald et al. 2013). Paleoindian sites in and around Boston record human presence at least by the time sea level was rising 3,000 years ago (Luedtke and Rosen 1993).

Around 2,000 years ago, sea level stabilized at present-day levels in Boston Harbor (fig. 36C; Jones and Fisher 1990). Since that time, the surface sediments have been subjected to a wave and current regime similar to the present-day coastal setting (Knebel and Circé 1995). Until the last 150 years or so, sea level rise has been more or less slow and steady. Over that time period, the islands began to take on shapes and features still recognizable today (Rosen and FitzGerald 2004). From 1000 CE to the 1850s (Industrial Revolution), sea level was rising at a rate of 0.52 mm (0.02 in) per year) but is presently rising in Boston Harbor at a rate of 2.85 mm (0.11 in) per year—a significant increase (Duncan FitzGerald, Boston University, coastal geologist, written communication, 25 May 2016).

Throughout the Holocene Epoch, the tides and waves in Boston Harbor have eroded, deposited, and reworked sediments along the coastlines of the Boston Harbor Islands (fig. 36D). Wetlands contain peat deposits that date to between 860 and 840 CE. Younger deposits contain pollen and other microfossils or macrofossils that illustrate differences in flora and fauna between pre- and post-European settlement (Jones and Fisher 1990; Patterson et al. 2005). Beginning with European settlement in 1630, Boston Harbor and the islands have been significantly modified by filling of coastal wetlands, armoring shorelines, and other land use, as indicated by the presence of artificial fill (**Qaf**) on the landscape (Colgan and Rosen 2001). Today this landscape presents a setting rich in natural and cultural resources for visitors to Boston Harbor Islands National Recreation Area.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. Figures in Appendix B display the map data draped over imagery of the national recreation area and vicinity. The Map Unit Properties Tables (in pocket) summarize this report's content for each map unit. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following sources to produce the digital geologic data set for Boston Harbor Islands National Recreation Area. These sources also provided information for this report.

FitzGerald, D. M., Z. J. Hughes, and P. Rosen. 2013. Surface geomorphology map of Boston Harbor National Recreation Area (scales 1:500 and 1:200). Unpublished digital data and maps. Boston University, Boston Massachusetts.

Thompson, P. J., J. P. Kopera, and D. Solway. 2011. A report on the bedrock geology of Boston Harbor to the National Park Service (scale 1:24,000). Working draft map (8-24-2011). Massachusetts Geological Survey, Amherst, Massachusetts.

Note: The source maps do not cover all of the islands in Boston Harbor Islands National Recreation Area. Some islands have only geomorphic coverage, some islands have only bedrock coverage, some islands have both, and some islands have neither because of a lack of reported bedrock and/or inaccessibility to an island for the geomorphic mappers. See table 6 and the Ancillary Map Information Document (boha_geology.pdf) in the GRI GIS data for more information. The GRI GIS data also include combined geomorphic map units, which are areas where units (polygons) depicting different features overlapped within a confined area creating a new map polygon. The components of the combined units are separated with "+".

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list. The following components are part of the data set:

- A GIS readme file (boha_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (tables 6–8);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (boha_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- ESRI map documents (boha_geology.mxd and bhbr_geology.mxd) that display the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (tables 7 and 8).

Table 6. Map coverage for islands in Boston Harbor Islands National Recreation Area

Island/Peninsula	Geomorphic Map Coverage?	Bedrock Map Coverage?
Bumpkin Island	Yes	No (none)
Button Island	No	Yes
Calf Island	Yes	Yes
Deer island	No	No (none)
Gallops Island	No	No (none)
Georges Island	Yes	No (none)
Grape Island	Yes	Yes
The Graves	No	Yes
Great Brewster	Yes	No (unconfirmed)
Green Island	No	Yes
Hangman Island	No	Yes
Harding Ledge	No	No (unconfirmed)
Langlee Island	No	Yes
Little Brewster	Yes	Yes
Little Calf Island	No	Yes
Long Island	Yes	No (none)
Lovells Island	Yes	No (unconfirmed)
Middle Brewster	No	Yes
Moon Island	Yes	Yes
Nixes Mate	No	No (none)
Nut Island	No	Yes (none exposed?)
Outer Brewster	No	Yes
Peddocks Island	Yes	No (none)
Pig Rock	No	No (unconfirmed)
Quarantine Rocks	No	No
Raccoon Island	No	Yes
Ragged	No	Yes
Rainsford Island	Yes	Yes
Sarah Island	No	Yes
Shag Rocks	No	Yes
Sheep Island	Yes	No (none)
Slate Island	Yes	Yes
Snake Island	Yes	No (none)
Spectacle Island	No	No (none)
Sunken Ledge	No	No (unconfirmed)
Thompson Island	Yes	No (none)
Toddy Rocks	No	No
Webb Memorial Park	No	Yes
Worlds End	No	Yes

Table from Thompson et al. 2011. “unconfirmed” = unconfirmed bedrock; “none” = no reported bedrock.

GRI Map Figures

Figures of the GRI GIS bedrock and geomorphic data draped over aerial imagery of the recreation area and surrounding area are included with this report as Appendix B. Not all GIS feature classes are included on the posters (tables 7 and 8). Geographic information and selected park features have been added to the posters. Aerial imagery and added geographic information are not included in the GRI GIS data sets, but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

Map Unit Properties Tables

The Map Unit Properties Tables list the geologic time division, symbol, and a simplified description for each of the bedrock and geomorphic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales (1:200, 1:500, or 1:24,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are expected to be horizontally within 10 cm (4 in), 25 cm (4.9 in), and 12 m (40 ft), respectively, of their true locations.

Table 7. Data layers in the Boston Harbor Islands National Recreation Area Bedrock GIS data (bhbr_geology.mxd).

Data Layer	On Appendix B Figures?	Google Earth Layer?
Geologic Attitude Observation Localities	No	No
Fold Symbology	Yes	No
Folds	Yes	Yes
Faults	Yes	Yes
Geologic Line Features (bathymetric lineament)	No	Yes
Observation, Observed Extent and Trend Lines (inferred trend of bedding)	No	Yes
Deformation Area Boundaries	No	No
Deformation Areas (brecciated melt zone)	No	No
Geophysical Data Boundaries	No	No
Geophysical Data (seismic low velocity zone)	No	No
Bedrock Geologic Contacts	No	Yes
Bedrock Geologic Units	Yes	Yes

Table 8. Data layers in the Boston Harbor Islands National Recreation Area Geomorphic GIS data (boha_geology.mxd).

Data Layer	On Appendix B Figures?	Google Earth Layer?
Glacial Area Unit Boundaries	Yes	Yes
Glacial Area Units (kettles)	Yes	Yes
Geomorphic Contacts	No	Yes
Geomorphic Units	Yes	Yes

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of February 2017. Refer to Appendix C for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/geology/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Massachusetts Geological Survey: http://www.geo.umass.edu/stategeologist/
- US Geological Survey: http://www.usgs.gov/
- USGS Publications: http://pubs.er.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- Geologic names lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Boston Harbor Islands National Recreation Area, held on 12 July 2007, or the follow-up report writing conference call, held on 7 April 2015. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Marc Albert	NPS Saugus Iron Works National Historic Site and Boston Harbor Islands National Recreation Area	Natural Resource Specialist
Richard Bailey	Northeastern University	Geologist
Mark Borrelli	NPS Geologic Resources Division	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Rebecca Haney	Massachusetts Coastal Zone Management	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Chris Hepburn	Boston College	Geologist
Beth Johnson	NPS Northeast Region	Network Coordinator
Joe Kopera	Office of the Massachusetts State Geologist	Geologist
Steve Mabee	Office of the Massachusetts State Geologist	State Geologist
Peter Rosen	Northeastern University	Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Writer, Graphic Designer
Don Wise	University of Massachusetts, Amherst	Geologist
David Woodhouse	Woodhouse Geosciences	Geologist

2015 Report Kick-off Participants

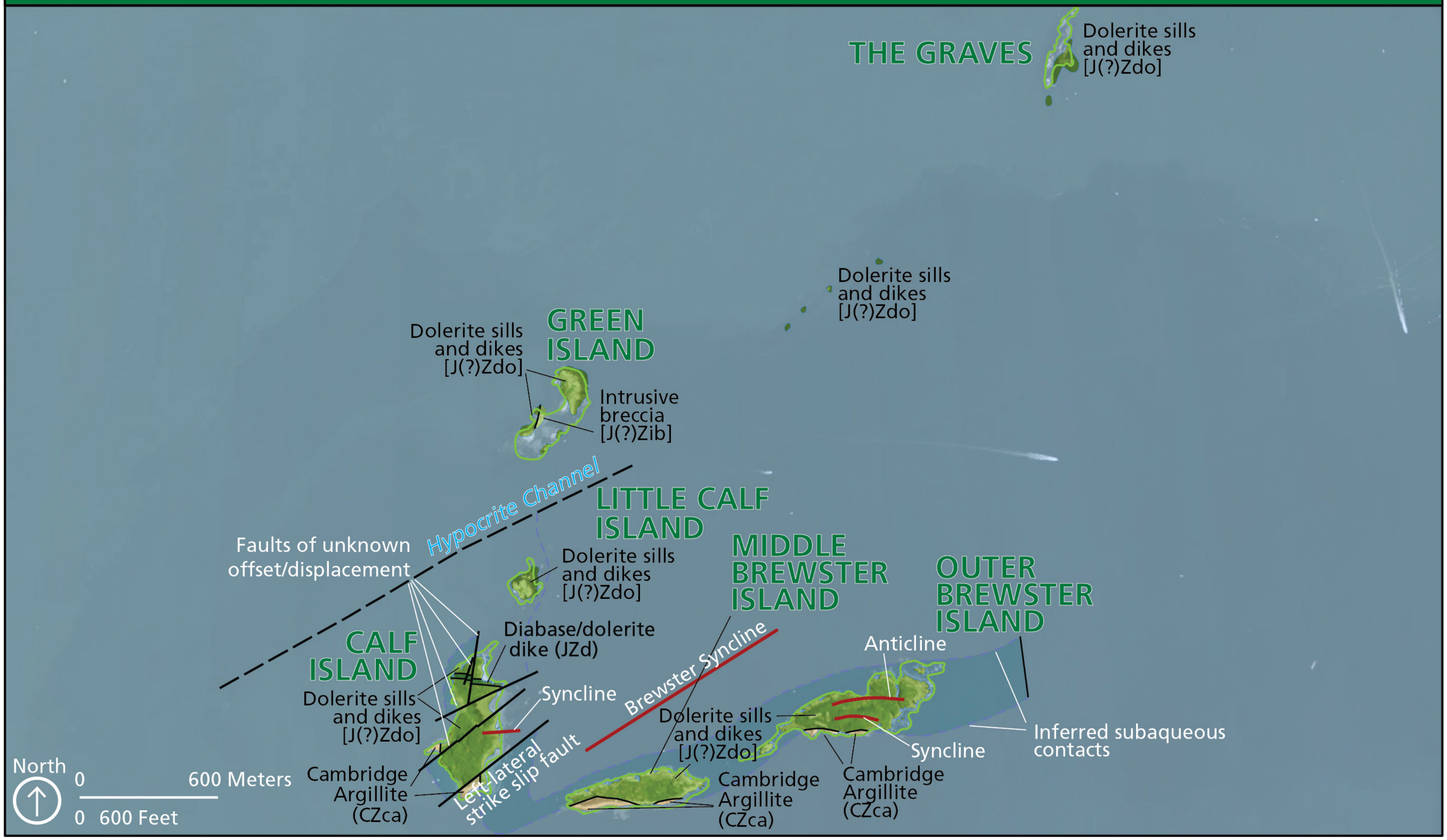
Name	Affiliation	Position
Marc Albert	NPS Saugus Iron Works National Historic Site and Boston Harbor Islands National Recreation Area	Resource Stewardship Manager
Amanda Babson	NPS Northeast Region	Oceanographer
Rebecca Beavers	NPS Geologic Resources Division	Coastal Geologist
Lynda Bell	NPS Water Resources Division	Sea-Level Specialist
Maria Caffrey	University of Colorado	Sea-Level Advisor
Tim Connors	NPS Geologic Resources Division	Geologist
Duncan FitzGerald	Boston University	Coastal Geologist
Rebecca Haney	Massachusetts CZM	Coastal Geologist
Zoe Hughes	Boston University	Coastal Geomorphologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Joe Kopera	Office of the Massachusetts State Geologist	Geologist
Peter Rosen	Northeastern University	Coastal Geologist
Peter Thompson	University of New Hampshire	Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Writer, Graphic Designer

Appendix B: GRI Geologic Map Figures

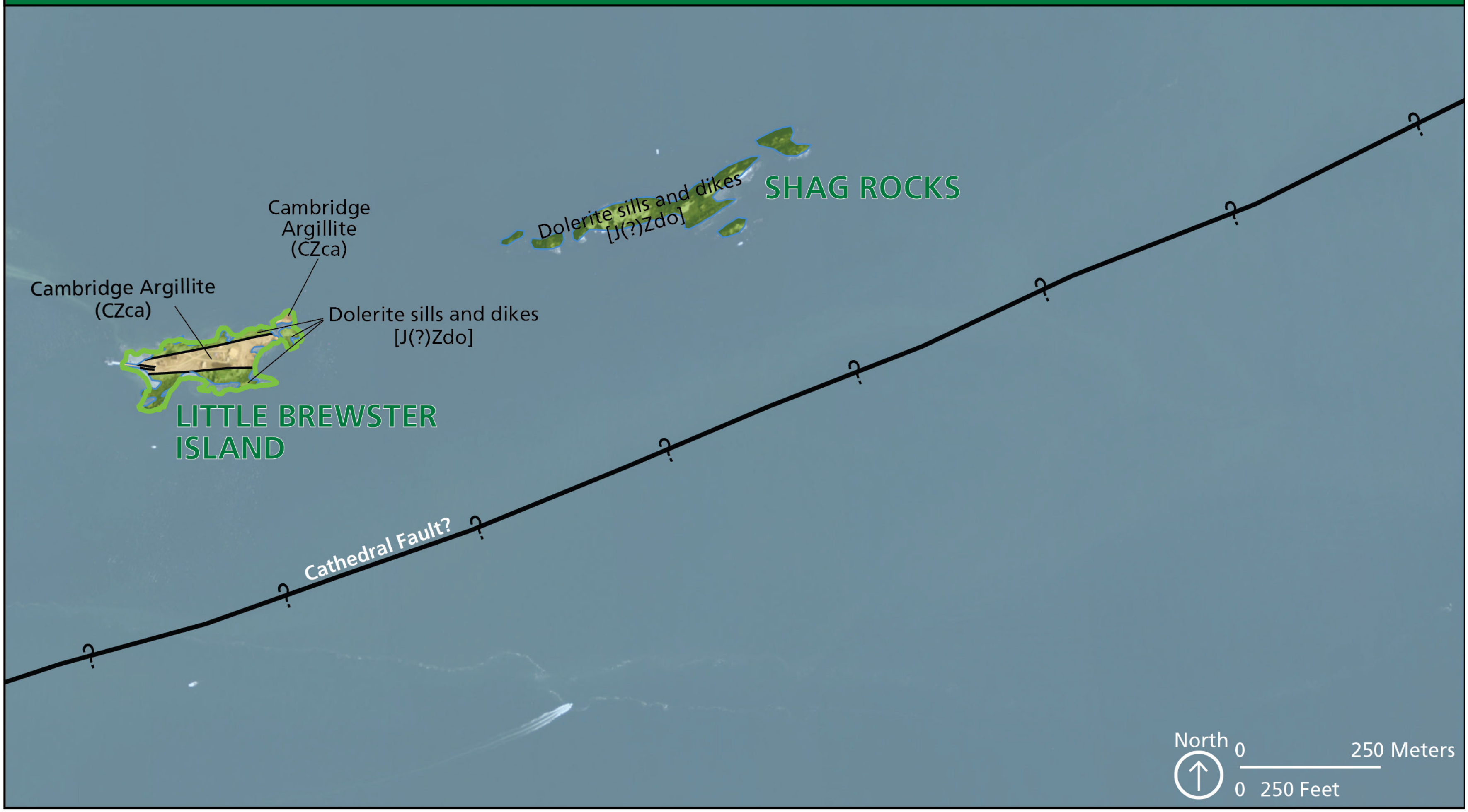
This Appendix contains maps showing bedrock and geomorphic map coverage for the islands in Boston Harbor Islands National Recreation Area. Table 6 in the Geologic Map Data section lists the map coverage available for each island. There are 7 bedrock island map figures and 13 geomorphic map figures. Extent maps for both bedrock and geomorphic data precede the map figures.

Bedrock Map Coverage and Extent of Island Maps

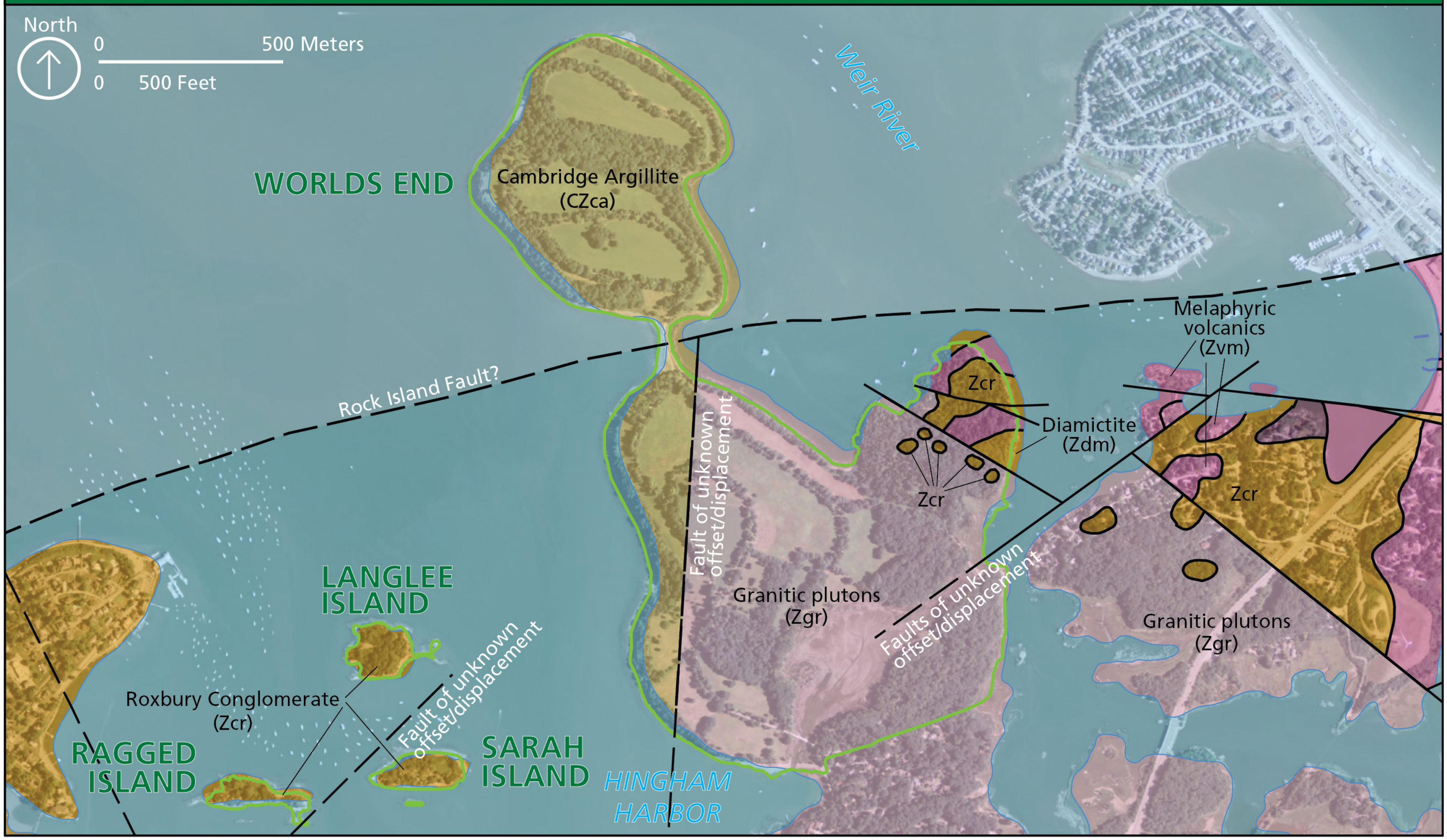
Bedrock Map 1: The Graves, Green, Little Calf, Calf, Middle Brewster, and Outer Brewster Islands



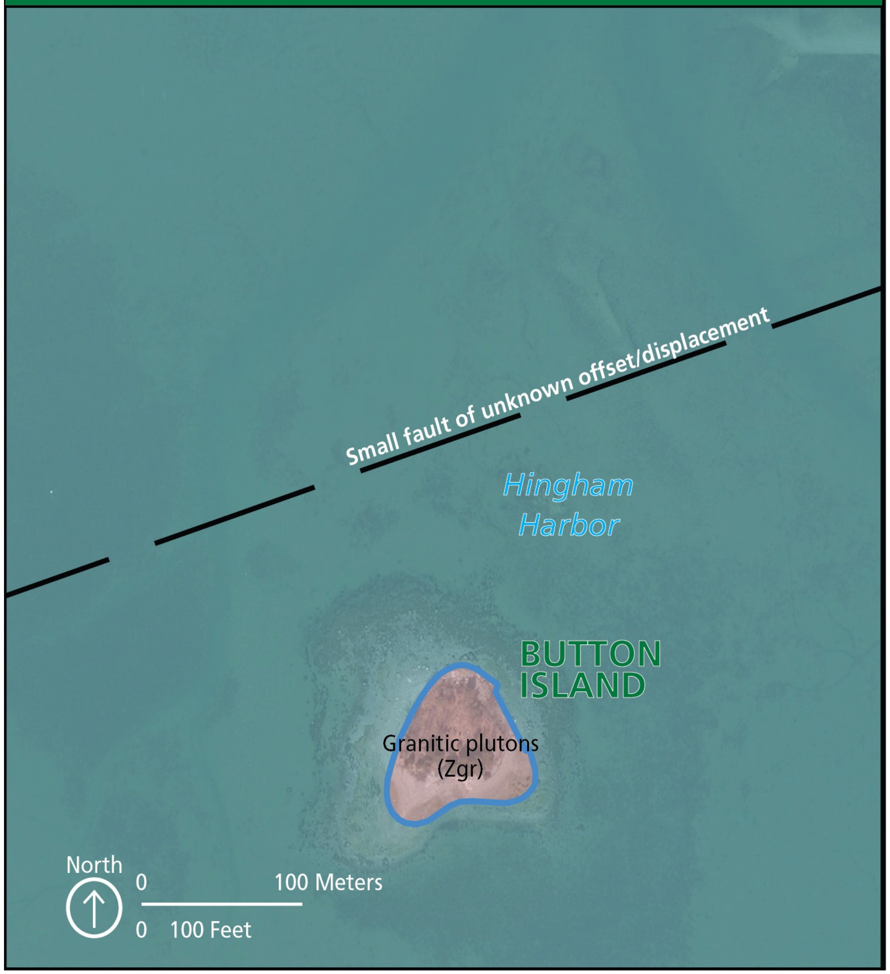
Bedrock Map 2: Little Brewster Island and Shag Rocks



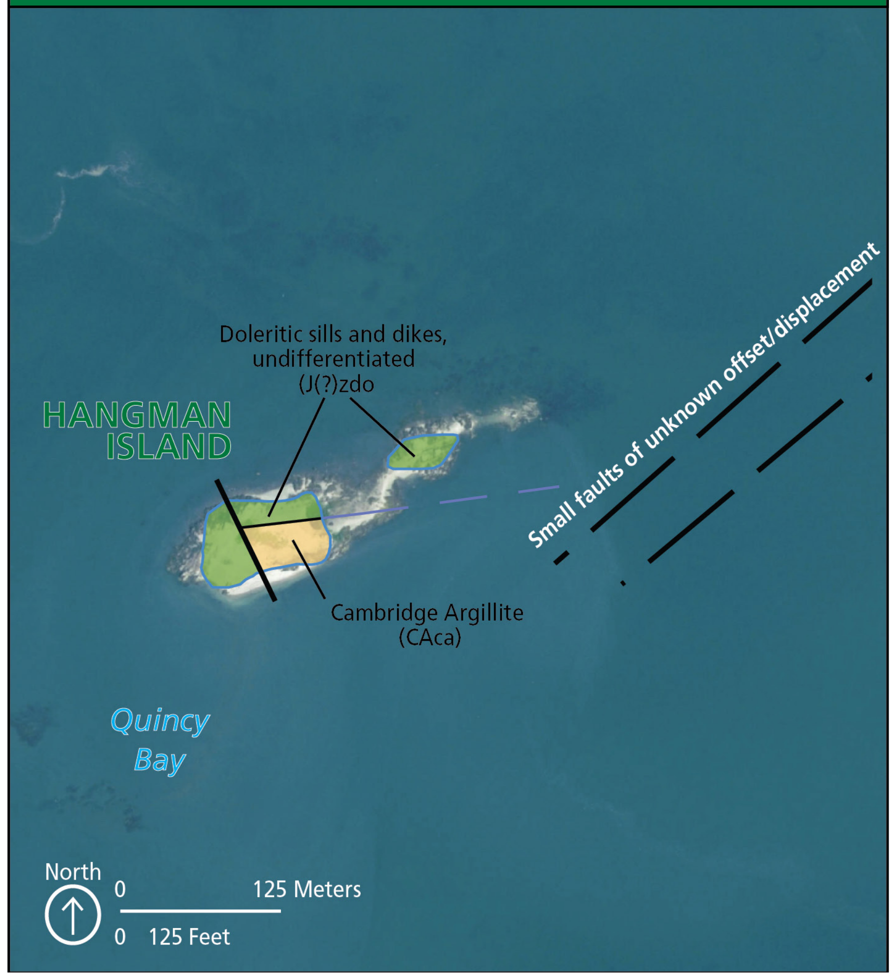
Bedrock Map 3: Worlds End, Langlee, Sarah, and Ragged Islands



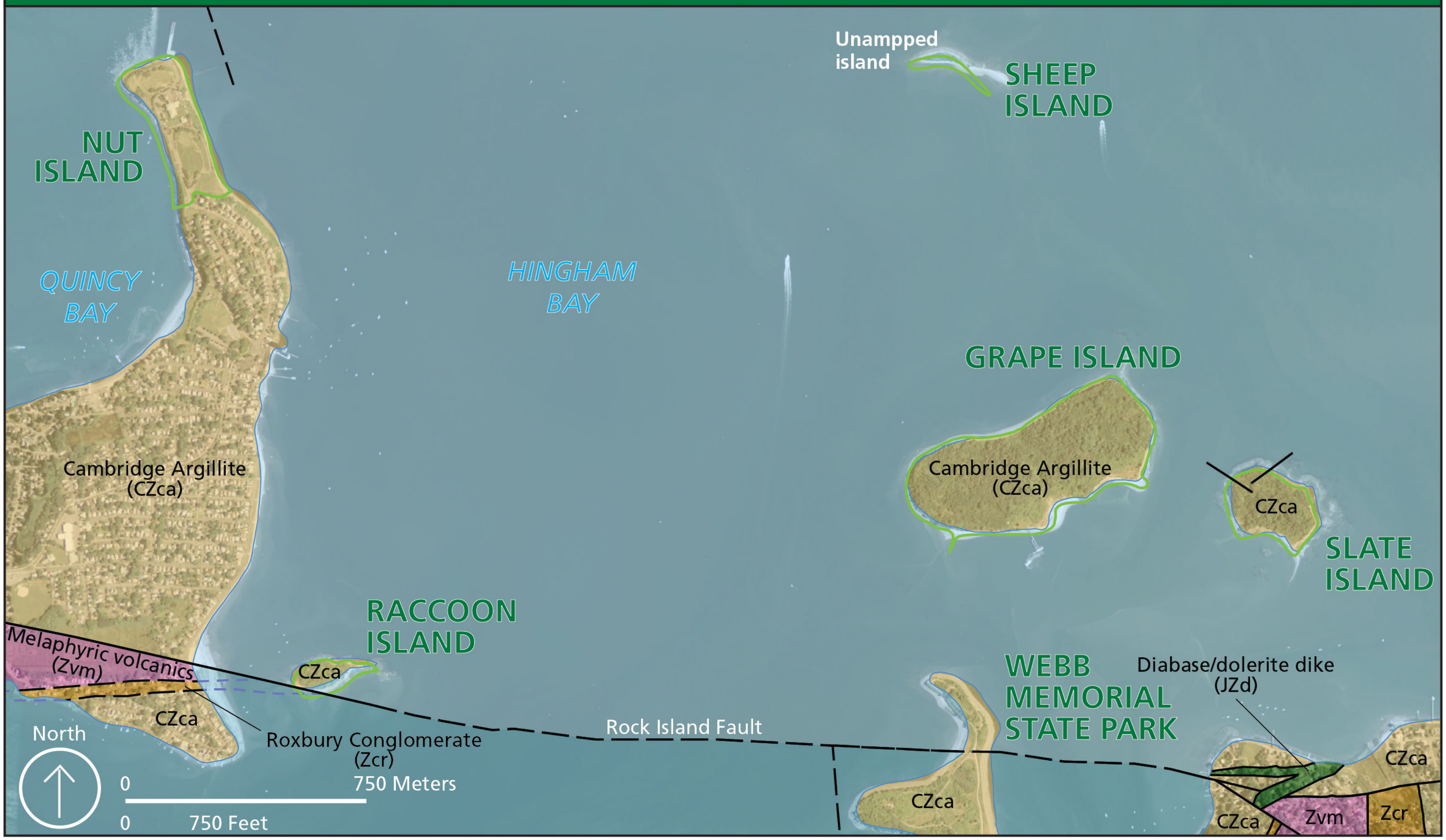
Bedrock Map 4A: Button Island



Bedrock Map 4B: Hangman Island

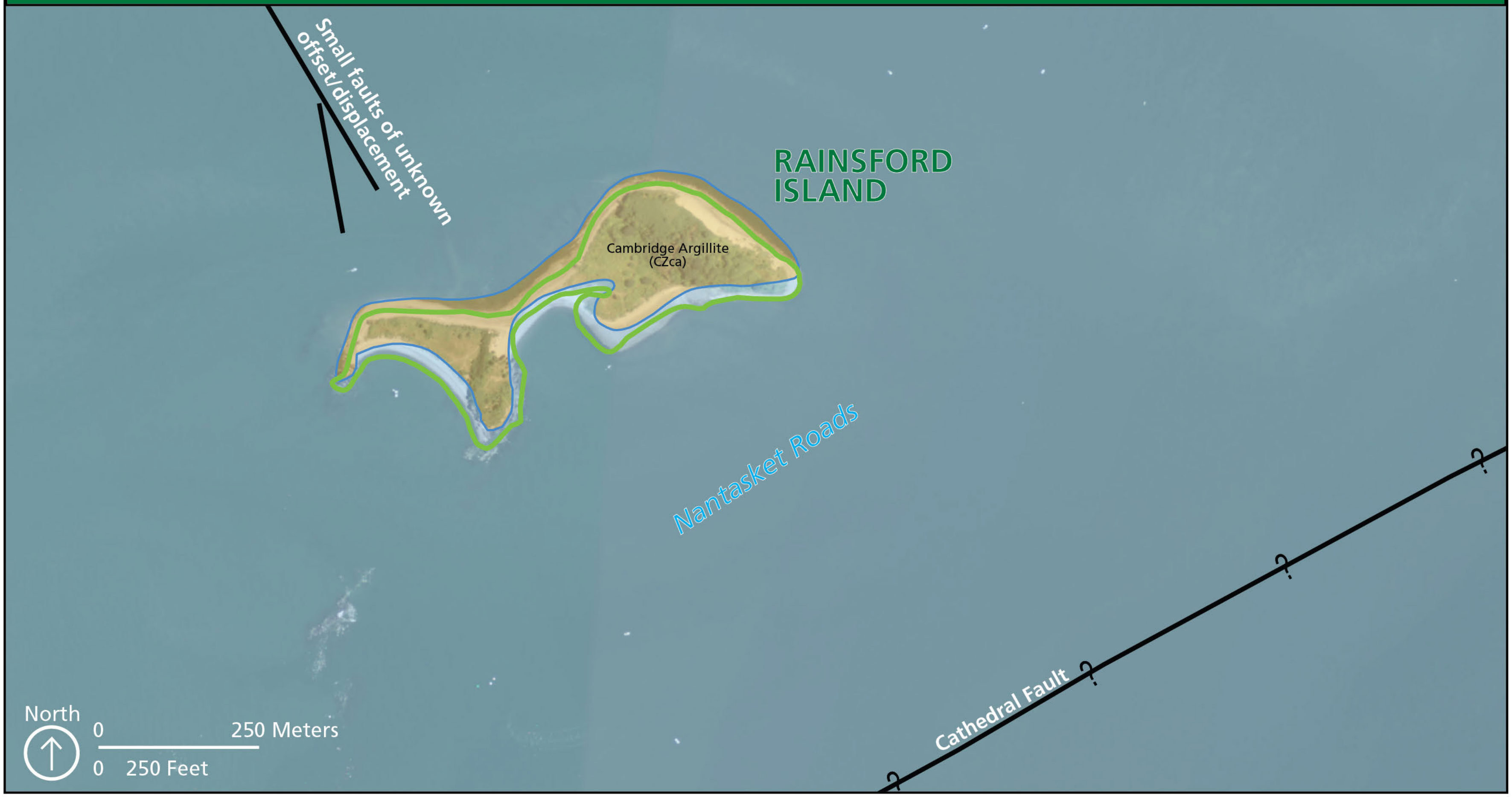


Bedrock Geologic Map 5: Webb Memorial State Park, Grape, Slate, Raccoon, and Nut Islands

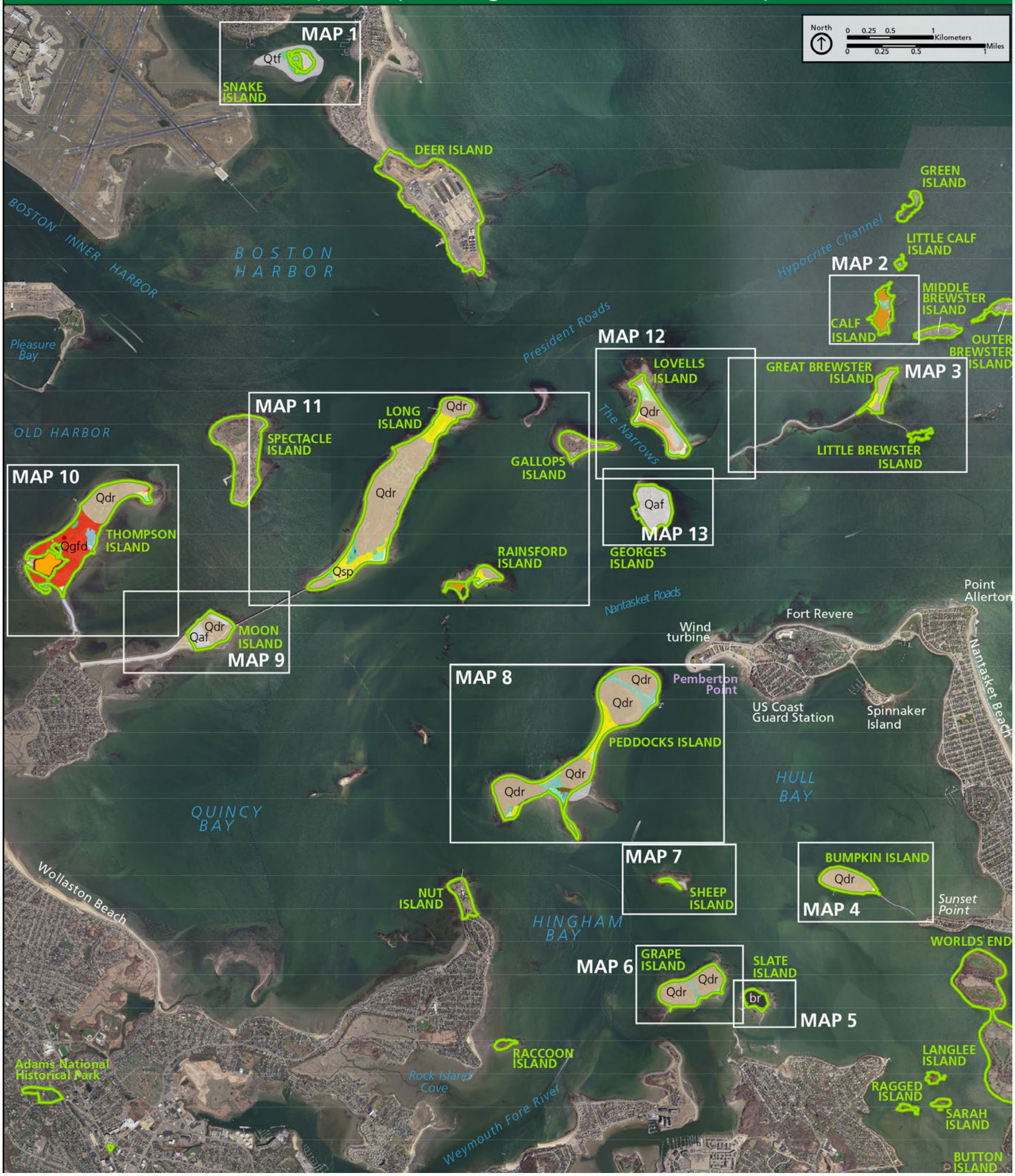


Bedrock Map 6: Moon Island

Bedrock Geologic Map 7: Rainsford Island

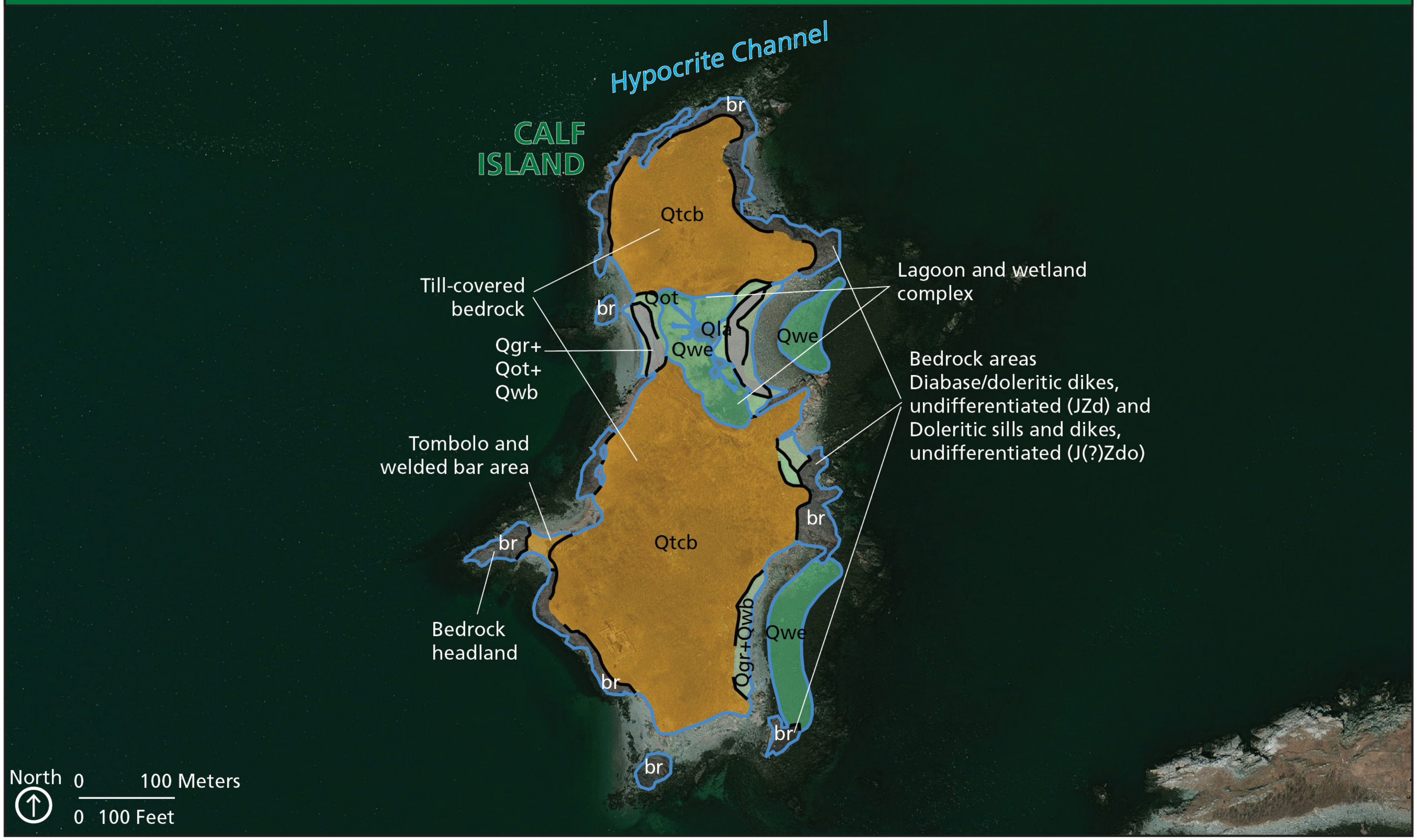


Geomorphic Map Coverage and Extent of Island Maps



Geomorphic Map 1: Snake Island

Geomorphic Map 2: Calf Island



Geomorphic Map 3: Great Brewster Island and Little Brewster Island

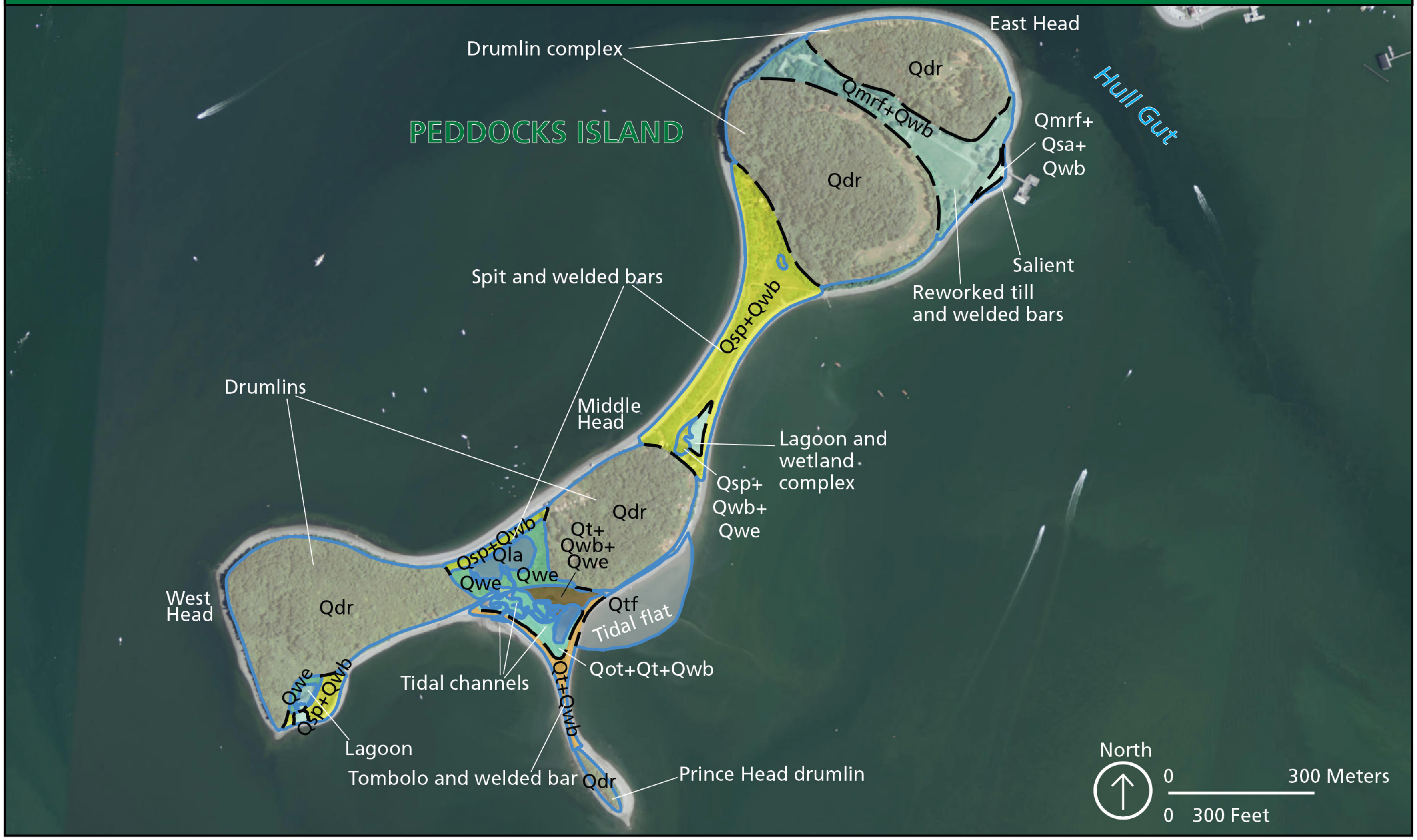
Geomorphic Map 4: Bumpkin Island

Geomorphic Map 5: Slate Island

Geomorphic Map 6: Grape Island

Geomorphic Map 7: Sheep Island

Geomorphic Map 8: Peddocks Island



Geomorphic Map 9: Moon Island

Geomorphic Map 10: Thompson Island

Geomorphic Map 11: Long and Rainsford Islands

Geomorphic Map 12: Lovells Island

Geomorphic Map 13: Georges Island

Appendix C: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2016).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by Congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089 (coral reefs) (1998)** calls for reduction of impacts to coral reefs. **Executive Order 13158 (marine protected areas) (2000)** requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), https://obamawhitehouse.archives.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

NPS 035/137021, March 2017

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U.S. Department of the Interior

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Bedrock Map Unit Properties Table: Boston Harbor Islands National Recreation Area

Gray-shaded map units are not mapped within Boston Harbor Islands National Recreation Area. Bold text refers to sections in report. Refer to the Geologic Map Data chapter for information about map coverage for each island.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MESOZOIC ERA and older	Diabase/doleritic dike, undifferentiated (JZd)	Diabase is an intrusive igneous rock with a relatively low silica content whose primary mineral constituents are labradorite and pyroxene. Dikes are igneous intrusions that cut across the fabric of the local bedrock. A large dike of **JZd** cuts across the northern end of Calf Island, otherwise, the dikes of **JZd** are relatively small.	**Bedrock Exposures**—the erosion resistance of the igneous dikes of **JZd** contributes to the longevity and relative stability of the outer islands. Intrusive features such as chilled margins, recrystallization, and cross-cutting relationships occur where **JZd** intrudes the argillite (**CZca**). **Faults**—**JZd** exposures are extensively faulted on Calf Island.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—local melting relationships (due to the presence of water, which lowered melting temperature) between **JZd** and **CZca** indicate the argillite was not completely lithified or dewatered when some of the dikes and sills intruded. Thus, some of these igneous intrusions are Neoproterozoic in age and may have formed in a plate margin, island arc, or back arc setting. **Pangaea Rifts Apart and the Appalachians Erode**—northeast-trending dikes could be Mesozoic in age as this is a common orientation for features associated with the breakup of Pangaea and the opening of the Atlantic Ocean. **JZd** is younger than **J(?)Zdo** sills and dikes.
MESOZOIC ERA and older	Intrusive breccia (J[?]Zib)	Breccia is a coarse-grained rock composed of angular, broken rock fragments held together in a fine-grained matrix. An intrusive breccia indicates explosive conditions, where the rocks mobilized and intruded into its present position along preexisting structures. The matrix material is clastic, not igneous. A deformation zone composed of **J(?)Zib** trends north to south on Green Island cutting across exposures of **J(?)Zdo**. A much smaller version occurs on Calf Island, cutting upwards into one of the **J(?)Zdo** sills.	**Bedrock Exposures**—zones of **J(?)Zib** occur within **J(?)Zdo** indicating the explosive intrusions were part of a later episode of tectonic activity. The breccia formed as a result of the intrusion of sills into water-saturated **CZca** sediment, much like the narrow zones along sills on other islands; only at Green Island, a large amount of the contact melt was mobilized to form a large breccia zone.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—**J(?)Zib** is part of a series of rocks spanning millions of years; it illustrates the long and complex history of the Avalon terrane prior to, during, and after its accretion onto North America. In particular, **J(?)Zib** records explosive volcanism during its intrusion.
MESOZOIC ERA and older	Doleritic sills and dikes, undifferentiated (J(?)Zdo)	Dikes are igneous intrusions that cut across the fabric of the local bedrock, whereas sills are intrusions that run parallel to the bedrock fabric or layering. "Dolerite" is a synonym of fine-grained diabase. **J(?)Zdo** intrudes **CZca**. **J(?)Zdo** was mapped at Calf, Little Calf, Grape, Green, Slate, Hangman, Outer Brewster, and Middle Brewster islands, as well as Shag Rocks and The Graves.	**Bedrock Exposures**—the erosion resistance of the igneous dikes and sills of **J(?)Zdo** contribute to the longevity and relative stability of the outer islands. Intrusive features such as chilled margins, recrystallization, and cross-cutting relationships occur where **J(?)Zdo** intrudes the argillite (**CZca**). Water content in the unlithified sediments of **CZca** lowered the melting temperature causing areas of melt rather than contact metamorphism during intrusion. This indicates some of the intrusions are Neoproterozoic in age. **Folds**—**J(?)Zdo** exposures are folded on Calf and Outer Brewster islands. **Faults**—**J(?)Zdo** exposures are extensively faulted on Calf Island.	**Abandoned Mineral Lands and Disturbed Lands**—diabase from **J(?)Zdo** was quarried from Outer Brewster Island. Rocks from Outer Brewster Island were used in buildings in Charlestown, Massachusetts.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—local melting relationships (due to the presence of water, which lowered melting temperature) between **J(?)Zdo** and **CZca** indicate the argillite was not completely lithified or dewatered when some of the dikes and sills intruded. Thus, some of these igneous intrusions are Neoproterozoic in age and may have formed in a plate margin, island arc, or back arc setting. **J(?)Zdo** sills and dikes are older than **JZd**.
PALEOZOIC ERA	Quincy Granite (SOqgr)	Granite is an intrusive igneous rock with relatively high silica content, rich in quartz (10% to 50%), and with more alkali feldspars than in granodiorite. Other constituents of **SOqgr** include the minerals plagioclase, muscovite, biotite, and/or hornblende. **SOqgr** was mapped on mainland Massachusetts outside of Boston Harbor Islands.	Not mapped within the national recreation area.	Not mapped within the national recreation area.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—**SOqgr** intruded the rocks of the Avalon terrane prior to its accretion onto North America but after it was separated from Gondwana.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOZOIC ERA and older	Cambridge Argillite (CZca)	Argillite is a compact rock derived from mudstone, siltstone, and/or shale that has been slightly metamorphosed, but typically lacks fissility or cleavage (though slaty cleavage does exist in **CZca** on Slate and Rainsford islands), meaning it does not break easily into layers. **CZca** is fine-grained, laminated, and gray, pale green, purplish gray, or black. It is slightly metamorphosed with some cleavage or foliation that dips southward. **CZca** is part of the Boston Bay Group along with **Zcr**. The units are interlayered somewhat with a conformable (no time gap or erosional break in deposition) contact. The lower beds of **CZca** grade out into the upper part of **Zcr**. **CZca** is more than 5,000 m (16,400 ft) thick under Boston Harbor. The rocks of **CZca** are tilted, allowing the thickness to be estimated from the bottom of **CZca** exposed in Boston to the top or youngest exposed argillite in the Brewster Islands. The argillite dominates bedrock in the central and north parts of the harbor. **CZca** was mapped at Calf, Moon, Rainsford, Hangman, Nut, Raccoon, Little Brewster, Middle Brewster, Outer Brewster, Grape, and Slate islands, as well as Webb Memorial State Park and Worlds End.	**Bedrock Exposures**—**CZca** is the primary bedrock unit in the harbor islands. The thin bedding, sorting, and fine grain size indicate **CZca** was deposited as a turbidite (i.e., settled out of suspension onto the seafloor from a turbidity current or submarine landslide). Other sedimentary features of this unit include cross-beds (inclined beds at angles to general layering; can indicate deposition by flowing water or wind), dewatering structures, and slump folds (soft-sediment deformation). An ash bed in **CZca** dates to younger than 570 million years old. **Folds**—slump and isoclinal folds occur in outcrops of **CZca** at Rainsford Island. **Faults**—an extension of the Rock Island fault cuts across **CZca** at Raccoon Island and the neck at Worlds End. **Paleontological Resources**—Precambrian microfossils (Neoproterozoic "ring fossils") exist in **CZca**. Other fossils in **CZca** elsewhere include microbial mats, *Aspidella*, and colonies of *Bavlinella* cf. *faveolata*; rocks in the national recreation area also may yield these fossils. Fossils are notable at Grape, Raccoon, and Slate islands.	**Abandoned Mineral Lands and Disturbed Lands**—slaty layers of **CZca** were quarried at Hangman and Slate islands. Quarrying of **CZca** reduced Nixes Mate to its current extent. **Paleontological Resource Inventory, Monitoring, and Protection**—Unauthorized fossil collecting may be taking place within the recreation area. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations.	**Formation of the Avalon Terrane and its Detachment from Gondwana**—the Boston Basin formed as a fault-bound depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **CZca** and **Zcr** were deposited in the Boston Basin as a sequence of continental to marine sediments filling a rift basin. **CZca** was deposited over at least 25 million years about 570 million years ago.
PALEOZOIC ERA and older	Diamictite (Zdm)	Diamictite is a pebbly to conglomeratic mudstone. Bedding structures may range from laminated to massive. **Zdm** formed by subaqueous debris flows as distinct layers (events) within the argillite (**CZca**). **Zdm** is prominent on Moon Island and was mapped at Worlds End.	**Bedrock Exposures**—pebbly, conglomeratic layers of **Zdm** occur within **CZca**.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—the Boston Basin formed as a fault-bounded depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **Zdm** was deposited as layers within **CZca** indicating a contemporaneous relationship.
PRECAMBRIAN	Roxbury Conglomerate (Zcr)	Conglomerate is a coarse-grained, clastic sedimentary rock with rounded to subangular fragments that range in size from sand to boulders. **Zcr** is part of the Boston Bay Group along with **CZca**. The members of **Zcr** contain conglomerate, melaphyric volcanics (**Zvm**), sandstone, and argillite in varying proportions. **Zcr** was mapped at Sarah, Langlee, and Ragged islands, as well as Worlds End.	**Bedrock Exposures**—**Zcr** is the other prominent sedimentary unit in the national recreation area and is coarser grained than **CZca**, indicating deposition in a higher-energy environment. **Zcr** is also referred to as "Roxbury Puddingstone" and is the state rock of Massachusetts.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—the Boston Basin formed as a fault-bounded depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **CZca** and **Zcr** were deposited in the Boston Basin as a sequence of continental to marine sediments that filled a rift basin. **Zcr** is younger than 595 million years old.
PRECAMBRIAN	Tuff (Zvt)	Tuff is a volcanic rock composed of cemented volcanic ash and lapilli (volcanic fragments between 2 and 64 mm [0.07 and 2.5 in]) in diameter) ejected from a volcano. **Zvt** was mapped at Worlds End outside the national recreation area.	Not mapped within the national recreation area.	Not mapped within the national recreation area.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—the Boston Basin formed as a fault-bounded depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **Zvm**, **Zvt**, and **Zvp** were deposited as layers within sedimentary rocks of the Boston Basin, indicating local volcanic activity coincident with sedimentation.
PRECAMBRIAN	Melaphyric volcanics (Zvm)	Unit was mapped and named based on the original description by Crosby (1893). "Melaphyric" is a now-obsolete term used to describe a dark-colored porphyritic rock composed of metamorphosed basalt embedded with feldspar crystals. **Zvm** was mapped at Worlds End.	**Bedrock Exposures**—layers of **Zvm** occur within conglomerate (**Zcr**), indicating intermittent volcanic activity during deposition.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—the Boston Basin formed as a fault-bounded depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **Zvm**, **Zvt**, and **Zvp** were deposited as layers within sedimentary rocks of the Boston Basin, indicating local volcanic activity coincident with sedimentation.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PRECAMBRIAN	Porphyritic volcanics (Zvp)	Unit was mapped based on description by Crosby (1893). "Porphyritic" refers to an igneous rock texture where phenocrysts (visible crystals) occur within an aphanitic (fine-grained, consisting of crystals that are too small to see with the naked eye) matrix. **Zvp** was mapped at Worlds End area outside park boundaries.	Not mapped within the national recreation area.	Not mapped within the national recreation area.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—the Boston Basin formed as a fault-bounded depression in the Avalon terrane when it was located at mid latitudes south of the equator, off the western coast of Gondwana. **Zvm**, **Zvt**, and **Zvp** were deposited as layers within sedimentary rocks of the Boston Basin, indicating local volcanic activity coincident with sedimentation.
PRECAMBRIAN	Granitic plutonic rocks, undifferentiated (Zgr)	**Zgr** is an example of a granitoid. The term "granitoids" refers to general bodies of intrusive igneous rocks dominated by quartz and feldspars. **Zgr** was mapped at Worlds End and Button Island.	**Bedrock Exposures**—areas of **Zgr** show visible crystals of quartz and feldspar in outcrops.	None reported.	**Formation of the Avalon Terrane and Its Detachment from Gondwana**—**Zgr** formed as igneous intrusions within the Avalon terrane and are the oldest bedrock map units.

Geomorphic Map Unit Properties Table: Boston Harbor Islands National Recreation Area

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Artificial fill (Qaf)	**Qaf** consists of imported sediments or modified glacial sediments used to develop infrastructure. Fill and/or modified glacial till are mapped on Georges, Moon, Snake, Long, Thompson, and Lovells islands.	**Boston Harbor**—**Qaf** was mapped as portions of coastal engineering structures to reduce erosion or protect certain reaches of shoreline.	**Coastal Erosion and Response to Climate Change**—mapped areas of **Qaf** are part of ongoing attempts to curb coastal erosion or protect infrastructure. Some of these structures are relevant to the history of coastal engineering. Many engineering are now obsolete. **Abandoned Mineral Lands and Disturbed Lands**—**Qaf**, which is indicative of past disturbances, composes large areas of some Boston Harbor Islands, including Georges and Spectacle islands.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qaf** is among the youngest geomorphic map units occurring on the landscape at Georges, Lovells, Long, and Moon islands. These features attest to the anthropogenic alteration of the Boston Harbor Islands landscape.
QUATERNARY	Drumlins (Qdr)	Hills of **Qdr** are mounded, spoon-shaped glacial till deposits that collected beneath an ice sheet. **Qdr** was mapped on Thompson, Moon, Long, Peddocks, Sheep, Bumpkin, Rainsford, Great Brewster, Lovells, and Grape islands.	**Sediment Supply and Island Erosion**—**Qdr** is heavily eroded by coastal processes at many island shorelines. **Qdr** provides the primary source of sediment for the surficial landforms throughout the area. **Glacial Features**—Boston Harbor is the only drowned drumlin field in the United States. Drumlins form when a glacier flows over a mass of sediment and indicate the direction of glacial flow by their long axis. **Paleontological Resources**—**Qdr** may contain foraminifera, ostracodes, bivalves, gastropods, sponges, stony corals, barnacles, crabs, worm tubes, hickory nuts, fish, reptiles, birds, dogs, deer, and other mammals. Islands with reports of fossils in surficial deposits include Calf, Deer, Georges, Great Brewster, Long, Lovells, Moon, Nut, Peddocks, and Rainsford.	**Coastal Erosion and Response to Climate Change**—bluffs of **Qdr** are retreating on northeast-facing headlands at Boston Harbor Islands and other areas facing wave energy. Bluff retreat is the subject of several ongoing efforts to determine the sediment budget and rates of shoreline change in response to sea level rise. **Paleontological Resource Inventory, Monitoring, and Protection**—Unauthorized fossil collecting may be taking place within the recreation area. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qdr** is likely Illinoian in age (800,000 to 300,000 years old). The cores of drumlins contain two glacial deposits throughout Boston Harbor.
QUATERNARY	Dune system (Qds)	**Qds** is sandy shoreline deposits in limited dunes stabilized by vegetation. Geomorphic Map Combinations—**Qds** overlaps with **Qsa**, **Qsp**, and/or **Qwb**. The largest exposure of **Qds** occurs on Lovells Island. **Qds** is also mapped as **Qds+Qsa**, **Qds+Qsp+Qwb**, and **Qds+Qsa+Qsp+Qwb** at Lovells Island. **Qds+Qsp+Qwb** is mapped on Long Island.	**Aeolian Features and Processes**—**Qds** forms as a result of aeolian (windblown) processes acting on small grains of sand.	**Loss of Aeolian Features**—areas of **Qds** are diminishing in the sediment-starved conditions at Boston Harbor Islands. Quantitative measurements of this loss will provide information for determining the system's sediment budget. Vegetation may help to stabilize these features.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qds** is part of the modern landscape formed by blowing winds sweeping small particles (winnowed from glacial deposits and reworked shoreline deposits) into dunes.
QUATERNARY	Glacio-fluvial deposits (Qgfd) Referred to as "glaciofluvial" deposits in the GRI report	**Qgfd** is glacial outwash and delta deposits of bedded sand and gravel. **Qgfd** was mapped on Thompson Island encompassing nearly half of the island area.	**Glacial Features**—meltwater, braided streams transported and deposited **Qgfd** as the glaciers retreated northward. Deltaic deposits occurred where the streams emptied into proglacial lakes or the ocean.	**Coastal Erosion and Response to Climate Change**—deposits of **Qgfd** are retreating on areas (e.g., Thompson Island) facing wave energy; rising sea level is predicted to increase shoreline erosion.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qgfd** was deposited as the glaciers were retreating leaving proglacial lakes and outwash plains in their wake.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Gravel ridge (Qgr)	**Qgr** occurs in areas of wave-built ridges consisting mostly of gravel with some coarse sand and shell fragments. **Qgr** commonly forms between two drumlins or welded to the side of a drumlin (**Qdr**). Sheltered areas behind **Qgr** may harbor marshes. Geomorphic Map Combinations—**Qgr** overlaps with **Qsa**, **Qot**, **Qsp**, and/or **Qwb**. **Qgr** was mapped on Calf and Slate islands (**Qgr+Qwb** and **Qgr+Qot+Qwb)** on Moon Island (**Qgr+Qwb**), and Lovells Island (**Qgr+Qwb** and **Qgr+Qsa+Qsp+Qwb**).	**Coastal Features**—the permeability of coarse sediment in ridges of **Qgr** allows tidal exchange with the ocean for brackish water wetlands without an inlet.	**Coastal Erosion and Response to Climate Change**—**Qgr** may form the border of small wetland and marsh areas. Permeable deposits of **Qgr** allow water to flow between the wetlands and the harbor. Rising sea level may reduce the "shelter" provided by **Qgr** to marshes.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qgr** is part of the dynamic shoreline system at Boston Harbor Islands. It began to develop about 3,000 years ago as the shorelines began to adopt their modern morphology.
QUATERNARY	Inlet (Qi)	**Qi** occurs as channels that allow water to flow between marshes or lagoons, which are sheltered behind barriers, and the open water of Boston Harbor. **Qi** was mapped on the southwestern corner of Thompson Island.	**Coastal Features**—**Qi** has distinct geomorphology and sedimentary characteristics including a main ebb channel, channel margin linear bars, swash bars and platforms, marginal flood channels, and ebb tidal deltas.	**Coastal Erosion and Response to Climate Change**—**Qi** connects wetland and lagoon areas (**Qwe**, **Qmp**, and **Qla**) to the open harbor.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qi** began to develop about 3,000 years ago.
QUATERNARY	Intertidal bar (Qib)	**Qib** was mapped as linear deposits of sediments that occur at sea level; these deposits are submerged at high tide and exposed at low tide. Two types of **Qib** exist: (1) sediment convergence sites, and (2) deposition sites with glacial till or lag cores. **Qib** extends in bars reaching offshore from Great Brewster, Bumpkin, Grape, and Thompson islands.	**Coastal Features**—**Qib** is associated with salients (**Qsa**) where sediment naturally accumulates, but also in areas where finer sediment was winnowed away by wave action or currents to leave just the coarsest portion behind as a bar.	**Coastal Erosion and Response to Climate Change**—because **Qib** is already regularly inundated by high tides, deposits of **Qib** may wash away to deeper areas or change location to areas with more sediment supply and less wave action.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qib** began to develop about 3,000 years ago.
QUATERNARY	Kettle (Qk)	**Qk** occurs as round or oblong depressions within glacial-fluvial sediment (**Qgfd**). In Boston Harbor, **Qk** occurs exclusively on Thompson Island in two areas on the southern end of the island.	**Glacial Features**—kettles formed as isolated ice blocks became buried in glacial deposits as the main glacier retreated away. Upon the ice block melting, a natural depression formed. Kettles may retain water as ponds or marshes. **Wetlands**—**Qk** is associated with freshwater (palustrine) wetlands, the least common wetland type present at the national recreation area.	None reported.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qk** formed after glaciers retreated from the area as deposits of remnant ice covered by outwash deposits.
QUATERNARY	Lagoon (Qla)	**Qla** is a body of water sheltered behind a barrier, but experiences some exchange with the open marine water of Boston Harbor. **Qla** is often associated with marshes (**Qmp**). Geomorphic Map Combinations—**Qla** overlaps with **Qt**, **Qwe**, and/or **Qwb**. **Qla** was mapped at Thompson, Peddocks, Calf, and Snake islands. **Qla+Qwe** was mapped on Long Island. **Qla+Qt+Qwb** was mapped on Peddocks Island	**Coastal Features**—**Qla** occurs with direct connections through a tidal inlet (**Qi**) at Thompson Island. **Qla** at Peddocks and Calf islands experiences minimal exchange during high tides or during storms as water overtops or percolates through the gravel barrier/ridge (**Qgr**). **Wetlands**—**Qla** is associated with estuarine wetlands, the most common wetland type present at the national recreation area.	**Coastal Erosion and Response to Climate Change**—areas of **Qla** are the subject of an ongoing study to determine if the rates of sediment accumulation on the bottoms of wetlands can keep pace with anticipated sea level rise.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qla** began to develop about 3,000 years ago.

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QUATERNARY	Marsh pond (Qmp)	**Qmp** is a shallow, water-filled depression in a marsh system that is devoid of vegetation. **Qmp** is only mapped at the southern end of Thompson Island.	**Wetlands**—**Qmp** is associated with estuarine wetlands, the most common wetland type present at the national recreation area. **Paleontological Resources**—**Qmp** may contain peat, charcoal, pollen, and/or other fossil remains. Islands with reports of fossils in surficial deposits include Calf, Deer, Georges, Great Brewster, Long, Lovells, Moon, Nut, Peddocks, and Rainsford.	**Coastal Erosion and Response to Climate Change**—areas of **Qmp** are the subject of an ongoing study to determine if the rates of sediment accumulation on the bottoms of wetlands can keep pace with sea level rise. **Paleontological Resource Inventory, Monitoring, and Protection**—Unauthorized fossil collecting may be taking place within the recreation area. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qmp** began to develop about 3,000 years ago.
QUATERNARY	Marine-reworked till (Qmrt)	Areas of **Qmrt** contain deposits of sediments in gaps between drumlins (**Qdr**). **Qmrt** typically consists of reworked older glacial sediments that accumulate to join drumlin islands together. Geomorphic Map Combinations—**Qmrt** overlaps with **Qsa** and/or **Qwb**. **Qmrt** occurs in the northern drumlin complex on Peddocks Island (**Qmrt+Qwb** and **Qmrt+Qsa+Qwb**) and at Grape Island as part of **Qmrt+Qwb**.	**Coastal Features—Qmrt** accumulates and is reworked by coastal processes such as waves, tides, and storms. **Glacial Features**—**Qmrt** contains till, deposited by glaciers. **Aeolian Features and Processes**—wind transport contributes to the accumulation of **Qmrt**.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qmrt** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qmrt** is part of the dynamic shoreline system at Boston Harbor Islands. It began to develop about 3,000 years ago as the shorelines started to adopt their modern morphologies.
QUATERNARY	Overwash terrace (Qot)	Areas of **Qot** are deposits in the lee of barriers or in the center of a salient. **Qot** consists of as layers of shell, gravel, or sand, with a shallow dip (tilted orientation) landward. Geomorphic Map Combinations—**Qot** overlaps with **Qgr**, **Qsa**, **Qt**, **Qwe**, **Qsp**, and/or **Qwb**. **Qot** occurs on Lovells and Calf islands. **Qgr+Qot+Qwb** was mapped on Calf and Slate islands. **Qot+Qsp+Qwb** was mapped at Snake and Long islands. **Qot+Qsa** was mapped on Thompson, Long, Lovells, and Grape islands. **Qot+Qwe** was mapped on Lovells Island. **Qot+Qt+Qwb** was mapped on Peddocks Island.	**Coastal Features**—**Qot** accumulates during storms when coastal processes such as waves and tides wash coarse deposits over barriers.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qot** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qot** is part of the dynamic shoreline system at Boston Harbor Islands. It began to develop about 3,000 years ago as the shorelines started to adopt their modern morphologies.
QUATERNARY	Salient (Qsa)	**Qsa** is a deposit of sediment which protrudes orthogonally from a shoreline and, depending on offshore features, commonly forms as an offshore bar or obtrusion. Geomorphic Map Combinations—**Qsa** overlaps with **Qds**, **Qgr**, **Qmrt**, **Qot**, **Qwe**, **Qsp**, and/or **Qwb**. **Qsa** occurs on Lovells, Georges, Sheep, Bumpkin, Rainsford, Slate, Grape, and Great Brewster islands, on the southern end of Thompson Island, and along the southwestern shore of Long Island. **Qds+Qsa,** and **Qds+Qsa+Qsp+Qwb,** and **Qgr+Qsa+Qsp+Qwb** were mapped at Lovells Island. **Qmrt+Qsa+Qwb** was mapped in the northern drumlin complex on Peddocks Island. **Qot+Qsa** was mapped on Thompson, Long, Lovells, and Grape islands. **Qsa+Qwe** was mapped on Thompson Island. **Qsa+Qsp+Qwb** was mapped on Lovells Island.	**Coastal Features**—**Qsa** accumulates as coastal processes such as longshore currents converge and drop their sediment loads. Where shallow platforms exist offshore, salient form an associated offshore bar. If deep channels exist offshore, the salient is limited to an obtrusion from the shore.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qsa** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qsa** is part of the dynamic shoreline system at Boston Harbor Islands. It began to develop about 3,000 years ago as the shorelines started to adopt their modern morphologies.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Spit (Qsp)	Deposits of **Qsp** are long, linear accumulations of sand and gravel that extend offshore from a curving shoreline. In Boston Harbor, spits form on both sides of a drumlin (**Qdr**) or in the sheltered space between two drumlins (or bedrock islands). They may eventually link the two islands. Geomorphic Map Combinations—**Qsp** overlaps with **Qds**, **Qgr**, **Qot**, **Qwe**, **Qsa**, and/or **Qwb**. **Qsp** was mapped at Long Island. **Qsp+Qwb** was mapped at Thompson, Lovells, Great Brewster, Peddocks, Long, Rainsford, and Snake islands. **Qsp+Qwb+Qwe** was mapped at Peddocks Island. **Qds+Qsp+Qwb** was mapped on Long Island. **Qds+Qsp+Qwb, Qds+Qsa+Qsp+Qwb,** and **Qgr+Qsa+Qsp+Qwb** were mapped at Lovells Island. **Qsa+Qsp+Qwb** was mapped at Lovells Island.	**Coastal Features**—**Qsp** accumulates as coastal processes such as longshore currents transport sediment along shorelines. Wave characteristics determine the direction of progradation (growth), whereas the dominant approach of wave energy determines the orientation. Overwash may fill in the lower-lying area between spits to create a linear island. **Aeolian Features and Processes**—wind transport contributes to the accumulation of **Qsp**.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qsp** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qsp** is part of the dynamic shoreline system at Boston Harbor Islands. It began to develop about 3,000 years ago as the shorelines started to adopt their modern morphologies.
QUATERNARY	Tombolo (Qt)	**Qt** is a sand or gravel spit (**Qsp**) formed in the lee of a topographic high (e.g., bedrock outcrop [**br**] or drumlin [**Qdr**]). Geomorphic Map Combinations—**Qt** overlaps with **Qla**, **Qtc**, **Qot**, **Qwe**, and/or **Qwb**. **Qla+Qt+Qwb** was mapped at Peddocks Island. **Qt+Qwb** was mapped at Calf, Peddocks, Grape, and Rainsford islands. **Qot+Qt+Qwb**, **Qt+Qtc+Qwb**, and **Qt+Qwb+Qwe** was mapped at Peddocks Island.	**Coastal Features**—**Qt** accumulates where coastal processes such as longshore currents are interrupted, causing the sediment load to be dumped and resulting in bar formation that grows outward from the mainland to connect with an island.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qt** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qt** began to develop about 3,000 years ago as the shorelines started to adopt their modern morphologies.
QUATERNARY	Tidal channels (Qtc)	**Qtc** occurs as channels within marshes (**Qmp**) or lagoon (**Qla**) systems that accommodate tidal water flow. Geomorphic Map Combinations—**Qtc** overlaps with **Qt** and/or **Qwb**. **Qtc** was mapped at Thompson and Calf islands. **Qt+Qtc+Qwb** was mapped at Peddocks Island.	**Coastal Features**—**Qtc** are the flow ways for water between the open harbor and sheltered wetlands (**Qwe**), marsh ponds (**Qmp**), and lagoons (**Qla**).	None reported.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qtc** began to develop about 3,000 years ago.
QUATERNARY	Till-covered bedrock (Qtcb)	**Qtcb** refers to glacial sediments (e.g., till) deposited over an obvious bedrock core. Two different tills where deposited across Boston Harbor: (1) an older till which formed drumlins (**Qdr**), and (2) a younger deposit than mantles the previous deposits. The younger sequence includes thin, discontinuous deposits of glacial drift (material transported and deposited by a glacier) consisting of gravel, sand, and till. **Qtcb** was mapped at Calf and Rainsford islands.	**Glacial Features**—**Qtcb** preserves two distinct glacial depositional episodes resulting in drumlins from an older glaciation buried in part by deposits from a younger glaciation. **Paleontological Resources**—**Qtcb** may contain foraminifera, ostracodes, bivalves, gastropods, sponges, stony corals, barnacles, crabs, worm tubes, hickory nuts, fish, reptiles, birds, dogs, deer, and other mammals. Islands with reports of fossils in surficial deposits include Calf, Deer, Georges, Great Brewster, Long, Lovells, Moon, Nut, Peddocks, and Rainsford.	**Paleontological Resource Inventory, Monitoring, and Protection**—Unauthorized fossil collecting may be taking place within the recreation area. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qtcb** as the cores of drumlins (**Qdr**) is likely Illinoian in age (800,000 to 300,000 years old). The younger drift was deposited in late Wisconsinan time (as much as 15,000 years before present).
QUATERNARY	Tidal flat (Qtf)	**Qtf** is composed of fine sediment that occurs in large, flat intertidal platforms. **Qtf** was mapped at Snake, Thompson, and Peddocks islands.	**Coastal Features**—**Qtf** accumulates as tides wash sediment in and out across a relatively level surface. **Wetlands**—**Qtf** is associated with estuarine and marine wetlands.	**Coastal Erosion and Response to Climate Change**—locations and morphology of **Qtf** will be impacted by rising sea level.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qtf** began to develop about 3,000 years ago.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Welded bar (Qwb)	**Qwb** is a spit (**Qsp**), tombolo (**Qt**), or gravel ridge (**Qgr**) that has welded to headlands at both ends, in essence binding the two headlands (i.e., drumlins or islands) together. Geomorphic Map Combinations—**Qwb** overlaps with **Qds**, **Qgr**, **Qsa**, **Qla**, **Qt**, **Qtc**, **Qmrt**, **Qot**, **Qwe**, and/or **Qsp**. **Qwb** was mapped at Rainsford Island. **Qds+Qsp+Qwb** was mapped at Long and Lovells islands. **Qds+Qsa+Qsp+Qwb**, **Qgr+Qsa+Qsp+Qwb**, and **Qsa+Qsp+Qwb** were mapped at Lovells Island. **Qgr+Qwb** was mapped at Calf, Lovells, Moon, and Slate islands **Qgr+Qot+Qwb** was mapped at Calf and Slate Islands. **Qmrt+Qwb** was mapped at Grape Island. **Qot+Qt+Qwb** was mapped at Peddocks Island. **Qsp+Qwb** was mapped at Thompson, Lovells, Great Brewster, Peddocks, Long, Rainsford, and Snake islands. **Qmrt+Qwb** and **Qmrt+Qsa+Qwb** were mapped in the northern drumlin complex on Peddocks Island. **Qla+Qt+Qwb**, **Qsp+Qwb+Qwe**, **Qt+Qtc+Qwb**, **Qot+Qt+Qwb**, and **Qt+Qwb+Qwe** are mapped at Peddocks Island.	**Coastal Features**—**Qwb** accumulates between headlands such as drumlins to an extent as to coalesce or join them, forming a new island.	None reported.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qwb** began to develop about 3,000 years ago as the modern shoreline morphology started to take shape.
QUATERNARY	Wetlands (Qwe)	**Qwe** occurs as vegetated areas that are constantly or nearly inundated with water (fresh, brackish, or salt). Geomorphic Map Combinations—**Qwe** overlaps with **Qt**, **Qla**, **Qot**, **Qsa**, **Qsp**, and/or **Qwb**. **Qwe** was mapped at Bumpkin, Peddocks, Long, Slate, Grape, Great Brewster, Calf, Snake, and Thompson islands. **Qla+Qwe** was mapped on Long Island. **Qot+Qwe** was mapped on Lovells Island. **Qsa+Qwe** was mapped on Thompson Island. **Qsp+Qwb+Qwe** and **Qt+Qwb+Qwe** were mapped at Peddocks Island.	**Wetlands**—**Qwe** includes salt marshes formed either at embayments or fringing the beach. Brackish to fresh fringing marshes may have originated as salt marshes in low-lying areas behind welded bars (**Qwb**). As the barrier widened and accumulated vertically, the exchange with the saltwater decreased. When the water chemistry changes sufficiently, transitional vegetation such as *Phragmites* can flourish. **Qwb** is associated with marine and estuarine wetland types at the national recreation area. **Paleontological Resources**—**Qwe** may contain peat, charcoal, pollen, and/or other fossil remains. Islands with reports of fossils in surficial deposits include Calf, Deer, Georges, Great Brewster, Long, Lovells, Moon, Nut, Peddocks, and Rainsford.	**Coastal Erosion and Response to Climate Change**—areas of **Qwe** are the subject of an ongoing study to determine if the rates of sediment accumulation on the bottoms of wetlands can keep pace with anticipated sea level rise. **Paleontological Resource Inventory, Monitoring, and Protection**—Unauthorized fossil collecting may be taking place within the recreation area. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**Qwe** contains pollen and peat that date to between 860 and 840 CE. Charcoal deposits record pre- and post-European settlement conditions. **Qwe** began to develop about 3,000 years ago.
Pre-QUATERNARY	Bedrock (br)	**br** refers to significant bedrock outcrops occurring at the shoreline both at high tide or for the majority of a tidal cycle. **br** was mapped on Calf, Slate, Rainsford, and Little Brewster islands. Bedrock was also mapped on Button, Grape, Green, Hangman, Langlee, Middle Brewster, Moon, Outer Brewster, Raccoon, Ragged, and Sarah islands, and The Graves. See Bedrock Map Unit Properties Table for more information.	**Coastal Features**—**br** occurs where coastal processes have scoured away or not deposited any sedimentary surficial cover.	See Bedrock Map Unit Properties Table.	**Ongoing Weathering, Glaciations, and Modern Landform Development**—**br** forms areas that were gouged or scraped by glacial ice, but either not covered by glacial deposits, or if covered, the mantling sediments have been eroded away. Bedrock ages range from as old as Precambrian (Neoproterozoic; ~600 million years old) to as young as Jurassic (145 million years old).